# NETL's ARRA Site Characterization Initiative: *Accomplishments*


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U.S. DEPARTMENT OF ENERGY | the ENERGY lab
National Energy Technology Laboratory

# NETL's ARRA Site Characterization Initiative: *Accomplishments*

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# TERMS AND ABBREVIATIONS

| **Term** | **Definition** |
|---|---|
| 2-D, 3-D | two-, three-dimensional |
| AAPG | American Association of Petroleum Geologists |
| AoR | area of review |
| ARRA | American Recovery and Reinvestment Act of 2009; Recovery Act |
| bgs | below ground surface |
| bbl | barrel, unit of volume (1 oil barrel = 42 U.S. gallons) |
| bbl/d/psig | barrels per day per pounds per square inch, gage |
| BPM | best practices manual |
| CBL | cement bond log |
| CCRP | Clean Coal Research Program (DOE/NETL) |
| CCS | carbon capture and storage |
| CCUS | carbon capture, utilization, and storage |
| Containment | Retention of injected $CO_2$ within the subsurface formation |
| $CO_2$ | carbon dioxide |
| $CO_2$-EOR | carbon dioxide-enhanced oil recovery |
| $CO_2$-PENS | $CO_2$-Predicting Engineered Natural Systems: quantitative, hybrid system process model, developed at LANL |
| DEM | digital elevation model |
| DFN | discrete fracture network |
| DGF | digital grouped formation |
| DOE | U.S. Department of Energy |
| ECBM | enhanced coalbed methane recovery |
| $ECO_2N$ | Fluid properties module for use with the TOUGH2 simulator to simulate geologic storage of $CO_2$ in saline aquifers, developed at LBNL |
| EPA | U.S. Environmental Protection Agency |
| EOR | enhanced oil recovery |
| FE | DOE Office of Fossil Energy |
| FEHM | Finite Element Heat and Mass Transfer Code, developed at LANL |
| FEPs | features, events, and processes (used in risk analysis) |
| FMI log | Fullbore Formation Microimager log (Schlumberger) |
| GHG | greenhouse gas |
| GIS | geographic information system |
| GLRM | graphical leakage risk matrix |
| graben | An elongate fault block that has been lowered relative to surrounding features as a direct result of faulting |
| Gt | gigatonnes (billion metric tons) |
| HR3D | high-resolution 3-D seismic imaging |
| IBDP | Illinois Basin Decatur Project |
| In Salah | Carbon storage project in Algeria |
| Isopach | A contour connecting points of equal thickness, displaying true stratigraphic thickness (e.g., of tilted strata) rather than true vertical thickness |
| KGS | Kansas Geologic Survey (also Kentucky Geologic Survey) |
| Knox Group | A geologic group in the southeastern United States containing frequent thick-bedded dolomites and limestones |
| KYCCS | Kentucky Consortium for Carbon Storage |
| LANL | Los Alamos National Laboratory |
| LAS | log ASCII standard (data format) |
| LBNL | Lawrence Berkeley National Laboratory |
| LLNL | Lawrence Livermore National Laboratory |
| Ma | million years ago |
| mD | millidarcy (a unit of permeability) |
| Miocene | The first geological epoch of the Neogene Period, from about 23 million years ago (Ma) to over 5 Ma |
| Moxa Arch | A geologic arch underlying part of southwestern Wyoming |
| MSHA | U.S. Mine Safety and Health Administration |
| MVA | monitoring, verification, accounting, and assessment |

| | |
|---|---|
| NATCARB | National Carbon Storage program |
| NETL | National Energy Technology Laboratory |
| P10, P50, P90 | Probability estimates (subscripts indicate probability (in percent) that actual value does not exceed the given value) |
| P-cable | proprietary HR3D offshore seismic imaging platform (Geometrics) |
| Petrasim | pre-processor for geologic simulation |
| Pliocene | Second and final epoch of the Neogene Period, from more than 5 to 2.58 Ma |
| PNNL | Pacific Northwest National Laboratory |
| QRDAT | Quantitative Risk & Decision Analysis Tool (Geomechanics Technologies) |
| R&D | research and development |
| RCSP | Regional Carbon Sequestration Partnership |
| RIC | NETL's Research Innovation Center |
| RMS | root-mean-square, a method of averaging used in statistics and engineering |
| RSU | Rock Springs Uplift |
| Sleipner | Norwegian offshore gas field, site of a carbon storage project |
| SPE | Society of Petroleum Engineers |
| SPEE | Society of Petroleum Evaluation Engineers |
| TDS | total dissolved solids |
| TOUGH2 | Simulation program for non-isothermal, multiphase flow in unfractured and fractured media that was developed at LBNL |
| TOUGHREACT | Simulation program for non-isothermal, multiphase flow in unfractured and fractured media with reactive geochemistry that was developed at LBNL |
| twtt | two-way travel time for seismic reflection |
| UBD | underbalanced drilling |
| UIC | Underground Injection Control, an EPA regulatory framework for $CO_2$ injection wells |
| USDW | underground source of drinking water |
| UT-Austin | University of Texas at Austin |
| VSP | vertical seismic profile |
| WPC | World Petroleum Council |
| WY-CUSP | Wyoming Carbon Underground Storage Project |

# EXECUTIVE SUMMARY

The availability of clean, affordable fossil fuels is essential for domestic and global prosperity and security well into the 21st century. However, a balance between energy security and concerns regarding the impact of increasing concentrations of greenhouse gases (GHGs) —particularly carbon dioxide ($CO_2$)—in the atmosphere is needed.

NETL's Storage Program is developing a portfolio of safe, cost-effective $CO_2$ storage technologies that will be available for commercial deployment beginning in 2025. Developing technologies that advance the goals of the Storage Program will help drive carbon capture and storage (CCS) toward commercialization. The deployment of technologies developed and validated by the Storage Program will also help to reduce GHG emissions to the atmosphere; improve production of additional domestic oil and gas resources through enhanced recovery operations using anthropogenic $CO_2$; reduce operating and maintenance costs of storage facilities; and reduce the environmental footprint of storage operations by maximizing reservoir efficiency.

NETL's Storage Program received approximately $100 million from the American Recovery and Reinvestment Act of 2009 (ARRA). These funds were distributed among nine projects with a focus on characterizing high-priority formations that have potential for future commercial-scale geologic $CO_2$ storage. The formations studied are representative of different depositional environments and geologic settings that have significant potential for carbon storage. The projects targeted not only the development of individual sites for carbon storage, but also the regional characterization of distinct high-potential geologic formations. Characterizing these formations provides greater insight into the capabilities of similar geologic formations across the United States to safely and permanently store $CO_2$. Knowledge gained from these efforts may be applied to similar settings with potential for carbon storage and, thus, contribute valuable information for future commercial-scale carbon storage projects within the study areas. In addition, baseline subsurface conditions must be characterized and subsurface response to injection of large quantities of $CO_2$ must be assessed as part of the U.S. Environmental Protection Agency's (EPA) Underground Injection Control (UIC) Class VI regulatory framework. Class VI permits are required prior to any $CO_2$ injection in the United States that is part of a carbon storage project. These characterization data contribute to the development of best practices for safe, long-term storage of $CO_2$.

The nine ARRA projects investigated deep geologic storage of $CO_2$ in onshore and offshore formations in the following locations:

- Wilmington Graben, Los Angeles Basin (California offshore)
- Newark Basin (New Jersey, Pennsylvania, New York)
- South Georgia Rift Basin (South Carolina, Georgia)
- Illinois and Michigan basins (Illinois, Indiana, Kentucky, Michigan)
- Black Warrior Basin (Alabama)
- Ozark Plateau Aquifer System (Kansas)
- Miocene-age resources (Texas offshore)
- Rocky Mountain Region (Colorado, Utah, Arizona, New Mexico)
- Rock Springs Uplift and Moxa Arch (Wyoming)

This document presents the accomplishments of the ARRA Site Characterization Initiative as they relate to the Office of Fossil Energy's (FE) Storage Program goals and, in particular, support for prediction of $CO_2$ storage capacity in geologic formations to within ±30 percent, and development of best practices related to site screening, selection, and initial characterization. A schema based in part on the NETL-developed document titled *Best Practices for Site Screening, Site Selection, and Initial Characterization for Storage of $CO_2$ in Deep Geologic Formations* was adopted to assist in correlating key project achievements and highlights as a means of unifying and summarizing accomplishments. The schema is based on critical components needed for geologic site characterization and includes the following categories: Test wells, core, and log data analysis; seismic data acquisition and processing; prospective reservoir $CO_2$ storage capacity assessment; containment and stratigraphic analysis; modeling and simulation efforts; risk assessment; and outreach and education. Key highlights and important findings from each of the nine characterization studies are presented for each component of the schema mentioned above. Information obtained in this way helps NETL/DOE assess the impact these nine projects have had on confirming $CO_2$ storage resources throughout the United States and should help in deciding where to invest future research and development efforts to meet Storage Program and DOE's Office of Fossil Energy goals. Industrial and academic stakeholders can use the lessons learned from these research efforts to develop CCS projects at both pilot and commercial scales.

A major objective of the ARRA Site Characterization Initiative was to develop comprehensive data sets of geologic properties (porosity, permeability, injectivity, reservoir architecture, caprock integrity, etc.) of formations of interest for carbon storage, and to augment existing large data sets through coordination with the National Carbon Sequestration Database and Geographic Information System (NATCARB) database and through participation in technical working groups on best practices for site characterization and storage site selection. These projects are also intended to determine the usefulness of specific geologic storage sites, develop best practices for characterization of such sites, and classify the depositional environments of various formations known to have excellent reservoir properties and amenable to geologic $CO_2$ storage. Lessons learned from monitoring the behavior of $CO_2$ in reservoirs during previous geologic investigations and the correlation of this behavior to the known depositional environment is important when considering similar depositional environments as possible storage sites. This knowledge enables the development of models to predict the behavior of $CO_2$ within storage reservoirs without having to duplicate the full effort expended by the original projects.

DOE has embarked on geologic characterization and classification of depositional environments through the Regional Carbon Sequestration Partnerships (RCSPs), which gathered data across the United States and parts of Canada on strata with large storage volume potential and published it in the *U.S. Department of Energy's Carbon Storage Atlas* (currently in its fifth edition and referred to as *Atlas V*). These new data from *Atlas V* are integrated into the NATCARB database and are available for use by various stakeholders. However, additional work is needed to qualify specific potential commercial storage sites with sufficient size and satisfactory geology and pressure characteristics to contain the area of elevated pressure and the active and ultimate plume of injected $CO_2$. It is also necessary to have the ability to handle multiple injection wells. The ARRA Site Characterization projects have spearheaded an effort to address data gaps and provide additional information to assist in locating storage projects in areas throughout the nation.

In general, geologic conditions in the study areas of the ARRA Site Characterization projects appear favorable for $CO_2$ storage in both on- and offshore settings; geologic features were successfully characterized and insight into hydrogeological properties achieved during the course of these projects. The project results determined the impact of fluid flow on $CO_2$ storage and, in some cases, defined the necessary boundary conditions for the models used in the risk analyses and $CO_2$ flow simulations. Regional mapping of the deep hydrogeology demonstrated that offshore sites add significantly to potential storage capacity, have the potential to allow discharge of untreated produced water directly into the ocean, avoid populated areas, and probably enjoy lower costs, especially where existing infrastructure is in place.

The projects comprising the ARRA Site Characterization Initiative resulted in improved storage capacity estimates for the formations under review. Current capacity estimates range from approximately 180 Gt (billion metric tons) to upwards of 640 Gt of $CO_2$ across all of the storage formations assessed under the ARRA Site Characterization Initiative. These projects have also enabled the construction and extension of models and improved the calculation of porosity, permeability, injectivity, and capacity. Several projects have resulted in innovative methods for integrating data from disparate sources to enhance modeling capabilities and have developed best-practices guides for site selection and characterization based on their particular experiences. For these to be widely useful, integration of the efforts of all the projects will be required.

The nine ARRA Site Characterization projects have significantly contributed towards advancing DOE's Fossil Energy Storage Program and American Recovery and Reinvestment Act goals, and progressed the prospect of greenhouse gas mitigation through geologic carbon storage. Each project worked to verify one or more geologic storage formations in its territory capable of (1) storing large volumes of $CO_2$, (2) receiving $CO_2$ at an efficient and economical rate of injection, and (3) safely retaining $CO_2$ over extended periods. This effort significantly increased the knowledge base regarding U.S. subsurface resources for geologic storage and helped to refine the national $CO_2$ storage capacity estimate as indicated in Atlas V. Beyond that, the work performed at the sites that were validated, moves the sites closer to receiving industrial volumes of $CO_2$, and provides valuable information for projects intending to inject into similar geologies. Finally, these projects, in their entirety, provide a wealth of information and experience, which will be captured in improved best-practice manuals for geologic carbon storage.

# NETL'S ARRA SITE CHARACTERIZATION INITIATIVE: *ACCOMPLISHMENTS*

# 1.0 INTRODUCTION TO THE ARRA SITE CHARACTERIZATION INITIATIVE

The American Recovery and Reinvestment Act of 2009 (ARRA) provided the Department of Energy (DOE) Office of Fossil Energy (FE) with funding for projects that promote the sustainable use of fossil fuels for generating electricity. Approximately $100 million was made available for site characterization activities for geologic storage of carbon dioxide ($CO_2$), the predominant greenhouse gas (GHG) from man-made sources. Nine projects were selected and conducted through the ARRA Site Characterization Initiative. The present report summarizes the accomplishments of these projects in the context of the DOE Storage Program's goals and critical components of geologic characterization for candidate storage sites. These ARRA-funded projects joined an established portfolio of projects managed by FE's Storage Program (the Storage Program is implemented by the National Energy Technology Laboratory [NETL]) and under development to provide safe, cost-effective $CO_2$ storage technologies with availability beginning in 2025.

## 1.1 Fossil Energy Goals and Carbon Management Approaches

DOE-FE's primary mission is to ensure our nation's access to traditional resources for clean, secure, and affordable energy while enhancing environmental protection. Carbon capture and storage (CCS) is a prominent technology being developed by DOE to reduce emissions of major GHGs from man-made sources (i.e., power generating and industrial facilities) to enable the continued use of fossil fuels while mitigating their effects on climate. Deploying CCS technologies on a commercial scale will require verification of geologic storage formations capable of (1) storing large volumes of $CO_2$; (2) accepting $CO_2$ at an efficient and economical rate of injection; and (3) safely retaining $CO_2$ over an extended period.[1] DOE's research and development (R&D) program includes projects to investigate geologic formations across various depositional environments to identify suitable candidates for effective geologic storage of $CO_2$. In particular, the efforts of the Regional Carbon Sequestration Partnerships (RCSPs), other large- and small-scale $CO_2$ injection projects, and the National Carbon Sequestration Database and Geographic Information System (NATCARB) have substantially increased our understanding of the potential to store $CO_2$ in geologic formations not previously studied in detail.

Geologic characterization provides the data needed to develop a robust understanding of the geophysical and geochemical conditions of potential $CO_2$ storage formations. These data are critical for the successful implementation of a carbon storage site because they provide information needed to demonstrate the ability of the targeted storage formation and overlying confining layers to effectively accept and permanently retain $CO_2$. Baseline subsurface conditions must be characterized and subsurface response to large quantities of injected $CO_2$ assessed as part of the U.S. Environmental Protection Agency (EPA) Underground Injection Control (UIC) Class VI regulatory framework, and also for establishing best practices for safe, long-term storage of $CO_2$. In the United States, Class VI permits are required prior to any $CO_2$ injection as part of a carbon storage project.

Identification of suitable geologic sites with adequate carbon storage potential involves a methodical analysis of the features of promising formations. While geologic formations are infinitely variable in detail, they are classified by geologists and engineers by their trapping mechanisms, hydrodynamic conditions, lithology, and depositional environment. DOE has primarily focused geologic storage R&D on three underground storage types: saline formations, oil and gas reservoirs, and unmineable coal seams, each with unique challenges and opportunities and each present in multiple sedimentary basins throughout North America (Figure 1). Other promising geologic storage types being investigated by NETL via characterization efforts are organic-rich shales and basalt formations. Each of these storage types is widely distributed throughout North America, and together have the potential to contain the total $CO_2$ emissions from large point sources into the distant future.[2]

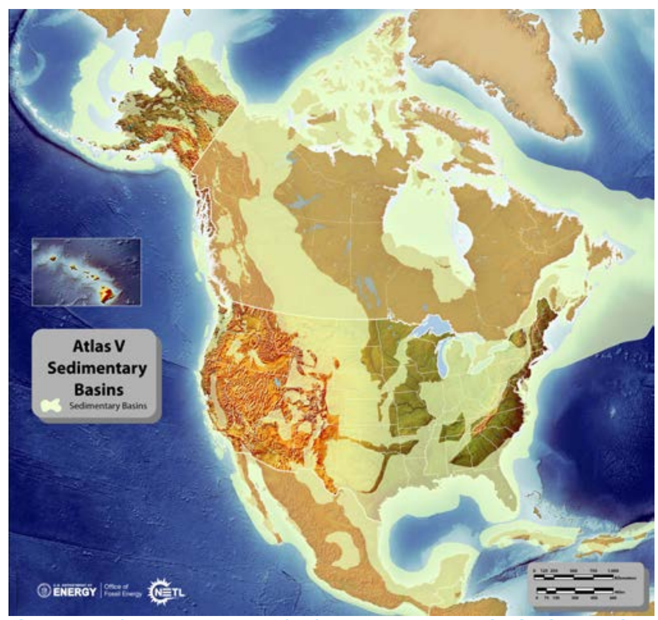



FIGURE 1. SEDIMENTARY BASINS IDENTIFIED THROUGHOUT NORTH AMERICA[2]

The potential resource for $CO_2$ storage in oil and gas formations, saline formations, and unmineable coal seams in North America is significant, with estimates between 2,619 Gt

[1] National Energy Technology Laboratory. 2010. *Best Practices for: Geologic Storage Formation Classification: Understanding Its Importance and Impacts on CCS Opportunities in the United States*. Available: http://www.netl.doe.gov/research/coal/carbon-storage/project-portfolio.

[2] National Energy Technology Laboratory. 2015. *Carbon Storage Atlas – Fifth Edition (Atlas V)*. Available: http://www.netl.doe.gov/research/coal/carbon-storage/atlasv.

(billion metric tons, or gigatonnes) and approximately 22,000 Gt of $CO_2$, representing at least several hundred years of emissions from large stationary sources. Currently, somewhat more than 3.071 Gt are emitted annually by major stationary sources in RCSP regions across the U.S. and parts of Canada.[2]

## 1.2 NETL's Storage Program

The DOE launched the Storage Program (formerly Carbon Storage Program) in 1997 with the goal of advancing CCS technologies with significant potential to reduce GHG emissions to the point of readiness for widespread commercial deployment. The NETL Storage Program's R&D objectives, as stated in the 2014 *Carbon Storage Technology Program Plan*[3], are (1) development and validation of technologies to ensure 99 percent storage permanence; (2) development of technologies to improve reservoir storage efficiency while ensuring containment effectiveness; (3) support for industry's ability to predict $CO_2$ storage capacity in geologic formations to within ±30 percent; and (4) development of best practice manuals (BPMs) for monitoring, verification, accounting (MVA), and assessment; site screening, selection, and initial characterization; public outreach; well management activities; and risk analysis and simulation.

The Storage Program has significantly advanced the CCS knowledge base in selected Technology Areas through a diverse portfolio of applied research projects. The portfolio includes industry cost-shared technology development projects, university research grants, collaborative work with other national laboratories, and research conducted in-house through the NETL Research Innovation Center (RIC). The Technology Areas comprising DOE's Storage program are shown in Figure 2. The Core R&D research component is a combination of three Technology Areas and is driven by the needed technology as determined by industry and other stakeholders, including regulators.

The Storage Infrastructure Technology Area comprises the RCSPs and other large- and small-volume field projects and "fit-for-purpose" projects, which are focused on developing specific subsurface engineering approaches to address research needs critical for advancing CCS to commercial scale. It is in this Technology Area that various CCS technology options and their efficacy are being confirmed. They represent the development of the infrastructure necessary for the deployment of CCS. The Infrastructure Technology Area hosts testing of new technologies and benefits from specific solutions developed in the Core R&D component. In turn, data gaps and lessons learned from small- and large-scale field projects are fed back to the Core R&D component to guide future R&D.

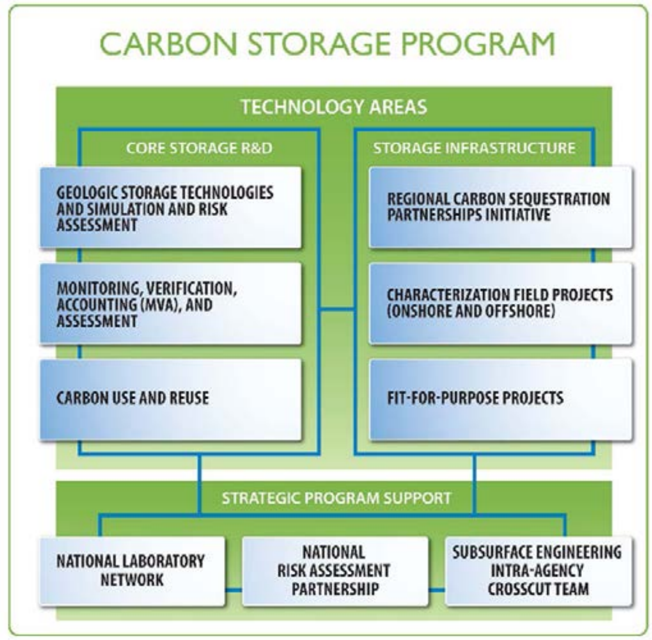



FIGURE 2. CARBON STORAGE PROGRAM STRUCTURE

A research focus of the Storage Program under the Infrastructure Technology Area is to classify the depositional environments of various formations that are known to have excellent reservoir properties and are amenable to geologic $CO_2$ storage. From the program's inception, this has been accomplished through the RCSPs, which have continued to characterize and refine geologic opportunities for carbon storage within each partnership's study region.[2] The partnerships continue to collect and integrate data on geologic formations into a national database (NATCARB) capable of graphically displaying the distribution of the assessed storage formations.

NETL's characterization activities originally were initiated as Phase I of the RCSP Initiative (Characterization Phase) and included cataloging of regional $CO_2$ sources, characterizing prospective CCS sites, and prioritizing opportunities for future $CO_2$ injection field projects. The characterization effort has evolved into a continuous activity conducted in parallel with the field projects and other projects collecting data on geologic formations for carbon storage. The RCSPs and other large- and small-scale projects have substantially increased the knowledge base regarding the potential to use different formations not previously explored for oil and gas extraction as storage reservoirs for $CO_2$. The RCSPs continue to support efforts by research organizations, state geologic surveys, and industry to gather existing data and collect new information for all storage types. However, more and better information on storage formations throughout North America is needed.[3]

Regarding approaches to and methods for site characterization, the DOE publication *Best Practices for: Site Selection, Site Screening, and Initial Characterization for Deep*

[3] *Carbon Storage Technology Program Plan (Program Plan)*. National Energy Technology Laboratory. December 2014.

*Geologic Storage of $CO_2$*[4] (BPM) deserves mention. This manual divides the field into the three phases of its title: (1) site screening, (2) site selection, and (3) initial characterization. The manual is exhaustive, presuming no prior knowledge and prescribing several activities to be reiterated in each of these phases, along with activities unique to each phase. It may be presumed that the projects conducted through the ARRA Site Characterization Initiative featured in this report have benefitted from (and contributed to) a knowledge base expanded beyond that available in the 2013 edition of the BPM.

## 1.3 ARRA Site Characterization Project Scope and Goals in Relation to the FE Storage Program Mission

A primary objective of this report is to determine the ARRA Site Characterization Initiative achievements in terms of Storage Program goals, notwithstanding the distinct goals of the Recovery Act. ARRA projects were by design not in the normal purview of the federal agencies conducting them. Fossil Energy Recovery Act projects were expected to leverage federal funding, stimulate private-sector investment, accelerate delivery of CCS technology, and demonstrate the integration of coal-based energy systems and industrial processes with capture and permanent storage of carbon dioxide in geologic formations. The specific objectives of components of the Fossil Energy research and development portion of the Recovery Act include logical extensions of several important ongoing Fossil Energy Coal Program baseline activities, of which the following are called out for specific relevance in a Fossil Energy Research and Development Program Plan:

- Accelerate integrated CCS demonstrations by expanding and extending the opportunity for several additional CCS demonstrations for both existing and new electricity generation plants.
- Accelerate the comprehensive characterization of large-volume geologic reservoirs, augmenting existing data under the Department's RCSPs.
- Develop the next generation of scientists and engineers by expanding ongoing training and research efforts conducted primarily through the Department's University Coal Research and Historically Black Colleges and Universities programs (an implicit aspect of the ARRA Site Characterization projects, but not explicitly addressed in the present report).

The ARRA Site Characterization project awards were used to augment existing Storage Program efforts in geologic carbon storage in a manner that was responsive to the objectives of the Recovery Act and its Fossil Energy implementation. Assessment of the value added by these projects toward Storage Program goals is helpful in situating the ARRA Site Characterization effort within the mainstream of FE work.

In adding to the understanding of the potential for the evaluated geologic formations to safely and permanently store $CO_2$, the work performed by these characterization efforts also supported the President's energy goals to:

- Develop and deploy near-zero emission coal-based technologies.
- Make the United States a leader on climate change mitigation.
- Transfer CCS technology globally.
- Reduce U.S. greenhouse gas emissions 80 percent by 2050.
- Increase CCS technology funding.

[4] National Energy Technology Laboratory. 2013. *Best Practices For: Site Selection, Site Screening, and Initial Characterization for Deep Geologic Storage of $CO_2$ (BPM)*. 2013 revised edition.

## 2.0 ARRA SITE CHARACTERIZATION INITIATIVE PROJECT PORTFOLIO

This section briefly describes the nine site characterization projects awarded under the ARRA initiative. DOE was able to enhance the national assessment of $CO_2$ storage resources in deep geologic formations through these nine field projects. These projects helped characterize additional promising geologic formations for $CO_2$ storage and provided greater insight into the potential for geologic reservoirs across the U.S. to safely and permanently store $CO_2$. Each project's study area is outlined in Figure 3 and further detail for each is available in Table 1.

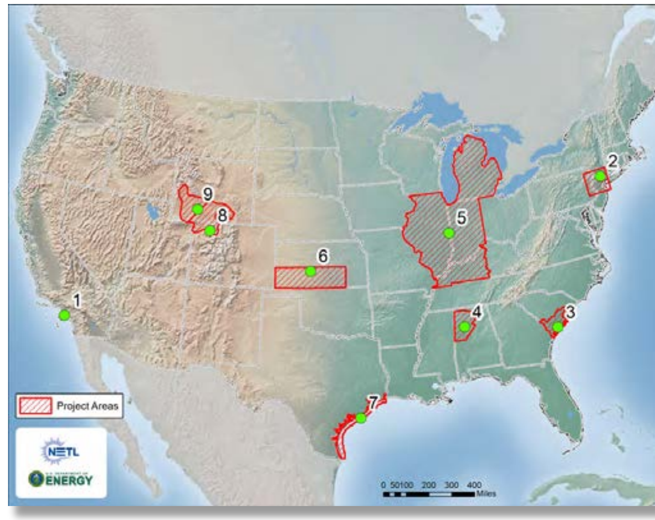



FIGURE 3. MAP DEPICTING ARRA SITE CHARACTERIZATION PROJECT LOCATIONS AND STUDY AREAS

TABLE 1. ARRA SITE CHARACTERIZATION PROJECTS

| Study Area | Project Performer | Project Title | Location |
|---|---|---|---|
| 1 | GeoMechanics Technologies | Characterization of the Pliocene and Miocene Formations in the Wilmington Graben, Offshore Los Angeles, for Large Scale Geologic Storage of $CO_2$ | Los Angeles Basin, Wilmington Graben |
| 2 | Sandia Technologies | Characterization of the Triassic Newark Basin of New York & New Jersey for Geologic Storage of Carbon Dioxide | Newark Rift Basin |
| 3 | South Carolina Research Foundation | Geologic Characterization of the South Georgia Rift Basin for Source Proximal $CO_2$ Storage | Mesozoic South Georgia Rift Basin |
| 4 | University of Alabama | Site Characterization for $CO_2$ Storage from Coal-fired Power Facilities in the Black Warrior Basin of Alabama | Black Warrior Basin, Alabama |
| 5 | University of Illinois–Illinois State Geological Survey | An Evaluation of the Carbon Sequestration Potential of the Cambro-Ordovician Strata of the Illinois and Michigan Basins | Knox Supergroup and St. Peter Sandstone, Illinois and Michigan Basins |
| 6 | University of Kansas | Modeling $CO_2$ Sequestration in a Saline Aquifer and Depleted Oil Reservoir to Evaluate Regional $CO_2$ Sequestration Potential of Ozark Plateau Aquifer System, South-Central Kansas | Arbuckle Group, Ozark Plateau |
| 7 | University of Texas at Austin | Gulf of Mexico Miocene $CO_2$ Site Characterization Mega Transect | State of Texas Submerged Lands |
| 8 | University of Utah | Characterization of the Most Promising Sequestration Formations in the Rocky Mountain Region | Colorado Plateau |
| 9 | University of Wyoming | Site Characterization of the Highest-Priority Geologic Formations for $CO_2$ Storage in Wyoming | Rock Springs Uplift and Moxa Arch |

These NETL-selected projects received funding to characterize promising geologic formations for $CO_2$ storage. This research further advances DOE's efforts to develop a national assessment of $CO_2$ storage capacity in deep geologic formations. It should be noted that though the ARRA Site Characterization portfolio complements the FE Storage Program, neither its goals nor the requirements placed on awardees were identical with those of the program. Education and training along with funding of advanced green technologies were explicit objectives of the DOE's portion of the Recovery Act. In addition, the ARRA Site Characterization projects were not scoped beyond initial characterization activities, and no injection permits were sought under the UIC Class VI category for carbon storage.

Formation types under evaluation included saline formations, depleting/depleted oil fields (but not specifically or primarily for the purpose of enhanced oil recovery), and unmineable coal seams. The characterization efforts included drilling stratigraphic wells to collect hole and sidewall core data on confining and injection zones, conducting comprehensive logging evaluations and formation evaluation tests, and analyzing the chemistry of formation rocks and fluids. The characterization efforts also include the acquisition of two-dimensional and three-dimensional seismic surveys that integrate rock property data acquired from new wellbores with other existing data to validate seismic responses.

Project personnel developed methods of integrating data from disparate sources to extend modeling efforts and reduce uncertainties, and in the process achieved comprehensive data sets of formation characteristics indicating porosity, permeability, reservoir architecture, caprock integrity, and related features. As a result, these projects developed highly qualified storage capacity estimates within their study areas. Revised storage volume estimates developed by these projects were used to update the storage capacities presented in *Atlas V*[2]; however, the capacities reported later in this report result from the work specific to the ARRA Site Characterization Initiative.

Combined, these projects contributed to the knowledge base of best practices for site characterization and approving storage site selection, and they supported the development of best practices manuals on site characterization for their regions and facilitated knowledge sharing within technical working groups. Information gathered from these projects has been incorporated into NATCARB to improve future $CO_2$ storage resource estimates in the United States. These efforts represent another step toward better understanding of the geology of potential storage formations in the United States.

While each project focused on the geology within its respective study region, each project exhibited a number of common characteristics which included: regional characterization; utilization of a combination of existing data and data from new well drilling and seismic lines; development of novel approaches to data integration and synthesis; and development of best practices for site selection and regional characterization. One of the ARRA Site Characterization Initiative's unique areas of focus for certain projects was to assess the potential for $CO_2$ storage in offshore geologic formations. For example, GeoMechanics Technologies implemented a comprehensive research program to better characterize Pliocene and Miocene sediments in the Wilmington Graben within the Los Angeles Basin for their potential for high-volume $CO_2$ storage. In addition, the University of Texas at Austin (UT-Austin) Bureau of Economic Geology investigated Texas's offshore subsurface Miocene formations in the Gulf of Mexico, advancing their assessment as candidate formations for geologic $CO_2$ storage.

## 2.1 Contributions of the ARRA Site Characterization Projects

A CCS project typically proceeds through a series of steps from initial site screening, selection, and potential characterization (Figure 4) through construction, injection, and closure, to long-term monitoring of the site for decades after injection has ceased. Information generated by site characterization efforts (such as the ARRA projects) contributes to most steps of a CCS project because, ultimately, it is the geology of a site that controls all aspects of the project, and the better the geology of a site is understood the lower the risk to the project and the greater the probability of a successful outcome. Specifically, the level of geologic characterization performed by ARRA Site Characterization projects was similar to the "Initial Characterization" portion of the site screening, selection, and initial characterization portion of a CCS project featured in Figure 4.[4]

ARRA Site Characterization project data collected were provided to the NATCARB database[5], giving users the ability to access actual field data and obtain detailed insight into ARRA project locations and operations. Examples of available data include seismic survey results, well and borehole locations and associated well logs, geographic information system (GIS) shape files, coring and chemical sampling data, and storage formation thickness and location contour maps. Where applicable, publicly-available data sources were collected and incorporated by NETL into the NATCARB database to supplement data collected from ARRA Site Characterization projects.

In addition to technical data (e.g., well logs, seismic, maps) from ARRA site characterization projects that were loaded into the online NATCARB viewer, new and refined estimates of $CO_2$ storage resources were evaluated, packaged, and distributed to the RCSPs for incorporation into state, regional, and national data that were provided to NETL for *Atlas V*. Not all ARRA Site Characterization projects provided NATCARB with $CO_2$ storage resource estimates (e.g., Newark Basin or South Carolina) or the area covered was relatively small in terms of a very large state (e.g., Wilmington Graben compared to California), but regardless of volume, a number of the projects strongly affected the overall resource estimate through changes in refinement and risk reduction. All projects conducting resource estimation utilized the DOE methodology to instill uniformity. The DOE storage resource methodology, which serves as the basis for the national storage resource estimate in Atlas V, uses a volumetric approach for estimating prospective $CO_2$ storage resource potential (highlighted in red

[5] NATCARB: A National Look at Carbon Sequestration. National Energy Technology Laboratory. Website: http://www.natcarbviewer.com

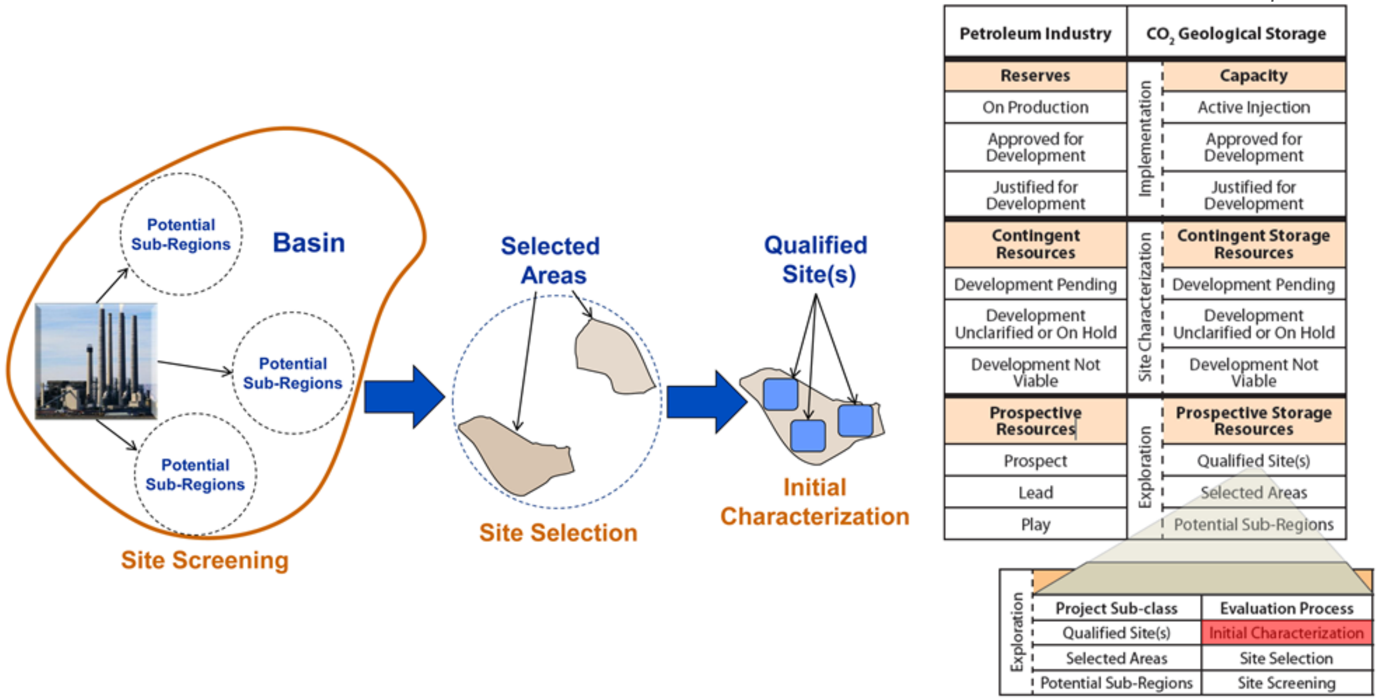



FIGURE 4. GRAPHICAL REPRESENTATION OF "PROJECT SITE MATURATION" THROUGH THE EXPLORATION AND EVALUATION PHASE, AS WELL AS COMPARISON WITH THE PETROLEUM INDUSTRY RESOURCE CLASSIFICATION AND PROPOSED $CO_2$ RESOURCE CLASSIFICATION—MODELED AFTER SOCIETY OF PETROLEUM ENGINEERS (SPE), THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS (AAPG), THE WORLD PETROLEUM COUNCIL (WPC), AND THE SOCIETY OF PETROLEUM EVALUATION ENGINEERS (SPEE) RESOURCE CLASSIFICATION SYSTEM.

on the resource classification table in Figure 4) in oil and gas reservoirs, saline formations, and unmineable coal seams.

## 2.2 Reporting Approach

NETL has received final reports from the nine ARRA site characterization projects. These reports constitute the detailed permanent record of the projects' accomplishments. No attempt is made in this report to duplicate that record; rather, the approach taken here is to present the ARRA Site Characterization Initiative's accomplishments via selections from the reported project accomplishments that most directly address Storage Program goals and highlight best practices for future CCS operations.

To assist in the program analysis for this final program report, details of each project's scope, objectives, activities, and accomplishments were obtained from project documents, including statements of project objectives, progress reports, proceedings from NETL's annual Storage R&D project review meetings, and project final reports. A schema based in part on *Best Practices for Site Screening, Site Selection, and Initial Characterization for Storage of $CO_2$ in Deep Geologic Formations*[4] was adopted to assist in correlating project achievements to those of other portfolio projects and to FE program goals as a means of unifying and summarizing accomplishments.

Portfolio achievements are reported following this schema under Section 3:

- Test Wells, Core, and Log Data Analysis
- Seismic Data Acquisition and Processing
- Prospective Reservoir $CO_2$ Storage Capacity Assessment
- Containment Analysis
  - o Stratigraphic Analysis
- Modeling and Simulation Efforts
- Risk Assessment
- Outreach and Education

# 3.0 PORTFOLIO ACCOMPLISHMENTS

The accomplishments of the ARRA Site Characterization projects have been presented in relation to NETL's Storage Program goals via the reporting schema discussed in Section 2.2 above. The project study regions include two offshore (one Pacific Ocean, one Gulf of Mexico), two western U.S., two southern U.S., two midwestern U.S., and one in the Mid-Atlantic States (Figure 3). These studies augment those performed by the seven RCSPs, with which several of the ARRA projects collaborated.

While the overall objective of the ARRA Site Characterization Initiative was to characterize high-priority geologic storage formations while providing greater insight into the potential for geologic reservoirs across the United States to safely and permanently store $CO_2$, each project had its own specific scope and focused on the geology within its respective study region (as mentioned in Section 2.0). Despite regional geologic differences across the project portfolio, the projects exhibited a number of common approaches towards characterization. In general, each project identified a study region/site with the mission to better characterize promising formations in those regions. Project personnel utilized existing data when available, and at times drilled new wells, acquired new seismic surveys, ran new well logs, and acquired core to supplement existing data. Geologic data were used both to better understand storage capacity and assess seal/caprock integrity, resulting in highly qualified storage capacity estimates in and around the projects' study areas. Revised storage volume estimates developed during the course of these projects were used to update the storage capacities presented in the *United States Carbon Utilization and Storage Atlas*, Fifth Edition (*Atlas V*)[2], and data were uploaded into the NATCARB Viewer.[5] In addition, the available data served as the foundation of geologic models used to simulate hypothetical $CO_2$ injections at sites within a given project's study region to assess feasibility for long-term storage.

Results obtained from the ARRA Site Characterization Initiative provided a foundation for validating that CCS can be commercially deployed throughout the United States. For instance, in addition to geologic insight, these projects provided substantial lessons learned and best practices on regional approaches to permitting and toward project implementation (e.g., wells, road access, coordinating with local government and utilities, etc.). In addition, several of the ARRA Site Characterization projects included aspects of public outreach and education within their scope. While the projects were exclusively characterization-based investigations, public outreach proved an effective means of transferring project information, lessons learned and best practices, benefits, and results to the public domain.

## 3.1 Test Wells, Core, and Log Data Analysis

Eleven new wells were drilled and one existing well deepened for characterization purposes under the ARRA Site Characterization projects (Figure 5). The chief objectives of these new wells were to obtain cores, run geophysical log suites across strata, implement fluid sampling for geochemical analysis, and perform other well testing in an effort to obtain more information about the subsurface. In general, drilling new wells provides access to the subsurface for additional data collection, formation evaluation and testing, injection, and monitoring. In some wells, the geological conditions encountered could differ from those predicted based on analysis of existing data alone. These may include differences in injection target thickness, porosity, permeability, or the presence of expected geologic strata.[6] While the purpose of drilling new characterization wells may be specific to acquiring new data, each well could vary significantly in the way it is designed, drilled, tested, and constructed/completed


FIGURE 5. DRILLING OPERATIONS AT VARIOUS ARRA SITE CHARACTERIZATION PROJECT SITES. THE IMAGES CORRESPOND TO DIFFERENT PROJECT SITES DRILLING NEW WELLS. TOP LEFT (UNIVERSITY OF ALABAMA), BOTTOM LEFT (SANDIA TECHNOLOGIES), TOP MIDDLE (GEOMECHANICS TECHNOLOGIES), BOTTOM MIDDLE (UNIVERSITY OF WYOMING), TOP RIGHT (UNIVERSITY OF UTAH), AND BOTTOM RIGHT (SANDIA TECHNOLOGIES).

6 World Resources Institute (WRI). CCS Guidelines: Guidelines for Carbon Dioxide Capture, Transport, and Storage. Washington, DC: WRI.

depending on factors such as the (1) potential use of the well after characterization; (2) the geologic conditions encountered; (3) total well depth; and (4) project funding.

In addition, project personnel acquired data from several other existing wells within their respective study areas. Existing wellbores near potential CCS sites may exist within the region and penetrate the potential injection and confining zone(s) of interest, providing valuable data about the subsurface. In many cases, it can be more cost effective to re-enter an existing wellbore and conduct a formation evaluation, well tests, or injection tests instead of drilling a new well.**Error! ookmark not defined.** All of the ARRA Site Characterization projects leaned heavily on existing well data for characterizing the subsurface within their respective study regions. In many cases, these existing data helped to supplement data obtained from new wells (when applicable). Data from new wells could be correlated with data from existing wells and seismic data to strengthen regional interpretations. Table 2 shows well utilization by project.

Specifics related to each project's individualized approaches in drilling new wells or utilizing data form existing wells can be found in final project reports on the DOE's Office of Science and Technical Information webpage. A selection of highlights from the ARRA Site Characterization projects pertaining to test wells, core, and log data analysis is presented in the accomplishment summaries below.

TABLE 2. PROJECT WELL UTILIZATION

| Project Performer | New/Existing | Well Name | Depth in meters (feet) | Summary |
|---|---|---|---|---|
| **Geomechanics Technologies** | New | DOE #1 | 1,655 (5,432) | Designed to test the Pliocene formation in the northern Wilmington Graben. A suite of well logs, including resistivity, gamma ray, density, cement bond and mud logs, were acquired. Twenty-nine sidewall cores and 2.89 meters (9.5 feet) of conventional core were recovered and analyzed. Pliocene section between 1,550 to 1,556 meters (5,086 to 5,106 feet) was perforated and fluid samples taken in situ and analyzed. |
| | New | DOE #2 | 2,331 (7,650) | Designed to test the Miocene Formation in the northern Wilmington Graben. Drill cutting samples were collected and analyzed for mud log and paleontologic identification. A suite of well logs, including resistivity, gamma ray, density, cement bond and mud logs, were acquired.. Thirty-eight sidewall cores were collected and the well was perforated between 1,418 and 1,431 meters (4,655 to 4,695 feet) into the Pliocene turbidites sands and shales. |
| | Existing - deepened | DOE #3 (SFI #1) | 2,145 (7,039) | DOE#3 deepened the existing SFI#1 well. Electric logs were run from 1,778 to 1,690 meters (5,835 to 5,545 feet). Mud log and paleo analysis to total well depth were also acquired. |
| | Existing | -- | -- | Lithology from 14 existing wells to create the project's 3D geologic model. |
| **Sandia Technologies** | New | Exit 14-W | 2,285 (6,855) | A well was drilled at the Exit 14 Tandem Truck lot along the New York State Thruway, including full penetration of the subsurface Palisades Sill. Deep coring and logging were completed; however, formation fluid samples within the well could not be obtained due to borehole restrictions. |
| | New | TW-4 | 600 (1,802) | Drilled on the Columbia University Lamont Doherty Campus. The well was continuous cored from 215 to 600 meters (650 to 1,800 feet) and logged to 570 meters (1,712 feet). The logging suite included Slimhole Platform Express, Borehole Compensated Sonic Tool, and Reservoir Saturation Tool. |
| | Existing - logged | TW-3 | 500 (1,500) | This well has a 16.5 centimeter (6.5 inch) borehole to total depth, which is large in diameter and permitted a suite of logging tools that were not able to be run in other wells. The logging suite included Slimhole Platform Express, Sonic Scanner Tool, combinable magnetic resonance tool, and Elemental Capture Sonde. Whole or rotary cores were not taken in TW-3 (only cuttings samples). |
| | Existing | -- | -- | Existing data were limited to two deep oil and gas wells in Pennsylvania and seven Newark Basin Coring |

| Project Performer | New/Existing | Well Name | Depth in meters (feet) | Summary |
|---|---|---|---|---|
| | | | | Project wells that were ~1,000 meters (~3,500 feet) deep. |
| University of Alabama | New | Gorgas #1 | 1,498 (4,915) | Reached total depth in the Copper Ridge Dolomite of the Knox Group. A diverse geophysical log suite was obtained from the well, and sidewall cores and whole cores were retrieved from selected intervals in the Cambrian-Pennsylvanian section. |
| | Existing | -- | -- | Data from 1,552 wells and 1,495 conventional core analyses were utilized. |
| University of Illinois | New | IBDP VW1 and VW2 | VM1 - 2,181 (7,156)<br>VM2 – 2,180 (7,154) | Acquired core from the previously planned Illinois Basin Decatur and Illinois Industrial Carbon Capture and Storage projects and monitoring wells (VW1 and VW2) in Decatur, Illinois |
| | New | CCS #1 | 2,200 (7,219) | This well served as the injection well for the Illinois Basin Decatur Project. The University of Illinois acquired mud and well logs to infer structural and stratigraphic formation information. |
| | Existing - injection test | Marvin Blan No. 1 | 2,467 (8,126) | Used for injection tests in that provide a basis for evaluating supercritical $CO_2$ storage in Cambro-Ordovician carbonate reservoirs throughout the Midcontinent. |
| | Existing | -- | -- | Other data sources included the Conoco Inc. Mark Turner #1 well on the Rough Creek Graben; Duke Energy #1 well on the Cincinnati Arch; more than 1,000 deep wells penetrating Mt. Simon Sandstone; and several wastewater injection wells for Potosi Dolomite. |
| University of Kansas | New | KGS #1-28 (Wellington) | 1,584 (5,200) | Drilled, cored, and logged these three wells. They were drilled to basement and provided over 820 meters (2,700 feet) of conventional core |
| | New | KGS #1-32 (Wellington) | 1,584 (5,200) | |
| | New | Cutter 1 | 7,700 | |
| | Existing | -- | -- | Acquired data from approximately 90,000 wells over the 64,700 $km^2$ (25,000 $mi^2$) study area. |
| University of South Carolina | New | Rizer #1 | 1,890 (6,204) | Drilling did not reach total planned depth due to challenges with the geology. The project team performed petrophysical and geochemical tests within the borehole. A total of 18 meters (59 feet) of conventional core and 106 rotary sidewall cores were collected. |
| | Existing | USGS Clubhouse Crossroads Test Hole No. 3 | -- | Cores collected to supplement Rizer #1 coring. Samples from this well were critical in caprock studies. |
| | Existing | Norris Lightsey #1 | 3,000 (914) | A wildcat well located on the northern up-dip margin of the basin. Available data for this well indicated that it was logged from surface to 2,973 meters (9,750 feet) bgs. It is one of the only wells within the basin that penetrates the Jurassic/Triassic sediments. |
| | Existing | -- | -- | The project team identified 27 wells onshore Georgia and South Carolina that are located in the South Georgia Rift Basin. Three wells are located offshore Georgia and are likely part of the SGR.<br><br>The project team also located cores from the Dorchester 211 well located in the South Carolina study area. |
| University of Texas | Existing | -- | -- | Well data collected was as follows: 12,750 wells were identified that penetrate the Miocene sediment; 6,893 wells found in Texas State waters; 3,445 wells had raster and/or digital logs; 424 wells contained Paleontologic data; and 241 had directional surveys. |

| Project Performer | New/Existing | Well Name | Depth in meters (feet) | Summary |
|---|---|---|---|---|
| | | | | These previously mentioned wells are a subset of a much larger set of wells and well data that were assembled for the Federal Waters of the northern and western Gulf of Mexico, which includes >65,000 wells, of which >18,000 wells have paleontological data stored in an HIS Petra database. |
| **University of Utah** | New | RMCCS State #1 | 2,970 (9,745) | This well was drilled in the Sand Wash Basin, Colorado near the town of Craig. A total of 40 meters (131 feet) of core was collected from across the Mowry, Curtis, and Entrada formations. Several downhole trips with a rotary sidewall coring tool were completed to obtain small plugs of the Carlile, Frontier, and Dakota formations. |
| | Existing | -- | -- | Records from >30,000 oil and gas wells were obtained primarily from the IHS commercial database for the Rocky Mountain region. In addition, raster images of geophysical logs from >18,000 oil and gas wells in the Colorado study area were acquired. |
| **University of Wyoming** | New | RSU #1 | 3,904 (12,810) | Two-hundred and seventy-nine (279) meters of core acquired and extensive logs run, including X-multipole array acoustilog, high definition induction log, compensated Z-densilog, compensated neutron log, gamma ray log, caliper log, and circumferential borehole imaging log. |
| | Existing | -- | -- | Two-hundred and sixty-nine (269) borehole records catalog for purposes of Area of Review (AoR) review and risk analysis |

**Note: the Illinois project also utilized cores and log data from two new wells drilled for the Illinois Basin Decatur Project (IBDP), a companion large-scale injection project.*

**Wealth of subsurface data acquired from Gorgas #1 well:** The nearest deep well within the University of Alabama study region was more than five miles away from the Gorgas test site. The project team drilled a new test well (Gorgas #1) at the William C. Gorgas Electrical Generating Plant site to supplement the regional geologic data available in order to further assess the prominent formations in the Black Warrior Basin. The Gorgas #1 borehole was spudded at a surface elevation of 376 feet in the Pratt coal zone of the upper Pottsville Formation and drilled to a total depth of 4,915 feet, reaching bottom in the Copper Ridge Dolomite. The project team had originally planned to drill deeper into the Copper Ridge, but an influx of fresh water (total dissolved solids content <10,000 mg/L) into the well slowed the drilling. The well was air-rotary drilled (surface-cased to > 300 feet) with stops to recover core from reservoir and seal intervals. The new Gorgas #1 well provided an abundance of data about the subsurface by enabling the project team to run a series of well logs, attain conventional and sidewall core, and perform several well tests. For instance, the sidewall and whole coring was used to assess reservoir and sealing properties (including porosity, permeability, microbial analysis, and oil saturation) across several formations (Figure 6). In addition, a suite of open-hole well logs (gamma ray, spontaneous potential, compensated neutron, and formation density log) and well tests (min-fracture tests and drill-stem tests) were conducted to determine fracture gradients in sealing strata and potential injectivity of candidate storage formations.

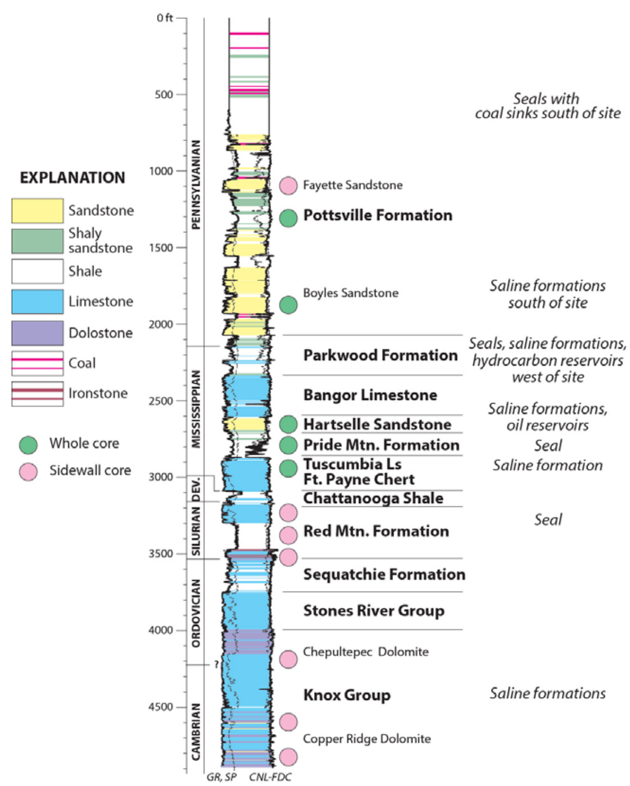



FIGURE 6. STRATIGRAPHIC COLUMN AND GEOPHYSICAL WELL LOGS OF THE GORGAS #1 BOREHOLE

Information collected from Gorgas #1 helped develop a detailed understanding about the stratigraphy at the Gorgas site (Figure 1) in which the stacked saline reservoirs throughout the Mississippian and Pennsylvanian-aged groups have regional significance. The University of Alabama identified over 1,500 existing wells within the test site region, and information provided from these wells was used to help interpret rock types and stratigraphic units expected across the study area. The Gorgas #1 well data helped to refine those stratigraphic interpretations to better understand $CO_2$ storage potential in the Black Warrior Basin.

**New and old test well data combine to help identify mafic confining units in the South Georgia Rift basin:** The South Carolina Research Foundation study focused on evaluating the feasibility and suitability of using the Jurassic/Triassic (J/Tr) sediments of the buried South Georgia Rift basin for $CO_2$ storage in southern South Carolina and southern Georgia. The J/Tr sequence, based on preliminary assessment of limited geological and geophysical data, has both the appropriate areal extent and multiple horizons with the potential to store significant amounts of $CO_2$. In addition, the presence of several igneous (mafic diabase) layers within the sequence was thought to provide adequate seals to prevent upward migration of $CO_2$ into the Coastal Plain aquifer systems. In the South Carolina portion of the basin, there was only one well (Norris Lightsey #1) that penetrated into J/Tr sequence. Due to the scarcity of data, a test bore hole (Rizer #1) was drilled to a depth of 1,890 meters (6,200 feet) to provide additional characterization information.

In general, the diabase units are typically less than 10 meters (33 feet) thick. These thin structures can be difficult to detect through surface seismic surveys and other non-invasive techniques, therefore make it challenging to understand their aerial extent over a large area. To better understand the location of the diabase units and their orientation, the South Carolina Research Foundation correlated well logs between the Riser #1 test bore and the Norris-Lightsey #1 (Figure 7).

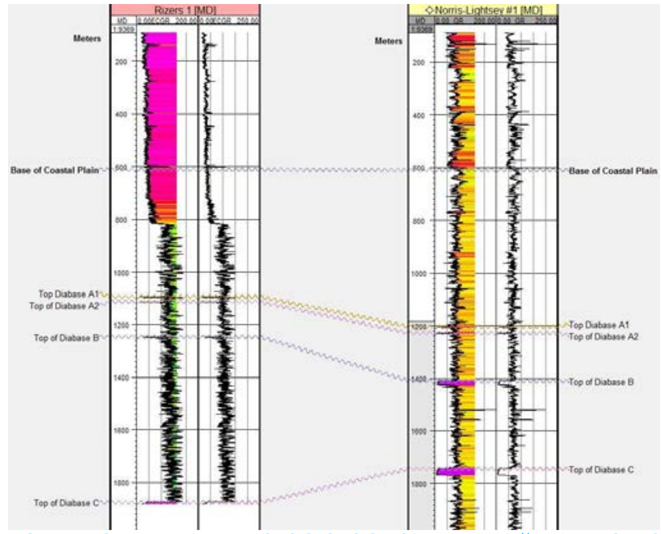



FIGURE 7. GAMMA AND LITHOLOGIC LOG FOR THE RIZER #1 AND NORRIS LIGHTSEY #1 WELL. THE UNITS LABEL A-F ARE THE DIABASE LAYERS.

As indicated in Figure 7 through the well correlation, the diabase units vary significantly in depth below ground surface between the two well sites, which are only 1.5 kilometers (0.93 miles) apart. This is a strong example of how new well data can complement, refine, or enhance existing geologic data when characterizing candidate $CO_2$ storage sites.

THE UNIVERSITY OF UTAH

**Collaboration improves characterization efforts – a team approach to mastering the subsurface:** Drilling a well to acquire geologic data, extract subsurface resources, or inject $CO_2$ can be costly to operators, whose characterization efforts typically involve more than simply drilling a borehole to a desired depth. As part of a geologic characterization effort, test wellbores are often logged with a variety of geophysical tools, core extracted for analysis, fluids sampled, and well tests conducted. The compilation of both fluid and rock samples supplements geophysical data collected from wireline tools, and helps the operator more effectively create a conceptual site model to evaluate $CO_2$ storage capacity and permanence.

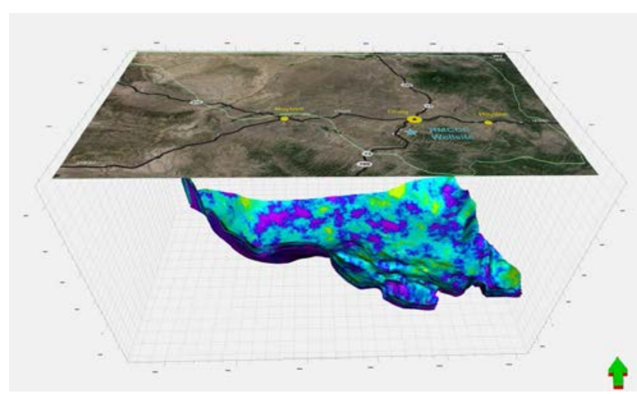


FIGURE 8. SAND WASH BASIN POROSITY MODEL USED TO INFER ABOUT STORAGE CAPACITY

The University of Utah drilled a characterization well near Craig, Colorado to a depth of nearly 9,800 feet and collected over 130 feet of rock core as well as a robust geophysical dataset via wireline logging techniques. The University of Utah's project partner (Shell Oil Company) provided cost-share for the collection of additional core samples from the Niobrara shale formation for oil and gas exploration purposes and enabled the well to be drilled to a greater depth. Shell Oil Company's cost share contribution enabled the well to be deepened for additional core sampling, formation top determination, and geochemical and geophysical property evaluation. (The Niobrara formation is a potential unconventional target for future geologic storage not in the original project plan.) The well was then logged using a full suite of geophysical tools, allowing incorporation of additional geologic data needed to complete a regional model (Figure 8) meant to illustrate $CO_2$ storage potential for the area near the Craig Power Station in northwestern Colorado.

GeoMechanics Technologies

**New test wells enable understanding of reservoir characteristics through injectivity and pressure fall-off testing:** Two new wells were drilled in the northern Wilmington Graben in the Los Angeles Basin as part of the GeoMechanics Technologies effort to further characterize Pliocene and Miocene sediments. The new wells were DOE#1 and DOE #2, in which DOE #1 (total vertical depth of 1,640 meters [5,382 feet]) was designed to test the Pliocene formation and DOE #2 (1,655 meters (5,432 feet])) was designed to test the Miocene formation. In addition to obtaining core and log data via new drilling, step-rate and pressure fall-off tests were conducted on each well to assess fluid injectivity potential and subsequent pressure response—important factors for determining if a candidate injection interval can accept $CO_2$ at a favorable rate without fracturing the storage reservoir or caprock units. Information derived from these tests also can indicate the injected fluid flow regime around the wellbore. Near the conclusion of the step-rate test, pressure declined rapidly to original reservoir conditions within about two days, and transient analyses indicated that the flow was radial in nature. Radial flow in geologic storage settings can be favorable because reservoir pore space and subsequent capacity is better utilized, which can reduce the overall aerial footprint of a $CO_2$ plume. In addition, these tests suggest the absence of natural fractures and compartments (reservoir characteristics that can impede radial flow and make prediction of $CO_2$ plume movement more challenging).

KU KANSAS GEOLOGICAL SURVEY The University of Kansas

**Well data from the University of Kansas ARRA Site Characterization project leveraged for other NETL-supported research:** The midcontinent of the United States has a long history of oil exploration and production and a geologic setting that appears to be amenable to using $CO_2$ for EOR and long-term storage. The Kansas Geological Survey (a division of the University of Kansas) worked with industry and academic partners to study $CO_2$ storage potential within the Ozark Plateau Aquifer System, focusing on the $CO_2$-EOR potential of a Mississippian cherty dolomite formation in the Wellington Field as well as storage in the underlying Cambro-Ordovician Arbuckle saline formation. The larger study in this project (spanning an area in south-central Kansas) was designed to evaluate the Arbuckle Group saline formation for $CO_2$ storage and the Chester and Morrow sandstone formations for EOR suitability.

FIGURE 9. CHARACTERIZATION WELL BEING INSTALLED IN THE WELLINGTON FIELD IN SUMNER COUNTY, KANSAS.

The University of Kansas and partners drilled and completed two wells (KGS #1-28 and KGS #1-32) to a depth of approximately 5,200 (Figure 9) in spring 2011. Approximately 1,300 feet of core was collected from possible injection and caprock formations and several wire line logs and drill stem tests were utilized to evaluate the condition of the newly installed wells and the surrounding environment. The data collected from these wells was used to refine geologic models for the area and estimate storage resources.

While the data obtained from these wells were instrumental in achieving the project's objective, their impact extends to other NETL-supported projects. For example, information obtained from the KGS#1-28 and KGS#1-32 wells is being utilized to develop a small-scale $CO_2$ injection project in the Wellington Field (also led by the University of Kansas and sponsored by NETL). Specifically, data obtained from these wells were used to help construct a porosity model of the Wellington Field, which is being used by the small-scale field test project team to accurately predict the spatial distribution of the expected $CO_2$ plume. In addition, these wells are capable of being instrumented with geomechanical stress and strain sensors to monitor and evaluate potential induced seismicity (felt seismic events as a result of fluid injection or extraction operations) within the Wellington Field.

## 3.2 Seismic Data Acquisition and Processing

A major characterization approach employed by the ARRA Site Characterization projects involved the collection and processing of seismic data (both existing and newly acquired).

Seismic technologies have benefited from many decades of development, testing, and optimization by the petroleum industry. As a result, seismic technologies (for both acquisition and processing) have become an important tool for reservoir characterization—and in some cases reservoir fluid monitoring—in producing oil and gas fields. Recently, certain seismic imaging techniques and approaches have transitioned and been tested successfully for subsurface characterization and reservoir monitoring at $CO_2$ storage projects.

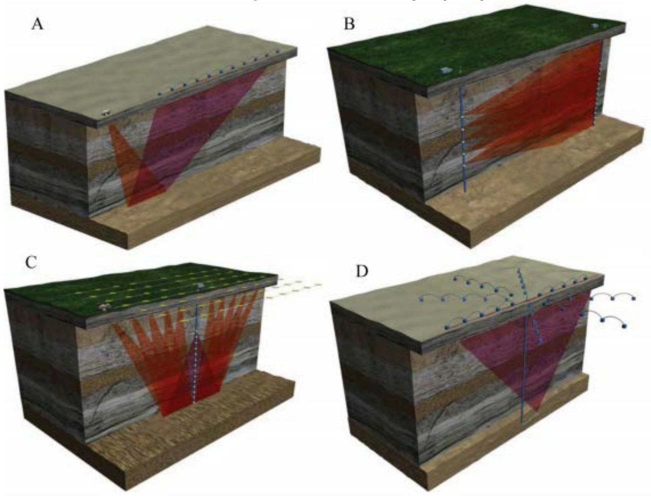



FIGURE 10. SCHEMATICS OF VARIOUS SEISMIC MONITORING TECHNIQUES: (A) 2D SURFACE SEISMIC; (B) CROSS-WELL SEISMIC, (C) THREE DIMENSIONAL (3D) VERTICAL SEISMIC PROFILE (VSP); AND (D) SURFACE-BASED MICROSEISMIC. IMAGES ARE NOT TO SCALE.[7]

Seismic monitoring strategies include both surface and borehole based techniques (Figure 10). Surface seismic surveys utilize surface sources to generate downward-propagating elastic waves, which are reflected back to the Earth's surface at layer boundaries due to changes in acoustic impedance properties of the rock medium. The reflected waves are recorded by ground motion sensors or geophones, and these arrivals are used to develop an image of subsurface geologic structure.[8]

A seismic reflection survey can be used for site characterization, and repeat surveys can provide time-lapse monitoring of the migration of the pressure front of $CO_2$ plume in the subsurface. Certain geologic features or noise from heavy equipment or related operations can degrade or attenuate a surface-based seismic signal and make it difficult for site operators to evaluate the collected data.

Each of the ARRA Site Characterization projects used seismic data to validate and/or help define the regional stratigraphic and structural framework—including characterization of potential injection and confining zones as well as identification of faulting—within their study areas (Table 3). This was accomplished through acquisition and processing of both new and existing seismic data. In many instances across the projects, older versions of 2D and/or 3D data were collected and reprocessed. Purchase and analysis of previously available seismic data helped the projects expand their characterization footprint within their respective study regions at a fraction of the cost of acquiring new seismic data over the same coverage area.[8]

TABLE 3. SUMMARY OF SEISMIC DATA COLLECTION FROM THE ARRA SITE CHARACTERIZATION PROJECTS

| Project Performer | Seismic Type | Data Type | Summary |
|---|---|---|---|
| **Geomechanics Technologies** | 2D and 3D | Existing | 3D exploration industry seismic surveys and 2D high-resolution seismic profile data available from government, academic, and commercial sources. |
| | 2D | New | 175 kilometers (108 miles) of new seismic data in northern Wilmington Graben. |
| **Sandia Technologies** | 2D | New | Nearly 35 kilometers (22 miles) of new 2D seismic survey acquired along the New York State Thruway and Garden State Parkway in Upstate New York and northern New Jersey. |
| **University of Alabama** | 2D | New | Two five-mile 2-D multi-channel seismic reflection lines were collected 1.28 kilometers (0.795 miles) north of the Gorgas site. |
| | VSP | New | Zero-offset VSP collected following the characterization borehole completion efforts that included using a receiver array comprised of four receiver levels separated by 15.2 meters (50 feet) that was lowered to the base of the hole and iteratively raised as measurements were taken. |
| **University of Illinois** | 2D | New | Acquisition and processing of approximately 201 kilometers (125 miles) of 2D seismic reflection surveys running west to east in the central Illinois Basin; specifically, near the Manlove Gas Storage Field in Champaign County, Illinois and the IBDP area. |

[7] Hamling, J., et al. (2011). Subtask 1.3 – Evaluation of geophysical technologies for application to CCS: Final topical report prepared for National Energy Technology Laboratory under Cooperative Agreement No. DE-FC26-08NT43291, Energy and Environmental Research Center, Grand Forks, ND.

[8] National Energy Technology Laboratory. (2012). Best Practices for Monitoring, Verification, and Accounting of $CO_2$ Stored in Deep Geologic Formations – 2012 Update. DOE/NETL-2012/1568.

| Project Performer | Seismic Type | Data Type | Summary |
|---|---|---|---|
| | VSP | New | Two 3D VSPs were acquired at the Marvin Blan No. 1 $CO_2$ storage research well in Hancock County, Kentucky. These surveys (one just before $CO_2$ injection and one immediately following injection) were combined to produce a time-lapse 3D VSP data volume in an attempt to monitor the subsurface changes caused by the injection. |
| **University of Kansas** | 3D | Existing | Acquired, processed, and interpreted 31 $km^2$ (12 $mi^2$) of multicomponent 3D seismic data near the Wellington field, and 310 $km^2$ (120 $mi^2$) of multicomponent 3D seismic data in southwestern Kansas. |
| | 3D | New | Obtained 51 $km^2$ (20 $mi^2$) of multicomponent 3D seismic data in southwestern Kansas. |
| **University of South Carolina** | 2D | Existing | A series of existing seismic lines produced by industry and academia were collected and converted from two-way travel time to depth in meters for portions of southern central South Carolina and Georgia. |
| | 2D | New | Collected approximately 240 kilometers (149 miles) of new seismic data in South Carolina and 81.3 km (50.5 miles) of new seismic in southern Georgia. |
| | 3D | New | Conducted in the area surrounding the proposed location of the characterization boring site (Rizer #1) to verify the diabase units observed in the Norris Lightsey # 1 well. |
| **University of Texas** | 2D | Existing | Access to a set of regional 2D seismic lines known as the "GulfSPAN Merge" that encompass a large portion of the Gulf of Mexico. |
| | 3D | New | High-resolution 3D seismic data acquired over three surveys totaling ~140 $km^2$ (46 $mi^2$) using a boat-deployed P-cable system in Texas state waters (seaward from the barrier islands) of the upper Texas coast. |
| **University of Utah** | 2D | Existing | Approximately 112 kilometers (70 miles) of existing two-dimensional seismic data in 11 lines, which were all located on the Trapper Mine property. |
| | 2D | New | Approximately 12 kilometers (8 miles) of new 2D seismic data in two lines, which were all located on the Trapper Mine property. |
| **University of Wyoming** | 3D | New | A 64 $km^2$ (25 $mi^2$) multicomponent 3D seismic survey encompassing the area surrounding the stratigraphic test well. |
| | VSP | New | Conducted a zero-offset VSP in the RSU #1 well with data collection through 76 down-hole receiver stations |

The characterization efforts also integrated seismic data with other methods of subsurface exploration such as rock property data acquired from new wellbores, log suites, core data, fluid samples, and laboratory analyses to validate seismic responses. The integration of these data is providing a better understanding of the subsurface properties needed to develop dynamic models to account for $CO_2$ migration.

Specifics related to each project's individualized approaches regarding seismic surveying can be found in final project reports on the DOE's Office of Science and Technical Information webpage. A selection of highlights from the ARRA Site Characterization projects pertaining to seismic data acquisitioning and processing is presented in the accomplishment summaries below.

Sandia Technologies, LLC

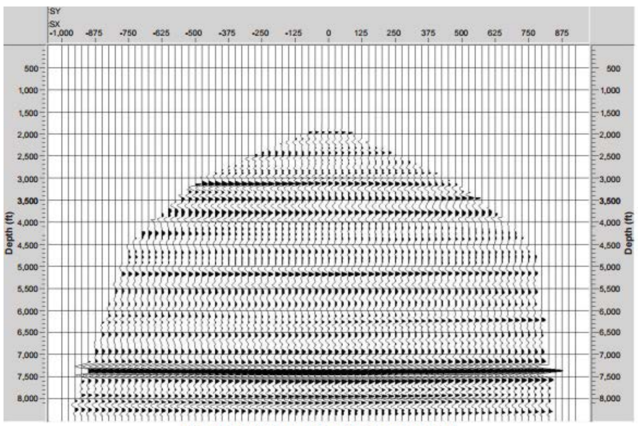
**Sandia Technologies, LLC provides case-study for 2D seismic acquisition in urban setting:** Sandia Technologies, LLC studied the Newark Rift Basin, which underlies an industrialized, developed region comprising parts of New York, New Jersey, and Pennsylvania. Specifically, the project characterized the suitability of Triassic age sedimentary formations for potential geologic $CO_2$ storage. This project achieved a higher resolution assessment of $CO_2$ storage potential by integrating data from seismic, borehole, and formation core results.

A unique aspect of this project involved the deployment of seismic acquisition equipment, including vibroseis trucks and sensors, along the busy highways of the New York State Thruway and Garden State Parkway between 6:30 PM and 6:30 AM. Traffic volume on these major roadways can be up to 200,000 cars per day. However, these roads were favorable for attaining rights-of-way in a major urban setting. The project team was able to acquire 2D seismic data along these roadways by acquiring the necessary permits and restricting traffic to one lane with the help of New York and New Jersey State Police providing traffic control. The result was acquisition, processing, and interpretation of approximately 35 kilometers (22 miles) of high-resolution 2D seismic lines.

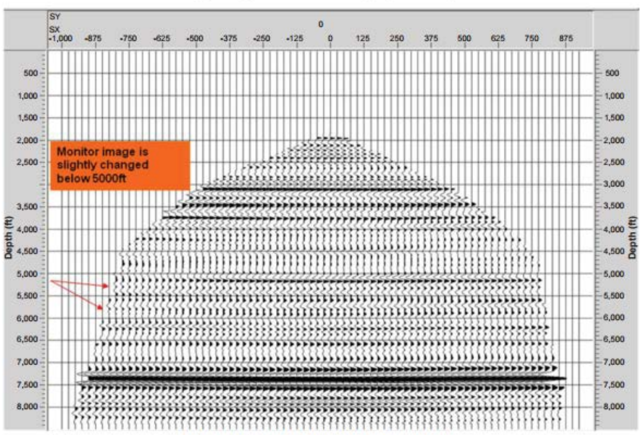
ILLINOIS STATE GEOLOGICAL SURVEY
PRAIRIE RESEARCH INSTITUTE

**Vertical seismic profile shows promise in detecting $CO_2$ plume at small-scale injection test:** The Illinois State Geologic Survey performed a $CO_2$ injection test into the Gunter Sandstone (injection interval between 1,535 – 1,605 meters [5,038 – 5,268 feet deep]) middle Knox Group using an existing well (Marvin Blan No. 1) in Hancock County, Kentucky and provided an estimate of the supercritical $CO_2$

storage volume in the entire Knox. The injection study occurred over a two day period in which 367 metric tons of $CO_2$ was injected. As part of this study, two 3D-VSPs were acquired—one just before $CO_2$ injection and one immediately following injection—to produce a time-lapse 3D-VSP data volume as a means to monitor the subsurface changes caused by the injection. Successfully imaging the injected plume of $CO_2$ in the subsurface in three dimensions could potentially act as a key monitoring technique for future subsurface storage verification tests.[9]




Depth-migrated monitor image (west-east).




Depth-migrated monitor image (west-east).

FIGURE 11. THREE-DIMENSIONAL TIME-LAPSE VSP SURVEY TAKEN AT THE MARVIN BLAN NO. 1 CO2 INJECTION TEST SITE. EXAMPLE PROFILES ACROSS THE VSP SURVEY SHOWING THE SUBTLE CHANGES WITHIN AND BELOW THE INJECTION ZONE OF THE WAVEFORM AMPLITUDES FOLLOWING INJECTION. POSITIVE REFLECTION AMPLITUDES ARE COLORED BLACK.[9]

While less than optimum surface access and ambient subsurface noise from a nearby active petroleum pipeline was believed to impact the quality of the results, changes in the seismic response post-injection were interpreted to result from the injection process (Figure 11). For example, the lateral and vertical extent of the plume could not be determined from post-injection data, but changes were evident between the pre- and post-injection surveys, including seismic amplitudes and waveforms that changed slightly in the injection zone below 1,534 meters (5,032 feet) (Figure 11). The project team also noted subtle changes throughout the data set, including at depths in intervals that were too distant or stratigraphically compartmentalized to be affected by the injection.[9] These results from a small-scale $CO_2$ injection may indicate the potential feasibility to track $CO_2$ plumes using time-lapse VSP, especially for $CO_2$ injection at larger scales.

THE UNIVERSITY OF TEXAS AT AUSTIN

**Riding the waves: Ocean waves and seismic waves help characterize the offshore subsurface in the Gulf of Mexico:** The University of Texas and partners characterized the Miocene-age sub-seafloor stratigraphy in the near-offshore portion of the Gulf of Mexico adjacent to the Texas coast. The large number of industrial sources of $CO_2$ in coastal counties and the high density of onshore urbanization and environmentally sensitive areas make this offshore region extremely attractive for long-term storage of carbon dioxide emissions from industrial sources. The study utilized a unique high definition 3D seismic (HR3D) survey system (known as the P-Cable system) to collect data from the offshore subsurface near the San Luis Pass in Texas state waters.

The unique P-Cable system (Figure 12) enabled the acquisition of HR3D of the shallowest 800 to 1,500 milliseconds (ms) (approximately 1 kilometer in depth) of the subsurface below the ocean floor. The University of Texas used these data to analyze the shallowest section of the geologic subsurface comprising the sealing units above potential offshore $CO_2$ storage sites. These data illustrated the stratigraphy and natural fluid flow system in unprecedented detail.

FIGURE 12. AERIAL PHOT OF THE R/V BROOKS MCCALL DUING ACTIVE HR3D (P-CABLE) SEISMIC ACQUISITION IN OCTOBER 2013, OFFSHORE SAN LUIS PASS, TEXAS.

In order to characterize regional seal performance and identify potential brine and $CO_2$ leakage pathways, three

[9] Hickman, J., (2014). Using time-lapse three-dimensional vertical seismic profiling to monitor injected fluids during geologic carbon sequestration, Kentucky Geological Survey, Series 12, Report of Investigation 26, 20 p.

HR3D seismic datasets were obtained that showed steady and significant improvements in data quality because of improved acquisition, sensor deployment, and data processing techniques. The project team was able to identify finely detailed faults and stratigraphy, as well as unconformable surfaces including what is likely a surface associated with the last Pleistocene glacial lowstand in the imaged portion of the seabed. The identification of a previously unrecognized gas chimney (due to gaps in commercial seismic data) that was clearly defined in the HR3D survey, indicates that HR3D surveys may be useful as both a characterization tool for the overburden of a potential carbon storage site and as an additional monitoring tool for future engineered injection sites in offshore applications.

**Synthetic Seismogram—Establishing the Time-Depth Relationship in the Black Warrior Basin:** The University of Alabama and partners created a correlation between the time and depth domains from seismic waves through the creation of a synthetic seismogram (Figure 13). A synthetic seismogram is a simulated seismic section computed from well data, which correlates the information gained down-hole with the seismic reflection data.[10] The project team used sonic and density log data in tandem with 2D seismic data and a check-shot survey to create the synthetic seismogram.

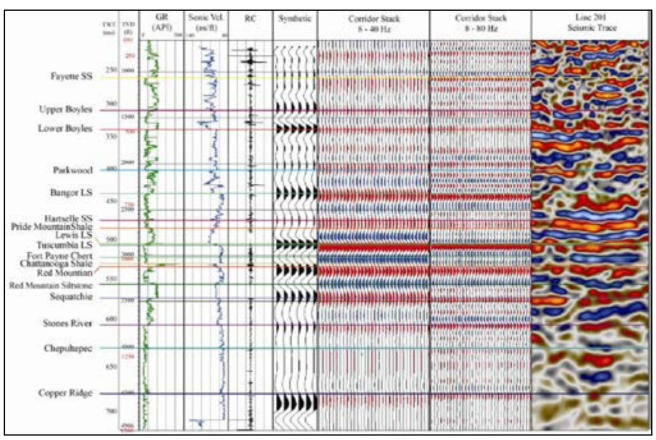



FIGURE 13. DOWN-HOLE LOGGING, SYNTHETIC SEISMOGRAMS, 2D, AND SEISMIC REFLECTION DATA FOR THE GORGAS #1 WELL. THE SCALE IS DEPTH IN UNITS OF FEET (BLACK), METERS (RED), AND TWO WAY TRAVEL TIME (TWT). THE GAMMA RAY LOG (GREEN) IS A REFERENCE LOG USEFUL IN IDENTIFYING SHALE UNITS. THE SONIC LOG (BLUE) IS ESPECIALLY USEFUL IN DIFFERENTIATING SANDSTONES FROM LIMESTONE. THE REFLECTION COEFFICIENT (RC; BLACK) IS CONVOLVED WITH A WAVELET THAT HAS BEEN EXTRACTED FROM THE 2D SEISMIC REFLECTION DATA TO DERIVE THE SYNTHETIC SEISMOGRAM (BLACK).

Because sonic logs and vertical seismic profiles are sparse near the Black Warrior basin study site, this type of data analysis is essential for providing seismic correlation representation of this region of the basin. In general, a check-shot survey provides borehole seismic data designed to measure the seismic travel time from the surface to a known depth. These data can then be correlated to surface seismic data through calibration of a sonic log and generation of a synthetic seismogram to confirm or modify seismic interpretations. Check-shots supply the most accurate time-to-depth conversion because they take a direct measurement of the time for a signal at the surface to reach a receiver at a given depth in the borehole.

The project team was able to interpret the seismic reflection profile from the synthetic seismogram (Figure 13) to ensure accurate ties between depths of units interpreted from the geophysical logs and reflectors on the seismic reflection profile. Formation horizons were selected for peaks that corresponded with unit contacts. In addition, the interpretation of this seismogram helped to resolve more detail concerning the thickness variation of units (which impacts $CO_2$ storage capacity assessments) and heterogeneity below the resolution of the surface 2D seismic reflection data. An example is the Parkwood Formation in which multiple peaks and troughs can easily be identified and correlated with the gamma ray and sonic velocity to determine heterogeneity of the formation. Both the synthetic and the corridor stack correspond well with the seismic trace (red = peaks; blue = troughs).

**Seismic analysis paramount in identifying transmissive faulting in South Carolina:** The project team collected approximately 240 kilometers (~149 miles) of new 2D seismic data in South Carolina and 81.3 kilometers (50.5 miles) of new seismic in southern Georgia in order to better define the extent of the South Georgia Rift Basin (SGR) and map potential reservoir and caprock units for $CO_2$ storage. However, the results of the seismic survey revealed that the South Carolina portion of the SGR basin has had a very complex structural history resulting in highly faulted Jurassic/Triassic sediments. Due to the severity of the faulting, the project team suggests that it is feasible to assume any $CO_2$ injected into these sediments would migrate upward into the overlying Coastal Plain aquifers, which contain USDWs.

[10] Box, R., Maxwell, L., and Loren, D. (2004). Excellent synthetic seismograms through the use of edited logs: Lake Borgne Area, Louisiana, U.S.: TLE, v. 23, no. 3, pp. 218–223.

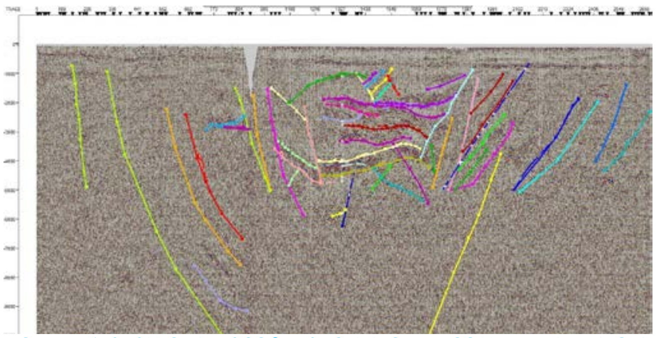


FIGURE 14. SEISMIC LINE SCO2-1 SHOWING THE COMPLEX FAULTING IN THE SGR

Seismic line SCO2-1 shows the complex faulting that resulted from an initial extensional structural style that occurred during Triassic and Jurassic to a compressional structural style that most likely occurred sometime between the Jurassic and Early Cretaceous time (Figure 14). Faults on the left side of the figure appear to have been normal faults that were associated with the initial basin formation. The remaining faults identified thus far appear to be related to the later compressional phase of the structural history of the basin. In fact, these seismic data were effective enough to identify three specific types of faults within this SCO2-1 line alone (Figure 14) including early extension faulting, reverse reactivation inversion, and transpressional overprinting.

It is important to note that for future commercial CCS operations, the successful characterization of a site is the most important step in confirming or rejecting that the candidate site would facilitate safe and economical $CO_2$ storage. Error! Bookmark ot defined. The University of South Carolina and partners utilized the 240 kilometers of seismic data to successfully identify risks to potential $CO_2$ storage in the South Carolina portion of their study region because of the extensive faulting. However, in Georgia, the project team suggests that there appears to be numerous sub-basins that have potential for storing $CO_2$ that were identified via both recent and legacy 2D seismic data.

University of Wyoming

**Using seismic and borehole data to extrapolate reservoir/caprock heterogeneity at the Rock Springs Uplift (RSU):** One of the most valuable outcomes of the Wyoming Carbon Underground Storage Program (WY-CUSP) study was the development of correlations between seismic attributes and log/core observations and analyses. These correlations allowed petrophysical parameters to be extrapolated to areas at a distance from the wellbore, so that the spatial heterogeneity of the properties within the reservoir/seal system could be included in a variety of evaluations. Understanding the variations within the reservoir/seal system enables more accurate models to be constructed and simulations to be run, increasing the ability to accurately predict and track injection operations. This project documented the geologic heterogeneity in three dimensions by acquiring a 3D seismic survey and drilling a stratigraphic test well at the selected $CO_2$ storage site. The 3D seismic survey area covered 65 square kilometer[s] (25 square miles) of the project area along the eastern flank of the RSU. WY-CUSP researchers integrated the 3D seismic survey data with well log results and core observations to construct 25 square kilometers (10 square miles) porosity, permeability, lithofacies, and fracture distribution volumes for the targeted Weber and Madison reservoirs (Figure 15).

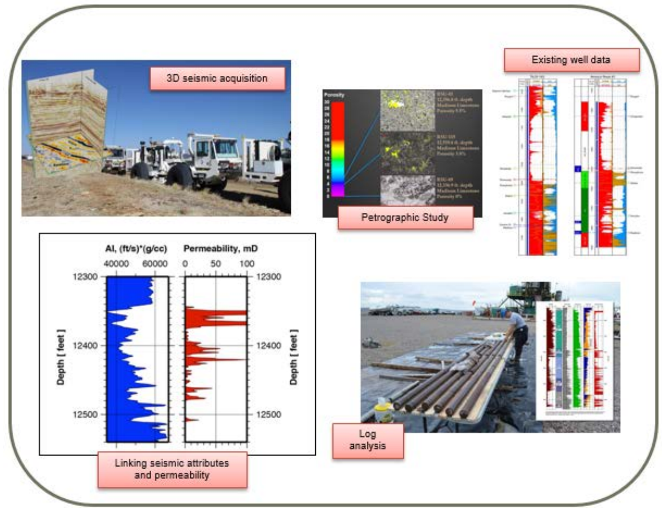



FIGURE 15. SEISMIC DATA, WELL DATA, AND WELL LOG DATA WERE CORRELATED TO ANALYZE HETEROGENEITY OF THE RESERVOIR/CAPROCK ACROSS THE STUDY AREA.

This information makes it possible to isolate individual reservoir horizons and construct maps of the distribution of seismic attributes and associated petrophysical properties (i.e., porosity and permeability) over the large area. The findings contributed to the study of potential artificial leakage pathways and helped to identify high-risk boreholes that may require remediation prior to any $CO_2$ injection. The geologic mapping identified seals and subseals regionally and locally. Target and seal thicknesses were compiled into a series of isopach maps to help identify the most appropriate injection horizons and associated seals.

## 3.3 Reservoir $CO_2$ Storage Capacity Assessment

One of the paramount principles of site characterization is to accelerate the comprehensive identification and characterization of potential large-volume geologic formations, which would enhance characterization efforts and refinement of geologic storage resource potential conducted by the RCSPs.

Understanding $CO_2$ storage potential is important for advancing CCS technologies toward commercialization. Government organizations, industry, and academia worldwide rely on $CO_2$ storage potential estimates for broad energy-related government policy and business decisions because dependable $CO_2$ storage estimates are necessary to ensure successful deployment of CCS technologies. The ARRA Site Characterization projects utilized both the U.S.-DOE developed methodology for estimating storage capacity and site- and project-specific approaches. The U.S.-DOE methodology (featured in the sidebar above) is intended for users such as the Regional Carbon Sequestration Partnerships, future project developers, and government entities to produce high-level $CO_2$ resource assessments of potential $CO_2$ storage reservoirs at the regional and national scale, but the methodology is conventional enough to be applied globally. The US-DOE methodology is based on volumetric methods for estimating subsurface volumes, in situ fluid distributions, and fluid displacement processes.[Error! Bookmark not defined.] These ethods are widely and routinely applied in petroleum resource, groundwater resource, underground natural gas storage volume, UIC disposal volume, and $CO_2$ storage volume estimates. The ARRA Site Characterization projects provided capacity estimates developed through the U.S.-DOE methodology to the NatCarb online database for refinement to the North American storage capacity resource assessment generated by the RCSPs. The projects in the ARRA Site Characterization Initiative have developed improved storage capacity estimates for the formations under review. Current capacity estimates range from approximately 180 Gt (billion metric tons) to upwards of 640 Gt of $CO_2$ across all of the storage formations assessed under the ARRA Site Characterization Initiative. This refined resource assessment is also featured in *the Carbon Utilization and Storage Atlas, Fifth Edition*. In several cases, these data represent a significant refinement of prior estimates, which had generally been made on a regional scale (Table 4).

TABLE 4. REVISED CAPACITY ESTIMATES BY PROJECT

| Project Performer | Storage Formations Investigated | Depositional Environment | Estimation Approach | Capacity Estimates – Million Metric tons | | |
|---|---|---|---|---|---|---|
| | | | | $P_{10}$ | $P_{50}$ | $P_{90}$ |
| GeoMechanics Technologies | Pico, Puente, and multiple others (sand) | Strandplain, Turbidite Clastic | U.S. DOE | 49.4 | 194 | 2,150 |
| Sandia Technologies | Stockton, Passiac, and Basalt Formations | Fluvial and Alluvial Clastics and Interflow Zone Basalts | Project-specific | -- | 15,000 | -- |
| South Carolina Research Foundation | Jurassic and Triassic saline formations | Fluvial/Alluvial between the Basalt Flows | Project-specific | -- | -- | -- |
| University of Alabama* | Pottsville, Parkwood, & Pride Mountain; Bangor & Tuscambia; Stones River Group, Knox Group, and Hartselle (sandstone, limestone, and dolostone) | Deltaic/Strandplain, Shallow Shelf Open, and Strandplain | U.S. DOE | 435 | 3,209 | 5,983 |
| University of Illinois | St. Peter (sandstone), Knox Supergroup (carbonate), and Maquoketa (shale) | Strandplain (Clastic), and Shallow-Shelf Open (Carbonate) | U.S. DOE | 47,000 | -- | 292,200 |
| University of Kansas | Arbuckle and Mississippian Chert Dolomite and Chester and Marrow Sandstone | Shallow Shelf and Metamorphosed Shallow Shelf (Carbonate) | Project-specific | 8,787 | -- | 75,465 |
| University of Texas at Austin | Multiple within Fleming Group including Lagarto & Oakville Formations | Fluvial-deltaic, Strandplain / Barrier Bar, Turbidite (Clastic) | U.S. DOE | -- | 86,000 | -- |
| University of Utah | Weber, Dakota, and Entrada Formations (sandstone) | Eolian and Strandplain Clastics | U.S. DOE | 13,500 | 53,220 | 143,710 |
| University of Wyoming | Tensleep, Madison, Weber, and Bighorn Formations (sandstone and limestone) | Strandplain, Eolian, Shallow-Shelf Open, and Shallow Shelf | Project-specific | -- | 17,000 | -- |

*Note: The subscript in $P_{10}$, $P_{50}$, and $P_{90}$ (also $P_{15}$ and $P_{85}$) indicates the probability that the true value of a resource is higher than the estimate is 100 – s, where s is the subscript. For example, a $P_{50}$ estimate means that there is a 50% chance of the actual value is higher than the estimated value, while $P_{90}$ indicates that there is only a 10% chance of the actual value being higher than the estimated value. Thus, $P_{50}$ is a median, $P_{10}$ is a low estimate; $P_{90}$ is a high estimate.*

**Represents $P_{15}$, $P_{50}$, and $P_{85}$ estimate for the University of Alabama project*

As mentioned, ARRA Site Characterization projects also utilized individual approaches toward integrating the characterization information and using it to develop a numerical model to estimate overall $CO_2$ storage capacity, simulate the injection and migration of $CO_2$ under different scenarios, and evaluate injectivity within each project's respective study regions. Specifics related to each project's individualized approach to estimate storage capacity can be found in final project reports on the DOE's Office of Science and Technical Information webpage; highlights are presented in the accomplishment summaries below.

**Over 100 years' worth of storage potential from power-generating facilities within the Black Warrior Basin identified:** The Black Warrior Basin in Alabama contains the William C. Gorgas and James. H. Miller, Jr. coal-fired power plants that serve the Birmingham-Tuscaloosa economic corridor and emit more than 24 million metric tons of $CO_2$ annually. However, the University of Alabama assessment of capacity and injectivity analysis indicates that significant $CO_2$ storage potential exists in the Cambrian through Pennsylvanian strata of the Black Warrior Basin. The greatest potential in terms of both capacity and injectivity lies in lower Pottsville sandstone; deep Knox carbonate also provides significant storage opportunities. Capacity was determined volumetrically using the U.S.-DOE methodology. At current $CO_2$ emission rates, the basin can potentially store more than 115 years of emissions from the Gorgas and Miller Plants. The Pottsville sandstone can store more than 50 years of emissions of $CO_2$ in a supercritical state making it an extremely important target for geologic storage. Also, the Knox Group can store approximately 25 years of emissions, and potential storage exists across most of the Black Warrior basin.

ILLINOIS STATE GEOLOGICAL SURVEY
PRAIRIE RESEARCH INSTITUTE

**Data availability, quality, and approach found to impact $CO_2$ storage estimation:** The Illinois State Geological Survey acquired extensive data sets that include geologic cross sections, maps, and 3D geocellular models to portray the regional-scale characteristics and spatial variability of the entire Cambrian-Ordovician strata in the Illinois and Michigan Basins and evaluate the geometries of the St. Peter Sandstone and Knox Supergroup units (e.g., Potosi Dolomite/Copper Ridge Group) in relation to the primary regional seal (Ordovician Maquoketa Group and Utica Shale) and potential secondary seals. In addition, core samples collected for petrophysical analysis from wells in Illinois (ADM Verification Well #1) and Kentucky (Marvin Blan No. 1) provided information on the reservoirs' pore types and petrophysical properties on both regional and local scales.

The Illinois State Geological Survey used multiple deterministic-based approaches, in conjunction with the probabilistic-based storage efficiency factors published in the U.S.-DOE methodology, to estimate the carbon storage resource of the St. Peter Sandstone and Knox Supergroup. The range in uncertainty of storage resource estimates varied as a function of data availability and quality and underlying assumptions used in the different approaches. In the first and simplest approach, storage resource estimates were calculated from mapping the gross thickness of the formation and applying a single estimate of the effective mean porosity of the formation (Figure 16 – top left). Results from this approach led to storage resource estimates ranging from 3.3 to 35.1 gigatonnes in the Michigan Basin and 1.0 to 11.0 gigatonnes in the Illinois Basin at the $P_{10}$ and $P_{90}$ probability levels, respectively.

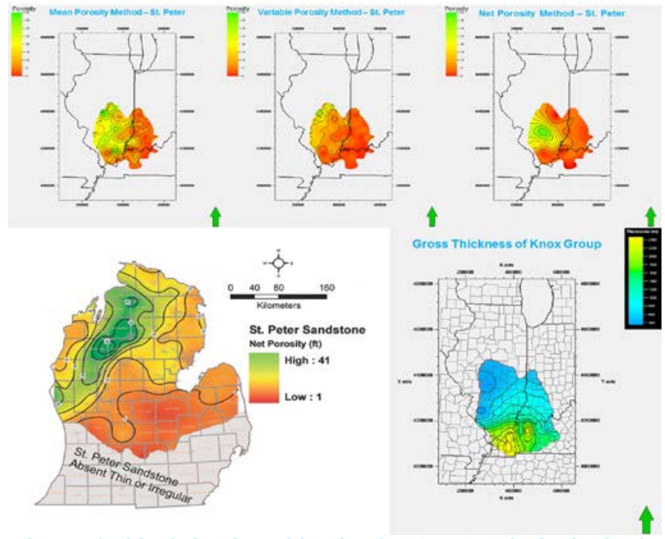



FIGURE 16. $CO_2$ STORAGE RESOURCE ESTIMATE APPROACHES FOR ST. PETER SANDSTONE AND KNOX GROUP

The second approach involved consideration of the diagenetic history of the formation throughout the two basins and used depth-dependent functions of porosity to derive a more realistic spatially variable model of porosity, rather than applying a single estimate of porosity throughout the entire potential reservoir domain (Figure 16 – top middle). This approach resulted in storage resource estimates of 3.0 to 31.6 gigatonnes in the Michigan Basinand 0.6 to 6.1 gigatonnes in the Illinois Basin.

The third approach attempted to account for the local variability in reservoir quality as a function of both porosity and permeability by using core and log analyses to calculate explicitly the net effective porosity at multiple well locations, and interpolate those results throughout the two basins (Figure 16 – top right). This approach resulted in storage resource estimates of 10.7 to 34.7 gigatonnes in the Michigan Basin and 11.2 to 36.4 gigatonnes in the Illinois Basin.

The final approach was to use advanced reservoir characterization as the most sophisticated means to estimate storage resource by defining reservoir properties for multiple facies within the St Peter Sandstone (Figure 16 – bottom left). This approach was limited to the Michigan Basin because the Illinois Basin data set did not have the requisite level of quality and sampling density to support such an analysis. Results from this approach led to a storage resource estimate of 15.4 gigatonnes to 50.1 gigatonnes for the Michigan Basin. The observed variability in results from the four different approaches was evaluated in the context of data and methodological constraints, leading to the conclusion that the storage resource estimates from the first two approaches may be conservative, whereas the net porosity-based approaches may overestimate the resource. Because of this uncertainty, regional estimates should not be considered as a substitute for site-specific characterization and assessment. As the site characterization process evolves from regional to site-specific, additional site-specific data will likely be collected and analyzed, thereby reducing uncertainty.

THE UNIVERSITY OF TEXAS AT AUSTIN

**A promising start to assessment and characterization of offshore $CO_2$ storage potential beginning in the Gulf of Mexico:** Subsurface environments in the offshore are a new and viable opportunity for the large-scale storage of $CO_2$ from anthropogenic sources. Preliminary investigations to characterize the complex geology of the subsurface in offshore environments are helping both researchers and policymakers evaluate the feasibility of carbon storage in an offshore setting. Currently, several research entities are correlating large volumes of existing geophysical data with core sample data to determine potential $CO_2$ storage volumes across several large areas in state and federal waters in the Atlantic Ocean and Gulf of Mexico.

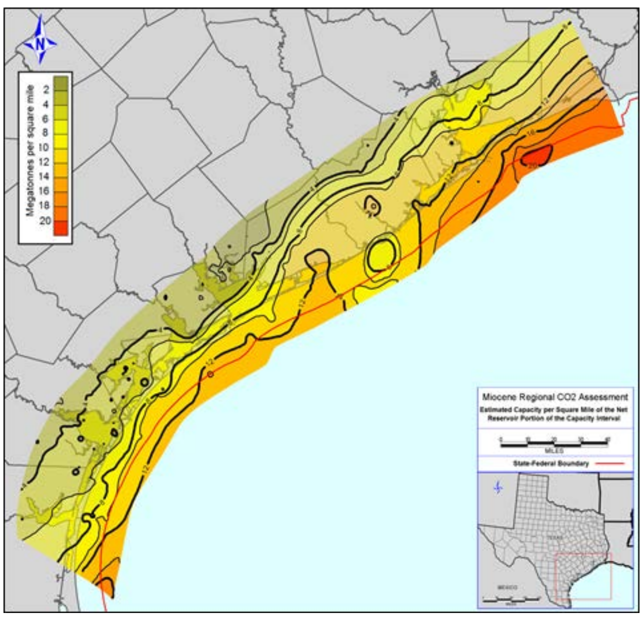



FIGURE 17. STATIC STORAGE CAPACITY PER SQUARE MILE WITHIN UT AUSTIN'S GULF OF MEXICO OFFSHORE STUDY REGION

As part of the ARRA site characterization initiative, the University of Texas at Austin (UTA) utilized well logs from over 3,300 wells and other data sources (such as paleontological markers) to evaluate formation tops and determine porosity for sand intervals within the state-owned portion of the offshore in the Gulf of Mexico. After the data were collected and processed, UTA conducted a statistical evaluation of the sand intervals within the Miocene-age offshore storage complex. Approximately 50 percent of the sands capable of storing $CO_2$ are relatively thin (less than 60 feet in thickness). Once sand thicknesses were established, UTA incorporated over 1,000 spontaneous potential and gamma ray logs into the regional capacity assessment (Figure 17) to produce a total estimated static storage capacity for the study area of 129 gigatonnes.

GeoMechanics Technologies

**The importance of identifying heterogeneity for capacity estimation:** Geomechanics Technologies performed a rigorous capacity assessment for an offshore turbidite setting—a depositional system that has not been rigorously assessed for $CO_2$ storage purposes. These turbidite deposits are found within the Pliocene and Miocene sediments in and surrounding the Wilmington Graben. The available and relevant data obtained by the project team included detailed stratigraphic and porosity/permeability information from across the Graben to help define the formation's heterogeneity. Heterogeneity of a storage setting's lithology can greatly affect its ability to store $CO_2$. Therefore, improving the knowledge of a storage system's geologic heterogeneity will improve storage estimate accuracy. The effort involved using lithology from 14 existing wells and 18 phantom wells (Figure 18), which are essentially virtual wells that are created from geologic data from other sources and are consistent with the general stratigraphic trend and turbidity environment. The background data were used to improve the representation of permeability heterogeneity in the models. In addition, to further define potential heterogeneity, multiple models with varying proportions of shales and sands were used. Formation stratigraphy models of the Pico, Repetto, and Puente lithologies within the Graben were created and mean porosity, volume, and percentage of each lithology type were calculated. These lithologic models were merged to represent a heterogeneous geologic model for the entire Wilmington Graben from basement to the top storage formation of interest (Pico Formation). Researchers used these models to run flow simulations to better understand formation injectivity, reservoir capacity, potential subsurface movement of injected $CO_2$, and pressure response. Results indicated capacities of 203 million metric tons ($P_{10}$), 796 million metric tons ($P_{50}$), and 2.15 billion metric tons ($P_{90}$).

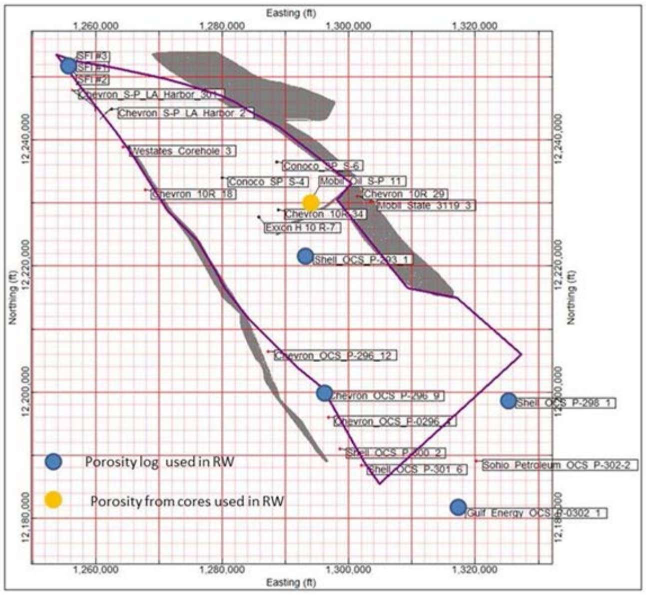



FIGURE 18. MAP DEPICTING LOCATION OF WELLS WITH POROSITY DATA USED FOR CAPACITY ESTIMATION. EXTENSIVE USE OF WELL DATA WAS USED AS INPUTS FOR THE MODELING ANALYSIS TO BETTER DEFINE GEOLOGIC HETEROGENEITY.

KU KANSAS GEOLOGICAL SURVEY The University of Kansas

**"Mega" scale simulation approached used to evaluate storage capacity in southern Kansas:** Simulations were constructed to evaluate commercial scale $CO_2$ injection into the Lower Ordovician Arbuckle Group saline aquifer at 10 sites, including those beneath the Wellington and Cutter oil fields. A "mega" scale simulation of the Arbuckle saline aquifer encompassing ~30,000 mi$^2$ spanning a majority of southern Kansas was used to evaluate storage capacity. The estimates of $CO_2$ capacity for the Arbuckle saline aquifer were based on potential injection volumes using a 16-layer Petrel model based on correlations of both vertical and horizontal permeability from whole core analyses obtained at Cutter and Wellington Fields. The properties of the resulting flow units that were mapped defined the safe rates of $CO_2$ injection, limited by the bottom-hole pressure. The modeling was conducted in two phases: (1) the injection of $CO_2$ at 10 sites where structural and stratigraphic conditions were similar to Wellington Field and (2) the injection at these 10 sites plus injection at 103 uniformly distributed wells in southern Kansas. The first model simulated injection for 50 and 100 years, and the second model for 150 years. Injections were limited to 5,900 metric tons/day per well, and injection pressure was limited to 150% of ambient pressure. The compositional simulation included structural, hydrodynamic, solubility, residual, and mineral trapping with a Cater-Tracy boundary to simulate an open boundary. In addition, as part of this study, modeling grids were refined within the vicinity of the 10 sites (Figure 19) to provide a more intensive analysis.

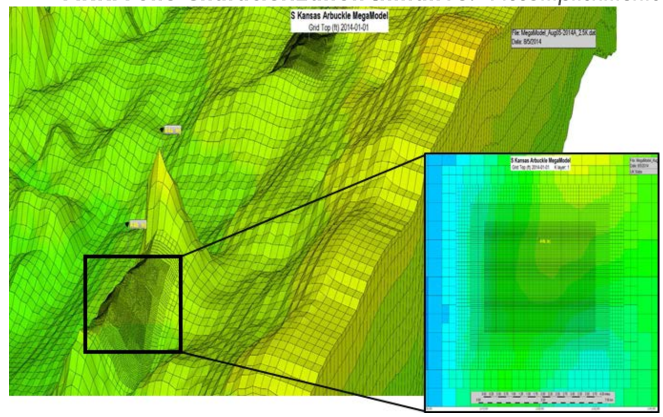


FIGURE 19. EXAMPLE OF LOCAL GRID REFINEMENT USED BY THE KANSAS GEOLOGICAL SURVEY IN THE MODELING FOR EACH OF THE 10 SITES IN THE WELLINGTON AND CUTTER FIELDS.

The simulations in the saline aquifer based on site specific data were compared to the resulting storage number with $P_{10}$ and $P_{90}$ values estimated using the U.S.-DOE methodology, which resulted in 8.8 and 75.5 billion metric tons respectively. However, the first generation simulation of 150 years of $CO_2$ injection estimated only approximately 4 billion metric tons of capacity. This simulation represents a partially closed system and could be considered conservative. Longer injection times and injection at additional wells could provide added storage and bring the simulation-based capacity number closer to the volumetric-based values from U.S-DOE. In addition, the Kansas Geological Survey's method of including site-specific conditions over a broader study area that accounts for heterogeneities, as well as basing $CO_2$ capacity from theoretical injection tests, is a unique approach for estimating $CO_2$ storage capacity across multiple sites.

## 3.4 Containment Analyses

The successful commercial-scale deployment of CCS will require assurance of containment of injected $CO_2$ at potential storage sites. The critical elements of $CO_2$ containment include the confining zones overlying the storage formation and any faults or fractures that occur within them. A confining zone is defined as one or more confining intervals that limit the vertical flow of $CO_2$ into other formations, USDWs, or the atmosphere. Examples of suitable confining interval(s) include shale and thick deposits of evaporate (such as gypsum or salt) that have relatively low permeability. The most significant aspects of containment within confining units are capacity, geometry, and integrity. Confining units must have adequate mechanical integrity as well as sufficient lateral extent to cover the structural, stratigraphic, or hydrodynamic storage reservoir in which the $CO_2$ is trapped. In addition, confining units should not contain transmissive faults in order to maintain an effective seal against the vertical migration of $CO_2$ or brine.[11] At supercritical conditions (common at most sites) $CO_2$ is lighter than saline water and oil but heavier than natural gas. In addition, unless an injection zone is strongly depressurized,

[11] Kaldi, J., Daniel, R., Tenthorey, E., Michael, K., Schact, U., Nicol, A., Underschultz, J., and Backe, G. 2013. Containment of $CO_2$ in CCS: Role of Caprocks and Faults. *Energy Procedia* 37. pp. 5403-5410.

$CO_2$ will be injected at pressure higher than hydrostatic, giving both $CO_2$ and associated saline water and other fluids energy to move outward from the injection area, including upward (referred to as buoyancy).[2] A confining zone must be regional in scale and separate the $CO_2$ injection zones from both the surface and USDWs over both the area where pressure is elevated such that saline water could be lifted to USDW and the area that will at some point in plume evolution be occupied by free-phase $CO_2$.

A number of factors affect the ability of confining zones to attenuate $CO_2$ movement and pressure perturbation, including the confining unit's rock texture, mineralogy, fabric alignment, abundance of organic material, diagenesis, macroscale sedimentary fabrics, burrows, and fractures, as well as the presence in the unit of laminae with high permeability. On a larger scale, the confining zones can be breached by (stratigraphic) lateral discontinuities, fracture networks, and faults. Since the modification of the stress field within a storage formation can be altered during and/or after injection of $CO_2$, and could potentially impact reservoir and confining zone mechanical integrity, it is critical for potential CCS site operators to understand the properties and limits of confining units at potential $CO_2$ storage sites. A primary objective of the ARRA Site Characterization projects was to perform stratigraphic assessments and investigate the containment mechanisms within their respective study regions. This includes studying the potential for stratigraphic trapping and other forms of containment (i.e., brine dissolution and mineralization). Specifics related to each project's individualized approach to assessing containment potential within their respective study region can be found in final project reports on the DOE's Office of Science and Technical Information webpage; and highlights are presented in the accomplishment summaries below.

**Long-term trapping of natural gas a good indicator of $CO_2$ containment potential:** For carbon storage to be successful, confining strata that ensure the safe permanent storage of $CO_2$ and protection of USDWs must be present. Virtually all commercial conventional reservoirs in the Black Warrior Basin are sandstone that is sealed by shale. Shale represents a low-permeability, dual porosity system in which gas is stored in free and adsorbed states. Laboratory analysis of shale from core taken from the Gorgas #1 test well was used to better understand how shale units function as seals for $CO_2$. Shale samples from the Pottsville Formation (Pennsylvanian), the Pride Mountain Formation (Mississippian), and the Red Mountain Formation (Silurian) were analyzed. X-ray diffraction, rock-eval pyrolysis, pressure-decay permeametry, porosimetry, fluid saturation, and $CO_2$ adsorption isotherm determination were used to evaluate the shale. Total porosity of the shale units ranged from 1 to 6 percent of bulk volume. Permeability of the shale formations parallel to bedding is less than 0.09 µD, indicating strong potential for containment, and permeability correlated well with total porosity in the shale.

While laboratory analysis of core suggests that properties associated with shale within the study area are favorable for $CO_2$ containment, the University of Alabama suggests that the preponderance of natural gas in commercial reservoirs within the study area indicates that the seals are capable of confining gas that is otherwise mobile and buoyant. Hydrocarbon traps can represent strong analogs for potential $CO_2$ traps because they have held buoyant oil or gas in place for possibly millions of years[12] and could contain $CO_2$ as well. This assessment provides a spatially broader perspective on trapping and containment capability than laboratory analysis of shale samples alone. In addition, this finding indicates that the principal geologic containment risks in the Black Warrior Basin are posed by natural fractures and faults, or new fractures and faults that could result from negligent $CO_2$ injection and subsequent over-pressurization.

**Paleozoic and Mesozoic rocks in the Rock Springs Uplift contain "world-class" confining layers seals:** Both the Paleozoic and Mesozoic stratigraphic sections within the Rock Springs Uplift contain several key confining layers. The micritic limestone in the upper Madison Formation (found at depths between 6,900 feet to 20,000 feet below ground surface [bgs]); the Amsden Formation (at approximately 7,700 feet bgs); and the Dinwoody Formation (found at depths between 5,000 feet to 17,000 feet bgs) are all robust confining layers that are continuous and have sufficient integrity to prevent the migration of $CO_2$ out of potential storage formations (Figure 20). The sealing quality of these confining layers explains the trapping of several gases (such as helium) in the Rock Springs Uplift in southwestern Wyoming.

[12] Bradshaw, J., Boreham, C., and la Pedalina, F. (2005). Storage retention time of $CO_2$ in sedimentary basins: Examples from petroleum systems. Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies (GHGT-7), September 5–9, 2004, Vancouver, Canada, v.I, 541-550.

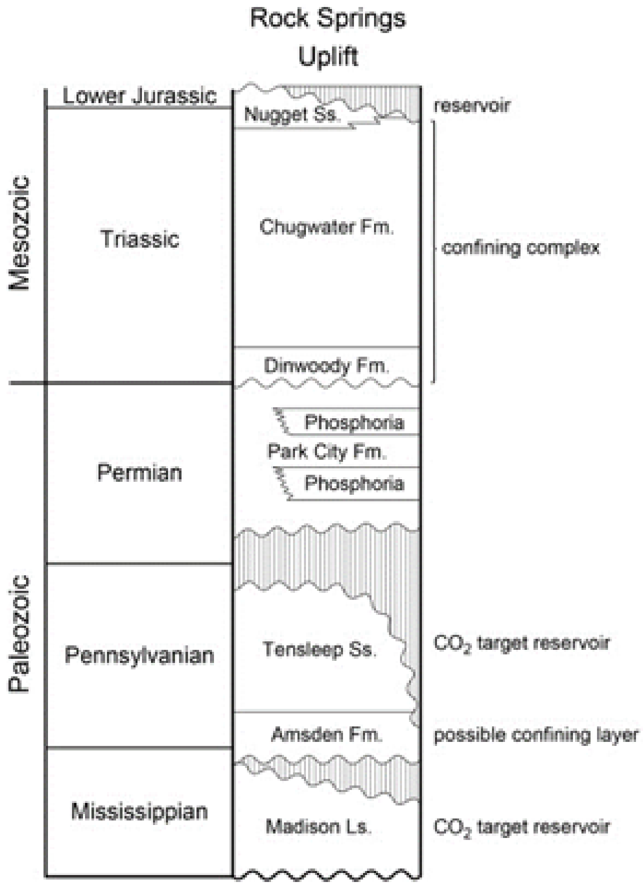



FIGURE 20. MODIFIED STRATIGRAPHIC COLUMN OF THE ROCK SPRINGS UPLIFT IDENTIFYING CONFINING LAYERS AND TARGET CO2 STORAGE FORMATIONS.

The University completed robust petrographic evaluations of capillary properties and rock strength of sealing formations present in the study area during the evaluation of $CO_2$ storage permanence of these confining layers. The project team also analyzed differences in dissolved gas compositions, rock/fluid inclusion volatiles, and the isotopic make-up of potential storage formations and confining units in order to determine whether any migration of fluids or fluid communication between the units was present. Seismic attributes (Figure 21 below) such as curvature, dip azimuth, dip magnitude, and energy-normalized amplitude gradient were used to evaluate the continuity of the confining layers in the storage area. The results from these evaluations demonstrated that the assemblage of confining layers in the stratigraphic interval (Figure 20 above) containing the Paleozoic reservoir rocks in the Rock Springs Uplift are continuous, impermeable, and capable of storing $CO_2$ over millions of years.

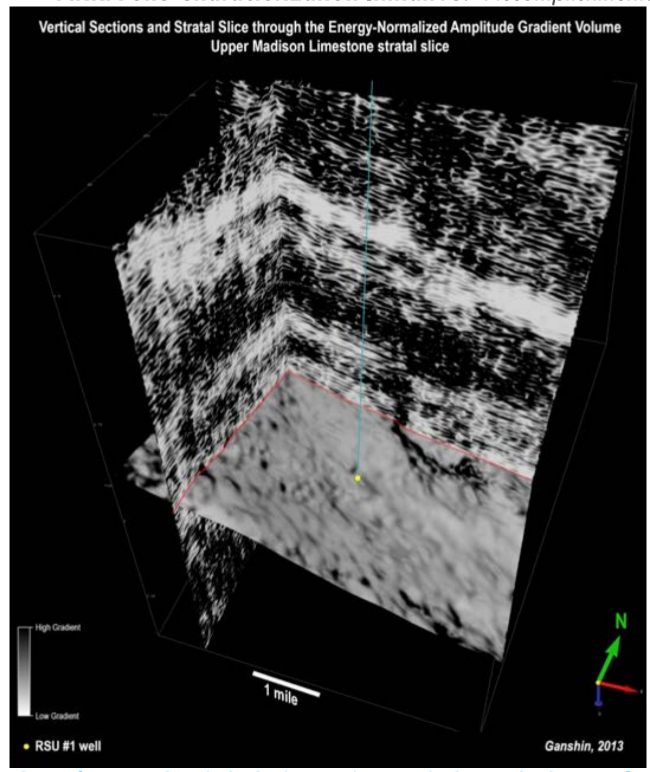



FIGURE 21. VERTICAL SECTIONS AND STRATA SLICE THROUGH THE 3-D SEISMIC SURVEY VOLUME OF THE UPPER MADISON LIMESTONE. THE HOMOGENOUS NATURE OF THE UPPER MADISON SUGGESTS THAT THIS INTERVAL HAS CONTINUOUS CONFINING INTEGRITY.

**Transmissive faulting in the South Georgia Rift Basin identified through integrated seismic and simulation approach:** The project—led by the South Carolina Research Foundation—determined that the mafic diabase intended as a confining layer was severely fractured, while intended sandstone reservoirs showed very poor porosity and permeability, giving rise to the hypothesis that the diabase could serve as a potential storage reservoir with the sandstone as a confining layer. This possibility was explored in a simulation which demonstrated that 30 million tons of $CO_2$ could be injected into multiple diabase units in the study area. Seismic interpretations suggested that some of the faulting in the study area may extend upward into the overlying Coastal Plain sediments, which contain USDWs.

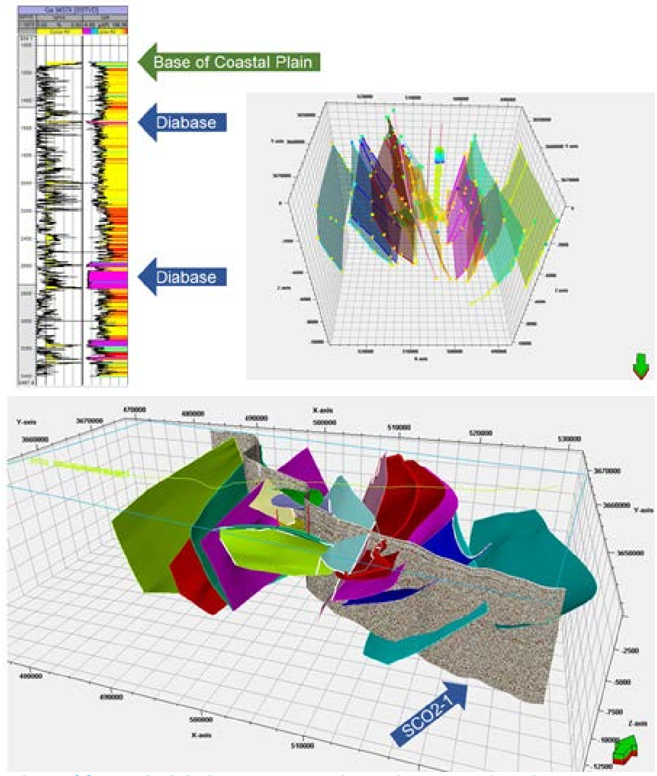



FIGURE 22. LITHOLOGIC INTERPRETATION FROM AN EXISTING WELL IN THE STUDY REGION SHOWING THE LOCATION OF POSSIBLE MAFIC DIABASE UNITS AND THE BASE OF THE COASTAL PLAIN AQUIFER (LEFT); AND A FAULT MODEL BUILT WITH SCO2-1 SEISMIC LINE DEMONSTRATING THE EXTENSIVE FAULTING IN THE STUDY AREA.

A total of 240 kilometers of new 2D seismic lines and a 3D seismic survey were acquired, processed, and interpreted in the South Carolina portion of the SGR basin. Seismic lines (SCO2-1 and SCO2-3 in particular) were reexamined to verify that faulting imaged by the initial interpretations was valid (Figure 22). The simulations demonstrated that these faults may provide a conduit for upward migration of $CO_2$ into the Coastal Plain aquifers, rendering the formation unsuitable for $CO_2$ storage given present geologic understanding. This combination of multiple approaches was used to provide a thorough assessment of storage potential in these diabase units. While the results were not favorable for future CCS in those formations, the investigation provides a valuable lesson in diligent characterization.

ILLINOIS STATE GEOLOGICAL SURVEY
PRAIRIE RESEARCH INSTITUTE

**Geochemical and fault analyses used to determine suitability of potential caprock in the Illinois Basin:** The Knox Dolomite and Maquoketa Shale were identified as primary caprock formations for the Illinois Basin due to their low permeability and relative formation thickness. However, the potential for the injected $CO_2$ to impact seal integrity due to geochemical reactions and/or migrate through transmissive faults within caprock were two significant concerns studied further by the Illinois State Geological Survey.

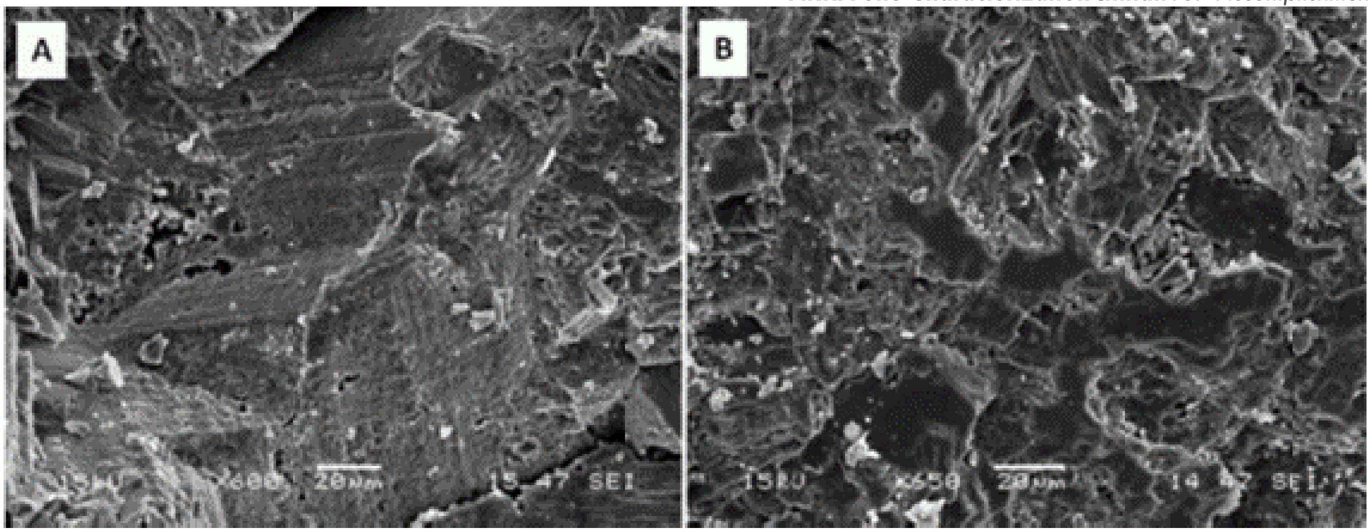



FIGURE 23. SCANNING ELECTRON MICROSCOPE IMAGES OF PRE- (A) AND POST-REACTION (B) POTOSI DOLOMITE TO $CO_2$ EXPOSURE. (A) PRE-REACTION SAMPLE SHOWS DOLOMITE CRYSTALS THAT ARE SLIGHTLY PITTED IN AREAS BUT MOSTLY CLEAN OF DEFECTS AND (B) SHOWS EXTREMELY ETCHED DOLOMITE CRYSTALS AND DISSOLUTION FEATURES.

Laboratory experiments were performed to identify the reaction mechanisms, kinetics, and solid-phase products that are likely to occur in the Knox Dolomite and the Maquoketa Shale when exposed to supercritical $CO_2$. Samples were obtained from the Illinois Basin Decatur Project, outcrops, and from existing cores from within the Illinois Basin. Experiments included high-pressure, high-temperature batch reactor experiments using samples from the Potosi Dolomite, Gunter and New Richmond Sandstone, and Maquoketa Shale.

Numerous analytical techniques were used to characterize the physical, geochemical, and mineralogical changes between the pre- and post-reaction products from the batch reactor experiments. These included standard petrography, scanning electron microcopy, X-ray diffraction, ion chromatography, and inductively coupled plasma analyses. Results were used to compare pre- and post-reaction petrographic and geochemical conditions, as well as kinetic and equilibrium predictions from numerical geochemical modeling.

Results indicated that the Knox Group could be sensitive to chemical reactions, including mineral dissolution, resulting from $CO_2$ storage (Figure 23). The findings also indicated that the reactivity and subsequent mineral dissolution would be short lived with equilibrium achieved shortly after exposure to a significant amount of $CO_2$. This, combined with the relatively thick primary and secondary seals make it highly unlikely that caprock integrity would be compromised. Establishing that geochemical reactions will not significantly impact caprock integrity is critical for the successful implementation of any carbon storage project.

GeoMechanics Technologies

**Fluid flow modeling approach used to assess $CO_2$ containment potential and highlight uncertain turbidite environment:** In order to demonstrate storage and sealing capability of the subsurface in the Wilmington Graben, the project team set up fluid flow models for two areas of interest in the Graben. The flow models included simulating injection at potential well locations at a constant pressure below fracture pressure over 30 years, with an additional 30 years of plume migration observation (Figure 24).

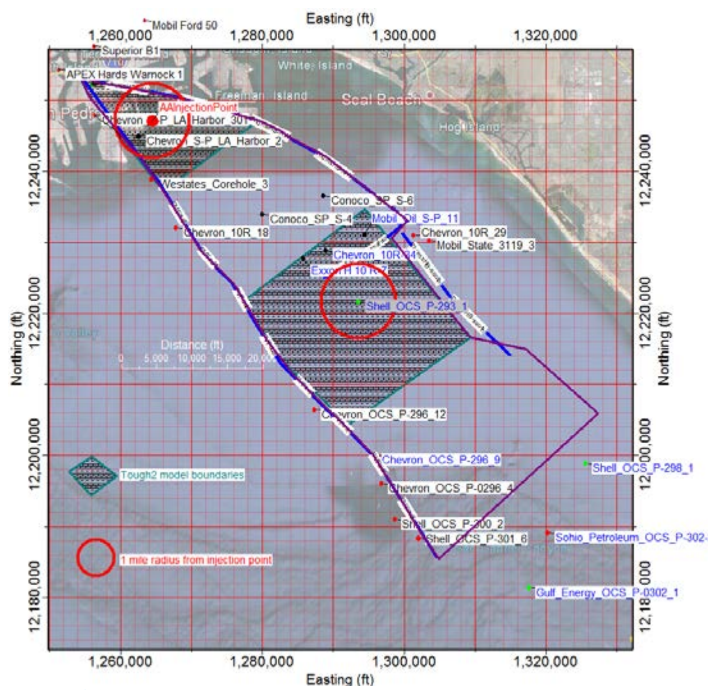



FIGURE 24. INTEGRATED FLUID FLOW MODELS (HATCHED AREA) USED BY GEOMECHANICS TECHNOLOGIES TO ASSESS CONTAINMENT POTENTIAL UNDER HYPOTHETICAL CO2 INJECTION IN THE WILMINGTON GRABEN.

The injection interval was located from 2,162 to 2,197 meters (7,093 to 7,208 feet) below the seabed in the Miocene sands for the northern Graben and at about 1,555 meters (5,100 feet) below the seabed in a sand interval approximately 50 meters (165 feet) thick in the central Graben. Given the presence of a turbidic environment in the Graben, making it by nature lithologically heterogeneous, several models were constructed to capture geologic variation, with various proportions of shales and sands throughout the Upper Repetto, which could potentially serve as a sealing caprock. Example model cases included high shale content models, assuming all sand/shale interbeds to be pure shale; in another variation a lower vertical permeability for the same shale material was assumed.

The simulation results indicate that even with higher shale content, lower vertical shale permeability, or better shale continuity due to modeling mesh refinement, $CO_2$ would not be fully contained within the desired vertical interval when injection is conducted at depths of around 1,525 meters (5,000 feet) below the seabed. The project team concluded from this modeling effort that large-scale $CO_2$ injection in the Wilmington Graben cannot be safely performed within the relatively shallow middle Pliocene formation. Results from this modeling study motivated efforts to further characterize the deeper Miocene formation for potential injection targets. The DOE #2 well drilled as part of this project encountered deeper target sand intervals on the order of 2,135 meters to 2,285 meters (7,000 to 7,500 feet) below the seabed. More importantly, the deeper sand intervals were overlain by relatively thick shale intervals (more than 30 meters [100 ft.] thick). In order to lower the risk of loss of containment during injection operations in the Graben, the project team suggests:

- A minimum injection depth of 7000 feet
- Minimum offset well spacing of 1 mile
- Maximum injection rates per well of approximately 200,000 metric tons per year

## 3.5 Modeling and Simulation Efforts

Modeling and simulation are used to test assumptions about the suitability of a potential storage formations to accept and retain $CO_2$ within the targeted zone, as well as to infer the potential of the candidate site to retain $CO_2$ over long periods. Mathematical models and numerical simulations are critical for the design, implementation, and analysis of $CO_2$ storage field tests; optimizing monitoring locations and protocols at $CO_2$ storage sites; as well as engineering and operating geologic $CO_2$ storage systems. In addition, models can be used for sensitivity analysis in assessing the importance of uncertainty in data.[4] Models must take such factors as rock porosity and permeability, temperature, faults and fractures, and multiphase flows into account. A primary objective of the ARRA Site Characterization projects was implementing modeling and simulation approaches for quantifying $CO_2$ storage capacity, risks, and uncertainty associated with risks in their respective study regions. In addition, The ARRA Site Characterization projects developed models to predict the movement of potential $CO_2$ plumes, as well as the pressure front, in the reservoirs that were studied via simulation of various injection operation scenarios (Figure 25). While the majority of the projects did not inject $CO_2$ as part of their study, reservoir simulation was the foundation that several projects used to predict the temporal and areal distribution of potential $CO_2$ and pressure plumes from theoretical $CO_2$ injections within their study areas. This type of analysis provided a unique, in-depth, and regionally-specific investigation of potential $CO_2$ storage potential for each project—a different approach to $CO_2$ storage potential estimation from the DOE methodology.**Error! Bookmark not defined.**

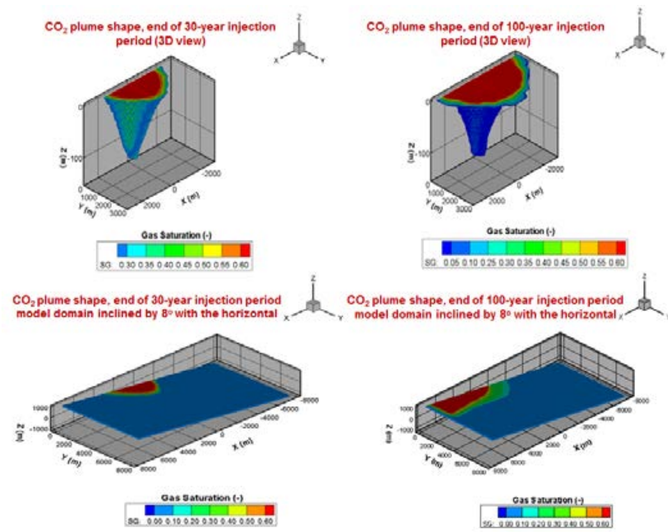



FIGURE 25. EXAMPLE OF $CO_2$ PLUME MODELING FROM THE SANDIA TECHNOLOGIES, LLC STUDY OF THE NEWARK BASIN. THE FIGURE DEMONSTRATES POTENTIAL PLUME EXTENT AT THE END OF A 30-YEAR $CO_2$ INJECTION (TOP LEFT), AT THE END OF A 70-YEAR OBSERVATION PERIOD (TOP RIGHT), AND WITH TILT TO THE STORAGE FORMATION (BOTTOM RIGHT AND LEFT).

The starting point for any reservoir model is a geologic model interpretation of the subsurface, which is developed from existing geologic and geophysical data as well as new data from dedicated characterization wells and seismic surveys. New site characterization data collected from the ARRA Site Characterization projects were combined with existing data within each project's study region and used to develop initial and boundary conditions for geologic models and reservoir simulations, as well as to establish baseline geochemical and geomechanical conditions.**Error! Bookmark not defined.** Using echnologies developed for hydrocarbon exploration and production, the geologic models were built using software platforms that enable integration, visualization, and analysis of multiple data types, including well logs, core, and seismic data.[13] Data such as porosity and permeability derived from well logs and laboratory measurements on core were analyzed using various geostatistical techniques to populate grid cells in a static geologic model with appropriate site/regional-specific reservoir properties. In addition, several projects have made extensive use of seismic data (surface 2D,

[13] Rodosta, T., Ackiewicz, M., and Albenze, E. (2014). Status update and results from the U.S. Department of Energy Regional Carbon Sequestration Partnership Initiative. *Energy Procedia* 63, pp. 6039-6052.

3D, and VSP) in developing their geologic models. Seismic data provides information on subsurface structures, lithology, and stratigraphic boundaries.

Overall, ARRA Site Characterization projects utilized individualistic approaches to develop numerical models and simulations as part of their studies. In most cases, these models helped to estimate overall $CO_2$ storage capacity, simulate the injection and migration of $CO_2$ under different scenarios, and evaluate injectivity within each project's respective study region. Specifics related to each project's individualized modeling and simulation approach can be found in the final project reports on the DOE's Office of Science and Technical Information webpage; highlights are presented in the accomplishment summaries below.

Sandia Technologies, LLC

**Reactive transport modeling sheds light on geochemical processes in the Newark Basin when samples were not available:** Flow and reactive transport modeling were conducted to demonstrate the feasibility of injecting one million metric tons per year of supercritical $CO_2$ over a 30-year facility life at a hypothetical site in the Newark Basin within a target storage formation located at a depth of ~1,500 meters (4,920 feet). Project partner Lawrence Berkeley National Laboratory performed the modeling using TOUGH2 and TOUGHREACT modeling platforms. The simulated $CO_2$ plume was predicted to extend to about 1,000 meters (3,280 feet) from the injection well after four years, and 2,000 meters (6,560 feet) after 30 years of injection.

As part of this study, the project team also planned to characterize dissolution of injected $CO_2$ into formation brine and better understand mineralization reactions of the injected $CO_2$ through reactive transport modeling, both of which impact long-term containment of $CO_2$ storage. Since deep formation fluid samples within the Tandem Lot #1 well could not be obtained due to borehole restrictions, and since deep fluid samples from within the basin were not found in the literature, the brine composition had to be reconstructed by geochemical modeling using shallow water chemistry data and other available information.

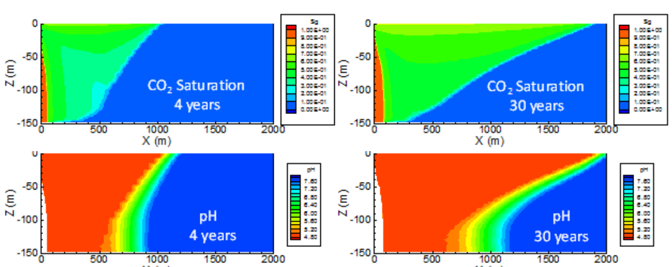



FIGURE 26. PREDICTED $CO_2$ SATURATION AND PLUME PH AFTER 4 AND 30 YEARS OF INJECTION. SIMULATIONS WERE PERFORMED WITH 2D RADIAL MODEL INCLUDING REACTIVE TRANSPORT

Some of the data required for hydrological and reactive transport modeling were developed through laboratory analyses of basin-specific core samples and shallow fluid samples recovered while drilling the project's deep exploratory well (Tandem Lot Well #1). The reaction path simulations show that under thermodynamic equilibrium, and without considering transport, the brine pH upon reaction with $CO_2$ drops to a value near 4, but then increases to about 5.5 in the case with dawsonite, and near 6 in the absence of dawsonite, as the formation minerals react with brine acidified with carbonic acid from $CO_2$ dissolution (Figure 26). Calcite was shown to dissolve, but it reaches equilibrium relatively quickly at a rock/water ratio about 0.1, since the dissolution of this carbonate mineral by $CO_2$ is self-limiting. In addition, through this effort, Sandia and the project team discovered that these chemical reactions can impact the physical properties of the subsurface. For instance, until the point when dawsonite (a sodium carbonate hydroxide) was predicted to become thermodynamically stable and allowed to form, the computed porosity change for this system was impacted only marginally.

KU Kansas Geological Survey, The University of Kansas

**Dynamic modeling at 10 regional sites and "MegaModel" commercial-scale simulation used to estimate storage capacity of the Arbuckle Group in southern Kansas:** The Kansas Geological Survey and partners conducted simulations to evaluate commercial-scale $CO_2$ injection into the Lower Ordovician Arbuckle Group saline aquifer at 10 sites in southern Kansas, including beneath the Wellington and Cutter oil fields. A "mega" scale simulation of the Arbuckle saline aquifer encompassing ~77,700 square kilometers (30,000 square miles) spanning a majority of southern Kansas was then conducted to evaluate storage capacity. The estimates of $CO_2$ capacity for the Arbuckle saline aquifer were based on injection volumes for a 16-layer Petrel model constructed on correlations of both vertical and horizontal permeability from whole core analyses, wireline logging, and 3D seismic porosity inversion obtained at Cutter and Wellington Fields located on the western and eastern portions of the southern Kansas study area.

The resulting flow unit properties were mapped to define safe rates of $CO_2$ injection, limited by the bottom-hole pressure. Simulations to estimate regional $CO_2$ storage capacity in the Arbuckle saline aquifer were conducted with CMG software running on a multi-parallel processing computer. The modeling was carried out in two phases: the injection of $CO_2$ at 10 sites in which structure and stratigraphic conditions were similar to Wellington Field, and injection at these 10 sites plus an additional 103 uniformly distributed wells in southern Kansas. The first model included injection for 50 and 100 years (roughly the life of an injection well) and the second simulated 150 years of injection. Injection volumes were limited to 5,900 metric tons per day per well and injection pressure to 150% of ambient pressure. The compositional simulation included structural, hydrodynamic, solubility, residual, and mineral trapping with a Cater-Tracy boundary to simulate an open boundary.

Simulation results indicated possible storage of 4.02 billion metric tons of $CO_2$ in the Arbuckle. Maximum bottom-hole pressure increased by 39.5% above ambient conditions, representing a gradient of 0.54 psi/foot, slightly above a normal hydrostatic pressure gradient in the region. The Arbuckle is under-pressurized relative to hydrostatic, so the pressure increase does not translate to a high-pressure gradient. The simulation results in the saline aquifer compared to the resulting storage estimate with the $P_{10}$ and $P_{90}$ values (8.8 and 75.5 billion metric tons respectively) estimated by the DOE methodology were slightly different. The results indicated that injection from additional wells and longer injection times could provide added recovery and bring the simulation-based capacity number closer to the volumetric-based values based on DOE methodology. In addition, the simulation represents a partially closed system and is thus conservative.

THE UNIVERSITY OF TEXAS AT AUSTIN

**Comparison of model complexity shines light on capacity estimation accuracy:** Both simple dynamic analytical and 3D numerical fluid flow simulations have been used to characterize the potential storage capacity of a specific reservoir within Texas's state waters. Simple dynamic analytical modeling was conducted for a discrete reservoir body in the Offshore Texas Miocene interval near San Luis Pass and assumed homogenous properties with high $CO_2$ sweep efficiency. Simulations using the simple dynamic approach included runs for 6,206 samples of porosity, permeability, and water saturation in a Gulf of Mexico Miocene gas reservoir. The resulting average capacity was found to be 30.3 megatonnes with an average fill time of 38.3 years.[14] The University of Texas at Austin also developed a homogenous 3D flow model that was run under various geologic and injection well quantity scenarios to show the $CO_2$ plume distributions after 100 years of injection. The dynamic analytical model is known to be overly optimistic, whereas the regional and 3D flow models attempt to more accurately model capacity.

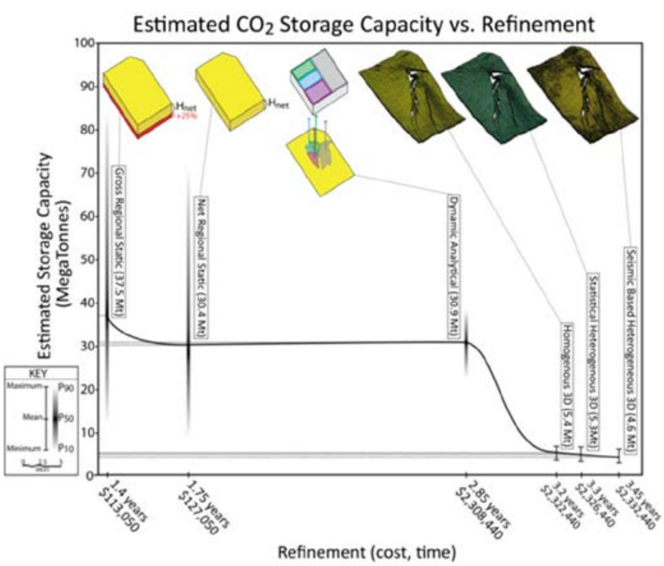



FIGURE 27. ESTIMATED $CO_2$ STORAGE VS. REFINEMENT. TIME AND COST FOR EACH STEP IS GIVEN ON THE X-AXIS. VERTICAL SHADING REPRESENTS PROBABILITY DISTRIBUTION AND VERTICAL BARS REPRESENT THE RANGE OF RESULTS. NOTE THAT THE HORIZONTAL SCALE IN THE KEY APPLIES TO ALL DIAGRAMS IN THE UPPER PORTION OF THE CHART.

The simple dynamic and 3D flow model capacity results are plotted along with normalized area and thickness regional capacity results (Figure 27) as a means of comparing results between approaches. Figure 27 also shows the value of estimated capacity vs. the amount of effort required to produce each refinement step (in cost and time).

The results indicate an 88% decrease in capacity from the initial dynamic estimate to the final 3D flow model results. Though this value is site specific, it highlights the need to consider the magnitude of error that can potentially be present in single value estimates of regional $CO_2$ storage capacity. The primary reason for the drastic difference in capacity between regional and site-specific models was found to be consideration of pressure. The dynamic regional estimate does not consider pressure and thus is likely to be overly optimistic. Pressure constraints and reservoir fracturing are not considered in the regional dynamic model approach, but are extremely limiting in 3D flow model simulations. Consequently, understanding and predicting pressure behavior and connectivity in a reservoir is key to understanding its storage capacity for $CO_2$ injection. The additional insight gained from using 3D flow models is significant and the additional time and cost is relatively minor. However, the primary benefit of the simple dynamic model is a basic understanding of fill time.

THE UNIVERSITY OF UTAH

The University of Utah built a 3D geocellular model of the Sand Wash Basin that included stratigraphic formation tops, well information, and well log images available from the project site data. Porosity values acquired from 20 existing wells within the Sand Wash Basin model boundary were assigned to the grid cells of the Dakota, Entrada, and Weber Formations. The constructed 3D model contains six formations beginning with the (uppermost) Cretaceous Dakota Formation and continuing to the (deepest) Weber Formation. The project team conducted a simulation of a hypothetical $CO_2$ injection via a single well into the deepest target formation (Weber) interval. An assumption was made that the overlying Chinle formation works as a perfect seal, thus flow would not be expected beyond the top of the Weber Formation.

Four independent variables were key factors for the model: thickness and permeability of the Weber Formation, permeability anisotropy ratio, and formation temperature. Likely variations in each factor were scaled to -1 and 1 for minimum and maximum of the range, respectively. Log-normal distribution was assumed for the permeability of the Weber Formation with a mean (υ = 100 mD) and standard deviation

[14] Jain, L., and Bryant, S. (2011). Time weighted storage capacity for geological sequestration, in Gale, J., Hendriks, C., and Turkenberg, W., eds., 10th International Conference on Greenhouse Gas Control Technologies, Volume 4: *Energy Procedia*, p. 4873-4880.

(σ=1). The thickness of Weber Formation ranged from 61 to 244 meters (200 to 800 feet) based on the project's initial geologic interpretation. The anisotropy ratio ($k_v/k_h$) was assumed to be constant but ranged from 0.1 to 1. Finally, reservoir temperature was assumed to be isothermal and its variation among the numerical experiments ranged from 65 to 92 °C (150 to 198 °F).

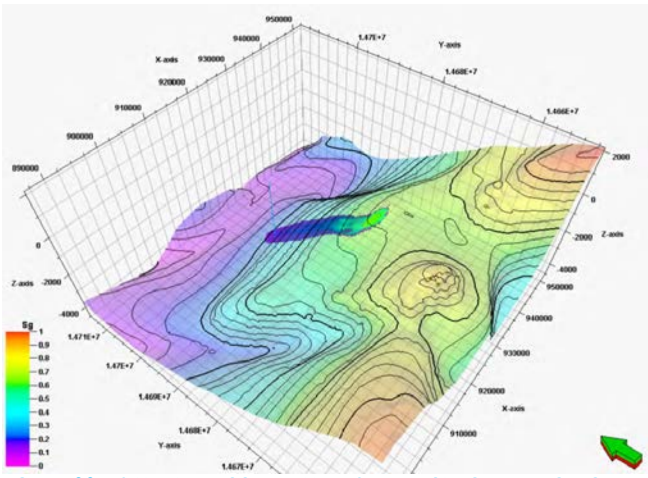



FIGURE 28. SIMULATED $CO_2$ PLUME DISTRIBUTION OF THE TOP OF THE WEBER AT 40TH YEAR AFTER THE $CO_2$ INJECTION ACTIVITY CEASES.

Given the design of experiment specified from the modeling assumptions, the project team numerically modeled 25 cases in which the key factors described above varied from case to case in all simulations. Supercritical-phase $CO_2$ was injected into the Weber Formation over a two-year period at a rate of 1 million metric tons per year, totaling 2 million metric tons. Total simulation time for this study was 100 years, which included the injection component. Both top and bottom layers of the model impose no-flow conditions, imitating the situation where the $CO_2$ injection formation was present under the regionally extended, low-permeability caprock and above basement rock. Figure 28 shows the simulated $CO_2$ plume distribution of one modeling iteration at the 40th year after the $CO_2$ injection activity ceases.

ILLINOIS STATE GEOLOGICAL SURVEY
PRAIRIE RESEARCH INSTITUTE

**Reservoir simulation of commercial injection volume into Knox illustrates injectivity and storage potential in vuggy environment:** The objective of the Knox injection modeling study was to provide guidance on reservoir and caprock properties, which are critical to the site selection process and the success of a potential storage project. In addition, because of the major uncertainties of the vugs on reservoir permeability in the region, the Illinois State Geological Survey and partners also focused on vuggy zone permeability, distribution, and interconnectivity in the Potosi Dolomite within the Knox Supergroup.

A new property modeling workflow was applied to best capture subsurface features associated with the vuggy environment. This workflow included seismic inversion data, which was the basis for porosity mapping and geobody extraction.[15] A static reservoir model was fully guided by PorosityCube interpretations and derivations coupled with petrophysical logs from three wells within the study region. The two main assumptions taken by the project team in this approach were (1) porosity features in the PorosityCube that correlate with lost circulation zones represent vugular zones and (2) that these vugular zones are laterally continuous. Extrapolation was conducted to populate the vugular facies and their corresponding properties outside the seismic footprint up to the boundary of the 48 by 48 kilometer (30 by 30 mile) model. Dynamic simulations were run using an injection target of 3.2 million metric tons per year for 30 years.

Reservoir simulation resulted in a cumulative injection of 39 million metric tons in 30 years with a single well, which corresponded to 40% of the injection target. The injection rate was approximately 3.2 million metric tons per year in the first six months as the well was injecting into the surrounding vugs; then the rate declined rapidly to 1.6 million metric tons per year in year three once the surrounding vugs were full and the $CO_2$ started to reach the surrounding matrix. In year 18, the injection rate declined gradually to 1.1 million metric tons per year and remained constant, implying that a minimum of three wells could be required in the Potosi Dolomite to reach the injection target (maintaining 3.2 million metric tons per year for 30 years). The injectivity evaluated was higher than expected likely because the facies modeling approach used (guided by the porosity map from the seismic inversion) indicated a higher density of vugs within the vugular zones.

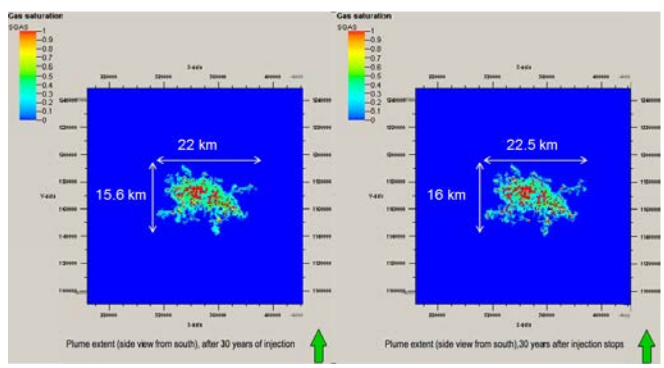



FIGURE 29. POTOSI DYNAMIC MODEL PLUME EXTENT, TOP VIEW. LEFT: AFTER 30 YEARS OF INJECTION. RIGHT: 30 YEARS POST- INJECTION.

A reasonably large and irregular plume extent was created (Figure 29) as the $CO_2$ followed the paths where vugs were connected. After 30 years of injection, the plume extended 22 kilometers (13.7 miles) in the east-west direction and approximately 16 kilometers (9.7 miles) in the north-south direction. The plume continued to migrate laterally after injection was complete, driven mainly by the remaining pressure gradient. After 60 years post-injection, the plume

[15] Adushita, Y., and Smith, V. 2014. The Potosi reservoir model 2013c, property modeling update, U.S. Department of Energy, topical Report DOE/FE0002068-16 48 p.

extended 22.5 kilometers (14.2 miles) in the east-west and 16 kilometers (10 miles) in the north-south directions and remains constant. The remaining pressure gradient has become very low.

Overall, developers of a planned CCS project targeting the Knox—compared to a reservoir dominated by intergranular porosity—should plan a relatively more extensive effort to confirm site-specific ability to track the $CO_2$ plume in the subsurface. This is important because flow in a Knox reservoir is more likely to be dominated by thin horizons of exceptionally high vuggy permeability. Thin vuggy horizons are more likely than intergranular-porosity-dominated horizons to be laterally discontinuous or intermittent. Additionally, vuggy horizons that are generally stratigraphically separate may be linked through vertical high-permeability zones, and a $CO_2$ plume may migrate relatively quickly in an unexpected direction. Lastly, $CO_2$ saturation in thin horizons can be difficult to image seismically.

## 3.6 Risk Assessment

Risk assessment is used in many disciplines and can be applied broadly to geologic $CO_2$ storage projects to understand and mitigate an array of potential impacts to a project. As applied to geologic storage, the primary focus is typically on the adverse impacts from a potential loss of $CO_2$ storage integrity resulting in the migration of $CO_2$ out of the confining zone. Often, numerical simulation and risk analysis are used iteratively in conjunction with site characterization, monitoring, and public outreach throughout all of the stages of a geologic $CO_2$ storage project (site screening, site selection, project design, project operation, and long-term stewardship) to help meet the goals of safe, secure, and verifiable permanent storage. A more comprehensive risk analysis would also explore the potential for adverse impacts from other project-related operational and financial events such as those that occur on the surface or in the policy arena.

Successful implementation of geologic $CO_2$ storage projects requires that project developers compare critical criteria among candidate sites including storage capacity, containment analysis, health and environmental safety, economics, regulatory framework, monitoring efficacy, and potential ancillary benefits such as enhanced hydrocarbon production. Risk assessment and numerical simulations will guide CCS implementation by providing stakeholders (operators, project developers, general public, and regulators) with information to predict the long-term fate of $CO_2$ including, but not limited to, the projected amount of long-term $CO_2$ storage, potential risks, and consequences of $CO_2$ leakage in that area, and probabilistic leakage rates from specific geologic formations in which $CO_2$ is injected.

There could be a number of uncertainties associated with any potential site at the start of the site selection process, prior to characterization. An initial risk analysis and numerical simulation conducted at this time will help bound these uncertainties, along with subsequent site characterization activities. However, uncertainties may still remain about site performance under $CO_2$ injection. Any remaining uncertainties about the site could then potentially be addressed through an effective site monitoring protocol. Monitoring and site characterization together can provide data critical for developing improved models, conducting associated risk analysis, and playing a role in accounting and verification. As seen from the ARRA Site Characterization Initiative, activities such as risk assessment, numerical simulation, site characterization, monitoring, and public outreach, are interdependent, but these types of activities were carried out in an integrated manner (Figure 30).[16]

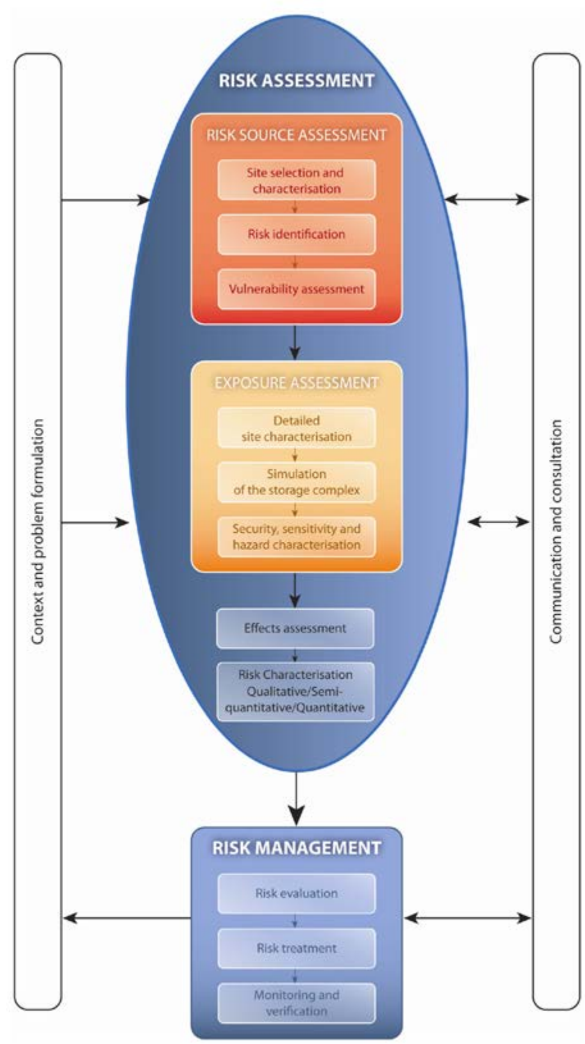



FIGURE 30. RISK MANAGEMENT WORKFLOW DIAGRAM FOR A COMMERCIAL-SCALE STORAGE DEPLOYMENT PROGRAM. ADAPTED FROM INTERNATIONAL ENERGY AGENCY GREENHOUSE GAS PROGRAMME.[17]

[16] National Energy Technology Laboratory. 2011. Best Practices for Risk Analysis and Simulation for Geologic Storage of $CO_2$. DOE/NETL-201/1459

[17] IEAGHG. 2009. A review of the international state of the art in risk assessment guidelines and proposed terminology for use in $CO_2$ geological storage. 2009/TR7.December 2009.

The risk assessment activities conducted through the ARRA Site Characterization Initiative occupy a spectrum ranging from determining uncertainty regarding capacity estimation and containment analysis through environmental impact assessment. (See Table 5, Risk Assessment Activities.) A few projects performed comprehensive risk assessments in which they made systematic efforts to identify risks pertaining to geologic carbon storage at their respective sites and evaluated them in terms of their likelihood and severity of consequences should they ever manifest. Some projects itemized specific operational risks (e.g., drilling risks) and some discussed specific mitigations (Table 5).

None of these projects reported attempting to develop a comprehensive risk management plan that included mitigation components. Given that these projects involved no appreciable $CO_2$ injections, this limitation may be reasonable; it does, however, mean that risk management may require further attention before industrial operations can commence.

TABLE 5. RISK ASSESSMENT ACTIVITIES

| Project Performer | Region | Formation(s) | Technical Risks Identified | Risk Assessment Approach |
|---|---|---|---|---|
| **Geomechanics Technologies** | Wilmington Graben | ▪ Repetto<br>▪ Puente | Lateral migration to poorly cemented offset wells | Detail well record review and reservoir-scale fluid and migration modeling. |
| | | | Injection well failure and transmission | Stress analysis and near-well migration modeling. |
| | | | Caprock integrity | Geomechanical analysis of fracture and fault activation risks. |
| | | | Natural seismicity | Historical review of impacts on oil and gas and gas storage operations from natural seismicity in the study region. |
| | | | Induced seismicity | Analog review, geomechanical analysis, and microseismic monitoring. |
| | | | $CO_2$ migration to sea floor and consequences | Analog review, rate assessment, and biologic impact estimate. |
| **Sandia Technologies** | Newark Rift Basin | ▪ Stockton<br>▪ Passiac<br>▪ Basalts | Public acceptance | Implementation of a public outreach program specifically designed to follow a top down, early engagement approach to inform local decision/policy makers of the project, field work plans and objectives, and expected impacts on the local community (seismic survey and drilling activities). |
| | | | Field operations | Detailed project health and safety plans developed for all field work. Plans were reviewed at the beginning of each work shift and at the beginning of any new activity to ensure that all site workers understood the work to be accomplished during the day and to designate clear lines of communication and responsibility. |
| | | | Drilling risks | Drilling plans for the deep and shallow stratigraphic boreholes were designed to emphasize protection of local sources of groundwater drinking water. |
| **University of Alabama** | Black Warrior Basin | ▪ Pottsville<br>▪ Parkwood<br>▪ Pride Mountain<br>▪ Bangor<br>▪ Tuscambia<br>▪ Hartselle<br>▪ Stones River Group<br>▪ Knox Group | ▪ Seal risk<br>▪ USDW's<br>▪ Injectivity<br>▪ Capacity<br>▪ Faults | Risk analysis matrix used to evaluate the severity and likelihood of risks affecting $CO_2$ storage opportunities in the Black Warrior Basin (based on matrix in the Schlumberger Hazard Analysis and Risk Control Standard 20) |
| **University of Illinois** | Illinois Basin | Knox Group | ▪ Wellbore stability<br>▪ Legacy wells<br>▪ Capacity<br>▪ Fractures<br>▪ Faults<br>▪ USDW's<br>▪ Injectivity<br>▪ Caprock Integrity | Screening criteria (risks) were spatially overlain on mapped geologic properties using geographic information systems. |

| | | | | |
|---|---|---|---|---|
| **University of Kansas** | Arbuckle Group and Ozark Plateau, southern Kansas | ▪ Arbuckle<br>▪ Mississippian Chert Dolomite<br>▪ Chester Sandstone<br>▪ Marrow Sandstone | ▪ Faults<br>▪ Fractures | Faults were identified and characterized for potential for leakage through (1) regional structure and isopach mapping across the study area; (2) local 3D seismic volumes; (3) potentiometric surfaces of regional aquifers; (4) use of geochemistry and stable isotopes to evaluate communication between hydrostratigraphic units; (5) utilization of well tests to evaluate the presence of conductive fractures and faults; and (6) lineament analysis of land surface to evaluate potential leakage from deeper aquifers. |
| **South Carolina Research Foundation** | South Georgia Rift Basin | ▪ Jurassic formations<br>▪ Triassic formations | Permeability | The effect of uncertainty in permeability heterogeneity in the injection reservoir on simulated $CO_2$ plume migration was evaluated through a spatially correlated random field of permeabilities ranging from 10 mD to 100 mD. |
| **University of Texas at Austin** | Texas State Waters | Miocene Sediments | ▪ Capacity<br>▪ Injectivity | CO2-PENS analysis (Predicting Engineered Natural Systems) for reservoir studies. |
| | | | Infrastructure | SimCCS analysis (spatial infrastructure model for carbon capture and sequestration) for optimization of infrastructure and costs. |
| | | | Environmental | Assessment of environmental risks specific to offshore settings through Environmental Defense Fund study. |
| **University of Utah** | Sand Wash Basin | ▪ Weber<br>▪ Entrada<br>▪ Dakota | ▪ Area of Review size<br>▪ Subsurface pressure build up | Applied a response-surface method – combined Monte Carlo sampling – to quantify major risk features, events, and processes (FEPs). |
| | | | Drilling risk | Formed a team of drilling experts to review the operation and identify the potential risks and rank their likelihood and severity. Each identified risk outside of safe operating conditions was treated with a mitigation plan until it fell within safe operating levels. |
| **University of Wyoming** | Rock Springs Uplift | ▪ Tensleep<br>▪ Madison<br>▪ Weber<br>▪ Bighorn | Artificial penetrations (producing and abandoned wells) | Development of a borehole and well catalog for southwest Wyoming, which includes well construction, formations penetrated, geospatial location, and assessment of leakage potential. |
| | | | Surface accumulation of $CO_2$ | Risk matrix created for surface accumulation of carbon dioxide leaking from an abandoned oil and gas well.  156 (out of 269 total) wells with elevated risk of surface accumulation of leaking carbon dioxide due to their proximity to surface depressions. |

Specifics related to each project's individualized approach to risk assessment strategy can be found in final project reports on the DOE's Office of Science and Technical Information webpage, and highlights are presented in the accomplishment summaries below.

GeoMechanics Technologies

**Seismicity risks evaluated in the Wilmington Graben – A regionally-significant issue:** GeoMechanics Technologies completed a comprehensive analysis of risks associated with $CO_2$ injection in the Wilmington Graben. Specifically, the project team assessed lateral $CO_2$ migration to offset wells, caprock integrity, and seismicity, which is an important risk consideration given the location of the Wilmington Graben.

The Southern California area is a highly seismically active region, with historically strong ground motion throughout the Los Angeles Basin (Table 6). The Southern California area is also a very prolific oil and gas producing region, with more than 100 years of production (and associated injection operations) from more than 50 medium to very large-scale oil and gas fields. There are more than 24,000 deep production and injection wells in Los Angeles and Orange Counties, including more than 1,000 wells within and a few miles of the Wilmington Graben. These wells have experienced decades of seismic activity with no dangerous release of gas to the surface during or following earthquakes. Table 6 details those seismic events considered 'major" (greater than magnitude 5.0). Notice that major earthquakes in southern California occur in deep (>7,620 meters [>25,000 feet]) brittle basement rock, and the shallower (3,048 meters [<10,000 feet]) soft sediments penetrated by wells that are less affected by deformation.

TABLE 6. MAJOR EARTHQUAKES (>5.0 MAGNITUDE) IN THE LOS ANGELES BASIN

| Name | Date | Magnitude | Depth (meters) | Fault/Location |
|---|---|---|---|---|
| Northridge | January 1994 | 6.7 | 14,478 | Northridge (Pico) – 35 miles northwest of Graben |
| San Fernando/Sylmar | February 1971 | 6.6 | 11,278 | San Fernando – 45 Miles north of Graben |
| Long Beach | March 1993 | 6.4 | 8,999 | Elsinor – 35 miles east of Graben |
| Elsinor | May 2010 | 6 | 10,058 – 11,887 | Elsinor – 35 miles east of Graben |
| Whittier Narrows | October 1987 | 5.9 | 15,598 | Puente Hills – 20 miles north of Graben |
| Lytle Creek | September 1970 | 5.2 | 8,397 | San Jacinto – 40 miles northeast of Graben |
| Sierra Madre | June 1991 | 5.8 | 18,402 | Sierra Madre – 30 miles north of Graben |
| Upland | February 1990 | 5.5 | 12,002 | San Jose – 30 miles northeast of Graben |
| Chino Hills | July 2008 | 5.5 | 8,999 | Yorba Linda Trend – 35 miles northeast of Graben |
| Malibu | January 1979 | 5.2 | 9,502 | Anacapa-Dume – 25 miles northwest of Graben |
| Pasadena | December 1988 | 5 | 7,902 | Raymond – 25 miles north of Graben |

Potential $CO_2$ injection wells within the region would likely not penetrate deep basement rocks where major earthquakes are generated. In fact, all injection scenarios envisioned within the Wilmington Graben would penetrate no deeper than 2,743 meters (9,000 feet), and the shallowest of the major earthquakes of the past century was sourced below 7,620 meters (25,000 feet).[18]

The closest fault to the Wilmington Graben (apart from its defining faults) is the Newport-Inglewood fault (of which the Thums-Huntington Beach fault is a splay), which lies just to the northeast (extending to the southeast). This is a right-lateral strike-slip fault "zone", consisting of a system of northwest-trending active strike-slip and oblique-slip faults, roughly parallel to the San Andreas Fault. The southern portion of the fault last moved in the 1933 Long Beach earthquake of magnitude 6.3, but there was no surface rupture. The estimated depth of this earthquake was approximately10 to 12 kilometers (33,000 to 39,000 feet).[19] The fault zone may include the Thums-Huntington Beach fault, defining the northeast edge of the graben. However, there has been no activity on this fault recorded in the past 200 years.

Though the Newport-Inglewood fault zone is clearly active, evidence suggests that it's splay, which defines the northeast boundary of the Wilmington Graben (the Thums-Huntington Beach fault), is most likely not. However, the graben's southwestern defining fault (the Palos Verdes fault) is thought to have ruptured at some point in the past 15,000 years and is thought to have a current slip rate of 3 millimeters/year. Furthermore, the Palos Verdes fault is a vertical right slip fault, with a visible expression on the seabed and reaching to a depth of about 13,304 meters (42,650 feet).[20]

The project team also investigated the risk to surface facilities in the study region. Concerning the seismic stability of surface facilities, data for the Wilmington Graben suggests that peak ground acceleration during an earthquake would be 60– 80% g (acceleration due to Earth's gravity) with a 2% chance of exceedance in 50 years (potentially damaging, but with a recurrence rate of only every 2,500 years), and less than 40% g, with a 10% chance of exceedance in 50 years (safe for a modern facility, and with a recurrence rate of every 500 years), based on United States Geological Survey (USGS) seismic hazard data collected using the USGS's Ground Motion Interpolator.

UNIVERSITY OF WYOMING

**Well database in the RSU provides means to assess leakage risk potential around candidate storage sites:** The University of Wyoming and project partners developed a borehole catalog database and risk assessment for southwest Wyoming. This approach included development of a catalog of boreholes in a hypothetical project area of review, identification of boreholes penetrating potential reservoirs and their seals, documenting construction of penetrating boreholes, and determining their potential leakage risks.

An AoR with a 16 kilometer (10 mile) radius was established centered on the location of the project's stratigraphic test well RSU #1. A 1.6 kilometer (1 mile) buffer encircling this AOR was also included. Statewide data for active and abandoned oil and gas wells were downloaded from the Wyoming Oil and Gas Conservation Commission website, which revealed that 262 wells of different types (oil, gas, injection, etc.) fell in this defined area around RSU #1. The associated data downloaded for each well encompassed 42 data columns of information, including API #, total depth, well class, longitude, latitude, status, status date, bottom formation, section, township, land type, county, etc. In addition to the data discussed above, and applications to drill sundries, well logs

[18] Southern California Earthquake Center (SCEC). Retrieved from: http://www.data.scec.org/significant/index.html

[19] Hauksson, E., and Gross, S. 1991. Source parameters of the 1933 Long Beach earthquake. Bull. Seism. Soc. Am. 81, 81-98.

[20] California Geological Survey. 2002. California fault parameters – Transverse Ranges and Los Angeles Basin, available at: http://www.consrv.ca.gov/cgs/rghm/psha/fault_parameters/htm/Pages/CA_flt_parameters_tr_la1.aspx#Palos%20Ve.HTM

and well records were downloaded and added to the geodatabase for the 262 wells in the footprint of the AoR and buffer.

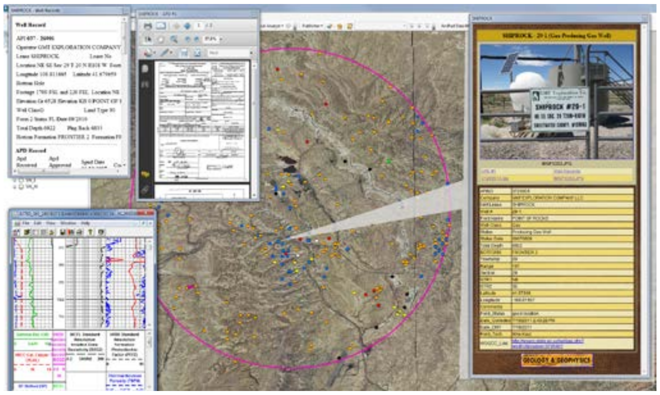


FIGURE 31. SCREEN CAPTURE OF THE RSU WELL CATALOG USER INTERFACE.[21]

The Rock Springs Uplift well data were organized into an interactive database that contains all of the data mentioned previously. A graphical user interface allows access to a well's records by simply clicking on the well symbol (Figure 31).

To address the need to convey risk assessments, a preliminary graphical leakage risk matrix (GLRM) was developed for assessing individual well leakage risk. The parameters found to be most important in assigning leakage risk were well penetration, well location, well status, well construction, cementing and plugging procedures, artificial and natural connectivity, surface $CO_2$ accumulation potential, and surface infrastructure proximity. Each of these parameters was assigned a weighting factor and a numerical constant that normalized all risk parameters to the same quantitative scale. The contributions from all these risk factors were summed to produce a cumulative leakage risk for each well displayed on the right-hand side of the GLRM.

Results from a subset of the data indicated that within the RSU AoR, 185 wells were permanently abandoned, of which thirteen have no recorded abandonment date. These wells have been assigned a 6, the highest level of risk (Nelson, 2013). Twenty-three wells abandoned between 1933 and 1962 were assigned a risk level of 5. An additional 100 wells fell in the 3-4 risk categories, and only seventeen wells abandoned since 1998 have risk levels of 1. A major permitting requirement of a Class VI well is the evaluation of the potential for $CO_2$ leakage from every artificial penetration in the AoR. If a well may be likely to allow $CO_2$ to escape, it must be remediated before a site construction or operating permit can be issued. Those wells with older abandonments pose a higher risk for leakage and should be evaluated accordingly. In addition, there were 156 (out of 269) wells with elevated risk of surface accumulation of leaking $CO_2$ due to their proximity to surface depressions.

The well catalog databases provide a means to utilize available well data to begin evaluating the risk factors identified by the GLRM. Thus, a cumulative leakage risk level calculated from these factors can be calculated for each well in the RSU AoR. This approach could be used to assess leakage risks from wellbores in other regions to inform candidate commercial $CO_2$ storage operations.

THE UNIVERSITY OF TEXAS AT AUSTIN

There are 45 individual industrial $CO_2$ sources within 200 kilometers (124 miles) of the Texas coast, each emitting more than one million metric tons of $CO_2$ per year. UT at Austin and partners analyzed the infrastructure requirements needed to capture, transport, and store $CO_2$ emissions from the major industrial sources in this region. The project team selected SimCCS—an economic-engineering optimization model—for CCS infrastructure. SimCCS was used to design a geospatially realistic pipeline network while simultaneously considering where and how much $CO_2$ to capture and store, as well as finding the lowest-cost routes. The 45 sources are spread along roughly 400 kilometers (248 miles) of Texas coast, and each source is within 115 kilometers (70 miles) of its closest offshore reservoir. Consequently, for modeling purposes, the 45 sources have been grouped into 13 separate regions. Typically, low-cost routes are identified using a shortest path algorithm run on a cost surface. The cost surface used in this study was modified for the Texas coast and considers sensitive and protected coastal areas.

The project team examined 18 different $CO_2$ management scenarios for the study ranging from capturing-transporting-storing five million metric tons of $CO_2$ per year through 90 million metric tons of $CO_2$ per year over a 50-year period. All infrastructure costs were capitalized over the 50-year time period using a 10% interest rate.

[21] Kirkwood R., & Myers J. 2012. Using GIS to Advance Geological Carbon Sequestration. 2012 ERSI International Users Conference, July 23-27, 2012, San Diego, CA.

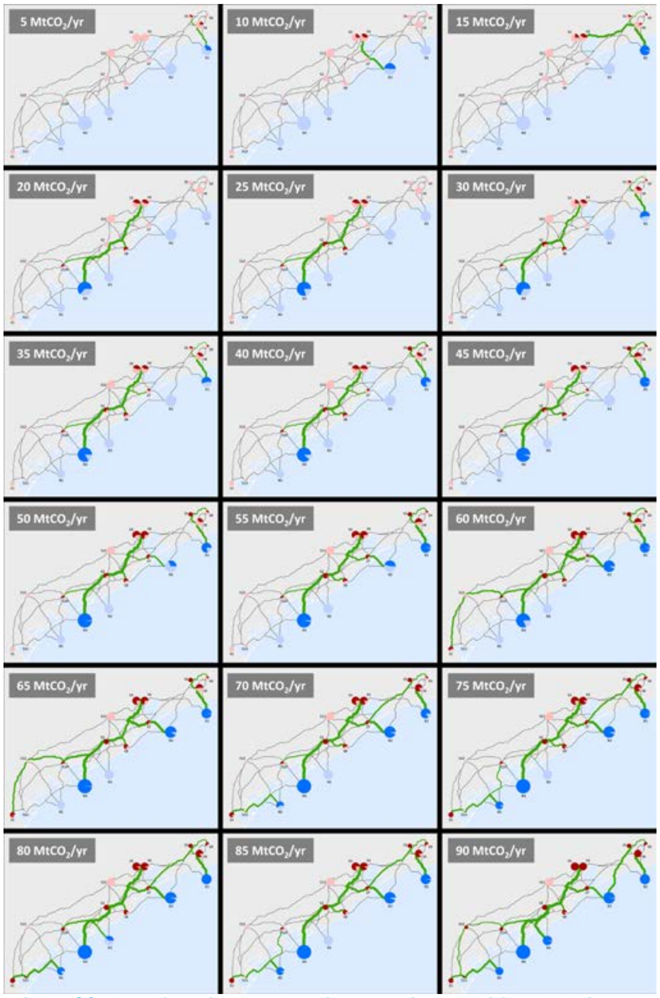


FIGURE 32. INFRASTRUCTURE MAP FOR THE EIGHTEEN $CO_2$ MANAGEMENT SCENARIOS. $MTCO_2$/YR = METRIC TONS OF $CO_2$ PER YEAR.

Figure 32 above illustrates the spatial layout of CCS infrastructure (capture, transport, and storage) for the 18 $CO_2$ management scenarios employed in this study. The candidate network (i.e., where pipelines could be built) is displayed as grey lines, while the actual pipelines built in each are displayed as green lines, where the width is proportional to pipeline diameter (4 to 12 inch pipe). As the $CO_2$ target amount increases in each management scenario, more infrastructure—capture, transport, and storage—is required, which typically means more sources being retrofitted, more (and larger) pipelines, and more storage operations coming online.

**Risk analysis matrix provides insight into the severity and likelihood of risks impacting $CO_2$ storage opportunities in the Black Warrior Basin:** A systematic assessment to evaluate geologic risks associated with geologic carbon storage in the Black Warrior Basin was performed. The University of Alabama and partners evaluated risks in terms of likelihood and severity, which were plotted on a matrix. The matrix provided a visual representation of the risks and how they are related. Likelihood was ranked in five classes from improbable to probable, and severity was ranked in five classes from light to multi-catastrophic. Reservoirs are considered viable where likelihood is improbable to unlikely or severity is light to serious, although operations should proceed carefully and strive continually for improvement.

Five major classes of geological risk were evaluated based on the evaluation of the Black Warrior basin and the Gorgas test site: (1) capacity risk, (2) permeability and injectivity risk, (3) sealing risk, (4) fault risk, and (5) risks to USDWs. In general, the risk of high-magnitude natural seismicity in the Black Warrior Basin is low, and careful monitoring of injection operations was considered to be sufficient to minimize the risk of induced seismicity. However, In the Gorgas area, the overall identified risks are highly varied (Figure 33).

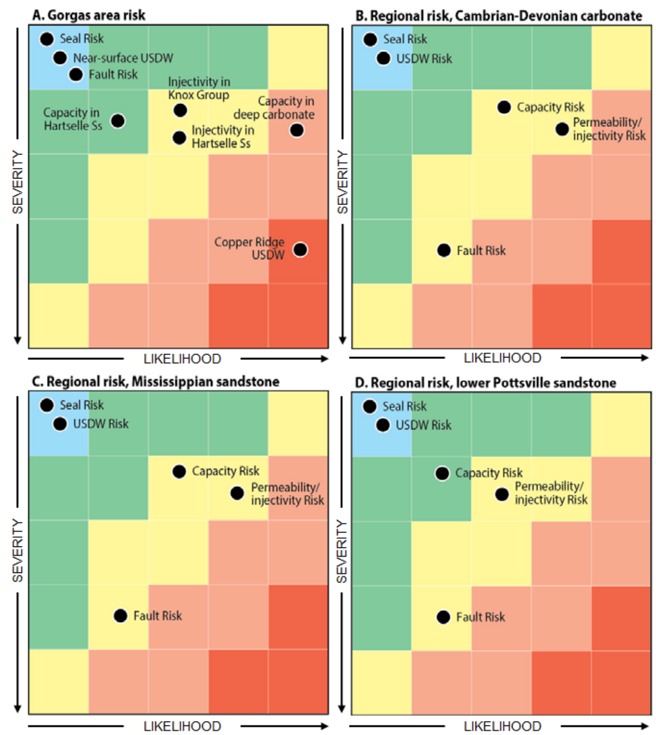


FIGURE 33. RISK MATRICES SHOWING RELATIONSHIPS AMONG GEOLOGIC RISKS ASSOCIATED WITH $CO_2$ STORAGE IN THE BLACK WARRIOR BASIN.

Results of the risk analysis suggest several key considerations within the study region. For example, although regional capacity in the Black Warrior Basin is high, it is concentrated in tight formations in which natural fractures support injectivity. Multiple widespread shale units make seal risk negligible in the Black Warrior Basin, and normal faults pose the most serious containment risk in the region. Therefore, the project team suggests that storage-related wells should be located in internally coherent structural panels, and plume modeling should be conducted to ensure that $CO_2$ does not migrate into fault zones at the millennial time scale. Identification of the deep USDW in the Copper Ridge Dolomite precludes commercial injection in the Cambrian-Ordovician carbonate in the Gorgas area, but opportunities exist further southwest where Knox strata contain saline fluid. The widespread shale units in the Mississippian-Pennsylvanian section are proven reservoir seals that protect shallow USDWs. Hence, minimizing fault risk is a central aspect of aquifer protection in the Black Warrior basin.

Sandia Technologies, LLC

**Project risks in heavily populated and industrialized area addressed through early public engagement and involvement:** The Newark Basin spans parts of New York, Pennsylvania, and a sizable portion of New Jersey, an area in close proximity to densely populated regions and a heavily industrialized section of the country. The project team, led by Sandia Technologies, LLC, found that given the proximal location of the study area to these high population and industrial areas, early outreach and public/stakeholder engagement was key to keeping the project on track and minimizing risks associated with public option and regulatory blow back.

The project team addressed risk assessment associated with public acceptance, field operations, and drilling-related risks through early involvement with key stakeholders. Each of these risks could, if mismanaged, have negatively affected project schedule, cost, or public perception. For instance, the project's public outreach program was specifically designed to follow a top down, early engagement approach to inform local decision/policy makers of the project, field work plans and objectives, and expected impacts on the local community (seismic survey and drilling activities). Meetings were held with both county and township boards early in the project to maintain information flow and overall awareness of the project. Principal outreach activities included participation in the local Clarkstown Environmental Summit and a half-day "open house" at the Exit 14-W well location during active field operations. As a result, all work was conducted without incident or protest from the local communities in proximity to the field work.

Field operations were designed to highlight and emphasize a "safety first" approach. The project team implemented a health and safety goal of "0" incidents in all field operations conducted during the project, which was reinforced with work crews prior to each shift. Detailed project health and safety plans were developed for all field work and were reviewed with all staff at the beginning of each work shift and at the beginning of any new activity. This ensured that all site workers understood the safety precautions needed and risks associated with the work tasks.

Plans for drilling the deep and shallow stratigraphic boreholes were designed specifically to protect local sources of USDWs, which are in short supply in Rockland County, New York. For the Exit 14-W deep stratigraphic borehole, the project team intentionally set intermediate surface casing at a depth just below aquifers tapped for public water supply. A deeper surface casing was set at 2.5 times the intermediate surface casing depth to ensure a double barrier between the utilized groundwater sources and borehole activities and to provide additional vertical protection of these sources from well influence.

KANSAS GEOLOGICAL SURVEY
The University of Kansas

**Finding fault: Assessing the risks of $CO_2$ injection in southern Kansas:** An important part of any carbon storage project is the identification and quantification of risks that could affect injection operations and permanent storage of $CO_2$ in the storage formation. In order to identify potential risks for $CO_2$ leakage within the respective study region, the University of Kansas and project partners identified and characterized a number of faults and fractures that could act as potential $CO_2$ migration pathways from potential storage reservoirs. On a regional scale, the research team evaluated regional structure trends and isopach mapping across 17 stratigraphic horizons and potentiometric surfaces of regional aquifers. The project team also evaluated local 3D seismic volumes, which were prevalent due to the long-standing oil and gas operations in the area, and determined geochemical isotope composition to evaluate communication between hydrostratigraphic units. Prior to the commencement of any $CO_2$ injection operations, the project team also evaluated several wellbores for the presence of conductive fractures and the interplay and distribution of saline aquifers underlying petroleum systems near potential carbon storage sites.

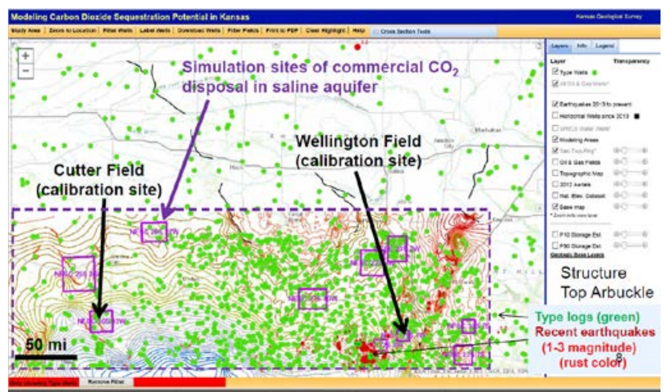


FIGURE 34. KANSAS INTERACTIVE $CO_2$ MAPPER LOCATED AT HTTP://MAPS.KGS.KU.EDU/CO2/

Each of these mechanisms required the development of a risk management plan focused on characterizing fractures or faults that might be encountered by a $CO_2$ plume. In early 2013, risk assessment was extended to earthquakes when regional seismicity began to increase. Seismicity followed a major increase in horizontal drilling and associated large-scale multi-well, multi-county brine injections. Since seismic events represent movement of faults, the locations of seismic events provide insight into the proximal location of important faults when considering future $CO_2$ storage within the region. The project team developed an interactive web-based map (Figure 34) that conveys location, magnitude, and timing of earthquakes and location of brine disposal and hazardous waste wells. The interactive mapper also provided access to key maps, static seismic volumes, modeling results, well data, gravity/magnetics, remotely sensed surface lineaments, and faults. Overall, this viewer allows stakeholders and the general public to visualize multiple types of critical data in relation to oil and gas or carbon storage operations throughout Kansas and an effort to provide proper context to the risks associated with $CO_2$ injection in the subsurface.

ILLINOIS STATE
GEOLOGICAL SURVEY
PRAIRIE RESEARCH INSTITUTE

**Visual review of potential risks through regional GIS screening:** To illuminate areas of higher or lower potential for $CO_2$ storage, the University of Illinois and partners identified screening criteria that were spatially overlain using geographic information systems (GIS) on geologic properties determined from the current Cambro-Ordovician regional assessment. While the screening criteria may not ultimately restrict $CO_2$ storage, they represent considerations that may guide the search for a candidate storage site to be studied in further detail in order to assess and determine geologic suitability for $CO_2$ storage. The key screening criteria identified are of primary importance to subsurface $CO_2$ storage and include adequate reservoir pore volume, depth, and salinity, as well as reservoir-seal continuity absent of major faulting. Additional considerations may include the proximity of wells or subsurface penetrations within the St. Peter Sandstone-Knox Group stratigraphic interval, such as EPA Class I disposal wells, $CO_2$ storage wells, and/or storage fields for natural gas. In Figure 35, the project team implemented selected screening criteria to focus on potential $CO_2$ storage areas in the Knox Group.

The proposed screening criteria were applied in a layered fashion to GIS-based maps based on current knowledge of Knox reservoir quality in order to define fairways most favorable for Knox project siting. The GIS format enables the addition of data layers in the future to further refine siting.

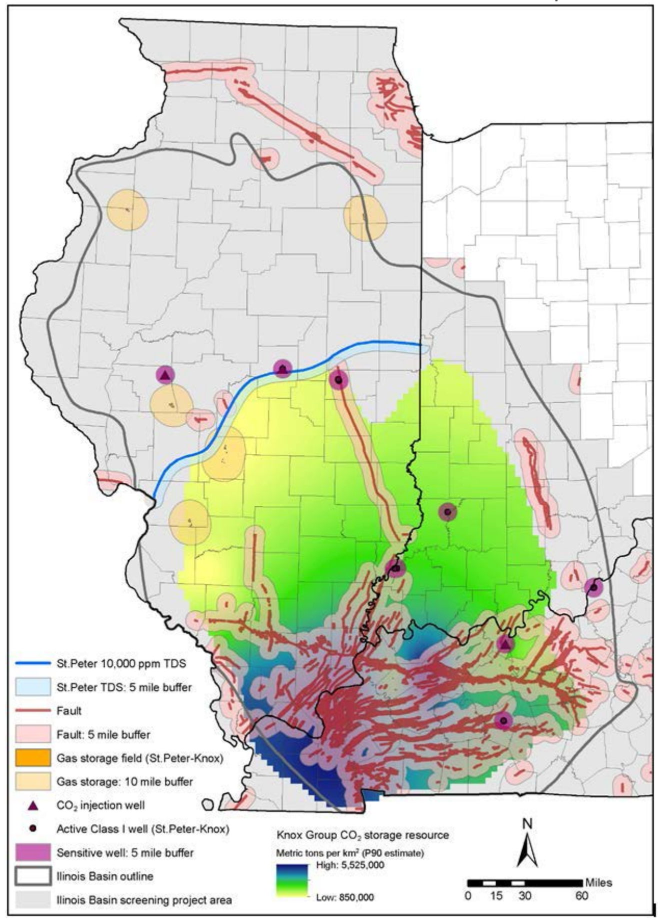



FIGURE 35. KNOX GROUP $CO_2$ STORAGE RESOURCE SHOWING OVERLAY OF ALL REGIONAL SCREENING CRITERIA

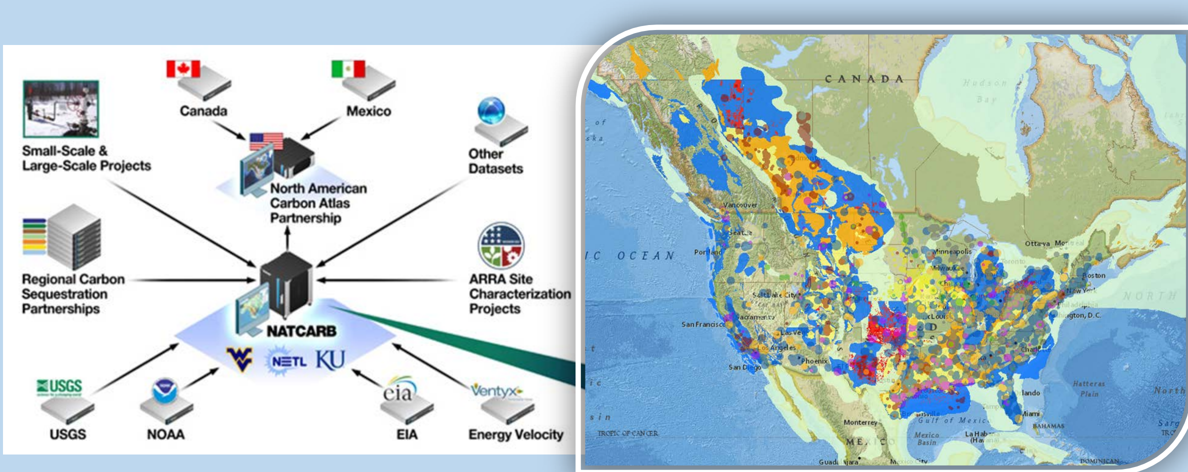
Figure 35 above shows an overlay of all screening criteria discussed, and faulted areas are a dominant visual feature on the map. Faults are generally concentrated in the southern, deeper potion of the Illinois Basin. Gas storage fields and sensitive wells are found along the margins of the Knox storage resource where the Knox Group reservoir is generally thinner. An example of potential storage fairway area free from the screening criteria and overlays is shown in darker green and blue-green colors in southern Illinois, southwest Indiana, and western Kentucky. Although some thick Knox reservoir is apparent in the extreme southwestern portion of the Illinois Basin in westernmost Kentucky, this area is near the limit of the current regional Cambro-Ordovician study and warrants further examination for potential future $CO_2$ storage projects.

## 3.7 Outreach and Education

$CO_2$ storage projects will likely unfold through a series of overlapping stages, from project conceptualization through post-closure monitoring and environmental stewardship. Throughout the life-cycle of a given CCS project, striving to develop and maintain good relations with the communities where projects are occurring and where infrastructure is located is critical to project success and perception. A critical goal of public outreach and education is to establish open lines of communication between project developers, the hosting

## ARRA Site Characterization efforts and NATCARB: Information and Visualization of CCS

The National Carbon Sequestration Database and Geographic Information System (NATCARB) is a geographic information system (GIS)-based tool developed to provide a view of CCS potential throughout North America. The interactive viewer shows disparate data such as stationary $CO_2$ sources, geologic $CO_2$ storage formations, and infrastructure identified from a variety of sources, including the ARRA Site Characterization projects. The inclusion of data collected by the ARRA Site Characterization projects improves storage resource estimation required for driving CCS toward commercialization, and providing all stakeholders with improved online tools for the display and analysis of CCS data. NATCARB organizes and enhances the critical geologic, geospatial, and geographic information relevant to CCS and develops the technology needed to access, query and model, analyze, display, and distribute $CO_2$ storage resource data. These data are generated, maintained, and enhanced locally for each of the ARRA Site Characterization projects. All map layers and data tables used to construct the national estimates of stationary $CO_2$ 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/index.html




community, and other stakeholders (including regulators) in order to provide a means to solicit input, build trust, and ensure that the project will be safely and responsibly carried out.[22] One of the primary lessons learned from the RCSPs' experience is that public outreach should be an integrated component of project management. Conducting effective public outreach will not necessarily ensure project success, but underestimating its importance can contribute to delays, increased costs, and community ill will. Effective public outreach involves listening, sharing information, and addressing concerns through proactive community engagement.

Several of the ARRA Site Characterization projects included aspects of public outreach and education within their scope. While the ARRA projects were exclusively characterization-based investigations ($CO_2$ was not injected), public outreach proved an effective means of transferring information, benefits, and results from the projects to the public domain. For example, three projects conducted open-house presentations for interested parties and two others developed a web presence, including one graphical leakage risk matrix tool capable of conveying risk assessments for individual well leakage risks to the public. One project even implemented a technology transfer program that extended throughout the project period. In addition, all of the information gathered from these projects has been incorporated into NATCARB to improve future $CO_2$ storage resource estimates in the United States and where data is accessible to the public; resulting resource estimates are presented in *Atlas V*.**Error! Bookmark not efined.**

Specifics related to each project's individualized approach to public outreach and education can be found in final project reports on the DOE's Office of Science and Technical Information webpage, and highlights are presented in the accomplishment summaries below.

**Sandia Technologies, LLC**

**Early outreach facilitates education of stakeholders and the public, preventing project opposition:** Successful implementation of an outreach program prior to and during

[22] National Energy Technology Laboratory. 2009. Best Practices for Public Outreach and Education for Carbon Storage Projects. DOE/NETL-2009/1391.

the field program to inform public, local and state officials, and other stakeholders of the project's goals and benefits helped the Sandia Technologies, LLC avoid opposition to field implementation. Sandia's public outreach program was specifically designed to follow a top down, early engagement approach to inform local decision/policy makers of the project, the field work plans and objectives, and expected impacts to the local community (for operations like seismic surveys and drilling activities). Timely meetings with both county and township boards were held to provide awareness of and information regarding the scope of the project. Sandia also sought to understand and mitigate stakeholder concerns in order to minimize misconceptions of what the project was trying to accomplish through scientific study versus standard oil and gas field operations implemented in nearby Marcellus Shale gas plays. All field work was conducted without incident or protest from the local communities affected by the work, and coverage of field activities was carried by both local and national media.

In addition, the project team contracted with an outreach consulting company to help create a comprehensive public relations plan that started at the state representative level and worked its way down to county and township leaders and, ultimately, to the local population. Principal outreach activities included participation in the local Clarkstown Environmental Summit and a half-day "open house" at the deep borehole location during active field operations.

THE UNIVERSITY OF UTAH

**Open houses connect project team members with the public:** The University of Utah held two project open houses to share project findings with interested stakeholders. The first open house was held at the Trapper Mine (location of the test well and seismic surveys) in Craig, Colorado on January 2012. Promotion for the open house occurred via ads in local newspapers and postcards mailed to stakeholders. This first open house included informational posters and documents (Figure 36) about the project spread throughout the venue and project team members who answered questions about the project. Topics covered included a general project overview, an overview of the project partners, information on carbon capture and storage, seismic testing, how a well for this type of project is drilled, safety of storing carbon underground, and an update on the current drilling project at Trapper Mine site. A tour of the drilling rig was offered in which interested participants were provided an overview of the rig and updated on drilling progress.

Over 20 individuals attended the open house, including two local county commissioners and a representative from a U.S. Senator's office. A second public open house provided an opportunity to view the core that was taken from the test well. Several members of the project team were present for the core viewing and were available to discuss the potential for long-term carbon storage sites with members from the media. This type of outreach approach helped to educate the public about the project and its perceived issues and promoted long-term carbon storage as a safe and effective strategy.

UNIVERSITY OF WYOMING

**Simple risk assessment tool for wells developed for landowners and CCS stakeholders:** In order to convey risk assessments associated with CCS to the general public in an honest and effective manner, the University of Wyoming developed and made available a preliminary graphical leakage risk matrix (GLRM) for assessing individual well leakage risk. The GLRM considers the parameters found to be most important to assigning individual well leakage risks including well penetration, well location, well status, well construction, cementing and plugging procedures, artificial and natural connectivity, surface $CO_2$ accumulation potential, and surface infrastructure proximity. Users can assign values for each of these factors, which are then weighted within GLRM. The contributions from all these risk factors are summed to produce a cumulative leakage risk for each well and displayed on a graphical user interface. This graphical and somewhat simplistic risk assessment mechanism was intended to


FIGURE 36. INFORMATIVE DOCUMENT PROVIDED AT THE FIRST PROJECT OPEN HOUSE. THIS IS ONE EXAMPLE OF SEVERAL TYPES OF EDUCATIONAL RESOURCES THAT WERE AVAILABLE TO THE PUBLIC

easily, effectively, and transparently convey risk levels of wells to interested stakeholders.

**Project site in Alabama facilitates training of personnel in the implementation of CCS technology:** In June 2011, the Research in Carbon Sequestration (RECS) program featured an excursion to the William C. Gorgas Electric Generating Plant, a 1,400 MW coal-fired power plant operated by Alabama Power and project site for the Black Warrior Basin investigation by the University of Alabama. The RECS program provides training in CCS through classroom instruction, group exercises, CCS site visits, and hands-on activities that include geologic storage site characterization, $CO_2$ monitoring and modeling, CCS deployment strategies, and communications training. RECS is led by CCS experts from industry, the research community, and non-governmental organizations and is hosted by Southern Company in Birmingham, Alabama. RECS participants were able to visit the project site and learn about the Black Warrior site characterization program directly from University of Alabama project staff. In addition, the project team provided RECS participants with an overview of geologic storage opportunities in the Black Warrior basin and discussed the local stratigraphy and the specific storage opportunities for carbon storage at the well.

ILLINOIS STATE GEOLOGICAL SURVEY
PRAIRIE RESEARCH INSTITUTE

**Open house provides opportunity for public engagement, as well as sharing of research findings, results, and benefits:** The Illinois State Geological Survey and partners held an open house for the general public and stakeholders at the conclusion of the small-scale $CO_2$ injection test at the Marvin Blan No.1 site to present results and provide an opportunity for discussion with project principal investigators. The open house meeting was held on the evening of October 28, 2010, in Hawesville, Kentucky, at the Hancock County Career Center (Figure 37). Information presented included summaries of project results by geologists and exhibits of rock core and log data from the well. The open house was attended by approximately 20 people, including three from the local news media. In addition, key county government officials were present to hear the results and ask questions about the 2-year project.

FIGURE 37. TOP – PROJECT TEAM MEMBERS PROVIDE A PROJECT SUMMARY TO OPEN HOUSE ATTENDEES. BOTTOM - KENTUCKY GEOLOGICAL SURVEY STAFF DISCUSSED CORES FROM THE KGS NO. 1 BLAN WELL THAT WERE ON DISPLAY AT THE OPEN HOUSE.

The Illinois State Geologic Survey and project team members determined that keeping research and outreach open and transparent was vital to project success. The project team started outreach and communications early in the project life-cycle; and the open house provided a means to continue outreach throughout the project. Key lessons learned from this open house for use by future CCS site operators included emphasizing the economic impacts of the project, which are of primary concern to local officials and residents. In addition, it is important to emphasize both the broader regional impact of the research and the local site-specific benefits (such as site reclamation, road repairs, and improvements to the benefit of the landowner and community).

THE UNIVERSITY OF UTAH

**Informative presentations to key stakeholders found to be key to project success:** Effective communication and public outreach were critical to the success of the Rocky Mountain Carbon Capture and Sequestration project. Investing the time necessary to understand the requirements and establish good relationships with federal, state and local government agencies as well as members of the media and individual citizens made challenging issues more manageable. Public outreach took a variety of forms, from informal meetings with stakeholders to public meetings with print and radio media in attendance.

One public engagement process completed by the project team involved contact and outreach to a broad spectrum of organizations and individuals at the local and regional level that included landowners, mineral rights owners, industry, state and local government/regulatory agencies, private citizens, and print/radio/television news media. Project team members from the Colorado Geological Survey developed presentation materials to communicate information about carbon storage in northwest Colorado and the proposed Craig Geologic Characterization project to key stakeholders (Figure 38). Contacting each of these stakeholders was necessary to inform the public of project activities, promote understanding of the technology, address fears and concerns, secure permissions and access, obtain permits, seek funding and in-kind contributions, and generate good will toward the research, development and potential future subsurface storage of carbon dioxide.

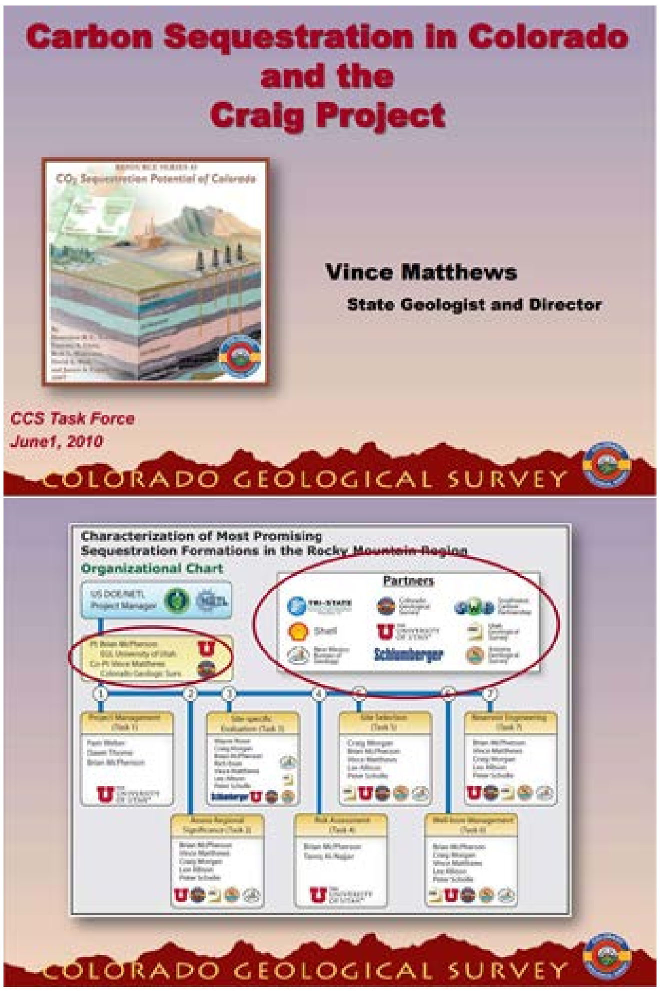



FIGURE 38. SCREENSHOT FROM OUTREACH PRESENTATIONS GIVEN BY THE COLORADO GEOLOGICAL SURVEY AS PART OF THE ROCKY MOUNTAIN CARBON CAPTURE AND SEQUESTRATION PROJECT.

Several presentations were given to the Colorado State Land Board, the State of Colorado's Carbon Sequestration Task Force, the Tri-State Generation and Transmission Association Board of Directors, the Trapper Mine Board of Directors, locally elected officials from the Town of Craig, and County Commissioners from Moffatt and Routt Counties. Each of these stakeholders were invested at some level in the region around the project. For example, the State Land Board holds title to some of the surface rights and most of the mineral rights to the land on which the project was located. The geologic characterization well and the seismic surveys were all located on the Trapper Mine property. Tri-State Generation and Transmission Association Board of Directors operates the Craig generating station located adjacent to the Trapper Mine and uses all of the coal it produces. The Town of Craig is located just a few miles from the Trapper Mine, Craig Station, and the project site. The project team also held a forum for presenting information to the public. This early communication with the public was an important aspect of the project that helped to develop a greater understanding of carbon storage in deep saline formations and built a foundation for good relationships. The Colorado Geological Survey also gave presentations to the state geologists of Utah, Arizona, and New Mexico to explain the project and how the information collected would be useful to their respective states. These presentation opportunities were a useful preliminary step for satisfying requirements from landowners, mineral rights owners, and various state and local agencies.

## 5.0 SUMMARY AND CONCLUSIONS

The American Recovery and Reinvestment Act of 2009 provided funds to the DOE of Energy Office-FE of Fossil Energy for projects promoting the sustainable use of fossil fuels in electricity generation. This funding enabled implementation of the ARRA Site Characterization Initiative in which the nine characterization projects joined an established portfolio of projects managed by FE's Storage Program, implemented by the National Energy Technology Laboratory, and under development to provide safe, cost-effective $CO_2$ storage technologies with availability beginning in 2025. The ARRA Site Characterization project awards were used to augmented existing Storage Program efforts in geologic carbon storage in a manner that was responsive to the goal of the Recovery Act and its Fossil Energy implementation. Specifically, the ARRA Site Characterization Initiative utilized approximately $100 million to conduct site characterization activities of promising geologic formations for the application of long-term $CO_2$ storage. These projects were successful in proving greater insight into the potential for geologic reservoirs across the U.S. to safely and permanently store $CO_2$.

The nine ARRA Site Characterization projects investigated deep geologic storage of $CO_2$ in onshore and offshore formations across several different regions in the United States. While the overall objective of the ARRA Site Characterization Initiative was to characterize high-priority geologic storage formations and provide greater insight into the potential for geologic reservoirs to safely and permanently store $CO_2$, each project had its own specific scope and focused on the geology within its respective study region. Despite regional geologic differences across the project portfolio, the projects exhibited a number of common approaches towards characterization. Each project had its own scope and focused on the geology within its respective study region. Notwithstanding this aspect, these projects exhibited a number of common characteristics that included region-scale characterization, utilization of a combination of existing and new geologic data, development of novel approaches to data integration and synthesis, and development of best practices for site selection and regional characterization. Specifically, common approaches across the ARRA Site Characterization Initiative projects included drilling stratigraphic wells to collect whole and sidewall core data on confining and injection zones, conducting comprehensive logging evaluations and formation evaluation tests, and analyzing the chemistry of formation rocks and fluids. For example, the ARRA Site Characterization projects drilled a total 11 new wells and deepened one existing well for characterization purposes. These new wells enabled the collection of cores, provided the ability to run log suites across strata, and facilitated fluid sampling for geochemical analysis, and allowed project teams to perform other well testing in an effort to obtain more information about the subsurface. In addition, the projects acquired data from a numerous volume of existing wells within their respective study areas, which provided data to supplement those acquired from new wells.

Characterization efforts also included the acquisition of 2D and/or 3D seismic surveys, as well as vertical seismic profiles, and integrated rock property data acquired from new wellbores with other existing data to validate seismic responses. In many instances across the projects, older versions of 2D and/or 3D data were collected and reprocessed; an approach that helped the projects to expand their characterization footprint within each of their respective study regions at a fraction of the cost of acquiring new seismic data over the same coverage area. The projects also developed methods of integrating data from disparate sources to extend modeling efforts and reduce uncertainties, and in the process achieved comprehensive data sets of formation characteristics that indicated porosity, permeability, reservoir architecture, caprock integrity, and related features.

The ARRA Site Characterization projects utilized individualistic approaches towards the integration of characterization data to develop a numerical models and simulations as part of their studies. In most cases, these models helped to estimate overall $CO_2$ storage capacity, simulate the injection and $CO_2$ migration under different scenarios, and evaluate injectivity within each project's respective study regions. A critical result from this work was the development of highly qualified storage capacity estimates in and around each project's study areas. Storage resource estimates developed by these projects were used to update the national storage capacity assessment found in the United States Carbon Utilization and Storage Atlas, Fifth Edition. The ARRA site characterization projects utilized both the U.S.-DOE developed methodology for estimating storage capacity, as well as site- and project-specific approaches. Current capacity estimates ranged from approximately 180 Gt to upwards of 640 Gt of $CO_2$ across all of the storage formations assessed under the ARRA Site Characterization Initiative.

The nine ARRA site characterization projects significantly contributed towards advancing the Storage Program and American Recovery and Reinvestment Act goals and the prospect of greenhouse gas mitigation through geologic carbon storage. Each project worked to verify one or more geologic storage formations in its territory capable of (1) storing large volumes of $CO_2$; (2) receiving $CO_2$ at an efficient and economical rate of injection; and (3) safely retaining $CO_2$ over extended periods. Taken together, these projects contributed to the knowledge base of best practices for site characterization and approving storage site selection, supported the development of best practices manuals on site characterization for their respective regions, and promoted knowledge sharing within technical working groups. Information gathered from these projects has been incorporated into NATCARB to improve future $CO_2$ storage resource estimates in the United States and enable interested stakeholders to view portions of project data online. This overall effort significantly increased the knowledge base relative to U.S. subsurface resources for geologic storage. Beyond that, the work performed at sites that were validated, moves them closer to readiness to receive industrial volumes of $CO_2$, and provides valuable information for designing future projects to inject $CO_2$ into similar geologies.

For more information on the Storage Program, or to download the existing DOE online technical resources, please visit the Storage Program Website:

http://www.netl.doe.gov/research/coal/carbon-storage

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