The Rock Springs Uplift
An outstanding geological CO₂ sequestration site in southwest Wyoming

Wyoming State Geological Survey
Challenges in Geologic Resource Development No. 2
Ronald C. Surdam and Zunsheng Jiao
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Plate 1. Geologic map and oil and gas fields of the Rock Springs Uplift area, Sweetwater County, southwest Wyoming.
Abstract

As global warming becomes ever more prominent in the public consciousness and regulation of carbon emissions increases, geological CO₂ sequestration will by necessity move from the domain of fantasy to the world of fact. The Wyoming State Geological Survey (WSGS) has identified a huge, nearly ideal geological CO₂ sequestration site in the Rock Springs Uplift of southwest Wyoming. Capable of safely storing 26 billion tons of CO₂, the site could sequester 485 years' worth of Wyoming emissions at current levels (54 million tons per year).

Introduction

At the request of Governor Dave Freudenthal, the WSGS investigated significant potential geological CO₂ sequestration sites in Wyoming. This investigation is particularly important because without the ability to geologically sequester CO₂, the future of IGCC (integrated gasification combined cycle) power plants and coal-to-liquids technologies will remain in the realm of conjecture. In the present national socio-economic and environmental setting, any coal- or hydrocarbon-based new energy-generating technology, or existing energy-producing facility required to reduce its carbon footprint, will depend on geological CO₂ sequestration.

To qualify as excellent, a geological CO₂ sequestration site must display the following characteristics: 1) fluid trap, either a doubly-plunging anticline or an up-dip stratigraphic trap (trap volume must be large enough to accommodate the amount of CO₂ to be sequestered); 2) a relatively thick reservoir interval with enough porosity (storage capacity) and permeability (deliverability) to facilitate injection of substantial amounts of CO₂; 3) a sealing, low permeability unit over the reservoir for an anticlinal structure, or an up-dip seal for a stratigraphic trap; and 4) reservoir conditions (temperature, pressure, and rock/fluid chemistry) that allow the reservoir to accept large amounts of CO₂ without incurring damage. A geological site with these characteristics could permanently sequester large amounts of CO₂ in the subsurface. The Rock Springs Uplift of southwest Wyoming (Plate 1) meets all of the above criteria and would be an ideal geological sequestration site.

The Uplift is a large (50 miles by 35 miles), doubly-plunging anticline characterized by more than 10,000 feet of closed structural relief (Figure 1). The potential CO₂ storage reservoirs are the Pennsylvanian Weber Sandstone (Figure 2) and the Mississippian Madison Limestone (Figure 3). The Weber Sandstone is approximately 700 feet thick, and the Madison Limestone is approximately 250 feet thick. Both units have substantial porosity (storage) and permeability (deliverability). Neither the Weber nor the Madison is exposed on the Rock Springs Uplift; the nearest surface outcrops of these units are 50 to 100 miles from the margins of the structure. Consequently, these two formations are far removed from any meteoric water recharge and have retained their original marine/evaporite character (saline). At the crest of the Uplift, the Weber lies 6,200 feet below ground and the Madison lies 7,500 feet below ground. On the flanks of the structure, these units lie 15,000 feet or more below
Figure 1. A vertical east-west seismic profile shows the Rock Springs Uplift is characterized by more than 10,000 feet of structural relief. Modified from Montgomery, 1996.
Figure 2. Weber Sandstone layer from 3-D structural/stratigraphic model constructed for the Rock Springs Uplift (see Figures 3 and 4).
Figure 3. Madison Limestone layer extracted from a 3-D structural/stratigraphic model constructed for the Rock Springs Uplift (see Figures 3 and 4).
ground. Within the Rock Springs Uplift, both the Weber Sandstone and the Madison Limestone have temperature and pressure attributes that make them ideally suited to accept huge amounts of injected CO$_2$.

Five thousand feet of low-permeability Cretaceous shales overlie the Weber and the Madison, and make an ideal seal for the CO$_2$ storage reservoirs (Figures 4-6). The composition of produced gas from the Weber and Madison units – sour and up to 80% CO$_2$ – demonstrates the sealing capacity of these shales. In strong contrast, gas produced from Cretaceous sandstones above the shales is sweet and typically less than 1% CO$_2$. This significant difference in fluid chemistry between the Paleozoic and Cretaceous stratigraphic units negates the potential for vertical fluid connectivity on the Rock Springs Uplift (Figures 4-6).

The available data show that fluid salinity in the Weber Sandstone generally exceeds 35,000 ppm, and fluid salinity in the Madison Limestone ranges from 50,000 to 80,000 ppm. Both the Weber Sandstone and the Madison Limestone within the Rock Springs Uplift are considered saline aquifers. EPA regulations do not allow water with salinity levels above 10,000 ppm to be treated for use as drinking water. In the Rock Springs Uplift, salinities of the two aquifers in question far exceed the acceptable level; these aquifers could not be used for drinking water.

Significant Cretaceous oil and gas production occurs on the Uplift, while significant Paleozoic oil and gas production occurs on Uplift margins (Brady Field, see Figure 7). On the Uplift, 75 wells have penetrated the Paleozoic: 30 of these are plugged and abandoned; 14 are shut in or abandoned but not plugged; and 31 are active. Therefore, there are 45 wells on the Uplift that could be used as monitoring wells for CO$_2$ sequestration activities.

The Jim Bridger Power Plant is located on the Rock Springs Uplift, so the Uplift is ideally situated for sequestration of CO$_2$ generated by this plant. The plant, which generates approximately 18 million tons of CO$_2$ per year, has the largest carbon footprint in Wyoming.

Applying the diagnostic protocol for CO$_2$ sequestration suggested by the Department of Energy (DOE) for the FutureGen project, the WSGS evaluated the CO$_2$ sequestration capacity of the Weber Sandstone and the Madison Limestone within the Rock Springs Uplift (Table 1). Results indicate that on the Uplift, the Weber Sandstone could accept 18 billion tons of CO$_2$ and the Madison Limestone could accept 8 billion tons of CO$_2$ (26 billion tons total).

In brief, the Weber Sandstone and the Madison Limestone within the Rock Springs Uplift have outstanding CO$_2$ sequestration potential. The Rock Springs Uplift satisfies geological CO$_2$ requirements superbly including: 1) thick saline aquifer sequence overlain by thick sealing lithologies; 2) structural closure; 3) huge area; and 4) suitable reservoir characteristics. The Rock Springs Uplift in southwest Wyoming is a truly outstanding CO$_2$ sequestration site (Figures 2-4).
Figure 4. An east-west stratigraphic cross section of the Rock Springs Uplift. The CO₂ sequestration target formations, the Weber sandstone and the Madison Limestone, are overlain by more than 5,000 feet of low permeability Cretaceous shales and bounded by two thrust faults. The solid red line represents the regional pressure seal (i.e., a surface separates the normal pressure regime above and abnormal pressure regime below).
Figure 5. Three-dimensional structural geologic model of the Rock Springs Uplift constructed using the formation tops picked from well logs. The target CO₂ sequestration reservoirs, the Weber and the Madison, are characterized by four-way closures and the 5000+ feet of overlying low-permeability Cretaceous shales. The overlay on top of the model is the surface geologic map.
Figure 6. An east-west cross section through the center of the 3-D structural geologic model of the Rock Springs Uplift (see Figure 3).
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<th>Weber</th>
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<th>Madison</th>
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**Calculated parameters**

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<td>7.00 %</td>
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**Fixed parameter**

| Mass of injected CO₂                 | 5.00 x 10⁷ | tonnes  | 5.00 x 10⁷ | tonnes  |

**Results**

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<td></td>
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<td>6.00 x 10⁸</td>
<td>short tons</td>
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**Current Wyoming CO₂ emissions (coal-fired and gas processing plant)**

**Number of years Wyoming CO₂ emissions could be sequestered in the Weber and Madison reservoirs, Rock Springs Uplift, Wyoming**

485 years
**Rock Springs Uplift**

The Rock Springs Uplift is a large (50 miles by 35 miles) doubly-plunging anticlinal (dome) structure located in southwest Wyoming (Plate 1). The Cretaceous Baxter Shale is exposed along the crest of the structure, and the lower Tertiary Fort Union and Wasatch Formations are exposed along the distal portions of the structure. East-west seismic lines across the Rock Springs Uplift demonstrate that the structure is asymmetric (Figure 1) with the steepest limb on the west flank. There are high-angle reverse faults and a series of normal faults beneath the steeper west flank of the anticline (Figure 1). Along the east flank of the structure at the west edge of the Washakie Basin, there is a reverse-fault system at depth that is not exposed at the surface (Figure 1). This series of reverse faults and associated folds are the site of deep hydrocarbon production known as the Brady fields.

As can be seen from Plate 1, a series of northeast-southwest faults exposed at the surface cut across the Uplift. These faults neatly compartmentalize hydrocarbon production in the Cretaceous stratigraphic section (Figure 8), and serve as boundaries to a series of slightly under pressured compartments: they act as seals rather than conduits for fluid flow.

For example, the Frontier, Dakota, Morrison, and Nugget production in the North Baxter Field was initially under pressured (0.30-0.42 psi/ft). At the Middle Baxter Field, the Frontier production was initially over pressured (0.54 psi/ft). At the South Baxter Field, the Frontier and Dakota production was initially under pressured (0.34 and 0.31 psi/ft, respectively). Production from these three fields, which all lie near each other at the crest of the Uplift, is compartmentalized by the NE-SW faults. No fluid connections exist between these fields, and, with all the production being anomalously pressured, the reservoirs are under depletion drive and strongly compartmentalized.

The Rock Springs Uplift is a topographic high that separates the Washakie Basin in the east from the Bridger Basin in the west. The Uplift displays more than 15,000 feet of structural relief relative to the surrounding basins (Montgomery, 1996). The top of the Precambrian basement is characterized by a lack of seismic reflection continuity. In the Rock Springs Uplift, the basement reaches approximately 1.5 second two-way travel time at its highest point, approximately 10,000 feet below ground (Figure 1). The basement in the adjacent Washakie and Bridger basins lies 20,000 to 30,000 feet deep.

The Uplift is a relatively young Laramide structure. Figure 9 shows an isopach map of the LaClede Bed of the Lamey Member of the Green River Formation. It is apparent from the isopach map that the Uplift postdates deposition of the LaClede Bed (~ 45 Ma). However, prior to deposition of the Sand Butte Bed of the Lamey Member (~ 44 Ma), part of the LaClede Bed located over the present position of the Rock Springs Uplift eroded (Surdam, Stanley (1980), and Roehler, 1992; Figure 9).
Figure 8. A structure contour map on the top of the Frontier Formation for the Middle Baxter Basin Field. The distribution of the production wells indicates that well-developed NE-SW faults neatly compartmentalized hydrocarbon production in the Cretaceous stratigraphic section.
Figure 9. An isopach map of the LaClede Bed in the Laney Member of the Green River Formation around the Rock Springs Uplift. The continuous contour line across the Uplift reveals that the Uplift postdates the deposition of the LaClede Bed (~45 Ma). Shading indicates areas where parts of the LaClede bed of the Laney Member eroded prior to deposition of the Sand Butte bed of the Laney Member.
Stratigraphy

The Upper Cretaceous Baxter Shale is exposed along the crest of the Rock Springs Uplift. Along the distal flanks of the structure, the Upper Tertiary Fort Union and Wasatch Formations are exposed. A thick stratigraphic section dominated by shale overlies the Mesozoic and Paleozoic stratigraphic sections. The Paleozoic stratigraphic section does not crop out on the Rock Springs Uplift. The nearest Paleozoic rock outcrops are located 50 to 100 miles from the margins of the Uplift (i.e., north flank of the Uinta Mountains, Thrust Belt, and the Rawlins Uplift, Wyoming).

Of special interest in the Rock Springs Uplift are the Weber Sandstone (Tensleep Sandstone equivalent) and the Madison Limestone. Both stratigraphic units are characterized by petrophysical parameters (porosity and permeability) that could support significant fluid storage and substantial fluid deliverability. Data from the Wyoming Oil and Gas Fields Symposium, Green River Basin (1979) suggest that the porosity of the Weber Sandstone ranges from 8% to 12%, and the porosity of the Madison Limestone ranges more widely and averages 10%. Evaluation of electric log parameters through the Weber and Madison wells on the Rock Springs Uplift support a typical subsurface porosity value of 10% for both formations.

The Pennsylvanian Weber Sandstone in the Rock Springs Uplift is approximately 700 feet thick (Ahern and others, 1981), and consists of fine- to medium-grained, eolian cross-bedded, quartz-rich sandstone with thin interbeds of limestone and dolomites (Mason and Miller, 2005). At the crest of the structure, the Weber Sandstone lies 6,210 feet below ground level. The Mississippian Madison Limestone consists of approximately 250 feet of blue-gray massive limestone and dolomite, and lies 7,500 feet below ground level at the crest of the Uplift. Within the Rock Springs Uplift, these two Paleozoic units are not in contact with meteoric water, and any potential recharge areas (formation outcrop areas) are located 50 to 100 miles outside the structure's margins. Drill stem tests support the conclusion that these Paleozoic units are not in contact with meteoric water because both units are slightly underpressured.

Fluid chemistry

Little information exists on directly measured fluid chemistry in either the Weber Sandstone or the Madison Limestone within the Rock Springs Uplift. Available data suggest that fluid salinity in the Weber Sandstone generally exceeds 35,000 ppm, and fluid salinity in the Madison Limestone ranges from 50,000 to 80,000 ppm. These few measured salinity values are supported by electric log parameters. Existing, pertinent information about formation chemistry suggests that on the Rock Springs Uplift, the Weber Sandstone and the Madison Limestone should be considered saline aquifers.

In modeling CO₂ injection into these two stratigraphic units, we assumed that 85% of total dissolved solids result from NaCl. We used a concentration of 0.5 molal, or 20,000 ppm of
dissolved NaCl, to construct fluid-flow models for both the Weber Sandstone and the Madison Limestone. These models demonstrated that the two targeted aquifers could store huge quantities of CO₂.

**Oil and gas production**

Forty-five separate oil and gas fields exist in the Rock Springs Uplift area. The age of reservoir rocks within the Uplift ranges from Tertiary to Mississippian, and most production comes from Upper Cretaceous reservoirs within the Mesaverde Group. Minor production comes from the Jurassic Morrison Formation at Crooked Canyon and the Baxter Basin North fields. Also, the Phosphoria Formation at Pretty Water Creek Field produces minor amounts of oil and gas. The main producing reservoirs at Brady South and Brady North fields include the Nugget Sandstone and the Weber Sandstone. The Brady South and Brady North fields are separated from the Rock Springs Uplift by an east-dipping thrust fault at depth (Figure 7).

If the Rock Springs Uplift became a regional repository for CO₂, it is possible that a small amount of the CO₂ could be used in enhanced oil recovery projects. The crestal Cretaceous oil fields have potential for enhanced oil recovery (Tertiary oil recovery using CO₂ flooding).

According to information from the Wyoming Oil and Gas Conservation Commission, 2,996 oil and gas tests were drilled in the Rock Springs Uplift (Figure 10). Of these, 593 were drilled through the Cretaceous and into the Jurassic Morrison Formation. Ninety-five of the 593 wells penetrated the Nugget Formation, but did not reach the Weber Sandstone. Fifty-five wells penetrated the Weber Sandstone but not the Madison Limestone, and 20 wells reached the Madison Limestone or deeper stratigraphic units. Fewer than half of the wells that penetrated potential sequestration targets were adjacent to the Rock Springs Uplift at Brady South, Brady North, and Table Rock fields. Fourteen abandoned wells that penetrate the Weber or Madison have not been plugged, and would be excellent candidates for monitoring wells should a CO₂ sequestration site be located on the Rock Springs Uplift.

The Brady fields on the southeast flank of the Rock Springs Uplift are of special interest because they produce the most hydrocarbons from the Weber Sandstone in southwest Wyoming (Figure 11). Both the Brady North and Brady South fields are structurally controlled traps, faulted on the northwest side (Figure 11). Several horizons produce gas and oil, including the Dakota, Entrada (Sundance), Nugget, and Weber stratigraphic units. Production at Brady South also includes the Blair, Frontier, and Phosphoria formations.

At the Brady North field, the Entrada produces from a reported pay zone 40 feet thick with a porosity of 11% and a permeability of 1.4-7.0 millidarcy (md). At this field, initial pressure measured 5,061 psi (shut in pressure (SIP)). The Entrada consists of eolian sands and is described as continuous and finely cross-bedded. Estimated ultimate recovery for the Entrada Sandstones is 5.0 billion cubic feet (BCF) of gas and 130 million barrels of oil (MMBO). The gas from this field contains 31% CO₂ with 15 ppm H₂S. With a water resistivity (Rₜw)
Figure 10. Map showing distribution of deep penetration wells in the Rock Springs Uplift. A total of 2,996 oil and gas tests have been drilled in the Rock Springs Uplift. Of those wells, 593 wells penetrated the Jurassic Morrison Formation or deeper.
Figure 11. A structure contour map on the Weber Sandstone for the Brady North and South gas fields. Both structural traps are bounded by a NE-SW thrust fault.
of 0.16, the water produced from the Entrada at Brady North has a total dissolved solids (TDS) level of at least 40,000. The Nugget produces from a pay zone averaging 72 feet thick, in eolian dunes separated by lithologic interdunes 4 to 8 feet thick with an average porosity of 11% and an average permeability of 20 md. Initial bottom hole pressure in the Brady North field was 5,080 psi. Estimated ultimate recovery for the Nugget is 10 MMBO. Gas in the Nugget is 68.36% CO₂ and contains no H₂S. The fluid produced has a Rₜₙ of 0.12 at 68°F, indicating a TDS of more than 70,000 ppm. At Brady North, the Weber produces from eolian sands with an average pay zone thickness of 188 feet. The porosity in the Weber averages 6.5% and permeability ranges from 0.01 to 74 md. Initial pressure in wells penetrating the Weber was 6,045 psi (SIP), and the Weber reservoir is described as having excellent continuity over the field area. Weber gas contains 40% CO₂ and 0.4% H₂S. Produced water from the Weber has a Rₜₙ of 0.097 at 68°F, which indicates a TDS value of more than 90,000 ppm.

The Brady South field produces from the Nugget and Weber formations. Here, the Entrada is water-wet and does not produce, and the Phosphoria Formation produces from just one well. Water and hydrocarbon characteristics of the Nugget and Weber reservoirs appear very nearly the same as at Brady North. At Brady South, the Nugget was developed early with the idea that a strong water drive was present on the west flank of the field due to increased pressure from the east flank of the Rock Springs Uplift. However, this hypothesis was proven false when wells drilled on the structural crest did not encounter water. This illustrates that the thrust fault on the structure’s west side provides a seal separating the field from the Rock Springs Uplift. The Weber discovery well, the 1 Champlin Brady unit 21-11, was drilled to the Flathead Sandstone, which lies below the Weber and the Madison. In this well, a drill stem test (DST) in the Madison recovered 5,535 feet of sulfur-rich water and 640 feet of mud-cut, sulfur-rich water with a shut-in pressure of 6,282-6,154 psi and a hydrostatic pressure of 7,183 psi. This test indicates that in the discovery well, the Madison Limestone is water wet, has substantial porosity and permeability, and is slightly underpressured.

**Coal resources**

The Rock Springs Uplift is rimmed by exposed coal-bearing rocks of Cretaceous and Tertiary age (Figure 12). Coal resources from the Green River coal fields are estimated at 237 billion tons, and commercial coal mining in this area began in the late 1800s along the west edge of the Rock Springs Uplift. Currently, two active coal mining operations are located along the east flank of the Uplift: the Black Butte surface mine located south of Interstate 80, and the Jim Bridger surface and underground mine north of Interstate 80. The Uplift produces approximately 10 million tons of coal per year, and the adjacent 2,110-megawatt Jim Bridger Power Plant uses coal from the two mines. The Jim Bridger Power Plant is the largest coal-fired power plant in Wyoming, and generates enough electricity to supply up to one million residential customers in six western states.
from the Wythe sandstone and Madison limestone by more than 3 miles of Mesozoic and Paleozoic stratigraphic sections.

and Jim Bridger surface and underground mines are both located on the east flank of the uplift. Minor Terry coal are separated

Figure 1. Map showing the coal outcrops and active mines in the Rock Springs uplift. The currently active Block Butte surface mine

Formerly called “Little Powder”

Black Butte Mine

Surface Mine

Black Butte Mine

Surface and Underground Mine

Jim Bridger Mine

Coal Power Plant

Exhibit approximately 10.5 million tons

2110 megawatts power production

Jim Bridger Power Plant

State Border

Township-Range Lines

Project Boundary

Uplift Boundary

Fuels

Coal Outcrops

Coal Mines

Legend
Production from the Jim Bridger underground operation is limited to Tertiary coal-bearing rocks of the Fort Union Formation. Projected depth of the underground workings ranges from 300 to 400 feet. Offset of bedding due to faulting within the mine lease boundary ranges from 40 to 70 feet. Outcrops of older Cretaceous rocks occur west of the mine and include, in descending order, the Lance Formation, Foxhills Sandstone, Lewis Shale, units of the Mesaverde group, and Baxter Shale. Near the coal mines, the underlying shale-rich Cretaceous sequence is approximately 1 mile thick. The actively mined coal-bearing rocks at this location are underlain by approximately 3 miles of combined Mesozoic and Paleozoic rocks.

**CO₂ sequestration capacity**

Using the diagnostic protocol for CO₂ sequestration suggested by the Department of Energy (DOE) for the FutureGen project, the WSGS evaluated the CO₂ sequestration capacity of the Weber Sandstone and the Madison Limestone within the Rock Springs Uplift (Table 1). Results indicate that, on the Uplift, the Weber Sandstone could accept 18 billion tons of CO₂ and the Madison Limestone could accept 8 billion tons of CO₂. Combined, these two stratigraphic units could store 26 billion tons of CO₂.

Currently, Wyoming emits approximately 54 million tons of CO₂ per year from coal-fired power plants and gas processing plants. At this rate, the two sequestration reservoirs in the Rock Springs Uplift could store CO₂ emissions from in-state facilities for 485 years.

It should be noted that the CO₂ plume resulting from the injection of 50 million tons of CO₂ in the Weber Sandstone would extend for only 3.5 square miles. The Weber sequestration zone within the Rock Springs Uplift measures 1,300 square miles in area. So, the Weber Sandstone could accept 50 million tons of CO₂ per year for 370 years before its CO₂ sequestration capacity is exceeded. The Jim Bridger Power Plant located on the Rock Springs Uplift currently emits approximately 18 million tons of CO₂ per year. The Weber and Madison sequestration reservoirs could accept emissions from this plant for 1,470 years.

**Monitoring CO₂ sequestration**

CO₂ sequestration involves injecting large amounts of the gas in supercritical condition into saline reservoirs. This process may significantly alter the physical and chemical condition of the targeted reservoir (i.e., increase reservoir pressure and temperature, decrease or increase reservoir rock porosity and permeability, and alter fluid-flow properties). The potential for leakage of the injected CO₂ is one of the most important criteria to consider when selecting a geological CO₂ sequestration site. When it occurs in high concentrations, such as during volcanic eruptions or lake turnovers, CO₂ can be lethal. Therefore, potential movement of CO₂ outside a selected geologic trap is a major concern, and in some cases, it may become an obstacle to the acceptance and widespread use of CO₂ sequestration. Therefore, the distribu-
Figure 13. The result of well-to-well tomography shows the significant velocity decrease caused by CO₂ injection. Right cross section is a velocity difference profile after injection of the CO₂ into the hydrocarbon-producing interval. Red and yellow colors represent the sections with notable velocity decrease caused by injected CO₂ or presence of a gas phase. Left logs show that the injected CO₂ resulted in a 10-20% drop in velocity of the reservoir rocks (seismic velocity slowdown).

Time-lapse 4-D seismic reflection surveying can be effectively used to monitor geological CO₂ sequestration. Seismic characterization of fluids in saline or hydrocarbon reservoirs during CO₂ injection relies on changes in bulk density and bulk modulus of the rock as the native pore fluids are displaced or altered. Changes on the order of a few percent in the pore fluid composition or fluid flow can result in significant variation in seismic attributes (such as interval velocity, instantaneous amplitude, phase, frequency, coherency, and impedance). The correlation between fluid composition, particularly with respect to a gas phase, and sonic velocity is a well-established fact. Among others, Timur (1987) demonstrated that at 10-15% gas saturation there is a notable decrease in sonic velocity. In well-to-well seismic tomography experiments, Lazaratos and Marion (1977) demonstrated that a 10-20% decrease in velocity resulted from the injection of the CO₂ into the reservoir (i.e., addition of a gas phase and changing from a single to multiphase fluid; Figure 13).
Over the last decade, Surdam and his research group have developed an innovative technology to detect and delineate natural gas accumulations in hydrocarbon reservoirs, reliable natural analogues to geological CO₂ sequestration (a gas phase stored in a reservoir for tens of millions of years). Using automatic, continuous interval velocity calculations, 3-D reservoir characterization, and geospatial modeling, this technology can delineate the position and size of the natural gas accumulation in the subsurface before drilling (Surdam and others, 2005). Vertical and lateral differences and distribution of important reservoir properties (porosity; permeability; and fluid composition) can be characterized within the horizontal limits of the survey by correlating different seismic attributes to reservoir properties. Such attribute correlations have proven effective in detecting changes in fluid saturation, pressures, and temperature, even using data not optimized for 4-D analysis (time is the fourth dimension). For example, using high-resolution 3-D seismic data and the newly developed technology, Surdam and his colleagues were able to discriminate in significantly greater detail the horizontal and vertical distribution of the gas-charged velocity anomalies associated with productive sweet spots within the Muddy Sandstone interval in the Riverton Dome, Wind River Basin, Wyoming (Figure 14). Interpretation of the 3-D seismic velocity anomalies and integration with information gleaned from detailed reservoir characterization resulted in a vastly improved understanding of the Riverton Dome Gas Field. This new understanding reduced uncertainty in the field by accurately predicting the relative productivity of six Muddy Sandstone wells. These wells initially produced from 1 to 4 MMCF (million cubic feet) per day (Figure 15).

Because time-lapse seismic is sensitive to changes in the injected CO₂ plume as it advances through a saline reservoir, this technique could provide the necessary information about storage and potential leaks. Key to time-lapse monitoring of CO₂ sequestration is effective reservoir modeling constrained by reasonable geologic characteristics adapted to measured changes in reservoir pressure, temperature, fluid composition, and bulk density between monitor well locations. Understanding the evolution of the CO₂ plume will help build better reservoir models and will substantially reduce uncertainty regarding geological CO₂ sequestration. It is necessary to conduct a 3-D survey before injecting CO₂ at the selected sequestration site. Data from the first survey can be used to generate a detailed 3-D reservoir model and establish the velocity baseline for subsequent velocity models of the site after sequestration. Later 3-D surveys – perhaps at one year and three years post-injection – can be used to accurately map the changes in the size of the CO₂ injection plume, along with CO₂ distribution, reservoir pressure, and rates of plume size change and reservoir pressure change. Information provided by 4-D seismic and 3-D reservoir characterization will play a key role in developing accurate reservoir models and in mapping the movement and stability of CO₂ during geological sequestration.
Figure 14. Three-dimensional anomalous velocity model showing the volume and shape of the abnormally slow velocity and gas-charged section in the Riverton Dome, Wind River Basin, Wyoming. The significant slowdown results from the presence of a gas phase; the seismic ray does not identify if the gas phase is natural gas or CO₂, so the technique can be used for detecting any gas phase.
Figure 15. Map view at the top of the Muddy Sandstone reservoir interval; the map is derived from a 3-D anomalous velocity volume constructed from a 3-D seismic survey at Riverton Dome in the Wind River Basin, Wyoming. Six recent Muddy Sandstone wells are plotted on the anomalous velocity map on the top of the Muddy Sandstone. Wells within the intense velocity anomaly (more than 1,500 m/s below the regional velocity/depth gradient) initially produced 3-4 MMCF per day; the well at the edge of the anomaly (less than 1,200 m/s below the regional gradient) initially produced 1 MMCF per day; and wells drilled outside the anomaly initially produced less than 1 MMCF per day and presently are shut in.
Conclusions

In summary, the Weber Sandstone and the Madison Limestone within the Rock Springs Uplift have outstanding CO$_2$ sequestration potential. Most importantly, the Rock Springs Uplift satisfies CO$_2$ sequestration requirements superbly, including: 1) thick saline aquifer sequence overlain by thick sealing lithologies; 2) structural closure; 3) huge area; and 4) required reservoir conditions. The Rock Springs Uplift in southwest Wyoming is a truly outstanding geological CO$_2$ sequestration site.

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