Geologic carbon sequestration in Wyoming: prospects and progress

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ABSTRACT

Coal supplies nearly 50 percent of electricity generation in the United States and 25 percent of the global energy supply; Wyoming produces approximately 40 percent of the coal consumed in the United States. It is likely that near-term energy strategies will include coal and other fossil energy sources in the fuel mix, therefore mitigating carbon dioxide emissions through geologic carbon capture and sequestration (CCS) is crucial. Here we discuss the current state of CCS technology across the globe and its future potential for development. We also outline the current regulatory structure for CCS in the United States, specifically Wyoming, and we introduce the study undertaken by University of Wyoming researchers and their collaborators to characterize Paleozoic deep saline aquifers on the Moxa Arch in southwestern Wyoming for long-term geologic carbon storage. The research presented in this special issue of *Rocky Mountain Geology* and future research that builds on these findings, such as the site characterization project underway on the Rock Springs Uplift in Wyoming, will be important steps to advance successful CCS technologies at a rate and scale that can make a meaningful impact on greenhouse gas emissions and to construct commercial geologic sequestration projects in the Rocky Mountain West.

KEYWORDS: geologic carbon dioxide sequestration, carbon sequestration regulation, deep saline formations, greenhouse gas emissions, Moxa Arch, Wyoming.

INTRODUCTION

Of the anthropogenic emissions of carbon dioxide (CO_2) to the atmosphere, more than 75 percent is contributed by combustion of fossil fuels for electrical power, industrial processes, and transportation (IPCC, 2007). A portfolio of technologies will be needed to help mitigate the impact of greenhouse gas emissions on climate, including energy efficiency, renewable fuels, and advanced transportation technologies. These pathways are part of the solution, but do not address pressing realities: coal supplies nearly 50 percent of electricity generation in the United States and 25 percent of the global energy supply (EIA, 2010a; Chu, 2009); and, the U.S., Russia, China, and India account for two-thirds of the world's known coal reserves, with the latter two countries accounting for 40 percent of the global population (CIA, 2009; Chu, 2009). As Secretary of Energy Steven Chu said in a recent editorial for *Science*, ". . . it is highly unlikely that any of these countries (the U.S., India, and China) will turn their back on coal any time soon, and for this reason, the capture and storage of CO_2 emissions from fossil fuel power plants must be aggressively pursued." According to the International Energy Agency (2009), up to a fifth of mitigation in 2050 will need to come from capture and storage of CO_2 from the power and industrial sectors. And because the state of Wyoming produces some 40 percent of the coal consumed in the U.S., it has a particular interest in demonstrating safe and successful long-term storage of CO_2.

Carbon capture and geologic sequestration (CCS) is a promising technology among the portfolio of approaches needed to address climate change. In its most simplified form, it entails capturing CO_2 emissions from a point source, transporting them to a storage location, and compressing and injecting them underground into a geologic storage site where CO_2 will be stored for thousands of years. In practice, of course, the process is much more complicated, particularly with regards to characterizing and monitoring potential sequestration sites. If commercialized, however, CCS technology could be deployed in many locations across the globe (Dooley et al., 2006; IEA, 2009).

This special issue highlights some of the work undertaken by University of Wyoming (UW) researchers to characterize a deep saline formation located in southwestern Wyoming—the Moxa Arch—for long-term geologic CO_2 storage. UW researchers and their collaborators have determined through their preliminary characterizations that the Moxa Arch has the appropriate thickness, reservoir properties, overlying low-permeability lithofacies, formation fluid compositions, and structural integrity to be developed as a commercial storage site. In addition, data and processes developed from this project have played a key role in formation of a new characterization and possible demonstration project that will drill a stratigraphic test well in correlative formations on the Rock Springs Uplift in southwest Wyoming (Fig. 1). The research presented here and future research that builds on these findings will be important steps to construct successful commercial geologic sequestration sites in the Rocky Mountain West.

CARBON SEQUESTRATION POTENTIAL

CO_2 sequestration is a fundamental process of the Earth's chemical cycle. In the natural world, carbon sequestration occurs through processes such as photosynthesis, calcification of CO_2 by phytoplankton, and mineralization in root systems (Chu, 2009). In addition, natural underground geologic formations have stored CO_2 for millions of years (Haszeldine, 2009). A number of these CO_2 fields are located in the Rocky Mountain region, including in western Wyoming along the crest of the Moxa Arch and on the Rock Springs Uplift (Allis et al., 2001; Huang et al., 2007). These deep natural reservoirs of CO_2 can help us understand the movement, properties, and long-term effects of storing CO_2 underground (IPCC, 2005).

Global estimates of sequestration storage capacity range from 1700 to nearly 11,000 gigatons of carbon dioxide (GtCO2) (Dooley et al., 2006; Orr, 2009). As a point of comparison, 30.4 $GtCO_2$ were emitted globally in 2008 (EIA, 2010b). It is unclear, however, how much of this CO_2 storage capacity will be technically accessible (Brennan et al., 2010; Van Noorden, 2010). Currently, more than 60 percent of anthropogenic CO_2 emissions, or 8100 large point sources (primarily fossil-fuel electric generating plants), could potentially utilize CCS technologies. Of the 1715 of these large point sources that are located in the U.S., 95 percent of them are estimated to be within 50 miles of a potential geologic storage formation (Dooley et al., 2006).

Candidate geologic CO_2 storage formations include deep saline formations, depleted oil and natural gas reservoirs, deep unmineable coal seams, and deep saline-filled basalt formations. Of these formations, by far the largest potential and widespread storage source is deep saline formations, which are characterized by porous limestone or sandstone rocks that generally contain brine and may be capped by low-permeability formations that prevent vertical flows of CO_2. Global estimates of storage capacity in deep saline formations are ~9500 $GtC0_2$, with 3630 $GtCO_2$ of this residing in formations of the U.S. Injecting fluid waste into these deep saline formations is already a global practice (Dooley et al., 2006).

CURRENT STATUS OF CCS TECHNOLOGY

Carbon injection into underground geologic reservoirs has been in practice for over 30 years in the form of enhanced oil recovery (EOR). Currently, around 30 megatons of CO_2 ($MtCO_2$) are injected into oil reservoirs in western Texas every year, though most of this CO_2 is obtained from natural sources and only 3 $MtCO_2$ are captured from anthropogenic emissions (IPCC, 2005; Orr, 2009). Acid gas (a mixture containing hydrogen sulfide and carbon dioxide) injection is another common commercial practice that utilizes underground geologic storage to sequester unwanted gases. Despite the similarities between EOR, acid gas injection, and carbon sequestration, CCS injection projects would need to be at much larger volumes and scales than past projects to have meaningful impact.

Oil and gas well construction technologies may be adapted to the CO_2 injection wells through use of special cements and downhole materials selected to withstand acidic conditions that can result when CO_2 mixes with water (Myhre and Stone, 2009). Once the CO_2 is injected underground, the properties of its

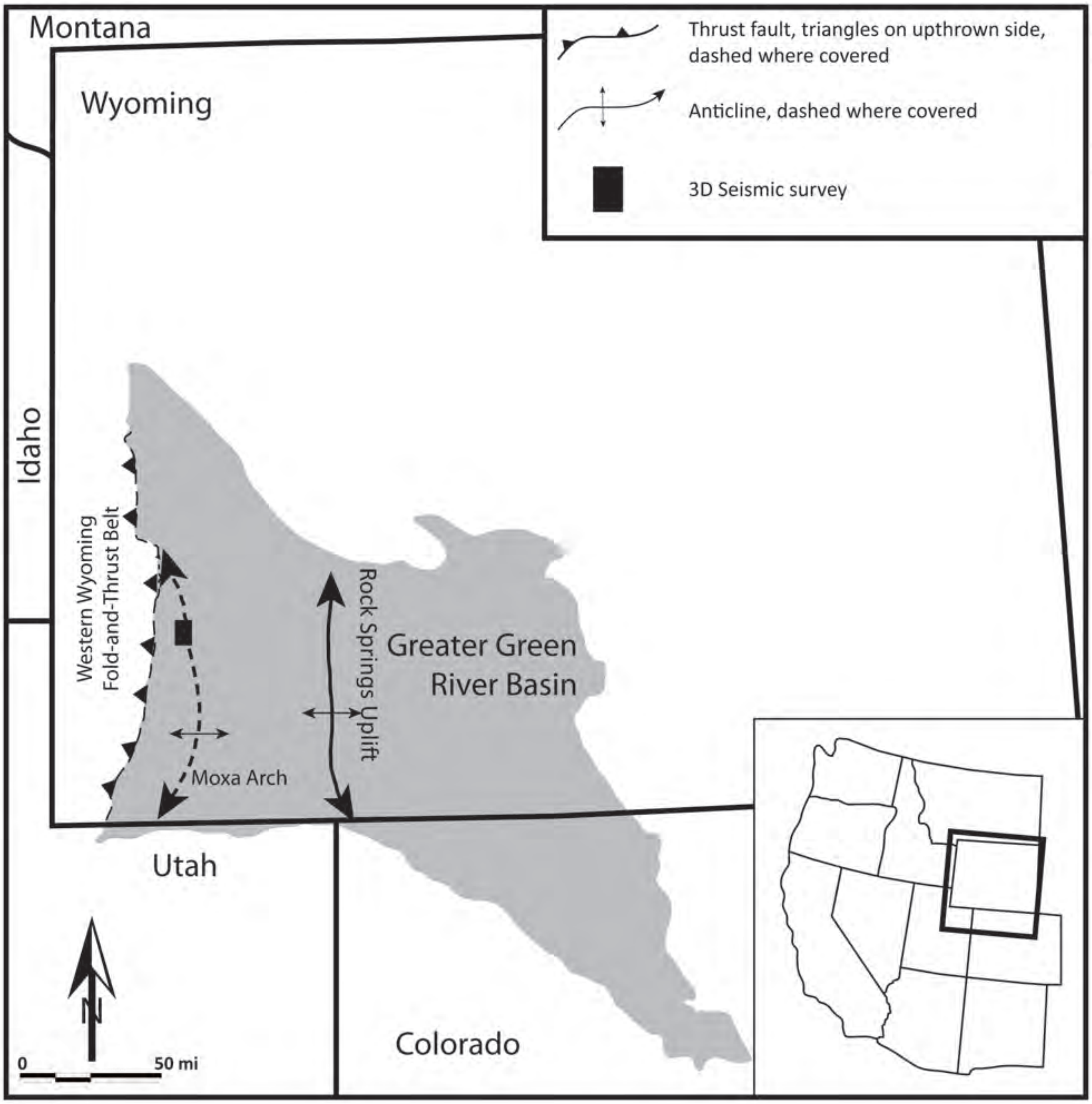

Figure 1. The Moxa Arch and Rock Springs Uplift potential carbon sequestration sites in the Greater Green River Basin of southwestern Wyoming. The black rectangle on the axis of the Moxa Arch marks the location of the detailed site characterization of the structure; a second site characterization project has begun on the Rock Springs Uplift. Figure modified from Campbell-Stone et al. (2010).

subsurface flows are complex, involving multiphase fluid flow, CO_2 dissolution into groundwater, mineral precipitation and dissolution, and water-rock interactions (Schnaar and Cullen, 2009). Physical and chemical trapping of CO_2 occurs through structural trapping, residual or pore space trapping, and dissolution or solubility trapping (Myhre and Stone, 2009). At depths below 2500 feet, supercritical CO_2 takes on a liquid-like density, which is an efficient storage form in the pores of sedimentary rocks (IPCC, 2005). Many research and development efforts are underway to model the location and behavior of underground CO_2 over time (Myhre and Stone, 2009).

Current cost estimates of the application of carbon sequestration technology to electricity production vary widely, and range as high as \$120–180/ton of CO_2 stored for first-of-a kind plants and \$35–70/ton of CO_2 stored for subsequent, "n^{th}-of-a-kind" plants (Al-Juaied and Whitmore, 2009). Carbon capture is the largest component of the cost of CCS, and research initiatives also are underway specifically to reduce the energy and cost component of this phase of the CCS process (IPCC, 2005). The increased energy requirements, which result in decreased net power plant output of 15–30 percent and doubled water requirements for post-combustion capture technology, are additional, significant concerns (Bauer, 2009).

While there are many current efforts to demonstrate CCS technology, no operational commercial-scale sequestration project associated with a major coal-fired power plant exists. There are, however, more than 20 experiments and pilot CCS projects operating throughout the world, though the largest captures one-tenth of the scale needed for a commercial power plant (Haszeldine, 2009). Of these 20 projects, four are fully integrated, commercial-scale plants (Sleipner, Snøhvit, In Salah, and Weyburn-Midale). Three of these projects inject CO_2 separated from natural gas production facilities, and the fourth captures emissions from a coal-based synfuels plant and injects them into an oil field for EOR purposes (IEA, 2009).

The Sleipner Project in the North Sea is a prime example of a large-scale CO_2 storage project in a saline formation. In this project, CO_2 separated from a gas field is re-injected approximately 1000 m below the floor of the North Sea into the Utsira saline formation (IEA, 2009). The Utsira Formation is a brine-saturated unconsolidated sandstone that has secondary thin shale layers that influence the movement of injected CO_2. Overlying the formation is a seal of thick shale, which secures the injected CO_2 in the formation (IPCC, 2005). The 1 million tons of carbon sequestered annually in this formation are equivalent to the emissions of a 150-megawatt (MW) coal-fired power plant (note that this is small compared to many coal-fired power generation facilities, which may be 1–2 gigawatt (GW) plants that emit on the order of 8 to 16 million tons of CO_2 annually). The CO_2 plume at the Sleipner site has been monitored over the past decade through seismic time-lapse surveys. These show the footprint of the plume to encompass 8 km^2; it is projected that over time the CO_2 will dissolve in the aquifer (IPCC, 2005). Injection of CO_2 since 1996 at the Sleipner site has demonstrated the safe and successful injection, storage, and monitoring of CO_2 in a deep saline formation.

U.S. AND WYOMING STATE GOVERNMENT SUPPORT AND REGULATION OF CCS

The United States federal government recognizes the importance of commercializing carbon capture and sequestration technology and is supporting CCS through a variety of initiatives. The 2009 American Reinvestment and Recovery Act invested \$3.4 billion in CCS research and development; this funding added to the regular Department of Energy (DOE) appropriations that support CCS activities (\$180 million in Fiscal Year (FY) 2010), including seven regional sequestration partnerships that are working to produce large-scale projects across the country. The International Energy Agency predicts that all nations with CCS targets will have to invest \$3.5 billion to \$4 billion in demonstration projects over the next decade to commercialize the technology by 2020 (Van Noorden, 2010); the Recovery Act funds combined with general appropriations mean that—at least for FY2010—the U.S. is thus far meeting this level of commitment.

Furthermore, in February 2010, the administration announced an Interagency Task Force on Carbon Capture and Storage, which was charged with seeking ways to overcome barriers to commercialization of CCS technologies. The Task Force, which was co-chaired by the Department of Energy and Environmental Protection Agency (EPA), submitted a plan to the president in August 2010 that identified barriers to CCS development and provided recommendations of how to overcome barriers and construct 5–10 commercial CCS projects by 2016 (Platts, 2010). In July 2010, the U.S. and 12 other countries also pledged to establish an international Carbon Capture Use and Storage Action Group that is charged with determining how best to enable deployment of carbon capture and storage technologies worldwide (Clean Energy Ministerial, 2010).

Geologic sequestration of carbon dioxide is unlikely to become widely adopted without a regulatory framework. Two items of most concern regarding regulations for CCS projects include issues of who owns the pore space in the rock that will be used to store CO_2 and long-term liability issues of geologic storage. In the U.S., the EPA has the authority to monitor carbon sequestration activities through the Safe Water Drinking Act and its Underground Injection Control (UIC) program, which is in place to protect underground sources of drinking water (USDWs). In 2008 the EPA proposed a new class of regulation well, Class VI, and has outlined minimum technical requirements for geologic site characterization, well construction, operation, monitoring, and post-injection site care (EPA, 2008). The State of Wyoming has primary enforcement authority for the UIC program; in Wyoming permits for geological sequestration of CO_2 will be issued by the Wyoming Department of Environmental Quality according to its proposed Water Quality Rules and Regulations, Chapter 24 (2010).

In the Rocky Mountain West, Wyoming was the first state to pass legislation on carbon sequestration. House Bill Nos. 89 and 90, signed into law in March 2007 and put into effect in July 2008, design a legal framework for storing carbon underground. The legislation designates that pore space is owned by the surface owner; however, the legislation does not specify what entity is liable if sequestered carbon migrates beyond its intended reservoir (Nowakowski, 2007). Wyoming convened a working group to further investigate appropriate financial bond and long-term liability structures, which released its recommendations in September 2009 (see Wyoming Carbon Sequestration Working Group, 2009). Wyoming House Bill No. 17 passed in 2010 provides for carbon sequestration financial assurances and regulation and was based upon recommendations of the Carbon Sequestration Working Group report. Colorado, Utah, North Dakota, and Montana, amongst other Western states, also have pursued or are pursuing putting relevant CCS legislation or regulations in place.

Public acceptance of CCS technology and its safety is crucial to its success. Experts have largely concluded that in properly designed and managed CCS projects there is little to no chance of appreciable leakage from geologic formations (Dooley et al., 2006). Many existing activities, such as natural gas storage, enhanced oil recovery, and deep underground disposal of acid gas have similar risk profiles as CCS (IPCC, 2005). However, there remain concerns of contamination of groundwater, leakage of CO_2, or induced seismicity. To address public safety concerns and long-term liability issues, state governments must pass legislation and regulations that establish ownership, liability, and regulatory regimes. The public also will need to be educated about how the technology works and how developers will mitigate risks (DOE-NETL, 2009). Most importantly, the industry needs to build a track record of safety built on careful site selection, characterization, injection practices, and monitoring (IPCC, 2005).

UNIVERSITY OF WYOMING MOXA ARCH AND WY-CUSP PROJECT

Paleozoic deep saline aquifers in southwestern Wyoming are the most promising targets for geologic CO_2 sequestration in the state and are possibly the most promising sequestration sites in the Rocky Mountain region. One of the geologic structures containing these deep saline aquifers—the Moxa Arch—is a 200-km-long, north–south trending anticline that plunges beneath the Wyoming Thrust Belt on the north and is bounded on the south by the Uinta Mountains. Several oil and gas fields along the Moxa Arch contain large, natural accumulations of CO_2. The largest of these is the LaBarge Platform, which encompasses approximately 2000 square km^2 (Huang et al., 2007).

The University of Wyoming and its collaborators identified Moxa Arch as a promising site for commercial-scale sequestration for a number of reasons: (1) it is a geological structure that has stored over 100 trillion cubic feet (TCF) of CO_2 for many millions of years (Lynds et al., 2010a); (2) several formations appear to be suitable sequestration reservoirs (at pressures and temperatures for which CO_2 will be supercritical); and (3) CO_2 is presently being produced and sold for enhanced oil recovery, and more CO_2 is potentially available for this and other uses, including for a future sequestration demonstration. Several deep saline formations may be suitable for storage of CO_2, foremost among them the Madison Limestone, Bighorn Dolomite, and Nugget Sandstone. These storage units are overlain by a series of impermeable lithologies that serve as regional hydrocarbon, CO_2, and helium seals, ensuring fluid containment.

The Madison Limestone is a proven storage reservoir. ExxonMobil has been producing natural gas on the north end of the Moxa Arch on the LaBarge Platform from the Madison Limestone, which contains CO_2, methane, nitrogen, hydrogen sulfide (H_2S), and helium. Farther south, the Moxa Arch also already is used for sequestration purposes: ExxonMobil has been injecting CO_2 (up to 25 million cubic feet per day (MMCFD)) and H_2S (up to 65 MMCFD) into the Madison Limestone at its Shute Creek Gas Plant, located 65 km south of the producing field (Campbell-Stone et al., 2010).

The papers in this special issue present results from a University of Wyoming/Wyoming State Geological Survey/DOE–funded project that address some of the different aspects of characterizing the Moxa Arch structure in southwestern Wyoming. The overarching goal for the project was to improve the understanding of CO_2 flow and trapping within the targeted reservoir and develop simulation models to predict how much CO_2 could be stored in this potential site. The project characterized the geology, hydrogeology, geochemistry, and geophysical properties of the Moxa Arch and used these data and other laboratory experimental activities to construct appropriate monitoring and performance assessment regimes. This issue includes papers describing two of the major potential reservoirs, the Bighorn and Madison Formations (Lynds et al., 2010b; Thyne et al., 2010), the geochemistry of the groundwaters contained within the target formations in the Greater Green River Basin (Smith et al., 2010), and the development of a multiscale parallel simulator for porous media fluid flow that can provide accurate predictions of migration and trapping of injected carbon dioxide (Douglas et al., 2010). The cyberinfrastructure to support collaborative geologic sequestration research is explored by Hamerlinck et al. (2010), and the economics of fossil fuel and wind energy production under various carbon taxation scenarios are discussed by Geiger et al. (2010). Other publications forthcoming from these and other members of the Moxa Arch research group will complete the site characterization of that geological structure.

Building on results of this Moxa Arch project, the University of Wyoming has begun the Wyoming Carbon Underground Storage Project (WY-CUSP), a partnership of the University of Wyoming, the Wyoming State Geological Survey, Baker Hughes, Inc., ExxonMobil, and Los Alamos National Laboratory. This project was funded by the U.S. Department of Energy and the State of Wyoming to assess the CO_2 storage potential of the Rock Springs Uplift, to develop a system for displaced fluid management, to plan monitoring and verification activities, and to design infrastructure in preparation for carbon sequestration. The target storage reservoirs on the Rock Springs Uplift are the Pennsylvanian Tensleep/Weber Sandstone and Mississippian Madison Limestone. These formations lie at depths of from 2 to 6 km below the surface, depending upon location on the anticline. The CO_2 accumulations and their extents appear to be controlled by faults with throws, and the project will work to understand the fault-dependent mechanisms that isolated the CO_2 traps on the Rock Springs Uplift to determine the feasibility of long-term storage at this site (Lynds et al., 2010a). An advantage of the Rock Springs Uplift study site is that it is adjacent to PacifiCorp's Jim Bridger power plant (a 2200 MW coal-fired power plant that emits 18 $MtCO_2$ per year), which is much larger than PacifiCorp's 700 MW Naughton power plant at Kemmerer on the Moxa Arch. Analysis has shown that CCS systems will be most economic when deployed with large baseload power plants and with reservoirs (most likely deep saline formations) that can ideally hold more than 50 years worth of the facility's CO_2 (Dooley et al., 2006).

The site characterization studies of the Moxa Arch and the Rock Springs Uplift site will provide critical scientific information needed for the University of Wyoming and its collaborators to select the best location to carry out a future geologic sequestration demonstration in southwestern Wyoming.

CONCLUSION

The Intergovernmental Panel for Climate Change has stated that for CCS to make significant cuts to global CO_2 emissions there must be thousands of large-scale geologic storage projects across the globe (IPCC, 2005). The International Energy Agency follows this up by saying that the cheapest way to provide 20 percent of the target to halve expected CO_2 emissions by 2050 is to employ CCS technologies; to meet this target, the volume of liquid CO_2 that would have be injected would be three times the current amount of petroleum used globally each year. In other words, the CCS industry would have to scale up to the size of the oil industry, or even larger, by mid-century to have a significant impact (Van Noorden, 2010).

To safely and successfully operate the thousands of carbon sequestration projects that will be required, careful characterization of the subsurface, good design of the injection project, advanced monitoring, and state-of-the-art computational modeling techniques are needed (Orr, 2009; Schnaar and Cullen, 2009). The International Energy Agency (2009) calls for more experience to improve predictions of CO_2 behavior underground and tools to identify suitable storage sites, particularly for deep saline formations. The research being undertaken at the University of Wyoming—some of which is presented here—is therefore crucial to advance CCS technologies at a rate and scale that can make a meaningful impact on greenhouse gas emissions.

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