The Wyoming Carbon Underground Storage Project: geologic characterization of the Moxa Arch and Rock Springs Uplift

Erin Campbell-Stone¹, Ranie Lynds³, Carol Frost⁴, Thomas P. Becker⁵, and Bridget Diema,

¹Department of Geology and Geophysics 3006, University of Wyoming, 1000 East University Ave, Laramie, WY 82071, USA
³ExxonMobil Production Company, 396 West Greens Road, WGR-756, Houston TX 77067, USA

Elsevier use only: Received date here; revised date here; accepted date here

Abstract

The state of Wyoming, in the northwestern United States, produces 40% of the nation’s coal, most of which is transported out of the state. The remainder is used at power plants within Wyoming to generate approximately 7% of U.S. electricity. Carbon capture and storage from these power stations could significantly reduce U.S. carbon emissions. Wyoming statutes and rules proposed by the U.S. Environmental Protection Agency and Wyoming Department of Environmental Quality regarding subsurface carbon storage require that CO₂ injection must not affect established or potential drinking water aquifers, oil and gas fields, or other mineral estates. Wyoming has several potential large-scale geologic carbon storage reservoirs that meet these criteria, in the form of saline aquifers in regional basins and uplifts. The Wyoming Carbon Underground Storage Project has recently been funded by the U.S. Department of Energy and the state of Wyoming to 1) assess the CO₂ storage potential of two possible locations in southwestern Wyoming: the Moxa Arch and the Rock Springs Uplift, 2) develop a system for displaced fluid management, 3) plan monitoring and verification activities, and 4) design infrastructure in preparation for geologic carbon sequestration. The Wyoming Carbon Underground Storage Project represents collaboration between the University of Wyoming, the Wyoming State Geologic Survey, ExxonMobil Corporation, Los Alamos National Laboratory, and Baker Hughes Incorporated. The authors are involved primarily in the geologic stratigraphic and structural characterization of the Moxa Arch and Rock Springs Uplift.

The Moxa Arch is an anticline that trends from the Uinta Mountains, 200 km north-northwest to the eastern front of the Wyoming fold-and-thrust belt. Potential storage reservoirs on this large geologic structure include the Jurassic Nugget Sandstone, the Mississippian Madison Limestone, and the Ordovician Bighorn Dolomite. The Nugget Sandstone is a heterogeneous and anisotropic eolian deposit that has been extensively exploited for oil and gas at certain locations on the Moxa Arch, which complicates its usage as a repository for carbon dioxide. The Madison Limestone is a proven storage reservoir; ExxonMobil has been injecting CO₂ (up to 25 MMCFD) and H₂S (up to 65 MMCFD) into the Madison Limestone on the Moxa Arch for seven years at the Shute Creek Gas Plant. The Bighorn Dolomite is stratigraphically complex with large variations in porosity and

E-mail address: erincs@uwyo.edu.
permeability due to primary burrowing and repeated dolomitization and dedolomitization. Depending on location on the anticline, the Nugget Sandstone lies 3 to 6.5 km below the surface (-1 to -4.5 km subsea), and the Bighorn Dolomite and Madison Limestone range from 4.5 to 8 km below the surface (-2.5 to -6 km subsea).

The Moxa Arch is structurally uncomplicated; it is a basement-involved anticline formed by a west-vergent Late Cretaceous-age thrust fault, with gently-dipping limbs (0 to 5 degrees). Leakage risk is extremely low because impermeable evaporite (anhydrite) intervals overly the potential reservoirs, and preliminary interpretation of seismic data reveal that few faults exist other than the main thrust. The Naughton Power Plant, a 707 MW coal-fired power station emitting up to 6 Mt of CO₂ per year, lies 30 km west of the crest of the anticline.

The Rock Springs Uplift, 100 km east of the Moxa Arch, extends 80 km north from the Wyoming-Utah border. The target storage reservoirs are the Pennsylvanian Weber Sandstone (correlative to the Tensleep Sandstone) and the Mississippian Madison Limestone. The Weber Sandstone exhibits wide variations in reservoir properties (porosity and permeability) due to dune/interdune/intradune facies changes, and appears to have experienced local secondary diagenesis that further reduced porosity. The Madison Limestone is expected to have similar reservoir properties to its lithologic correlative on the Moxa Arch. The Weber Sandstone and Madison Limestone range in depth from 2 to 6 km below the surface (0.3 to -4.5 km subsea), depending on location on the anticline.

The Rock Springs Uplift offers challenges for structural analysis. Like the Moxa Arch, the Uplift was formed by a Late Cretaceous-age west-vergent basement-involved reverse fault, but the limbs of the fold are at steeper dips (approximately 15 degrees on the west limb, shallower on the east limb), and these limbs are cut at depth by additional reverse faults. In a hydrocarbon field on the southeastern flank of the uplift there is a possibility that condensate is migrating from the Weber Sandstone along one of these reverse faults, suggesting that the trap is breached. In addition, a series of east-west trending normal faults cut Cretaceous shales at the surface, possibly with throws that exceed the thickness of the uppermost regional seal. It is necessary to determine if these east-west faults also compromise the Triassic units that could provide a seal above the Weber Sandstone. The Jim Bridger Power Plant (coal-fired) is located on the east flank of the Rock Springs Uplift; it has 2200 MW capacity and emits up to 18 Mt of CO₂ per year.

Future U.S. energy demands will draw heavily on Wyoming’s coal-fired power plants, and the state is taking steps to sequester the produced carbon. Wyoming hosts several large geologic traps that if properly risked and evaluated have promise as long-term, stable repositories for anthropogenic carbon dioxide. Based upon our preliminary assessment of the multiple elastic and carbonate receiving formations in the Moxa Arch and Rock Springs Uplift, and the experience of successful injection at ExxonMobil’s Shute Creek Gas Plant, these geologic structures in southwestern Wyoming are among the most promising large CO₂ geologic storage sites in the United States.

© 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.

Keywords: Geologic carbon sequestration; Wyoming; Moxa Arch; Rock Springs Uplift

1. Introduction

The state of Wyoming possesses several geologically appropriate locations with great promise for underground storage of carbon dioxide in the United States due to an abundance of subsurface traps, reservoirs, and sealing intervals. In southwestern Wyoming, two geologic structures, the Moxa Arch and the Rock Springs Uplift (Figure 1), have been
studied to evaluate their potential for geologic sequestration of carbon dioxide. This paper discusses the general sequestration attributes of the two sites and highlights their similarities and differences.

2. Geologic Setting

2.1 Moxa Arch

The Moxa Arch is a gently-dipping, doubly plunging anticline that extends from beneath the Uinta Mountains at the Utah/Wyoming border, north to the town of La Barge, Wyoming, where it turns northwest and plunges beneath the western Wyoming fold-and-thrust belt (Figure 1). This structural history has been well-documented and indicates uplift along a basement-involved thrust fault beginning in the Late Cretaceous and continuing through the early Eocene (e.g., [1]). The limbs of the structure have a maximum dip of 5 degrees on the eastern limb, and 3D seismic and well data indicate major faulting is essentially limited to the basement-involved thrust along the southwestern edge of the structure.

Significant accumulations of methane, CO₂, H₂S, and other gases are stored within the pore space of the early Carboniferous (Mississippian) Madison Limestone around the crest of the Moxa Arch. This gas is currently being produced by ExxonMobil, and the waste stream of naturally occurring carbon dioxide and hydrogen sulfide is being re-injected into the Madison below the gas-water contact at the Shute Creek Gas Plant at rates of ~60 MMCFD (~2650 tonnes/day). The ~240 meter-thick Madison Limestone has been affected by limited dolomitization, hydrothermal brecciation [2], stylolitization, karsting, and fracturing that has influenced the formation’s porosity and permeability.

Figure 1. Location map of the Moxa Arch and Rock Springs Uplift in southwestern Wyoming. The shaded area indicates the Greater Green River Basin. The Moxa Arch is a current injection site for CO₂ and H₂S; the Rock Springs Uplift is being evaluated as a potential CO₂ repository.
Porosity ranges from 0 – 35% and appears to be primarily related to stratigraphic trends and diagenesis [3]. Permeability has a generally positive correlation to porosity, but is also affected by fractures and microfractures; permeability values range from 0.001 to 100 md [3] The Madison Limestone lies at depths of 4.5 to 8 km below the surface depending on location within the area of study, with multiple potential seals overlying the reservoir.

The 100-meter thick Mississippian to early Pennsylvanian Amsden Formation overlies the Madison Limestone (Figure 2), and consists of interbedded red clastic shales and sandstones, anhydrite, dolostone, and limestone, overlain by increasingly pure limestone [4]. This unit separates the Madison Limestone from the Pennsylvanian Weber/Tensleep Sandstone, which is a series of cross-bedded quartz-rich eolian dune facies interbedded with discontinuous interdune siltstones and claystones. Unlike the Madison, the Weber/Tensleep does not have a large gas accumulation within it, suggesting the Amsden is a potential seal between the two units. Although oil and gas is commonly produced from the Weber/Tensleep throughout Wyoming, at the Moxa Arch it was determined to have insufficient porosity and permeability for a suitable storage reservoir based on drill stem tests, core plug data, and wireline logs.

2.2. Rock Springs Uplift

The Rock Springs Uplift, located east of the Moxa Arch (Figure 1), is also a Late-Cretaceous to Early Eocene-age basement-involved anticlinal structure. However, the limbs of the Rock Springs Uplift are dipping at least twice as steeply as the Moxa Arch, and a series of east-west oriented normal faults are common across the structure. This structure is being evaluated by the Wyoming Carbon Underground Storage Project (WYCUSP) for suitability as a storage location for subsurface carbon dioxide. Because of its proximity to the large Jim Bridger Power Plant and its similarities to the proven storage reservoir on the Moxa Arch, the Rock Springs Uplift warrants thorough evaluation as a potential storage site. During fall of 2010, WYCUSP will drill a stratigraphic test well and will be collecting 3-D seismic data over a five-square mile area around a possible injection site near the power plant.

The Madison Limestone is also being considered as a potential storage reservoir on the Rock Springs Uplift site, because of its similarity to the Madison on the Moxa Arch from preliminary core examination. The Madison is approximately 4 km deep at the stratigraphic test well location.

The Pennsylvanian Weber Sandstone is a second potential reservoir. Although the Weber has been a prolific hydrocarbon producer on the southeast flank of the Rock Springs Uplift, it can exhibit extremely low porosity as a result of diagenetic destruction of porosity [5]. Therefore, WYCUSP will be testing core from the Weber extensively to evaluate its reservoir characteristics at the potential injection site on the northeast flank of the anticline.

The numerous normal faults that cut the Rock Springs Uplift could present a threat to the integrity of the trap. Logs indicate that these normal faults have up to 240 m of throw [7], but it is currently unclear if these faults cut down to the depth of the relevant reservoirs and seals. Although some of these normal faults may compartmentalize shallow Cretaceous reservoirs near the crest of the anticline [8], minor reverse faults on the southeast flank of the Rock Springs Uplift appear to have behaved as conduits rather than seals [5]. In all cases, 3-D seismic data will be crucial to assessing whether faults are present in the storage field and if they pose a risk.
3. Seal Evaluation

Understanding the distribution and effectiveness of seals and sealing mechanisms for CO₂ storage is as important as defining the reservoir and mapping out the structural trap. Seal characteristics are frequently overlooked in the effort to identify adequate storage locations, making thorough seal analyses relatively rare (good examples include [9], [10] and [11]). The petroleum industry has carefully studied these parameters and their implications for holding large buoyant columns in the subsurface over geologically significant periods of time. Generally, seals need to have adequate mechanical strength and sufficiently low capillary entry pressure to ensure their effectiveness (e.g., [12], [13]), and these parameters are quantifiable through routine analyses. Feasibility studies of CO₂ storage could benefit from knowledge gained in the hydrocarbon industry, as well as an array of possible tests for seal assessment.

In petrolierous basins, hydrocarbons can serve as a potential leak test to determine if a proposed site is capable of holding a buoyant column in the subsurface. If a potential sequestration site is located within such a basin and contains a porous and permeable reservoir, the absence of a hydrocarbon column may be attributable to 1) the lack of any hydrocarbons within the trap fetch area, or 2) a compromised trap/seal. Analysis of fluid inclusion volatiles (FIV) can help distinguish between these two potential possibilities.

3.1 FIV Methodology

The conversion of smectite to illite, the maturation of organic matter to petroleum, and the formation of several different types of pore-occluding diagenetic cements occurs at coincident temperatures of ~100 °C. The products of these reactions (hydrocarbons, water, and silica) migrate into available pore space. The silica precipitates as overgrowths and often traps the other fluid phases in the pore space as inclusions. Hydrocarbons, if present, can be detected by analyses of fluid inclusion volatiles. The technique works by crushing a small sample of cuttings twice, in a vacuum, and analyzing molecular weights of volatiles liberated from inclusions via a quadrupole mass spectrometer (e.g., [14]). Analyses of thousands of wells from around the world demonstrate that this technique is highly reliable in determining whether a trap has been charged with hydrocarbons, or is in a hydrocarbon “migration shadow”.

3.2 FIV results and conclusions

Cuttings were analyzed for fluid inclusion composition from the T62X-16S well on the northern Moxa Arch and the Amoco-Texas #1 on the western Rock Springs Uplift (Figure 1 and Figure 3). On the Moxa Arch, results show that hydrocarbons are present within the fluid inclusions in all of the Mississippian through Permian reservoirs. Distinctive reductions in the concentration of methane (C₁), propane (C₃), and other hydrocarbon constituents within the Amsden Formation and above the Phosphoria Formation suggest these are sealing intervals that prevented hydrocarbons from migrating upward. These interpretations are verified by what is known about the present day distribution of gas accumulations on the Moxa Arch. The Texas-Amoco #1 well on the Rock Springs Uplift, located over 100 km southeast from the T62X-16S, shows nearly identical results, indicating that hydrocarbons were present within the trap, although the exact amounts can only be speculated. However, the vertical segregation of the hydrocarbons in the inclusions by density suggests there was a stable column present. The present lack of a large hydrocarbon column in Mississippian through Permian reservoirs in the Texas-Amoco #1 hints that the trap was breached at this location. In this well very little gas is observed within the Weber Sandstone, yet all gases disappear above the Phosphoria Formation.

The FIV results indicate that the Amsden Formation is acting as a seal to the Madison Formation, and the Dinwoody and Woodside formations prove to be excellent seals, preventing essentially any buoyant phases from vertical migration above the Phosphoria formation. The 45-meter thick Triassic Dinwoody Formation consists primarily of interbedded siltstone, with minor limestone, dolostone, and rare thin beds of anhydrite [15]. The 90-meter thick Woodside Formation consists of laminated siltstone, dolostone, and impure halite. Both halite and anhydrite are known as excellent seals for CO₂ (e.g., [16][11]).

FIV analyses from two wells in two different locations within the Green River Basin (Figure 1) suggest that there are multiple seals within the Upper Paleozoic section, which are capped by lowermost Triassic rocks with excellent seal properties. This seal redundancy speaks to the great potential for carbon sequestration within Wyoming, and illustrates that understanding the distribution of sealing facies (e.g., halite and anhydrite – particularly the lower Triassic interval) and their breach points, is imperative for risking potential sites for CO₂ sequestration. The Rock Springs Uplift will require further study to document the effectiveness of the Triassic seal throughout the structure and to understand why the Weber Sandstone, in some locations, contains so little gas in the trap.
Figure 3. FIV analysis of well T62X-16S from the Moxa Arch and Amoco-Texas #1 from the Rock Springs Uplift. Both analyses indicate lower Triassic units have not hosted hydrocarbons in the past or present, and should act as seals above CO$_2$ storage reservoirs.
4. Conclusions

Because of the similarities between the Rock Springs Uplift, a potential CO₂ reservoir, and the Moxa Arch, a proven storage reservoir, the Rock Springs Uplift warrants further study as a repository for CO₂ to be recovered from the Jim Bridger Power Plant. FIV results demonstrate that the system has had an effective reservoir/seal combination. Although the reservoirs and seals on the two anticlines are similar, the Rock Springs Uplift has structural complexities which are being thoroughly studied to ensure secure trapping of the CO₂.

5. Acknowledgements

Support from Michael Parker, Aaron Liesch, Jack Neal, David Bouquet, and Ruediger Jantschik of ExxonMobil Production Company is gratefully acknowledged. Results of the FIV analyses were compiled and interpreted by Steve Becker of the ExxonMobil Upstream Research Company. This work was supported by the Department of Energy National Energy Technology Laboratory under Award Number DE-NT0004730 and is currently supported under Award Number DE-FE0002142.

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

6. References
