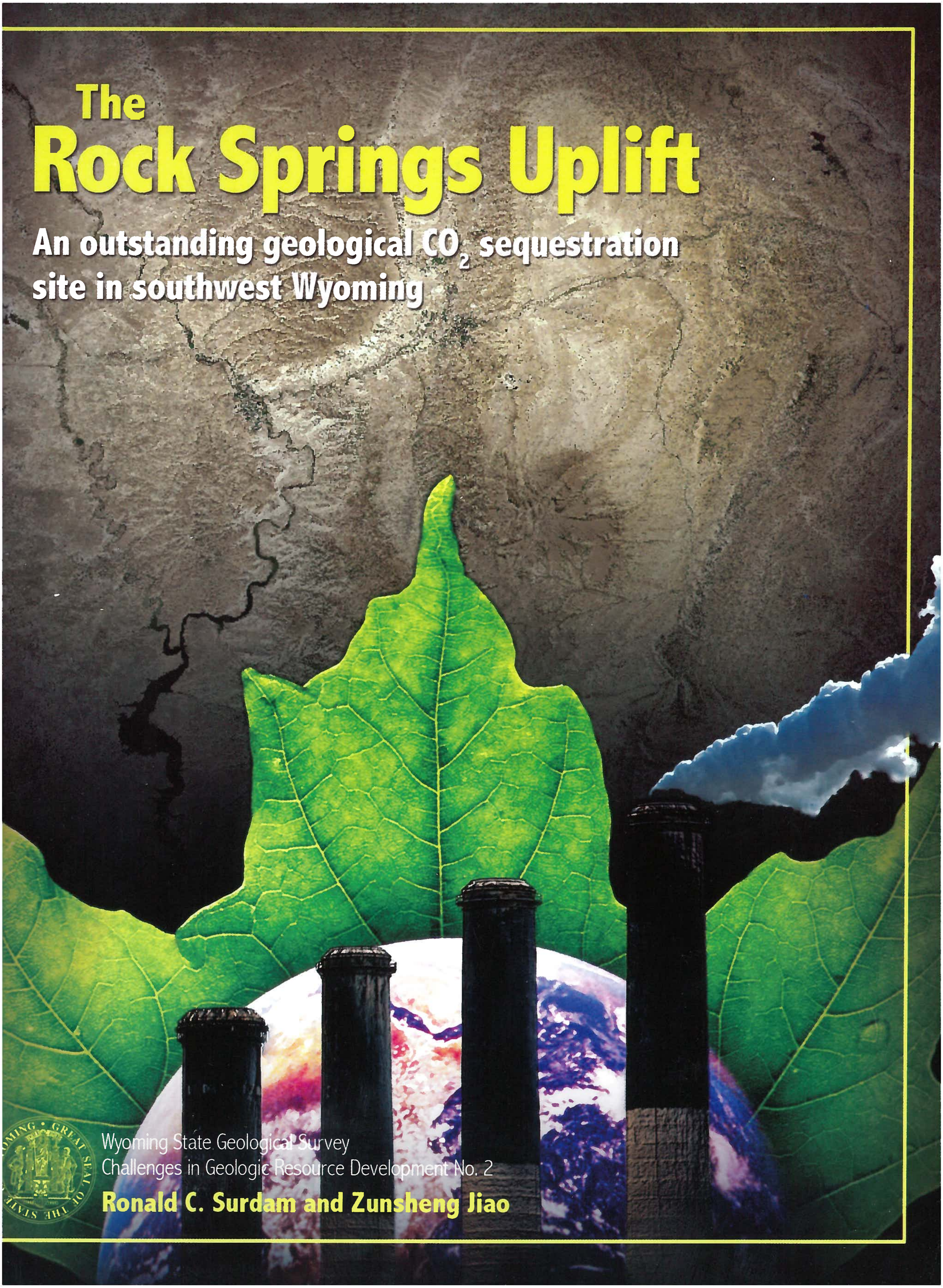

The Rock Springs Uplift

An outstanding geological CO_2 sequestration site in southwest Wyoming

Wyoming State Geological Survey
Challenges in Geologic Resource Development No. 2

Ronald C. Surdam and Zunsheng Jiao

Wyoming State Geological Survey
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Cover Composite: Aerial photo of Rock Springs Uplift, Jim Bridger power plant stacks, earth and leaf stock photo.

THE ROCK SPRINGS UPLIFT

An outstanding geological CO_2 sequestration site in southwest Wyoming

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Abstract

As global warming becomes ever more prominent in the public consciousness and regulation of carbon emissions increases, geological CO_2 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 CO_2 sequestration site in the Rock Springs Uplift of southwest Wyoming. Capable of safely storing 26 billion tons of CO_2, 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 CO_2 sequestration sites in Wyoming. This investigation is particularly important because without the ability to geologically sequester CO_2, 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 CO_2 sequestration.

To qualify as excellent, a geological CO_2 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 CO_2 to be sequestered); 2) a relatively thick reservoir interval with enough porosity (storage capacity) and permeability (deliverability) to facilitate injection of substantial amounts of CO_2; 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 CO_2 without incurring damage. A geological site with these characteristics could permanently sequester large amounts of CO_2 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 CO_2 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

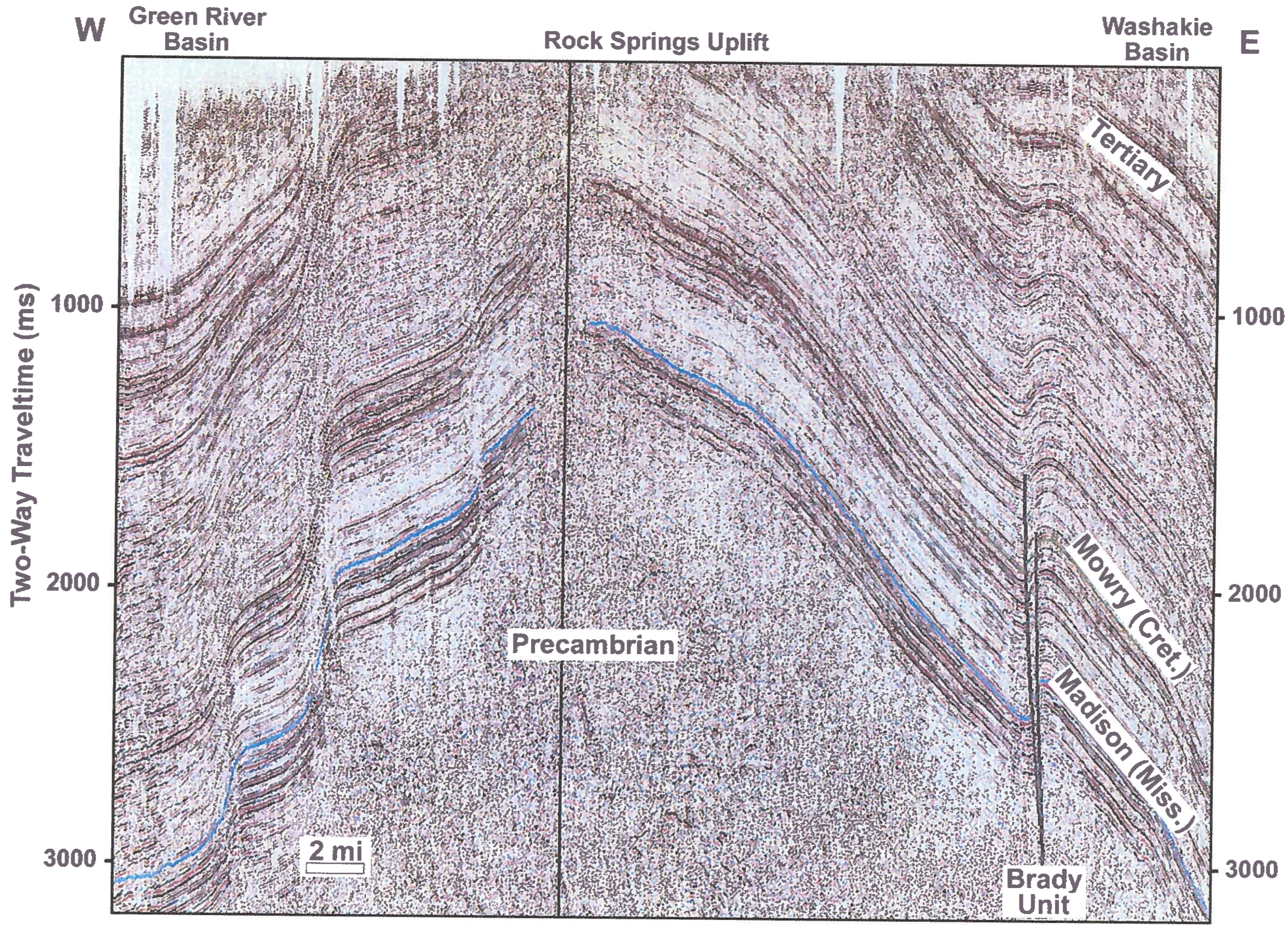


Figure 1. A vertical east-west seismic profile shows the Rock Springs Uplift is characterized by more than 10,000 feet of structural relief. Modified from Montgomery, 1996.

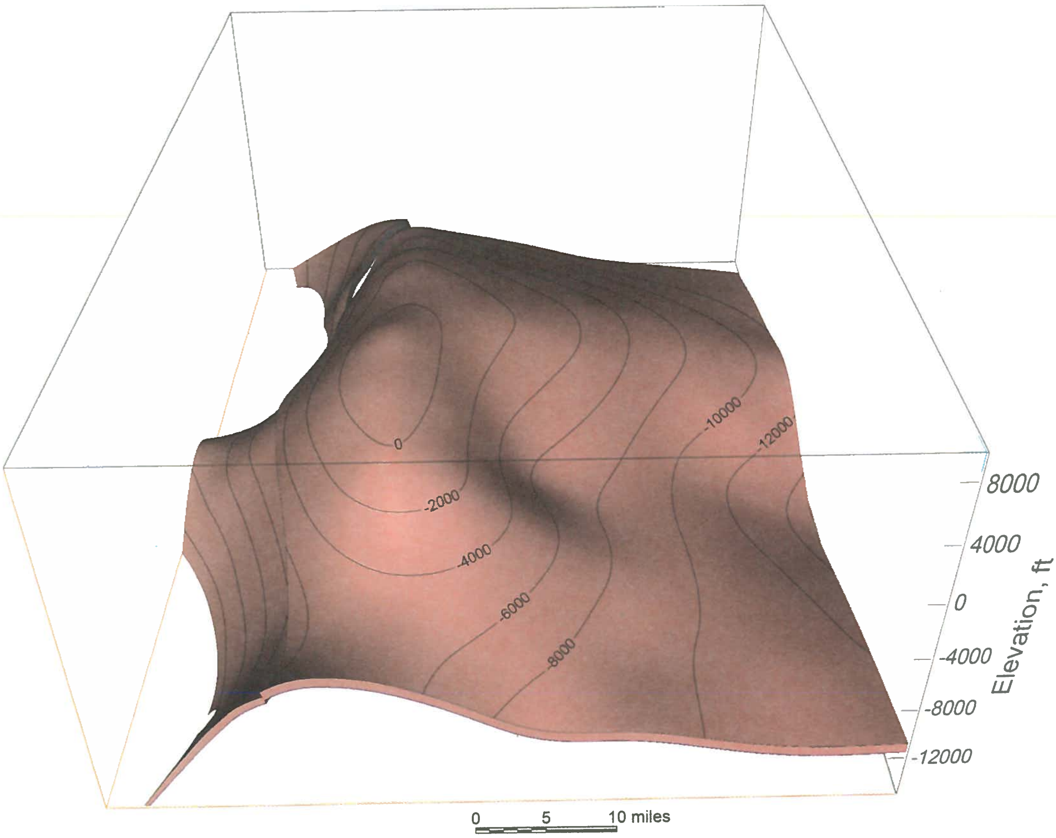


Figure 2. Weber Sandstone layer from 3-D structural/stratigraphic model constructed for the Rock Springs Uplift (see Figures 3 and 4).

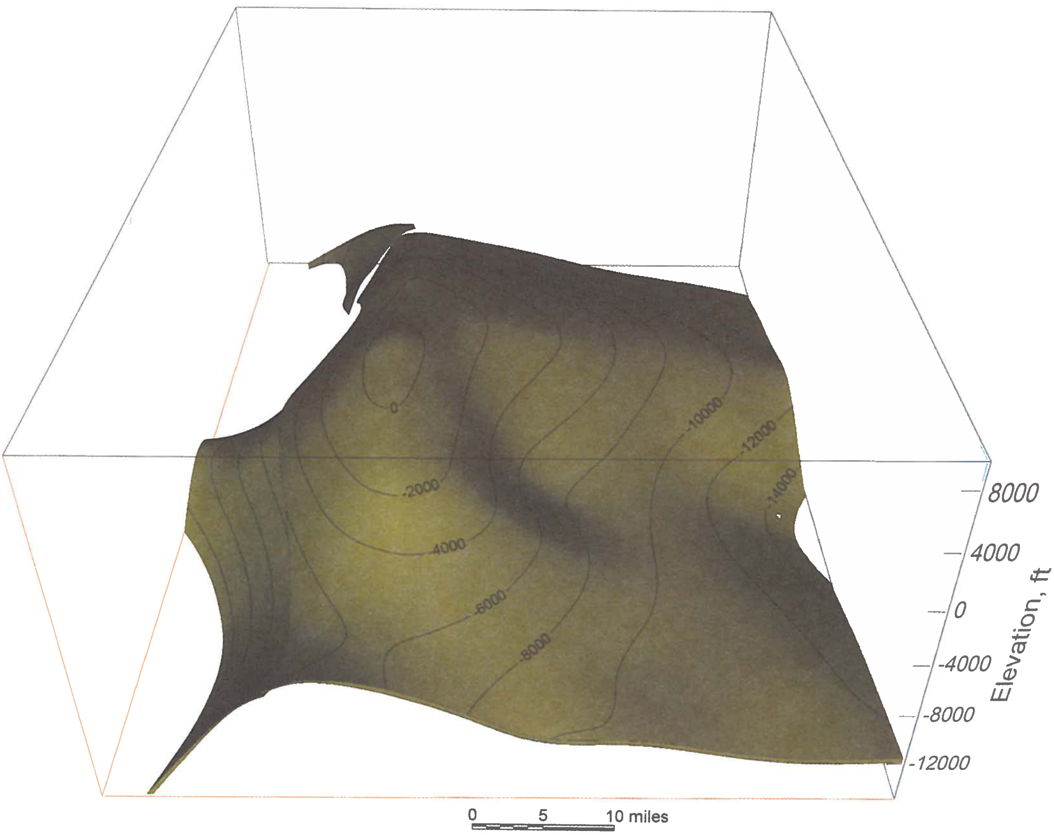


Figure 3. Madison Limestone layer extracted from a 3-D structural/stratigraphic model constructed for the Rock Springs Uplift (see Figures 3 and 4).

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**).

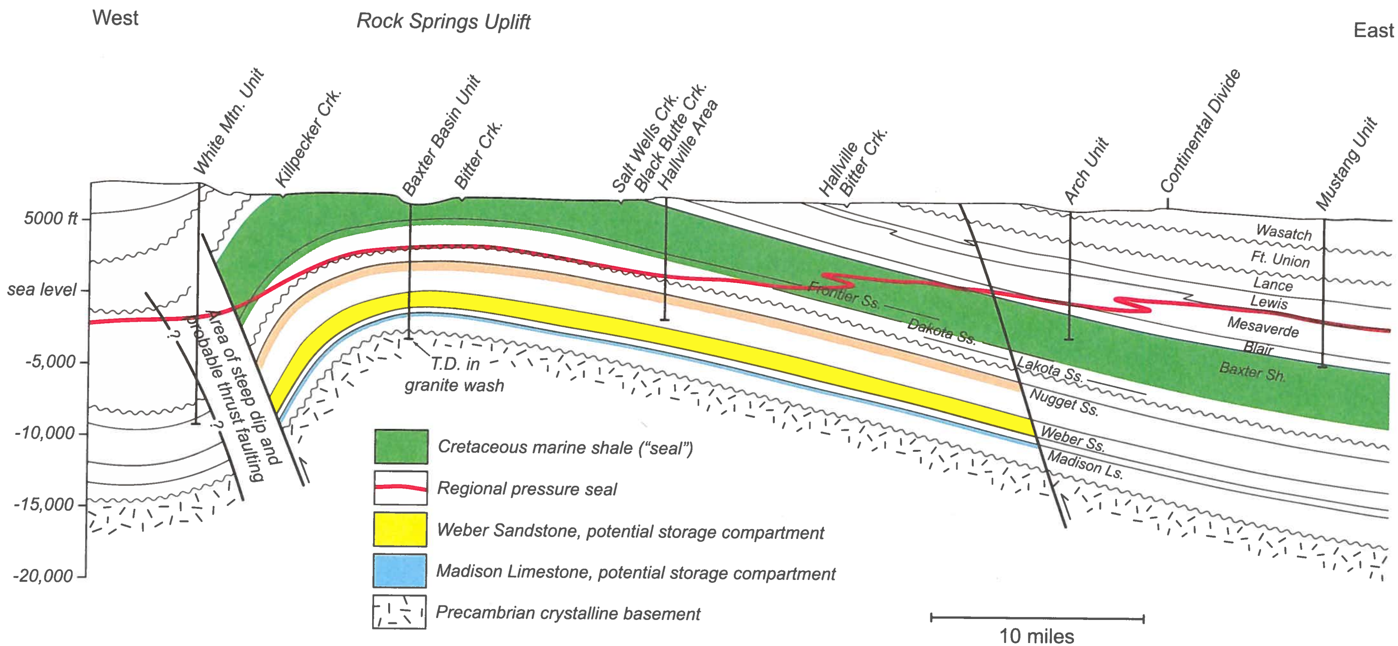


Figure 4. An east-west stratigraphic cross section of the Rock Springs Uplift. The CO_2 sequestration target formations, the Weber sandstone and the Madison Limestone, are overlain by more than 5,000 feet of low-permeability Cretaceous shales and bounded by two thrust faults. The solid red line represents the regional pressure seal (i.e., a surface separates the normal pressure regime above and abnormal pressure regime below).

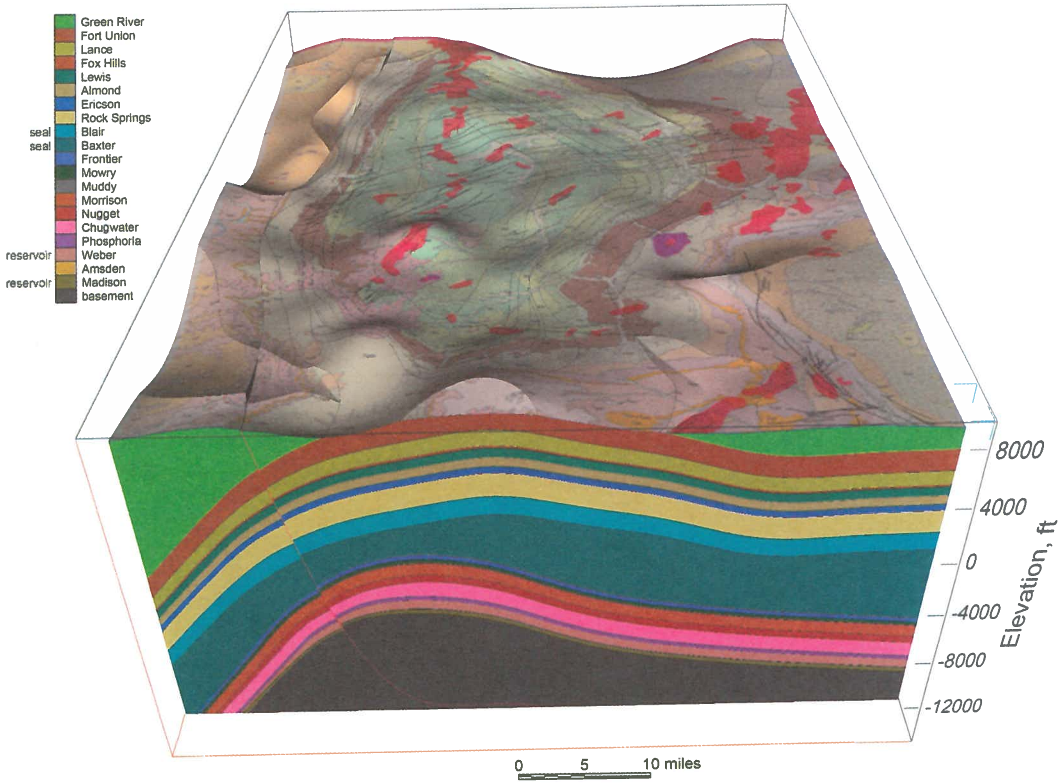


Figure 5. Three-dimensional structural geologic model of the Rock Springs Uplift constructed using the formation tops picked from well logs. The target CO_2 sequestration reservoirs, the Weber and the Madison, are characterized by four-way closures and the 5000+ feet of overlying low-permeability Cretaceous shales. The overlay on top of the model is the surface geologic map.

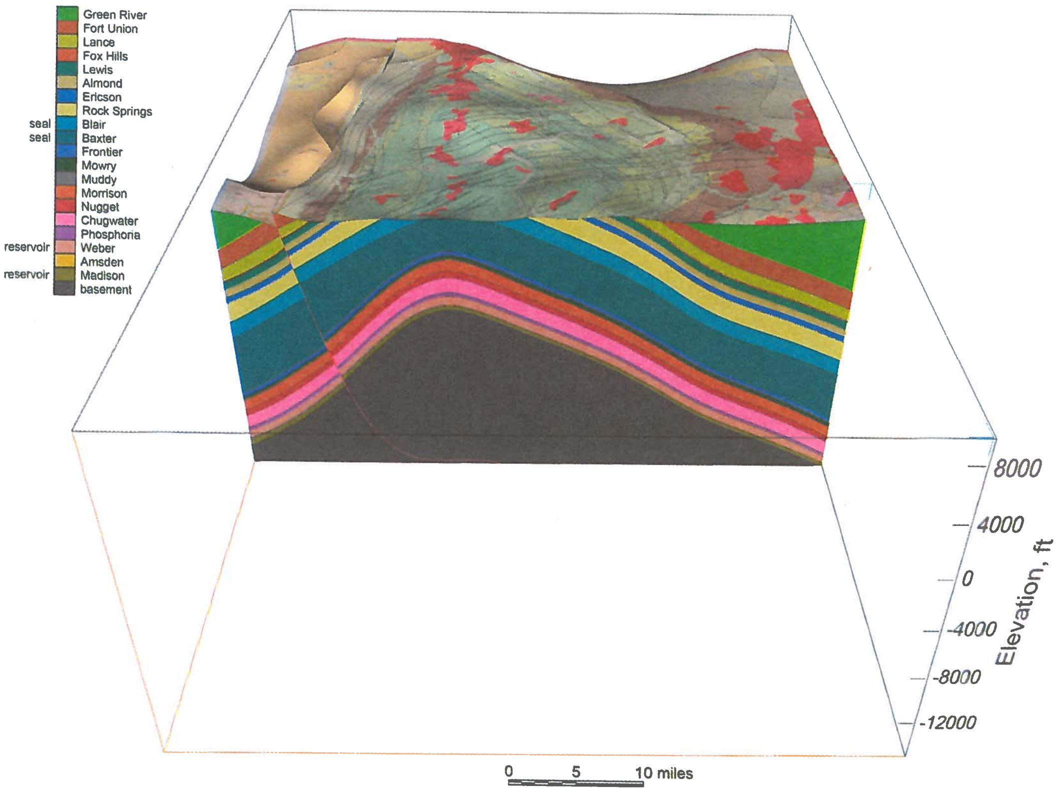


Figure 6. An east-west cross section through the center of the 3-D structural geologic model of the Rock Springs Uplift (see ***Figure 3***).

Table 1. Sequestration capacity of the Weber Sandstone and Madison Limestone, Rock Springs Uplift, Wyoming.

Input parameters	Weber		Madison	
	Value	*Unit*	*Value*	*Unit*
Formation depth	1,893	meters	2,286	meters
Formation thickness	225	meters	98	meters
Effective porosity	10.0	%	10.0	%
Temperature	60	°C	71	°C
Dissolved NaCl	0.5	molal	0.5	molal
Calculated parameters				
Formation pressure (observed)	$1.85 \cdot 10^7$	Pa	$2.24 \cdot 10^7$	Pa
CO_2 density (in reservoir condition)	$6.88 \cdot 10^2$	kg/m³	$6.90 \cdot 10^2$	kg/m³
CO_2 fugacity coefficient	$4.82 \cdot 10^{-1}$		$4.81 \cdot 10^{-1}$	
CO_2 Henry's constant	$3.98 \cdot 10^8$	Pa	$4.73 \cdot 10^8$	Pa
CO_2 aqueous mass fraction	$5.48 \cdot 10^{-2}$	kg/m³	$5.57 \cdot 10^{-2}$	kg/m³
Aqueous density	$1.01 \cdot 10^3$	kg/m³	$1.01 \cdot 10^3$	kg/m³
Water content (steady state)	7.00	%	7.00	%
Fixed parameter				
Mass of injected CO_2	$5.00 \cdot 10^7$	tonnes	$5.00 \cdot 10^7$	tonnes
Results				
Formation supercritical CO_2 capacity	$2.06 \cdot 10^1$	kg/m³	$2.07 \cdot 10^1$	kg/m³
Formation dissolved CO_2 capacity	3.88	kg/m³	3.93	kg/m³
CO_2 plume area	9.06	km²	$2.07 \cdot 10^1$	km²
CO_2 plume volume	2.04	km³	2.03	km³
Supercritical CO_2	$4.21 \cdot 10^7$	tonnes	$4.20 \cdot 10^7$	tonnes
Dissolved CO_2	$7.91 \cdot 10^6$	tonnes	$7.98 \cdot 10^6$	tonnes
CO_2 (mcf)	$6.58 \cdot 10^5$	mcf	$7.79 \cdot 10^5$	mcf
CO_2 (square miles)	3.54	mi²	8.09	mi²
Plume radius	1.06	mi	1.60	mi
Rock Springs Uplift (area bounded by Tfu outcrop)	$1.30 \cdot 10^3$	mi²	$1.30 \cdot 10^3$	mi²
Total CO_2 injection capacity	$1.84 \cdot 10^{10}$	tonnes	$8.04 \cdot 10^9$	tonnes
Total CO_2 that can be injected into the Weber and the Madison	**$2.64 \cdot 10^{10}$ tonnes**			
Current Wyoming CO_2 emissions (coal-fired and gas processing plant)	**$5.44 \cdot 10^7$ metric tonnes $6.00 \cdot 10^7$ short tons**			
Number of years Wyoming CO_2 emissions could be sequestered in the Weber and Madison reservoirs, Rock Springs Uplift, Wyoming	**485 years**			

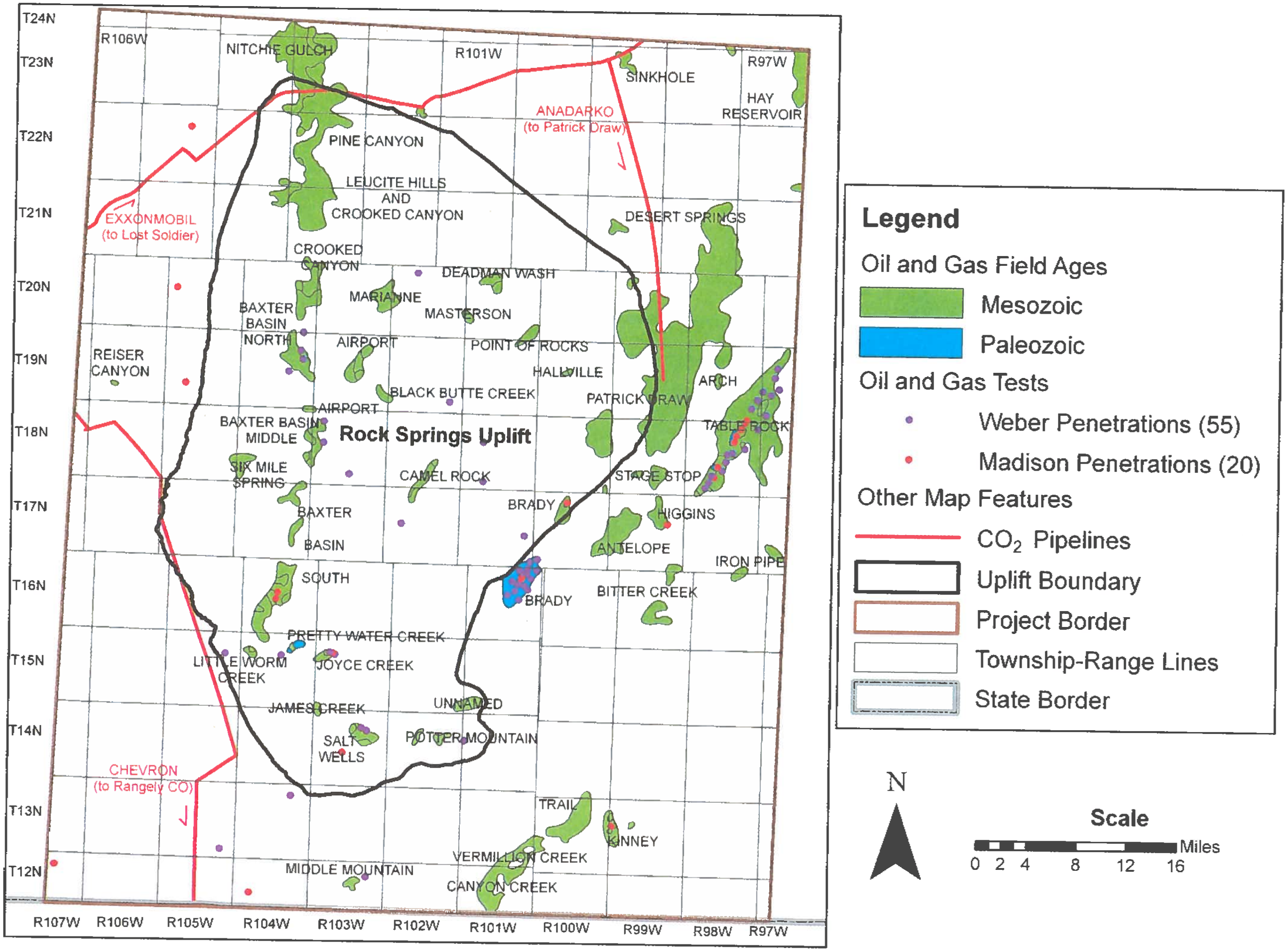


Figure 7. Map showing the distribution of oil and gas fields in the Rock Springs Uplift area.

Rock Springs Uplift

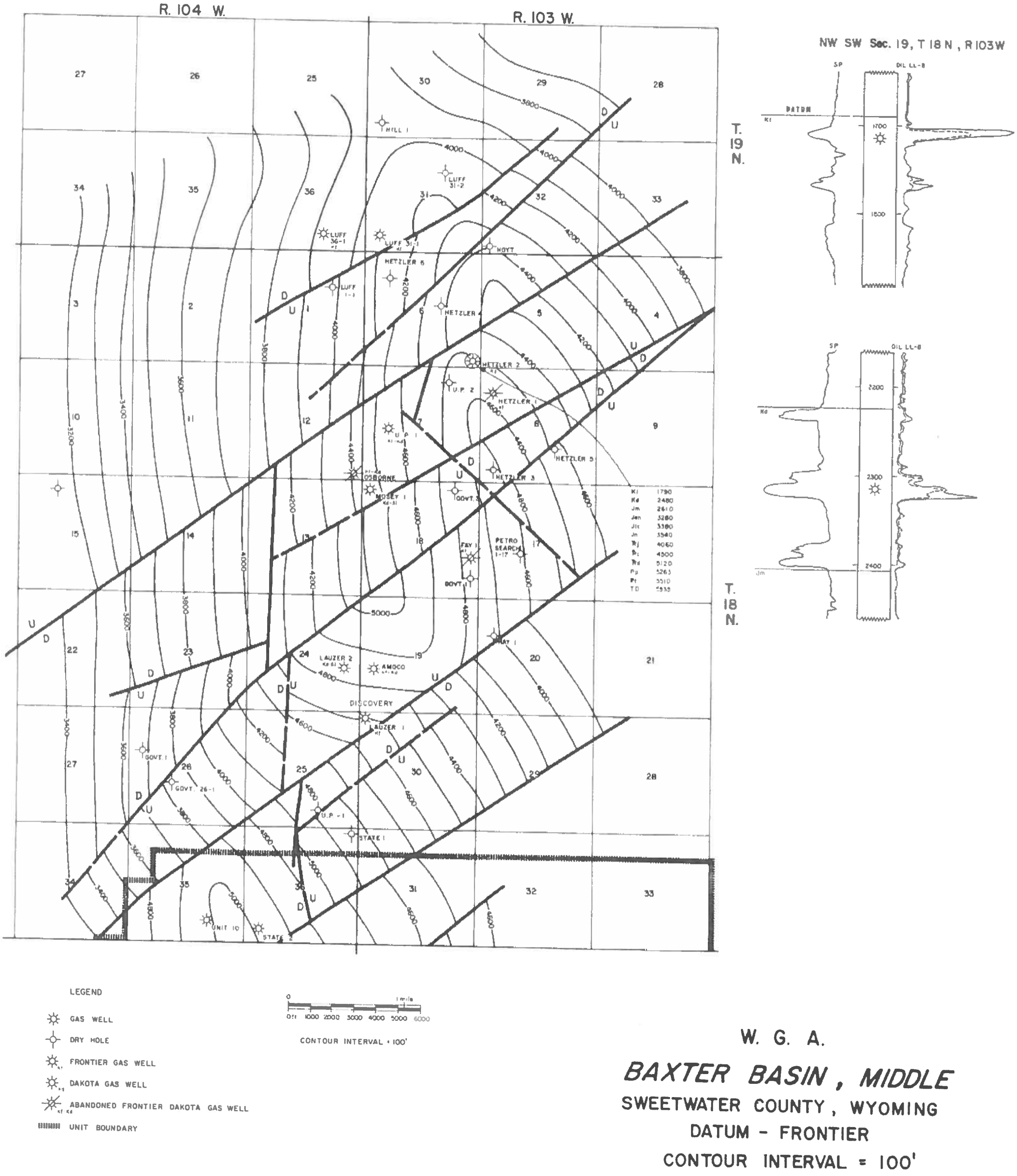
The Rock Springs Uplift is a large (50 miles by 35 miles) doubly-plunging anticlinal (dome) structure located in southwest Wyoming (**Plate 1**). The Cretaceous Baxter Shale is exposed along the crest of the structure, and the lower Tertiary Fort Union and Wasatch Formations are exposed along the distal 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 underpressured 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 underpressured (0.30-0.42 psi/ft). At the Middle Baxter Field, the Frontier production was initially overpressured (0.54 psi/ft). At the South Baxter Field, the Frontier and Dakota production was initially underpressured (0.34 and 0.31psi/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 Laney 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 Laney 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**).



from WGA - Oil and Gas Fields, GGRB, 1979

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.

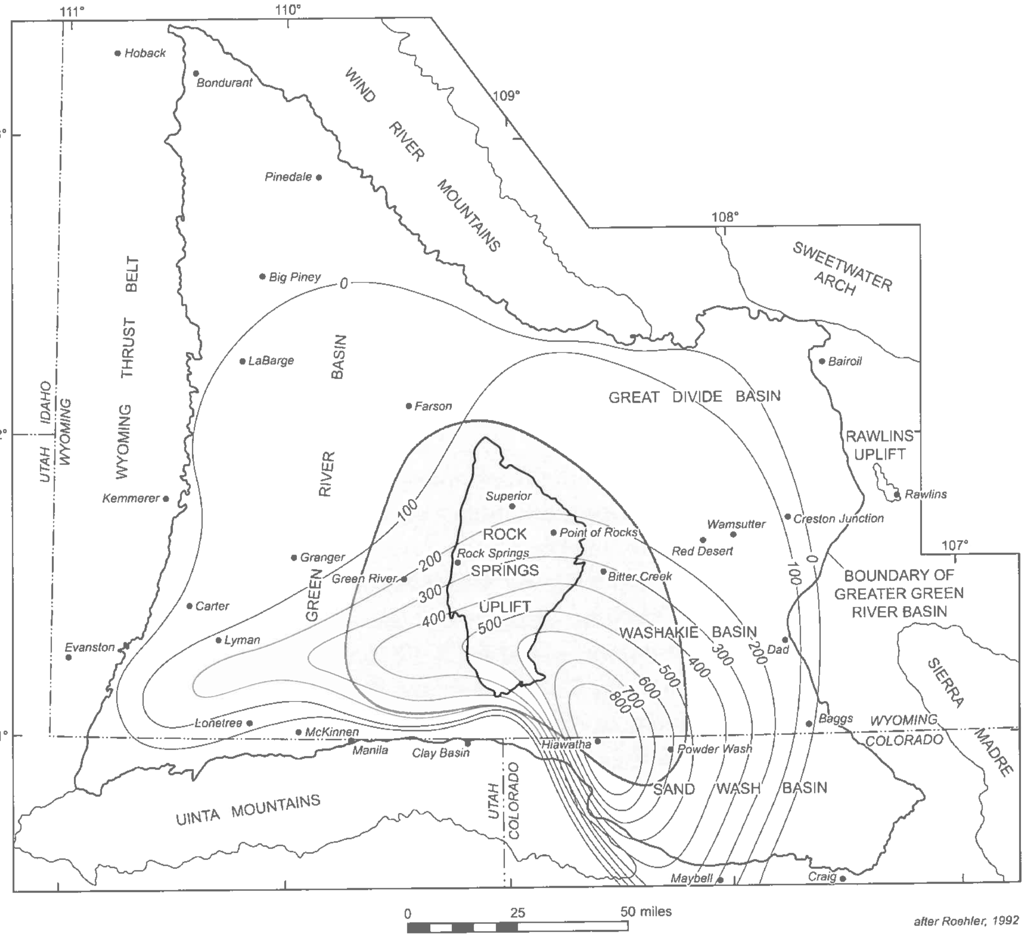


Figure 9. An isopach map of the LaClede Bed in the Laney Member of the Green River Formation around the Rock Springs Uplift. The continuous contour line across the Uplift reveals that the Uplift postdates the deposition of the LaClede Bed (~45 Ma). Shading indicates areas where parts of the LaClede bed 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 CO_2 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 CO_2.

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 CO_2, it is possible that a small amount of the CO_2 could be used in enhanced oil recovery projects. The crestal Cretaceous oil fields have potential for enhanced oil recovery (Tertiary oil recovery using CO_2 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 CO_2 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% CO_2 with 15 ppm H_2S. With a water resistivity (R_w)

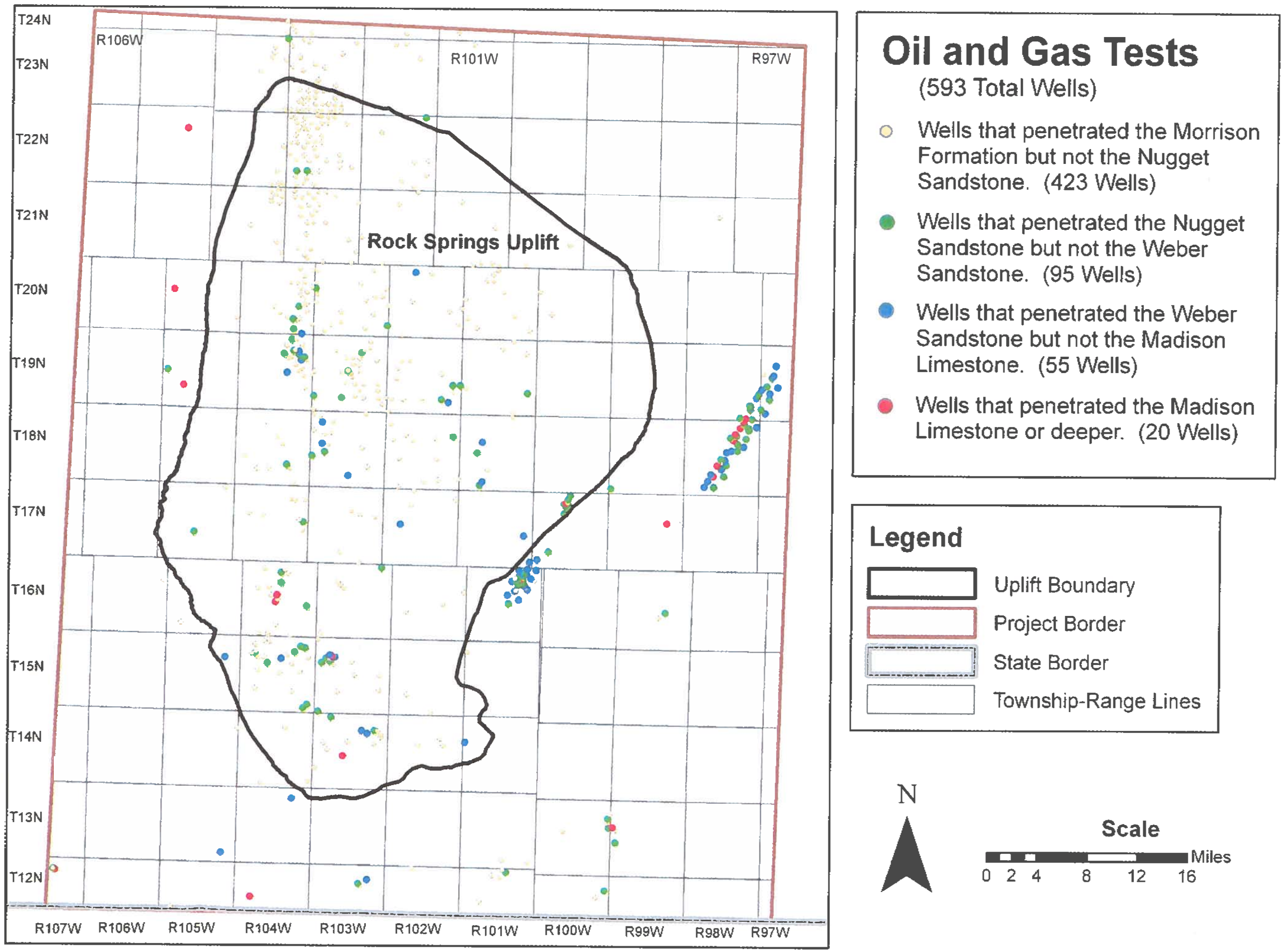


Figure 10. Map showing distribution of deep penetration wells in the Rock Springs Uplift. A total of 2,996 oil and gas tests have been drilled in the Rock Springs Uplift. Of those wells, 593 wells penetrated the Jurassic Morrison Formation or deeper.

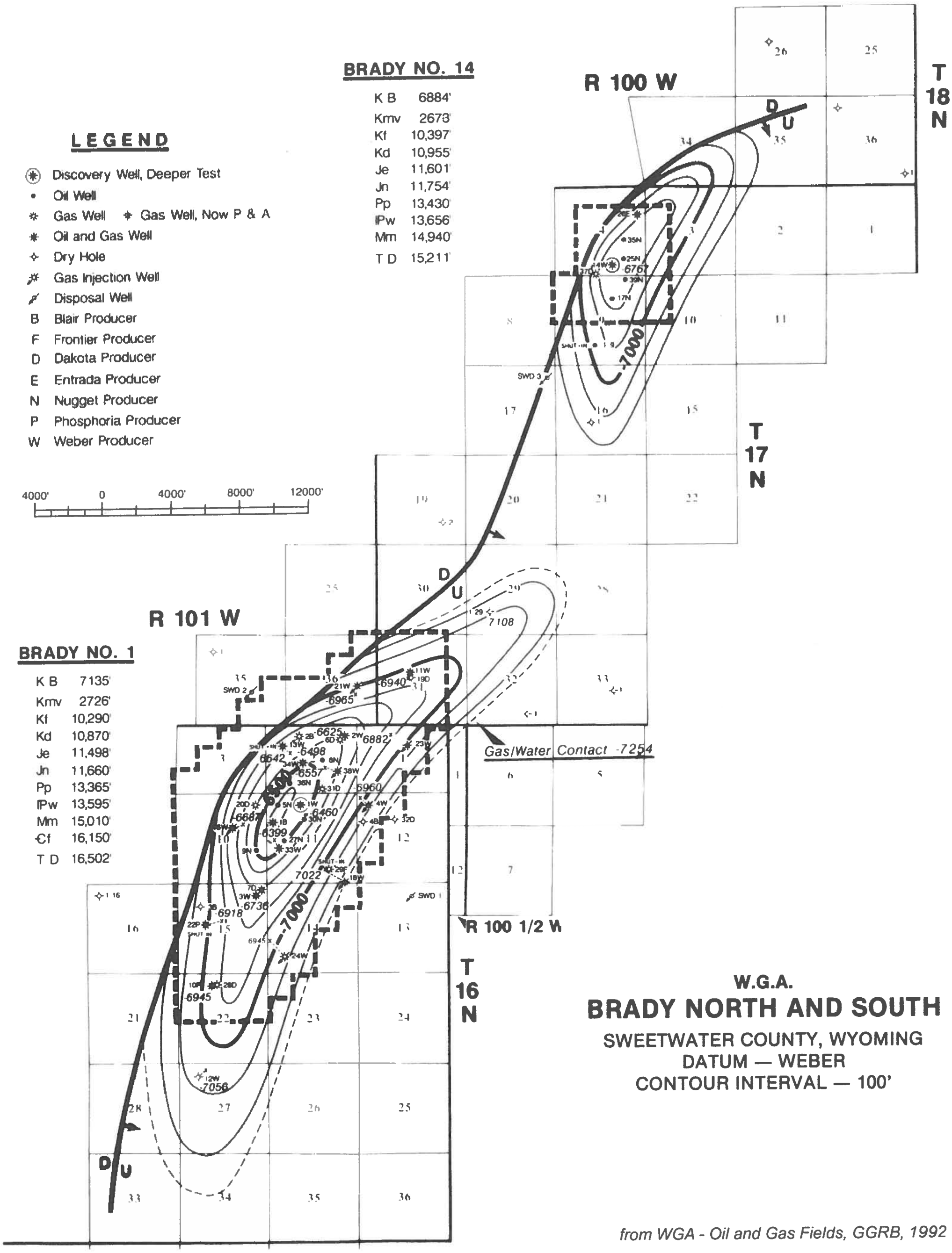


Figure 11. A structure contour map on the Weber Sandstone for the Brady North and South gas fields. Both structural traps are bounded by a NE-SW thrust fault.

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% CO_2 and contains no H_2S. The fluid produced has a R_w 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% CO_2 and 0.4% H_2S. Produced water from the Weber has a R_w 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 indicates 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.

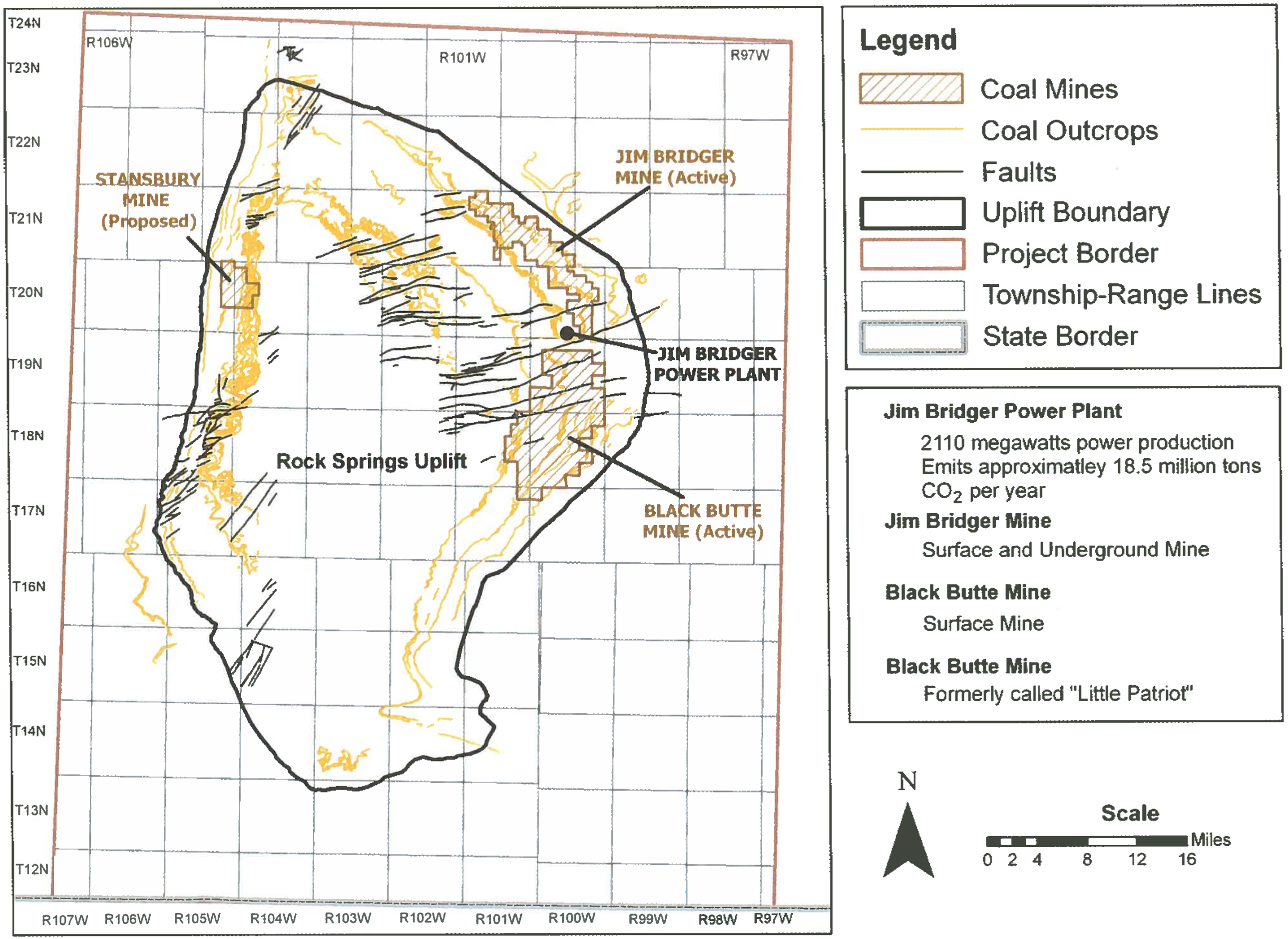


Figure 12. Map showing the coal outcrops and active mines in the Rock Springs Uplift. The currently active Black Butte surface mine and Jim Bridger surface and underground mine are both located on the east flank of the Uplift. Mined Tertiary coals are separated from the Weber Sandstone and Madison Limestone by more than 3 miles of Mesozoic and Paleozoic stratigraphic sections.

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.

CO_2 sequestration capacity

Using 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. Combined, these two stratigraphic units could store 26 billion tons of CO_2.

Currently, Wyoming emits approximately 54 million tons of CO_2 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 CO_2 emissions from in-state facilities for 485 years.

It should be noted that the CO_2 plume resulting from the injection of 50 million tons of CO_2 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 CO_2 per year for 370 years before its CO_2 sequestration capacity is exceeded. The Jim Bridger Power Plant located on the Rock Springs Uplift currently emits approximately 18 million tons of CO_2 per year. The Weber and Madison sequestration reservoirs could accept emissions from this plant for 1,470 years.

Monitoring CO_2 sequestration

CO_2 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 CO_2 is one of the most important criteria to consider when selecting a geological CO_2 sequestration site. When it occurs in high concentrations, such as during volcanic eruptions or lake turnovers, CO_2 can be lethal. Therefore, potential movement of CO_2 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 CO_2 sequestration. Therefore, the distribu-

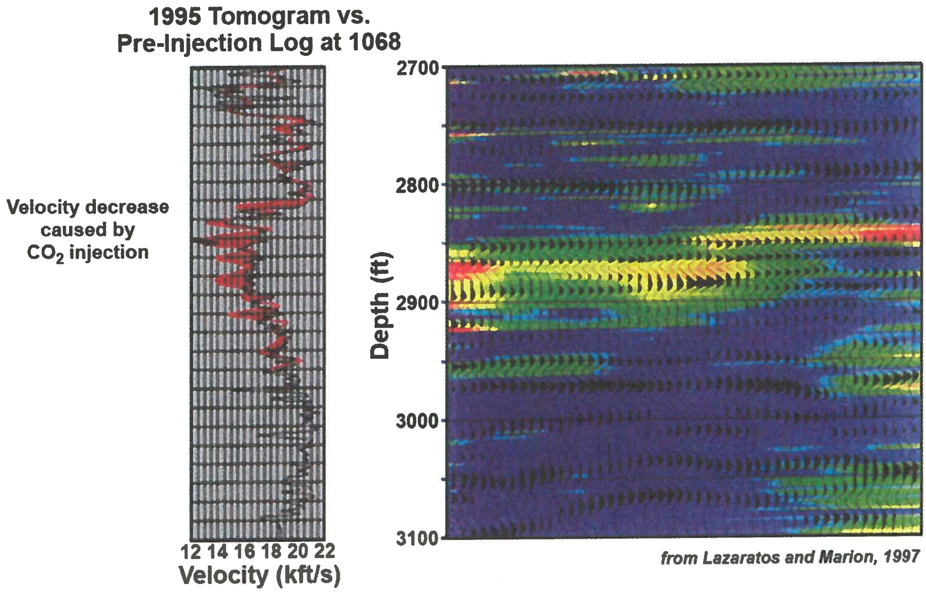


Figure 13. The result of well-to-well tomography shows the significant velocity decrease caused by CO_2 injection. Right cross section is a velocity difference profile after injection of the CO_2 into the hydrocarbon-producing interval. Red and yellow colors represent the sections with notable velocity decrease caused by injected CO_2, or presence of a gas phase. Left logs show that the injected CO_2 resulted in a 10-20% drop in velocity of the reservoir rocks (seismic velocity slowdown).

tion, migration pathway, and long-term fate of the injected CO_2 need to be reliably monitored during injection and storage.

Time-lapse 4-D seismic reflection surveying can be effectively used to monitor geological CO_2 sequestration. Seismic characterization of fluids in saline or hydrocarbon reservoirs during CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 plume will help build better reservoir models and will substantially reduce uncertainty regarding geological CO_2 sequestration. It is necessary to conduct a 3-D survey before injecting CO_2 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 CO_2 injection plume, along with CO_2 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 CO_2 during geological sequestration.

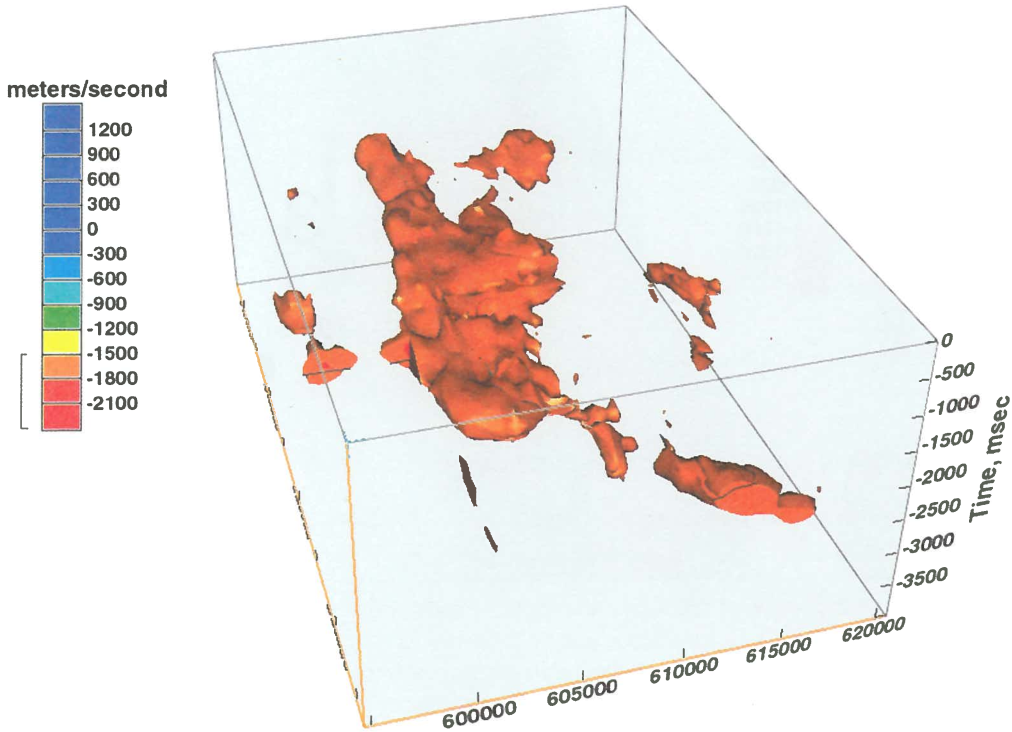


Figure 14. Three-dimensional anomalous velocity model showing the volume and shape of the abnormally slow velocity and gas-charged section in the Riverton Dome, Wind River Basin, Wyoming. The significant slowdown results from the presence of a gas phase; the seismic ray does not identify if the gas phase is natural gas or CO_2, so the technique can be used for detecting any gas phase.

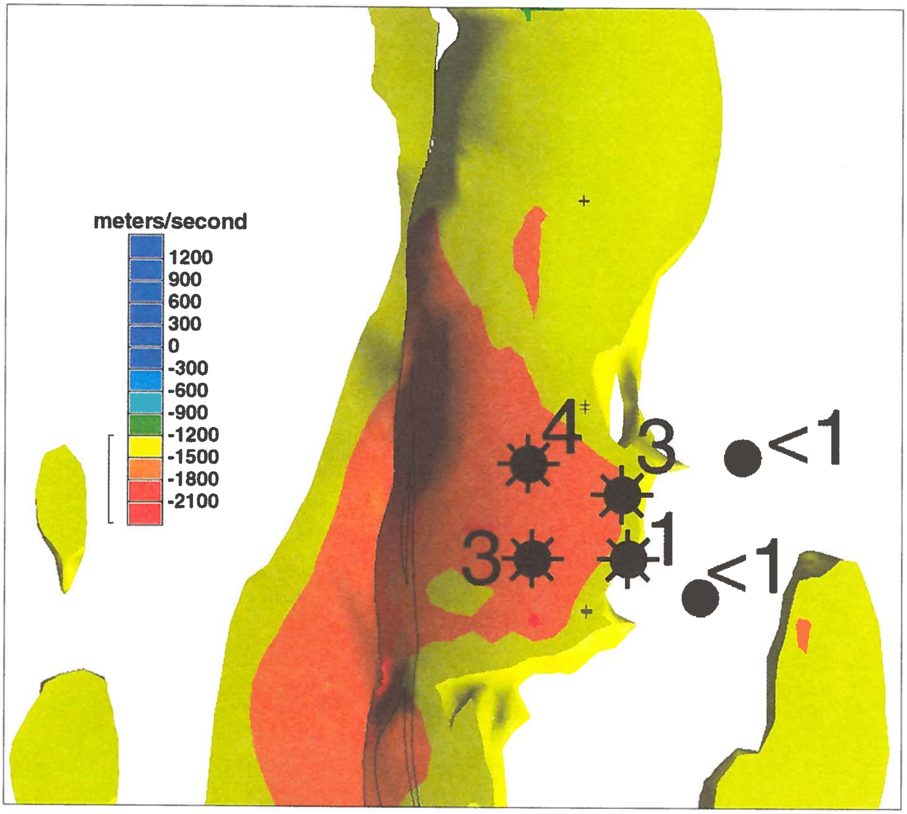


Figure 15. Map view at the top of the Muddy Sandstone reservoir interval; the map is derived from a 3-D anomalous velocity volume constructed from a 3-D seismic survey at Riverton Dome in the Wind River Basin, Wyoming. Six recent Muddy Sandstone wells are plotted on the anomalous velocity map on the 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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The Wyoming State Geological Survey acknowledges the support and encouragement Governor Dave Freudenthal and his energy advisor Rob Hurless gave to this project. In addition, the authors would like to acknowledge the exemplary support provided by Robert Meyer of the Wyoming State Oil and Gas Conservation Commission.

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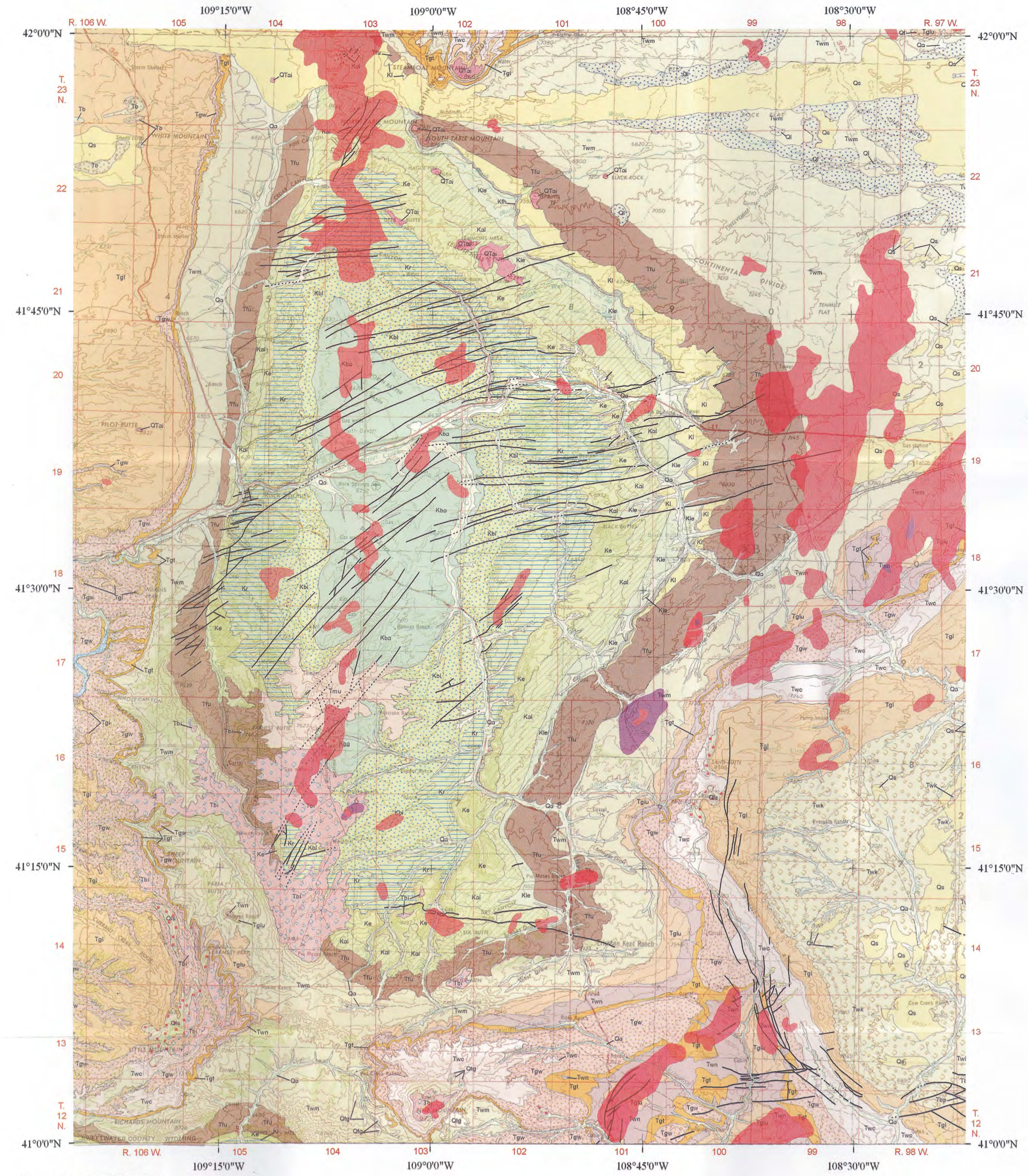
WYOMING STATE GEOLOGICAL SURVEY
Ronald C. Surdam, State Geologist
Laramie, Wyoming

Geology - Interpreting the past to provide for the future

CHALLENGES IN GEOLOGIC RESOURCE DEVELOPMENT NO. 2
Geologic Map and Oil and Gas Fields of the Rock Springs Uplift Area
Plate 1



Digital Cartography: Phyllis A. Ranz

Scale 1:250,000, 1 inch equals approximately 4 miles
10 8 6 4 2 0 10 20 30 Miles
10 5 0 10 20 30 Kilometers

MAP LOCATION

MAP SYMBOLS

Formation contact

Fault, dotted where concealed

Mesozoic and younger oil and gas fields

Paleozoic oil and gas fields

GEOLOGIC MAP AND OIL AND GAS FIELDS OF THE ROCK SPRINGS UPLIFT AREA, SWEETWATER COUNTY, SOUTHWESTERN WYOMING

Compiled by
D.W. Lucke, J. F. McLaughlin, and R. W. Jones
2007

EXPLANATION

DESCRIPTION OF MAP UNITS

Qs — **Sand dunes** (Holocene and Pleistocene)—Windblown sand in active and stabilized dunes; thickness variable.

Ql — **Playa lake deposits** (Holocene and Pleistocene)—Mostly clay, silt, and fine sand; some evaporite minerals and alkali deposits; thickness variable.

Qa — **Alluvium** (Quaternary)—Alluvial deposits within and terrace deposits along major streams; may include alluvial fan deposits, landslide deposits, and colluvium; thickness up to approximately 40 feet.

Qt — **Terrace deposits** (Quaternary)—Stream deposited gravels above present stream levels; thickness variable.

Qls — **Landslide deposits** (Quaternary)—Active and inactive landslides, debris flows, and other mass earth movements; thickness variable.

Qtg — **Older gravel, pediment, and fan deposits** (Quaternary)—Mostly locally derived clasts; may include some Tertiary gravels; thickness variable.

QTal — **Alkalic volcanic rocks** (Pleistocene to Pliocene)—Ultrapotassic, mafic rocks (lamproites) of the Leucite Hills volcanic field, consisting of mesas and buttes composed of flows, plugs, volcanic necks, dikes, cinder cones, volcaniclastics, and rubble zones. Erupted and intruded from approximately 3.0 to 0.89 Ma (Mega-annum, or million years before present) onto Tertiary and Cretaceous rocks on the north and northeast part of the Rocks Springs uplift.

Tmu — **Miocene(?) rocks, undivided** —Pale green to tan tuffaceous sandstone and claystone; locally conglomeratic near base (Love and Christiansen, 1985); unconformably overlies Bishop Conglomerate and older rocks in southern part of Rock Springs uplift; thickness unknown.

Tbp — **Browns Park Formation** (upper Oligocene(?) and Miocene)—White sandy tuff and white or light gray tuffaceous sandstone, clean sandstone, and sandy mudstone; locally contains thin layers and lenses of greenish gray clayey mudstone; sandstone is conspicuously cross-bedded in some extensive areas; lower part conglomeratic (Bradley, 1964). Reported maximum thickness to southeast in Colorado is 1,200 feet (Sears, 1924), but only the lowermost part of the Browns Park is exposed in the extreme southeastern part of the map area.

Tbi — **Bishop Conglomerate** (Oligocene)—Well-rounded cobbles and boulders of red quartzite, metamorphic rocks, and gray chert and limestone (Love and Christiansen, 1985) derived from Uinta Mountains and angular fragments of brown sandstone and quartzite derived from local erosion of Cretaceous rocks, all in a gray to white tuffaceous sandstone matrix; unconformably overlies all older rocks. Thickness highly variable, ranging from a maximum of 164 feet nearest the Uinta Mountain front (in the southern Green River Basin) thinning to 0 within about 35 miles to the north (Murphey and Evanoff, in preparation).

Twk — **Washakie Formation** (middle and upper Eocene)—Restricted to the Washakie Basin, correlates in part to the Bridger Formation to west; mostly reworked airfall volcanic ash deposited in fluvial (flood-plain) environments; a total of 3,177 feet thick in reference sections (Roehler, 1992a) described below:

Adobe Town Member—Gray, green, and red tuffaceous mudstone alternating with gray tuffaceous and arkosic sandstone and minor thin beds of green shale, gray and green tuff, and gray siltstone and conglomerate; unconformity at base; thickness 2,326 feet in reference section (Roehler, 1992a)

Kinney Rim Member—Gray, green, and some red mudstone and interbedded gray and gray-green sandstone, gray limestone and siltstone, and gray to white tuff; thickness 851 feet (Roehler, 1992a)

Tb — **Bridger Formation** (lower and middle Eocene)—Greenish gray, olive drab, and white tuffaceous sandstone and claystone, derived primarily from reworked volcaniclastics and ash fall tuffs from Absaroka Range; minor lenticular marlstone beds (lacustrine) and conglomerate; maximum of 2,764 feet thick in southern Green River Basin near Cedar Mountain (Murphey and Evanoff, 2007), but only lowermost part of Bridger exposed in northwestern part of map area.

Green River Formation (lower Eocene)—Oil shale, light-colored tuffaceous marlstone, and sandstone deposited in predominantly lacustrine environments; subdivided into three major members (Laney, Wilkins Peak, and Tipton Tongue or Member) and two minor members (Luman Tongue and Godiva Rim Member). Roehler (1992a) measured a total of 2,763 feet for this formation in his Green River Basin reference section and 1,914 feet in his Washakie Basin reference section.

Tgl — **Laney Member, undivided** —Buff, chalky to platy marlstone; buff to white sandy tuff and white chalky volcanic ash; brown to light ash gray shale; papery, low-grade oil shale; brown muddy sandstone; thin algal-limestone beds, stromatolites, and nodular masses in some areas. Thickness variable (ranges from 400 to 1,900 feet in Washakie Basin, 600 feet near Green River, 370 feet near Twin Buttes 23 miles south of Green River) (Bradley, 1964) but average is about 1,200 feet.

Godiva Rim Member of Roehler (Not shown on geologic map)—Mostly gray mudstone and thinly bedded brown oil shale and gray sandstone; restricted to Washakie and Sand Wash basins; intertongues with Cathedral Bluffs Tongue of Wasatch Formation to north and east; thickness ranges from 0 in west to 350 feet at type area (Roehler, 1992b).

Tgw — **Wilkins Peak Member**—Green, brown, and gray tuffaceous sandstone, shale, and marlstone, with evaporites (halite, trona, nacholite, and related minerals) in subsurface sections (Love and Christiansen, 1985); deposited mostly in the Uinta Mountain trough in the deeper parts of the southern Green River and southwestern Washakie basins. Total thickness ranges from 0 to more than 1,200 feet; composed of a lower part ranging from 0 to 200 feet thick, a middle part ranging from 0 to more than 900 feet thick, and an upper part ranging from 0 to approximately 100 feet thick (Roehler, 1992 b).

Tgt — **Tipton Tongue or Member**—Dark brown and gray oil shale and marlstone, thin interbedded tan algal limestone and tan-brown dolomite; thin gray tuff beds, and thin beds of fossiliferous sandstone and interbedded carbonaceous shale near base; 158 to 183 feet thick.

Tglu — **Luman Tongue** —In the Green River Basin, composed of 293 feet of brown to gray brown oil shale, gray sandstone, gray and brown shale, dark brown carbonaceous shale, and brown mollusk-bearing limestone sandstone. In Washakie Basin, composed of 229 feet of gray, green, and red mudstone and interbedded gray and red sandstone with minor thin beds of gray shale, gray-brown oil shale, brown carbonaceous shale, and coal.

Wasatch Formation (lower Eocene)—Drab to variegated claystone and siltstone, carbonaceous shale and coal, buff sandstone, arkose, and conglomerate; divided into a lowermost main body and three equivalent or overlying members or tongues.

Twc — **Cathedral Bluffs Tongue**—Consists of: 1) a lower gray and green mudstone unit with some tan and gray siltstone, gray sandstone, brown carbonaceous shale, and tan oolitic and algal limestone of a mixed fluvial, lacustrine, and mudflat environment; 2) a middle red and maroon variegated mudstone unit with some interbedded gray, green, orange, and brown mudstone and gray claystone and sandstone deposited in a fluvial (flood-plain) environment; and 3) an upper gray and green mudstone and shale unit with thin interbedded red mudstone, tan and gray sandstone and siltstone, brown carbonaceous shale, and tan and gray oolitic and algal limestone. Mostly fluvial rocks that intertongue with and are lateral equivalents of the Wilkins Peak Member of the Green River Formation or serve to separate the Tipton Member from the Laney Member where the Wilkins Peak is absent. Thickness ranges from 0 to more than 1,500 feet along the Uinta Mountain trough to more than 2,000 feet in the center of the Washakie Basin.

Twn — **Niland Tongue**—Interbedded brown sandstone, carbonaceous shale, and coal form lacustrine, fluvial, and paludal (swamp) origin; occurs between Luman Tongue and the Tipton Member of the Green River Formation; where Luman Tongue is very thin or absent, the Niland Tongue is mapped with the main body of the Wasatch. Thickness ranges from 0 to more than 400 feet in the southwestern part of the Rock Springs uplift, western Sand Wash Basin, and southwest Washakie Basin.

Ramsey Ranch Member of Roehler (Mapped with the main body of the Wasatch, not shown on geologic map)—Gray shale, brown or black carbonaceous shale, coal, and thin interbedded gray fossiliferous limestone and brown oil shale; mostly of paludal and lacustrine origin; more than 600 feet thick in southern Green River Basin along the Uinta Mountain trough, about 400 feet thick at the south end of the Rock Springs uplift, and approximately 800 feet thick in the axis of the Washakie Basin (Roehler, 1992b).

Twm — **Main body of Wasatch Formation**—Drab sandstone, drab to variegated claystone and siltstone interfingering with locally derived conglomerates around basin margins; interfingers primarily through changes in depositional environments with members and tongues of the Green River Formation; thickness varies from approximately 1,000 feet in outcrops in the central and northern Rock Springs uplift and at basin margins, to more than 4,000 feet in the center of the southern Green River Basin along the Uinta Mountain trough, more than 4,000 feet in the Washakie Basin, to more than 6,000 feet in the Sand Wash Basin, and to more than 9,000 feet in the northern Green River Basin (Roehler, 1992b).

Tfu — **Fort Union Formation** (Paleocene)—Brown to gray sandstone, gray to black shale, and coal beds (Love and Christiansen, 1985); thickness ranges from less than 1,000 feet to 1,900 feet (Lillegraven, 1990).

Kl — **Lance Formation** (Upper Cretaceous)—Interbedded tan and gray sandstone and siltstone, gray shale, dark gray and dark brown carbonaceous shale, and coal; dolomite and hematite concretions common; thickness up to 1,000 feet on east side of Rock Springs uplift, increasing eastward into Washakie and Great Divide Basins (Roehler, 1993) and thins to feather edge on northwest and southeast sides of uplift where it has been removed by post-Lance Formation erosion.

Kfh — **Fox Hills Sandstone** (Upper Cretaceous)—Tan, brown, gray, or white sandstone and some interbedded tan or brown siltstone and gray shale; local interbeds of gray dolomite, gray or brown carbonaceous shale, and coal; thickness from 75 to 225 feet on east side of Rock Springs uplift (Roehler, 1993), thins to feather edge on northwest and southeast sides of uplift where it has been removed by post-Lance Formation erosion.

Kle — **Lewis Shale** (Upper Cretaceous)—Dark gray shale and some thin, interbedded, ledge-forming tan or brown very fine- to fine-grained sandstone and siltstone; some dolomite concretions; deposited in nearshore marine environment; upper part intertongues with Fox Hills Sandstone; thickness from 600 to 700 feet (Roehler, 1993).

Mesaverde Group (Upper Cretaceous)—total thickness is approximately 3,500 feet (Roehler, 1993), ranging from less than 2,000 feet to more than 5,000 feet (Roehler, 1990). The group consists of four formations, in descending stratigraphic order:

Kal — **Almond Formation** —White and brown soft sandstone, gray sandy shale, coal, and carbonaceous shale; lower part of formation predominantly gray carbonaceous shale and thin interbedded gray shale and sandstone, with rare thin beds of coal deposited in coastal plain environment; middle of formation mostly carbonaceous shales, bay-fill shales, splay sandstones, and coal beds deposited in a barrier plain/marsh environment; upper part of formation mostly linear sheets of marine shoreline sandstones that prograde eastward into marine shales of the Lewis Shale (Roehler, 1990). Roehler (1990) measured a maximum of 623 feet of Almond Formation north of Rock Springs.

Ke — **Ericson Sandstone**—White massive sandstone, lenticular chert-grit conglomerate in upper part; 471 feet thick north of Rock Springs; 238 feet thick in east Flaming Gorge; divided into lower Trail Member, middle Rusty zone, and upper Canyon Creek Member; upper and lower members mostly freshwater sandstones deposited in an alluvial plain, middle member is mostly non-carbonaceous, freshwater flood plain deposits, consisting of tan or light gray, very fine to fine-grained sandstone and medium gray to gray-green shale.

Kr — **Rock Springs Formation**—White to brown sandstone, shale, carbonaceous shale, and claystone with numerous coal beds deposited in a delta plain environment; the delta environments grade eastward into marine shoreline sandstone deposits and farther eastward into marine shelf, slope and basin environments. Thicknesses range from maximums of 1,665 feet north of Rock Springs and 1,913 feet near east Flaming Gorge to approximately 1,100 feet in the southeastern Rock Springs uplift (Roehler, 1990).

Kbl — **Blair Formation**—Shale, dark gray with thin interbedded very fine-grained tan sandstone and siltstone, and rare thin layers of rounded limy siltstone concretions; most sandstone occurs in thin parallel beds or parallel laminae, some small-scale trough cross-beds; deposited in marine shelf and slope; 1,293 feet thick north of Rock Springs, 2,005 feet thick in east Flaming Gorge (Roehler, 1990).

Kba — **Baxter Shale** (Upper Cretaceous)—Gray to black soft sandy shale and shaly sandstone; approximately 4,500 feet thick (Roehler, 1990), but base of unit not exposed in the Rock Springs uplift.

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(Asterisks indicate principal sources for geologic map)

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