

GEOLOGIC CO₂ SEQUESTRATION POTENTIAL OF THE WYODAK-ANDERSON COAL ZONE IN THE POWDER RIVER BASIN

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EXECUTIVE SUMMARY

Coal-fired electricity-generating power plants in southeastern Montana and northeastern Wyoming generate about 43.6 million short tons (39.6×10^9 kg) of CO₂ annually, which is emitted directly to the atmosphere. These power plants overlie or are proximal to large coal deposits in the Powder River Basin, the No. 1 coal-producing and second most prolific coalbed natural gas-producing area in the United States.

The geologic factors that control coalbed natural gas accumulation are similar to those that would control the CO₂ sequestration potential of a coal seam. A geologic model was constructed and used to evaluate the CO₂ sequestration potential of the areas underlain by nonsurface minable portions of the Wyodak-Anderson coal zone in the Powder River Basin. The CO₂ sequestration potential for the areas where the coal overburden thickness is >1000 ft (305 m) is 6.8 billion short tons (6.2×10^{12} kg). The coal resources that underlie these deep areas could sequester all the current annual CO₂ emissions from nearby power plants for the next 156 years.

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BACKGROUND/INTRODUCTION

As one of seven Regional Carbon Sequestration Partnerships (RCSPs), the Plains CO₂ Reduction (PCOR) Partnership is working to identify cost-effective CO₂ sequestration systems for the PCOR Partnership region and, in future efforts, to facilitate and manage the demonstration and deployment of these technologies. In this phase of the project, the PCOR Partnership is characterizing the technical issues, enhancing the public's understanding of CO₂ sequestration, identifying the most promising opportunities for sequestration in the region, and detailing an action plan for the demonstration of regional CO₂ sequestration opportunities. This report focuses on the results from an analysis of the geologic CO₂ sequestration potential of the subbituminous coal in the Powder River Basin.

Enormous deposits of lignite and subbituminous coal underlie the western area of the PCOR Partnership region. These coal deposits have two key attributes that warrant their evaluation as a geologic CO₂ sequestration option. First, they are located in close proximity to 17 large CO₂ emission sources. Second, it has been suggested that they could have a large capacity for CO₂ storage (Stricker and Flores, 2002).

There are 31 surface coal mines in the western area of the PCOR Partnership region. These mines supply coal to 17 coal-fired power plants located within 100 miles (161 km) of the mines and to 127 other power plants elsewhere in the United States. In 2001, the 17 minemouth or nearby power plants emitted an estimated 84 million short tons (76 million metric tons) of CO₂ (Stricker and Flores, 2002).

Evaluating the geologic CO₂ sequestration potential of a coal deposit requires information about its geologic, hydrologic,

compositional, and physical properties. The PCOR Partnership region includes the Powder River Basin, which is the No. 1 coal-producing and the second most prolific coalbed natural gas-producing area in the United States (Energy Information Agency, 2002; Nelson, 2000, 2001; Wood et al., 2002). The geologic variables that control coalbed natural gas accumulation are similar to ones that would control the CO₂ sequestration potential of a coal seam (Pashin et al., 2001).

GEOLOGIC OVERVIEW

A map of the Powder River Basin is shown in Figure 1. The Powder River Basin is located in the Rocky Mountain foreland of northeastern Wyoming and southeastern Montana. It is an intermontane sedimentary basin with an areal extent of approximately 25,800 mi² (66,822 km²). The sedimentary rocks that fill the basin reach a maximum thickness of 18,000 ft (5486 m). The Powder River Basin is structurally asymmetrical with an axis that trends northwest to southeast. The structural axis is located along the western margin of the basin (Figure 1). The sedimentary rocks have an average dip of 2–5 degrees to the west along the eastern margin of the basin and 20–25 degrees to the east along the western margin of the basin (Choate et al., 1984; Law et al., 1991; Montgomery, 1999).

COAL-BEARING FORMATIONS

The Powder River Basin contains the largest coal deposits in the United States. The coal resources are predominantly located in the Paleocene-age Fort Union Formation and the Eocene-age Wasatch Formation. These formations contain an estimated 1.3 trillion short tons (1.18×10^{15} kg) of mostly low-ash, low-sulfur lignite and subbituminous coal (Choate et al., 1984).

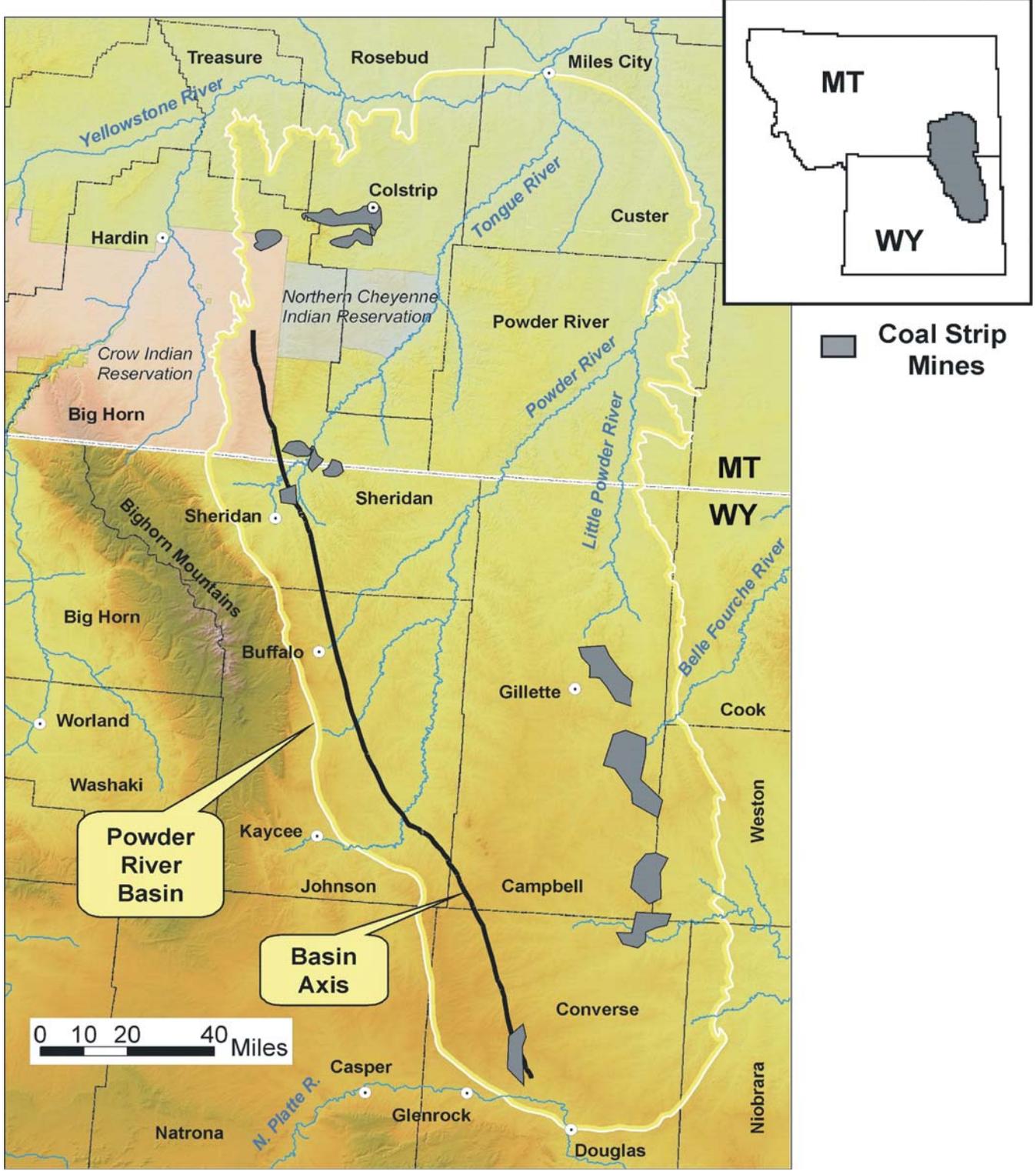


Figure 1. Map showing the location and areal extent of the Powder River Basin.

The Fort Union Formation crops out in a band around the margin of the basin and is overlain by the Wasatch Formation in the central part of the basin. The Fort Union Formation ranges in thickness from 2300 ft (700 m) on the east side of the basin to 6000 ft (1829 m) in the center of the basin. The Wasatch Formation ranges in thickness from 1000 ft (305 m) to 2000 ft (610 m) (Choate et al., 1984; Law et al., 1991; Montgomery, 1999).

STRATIGRAPHY

Figure 2 shows a representative stratigraphic column showing the major subdivisions and coal zone locations in the Fort Union Formation and Wasatch Formation in the Powder River Basin. The Fort Union Formation is stratigraphically subdivided into three gross depositional units, which in ascending order are the Tullock, Lebo Shale, and Tongue River (Choate et al., 1984; Flores et al., 1999; Flores and Bader, 1999).

The Tullock Member consists predominantly of sandstone interbedded with siltstone and mudstone. The Lebo Shale Member consists mainly of mudstone with subordinate amounts of siltstone and sandstone. Coal seams are sparse in these two members (Choate et al., 1984; Flores et al., 1999).

The Tongue River Member consists of abundant and thick coalbeds interbedded with sandstone, siltstone, and mudstone. The coal seams range from a few inches to over 200 ft (61 m) thick (Choate et al., 1984; Flores et al., 1999; Flores, 1993; Law et al., 1991).

The thickness and lateral continuity of the coal seams in the Tongue River Member are highly variable. The individual coal seams split and merge over distances ranging from a few hundred feet to several miles (Choate et al., 1984; Flores et al., 1999; Law et al., 1991).

The Wasatch Formation is lithologically similar to the Tongue River Member of the Fort Union Formation. Coal is abundant in the Wasatch Formation (Choate et al., 1984).

COALBED CHARACTERISTICS

Overburden thickness is a critical property that affects the suitability of a coal deposit for geologic CO₂ sequestration. Only areas where the coal seam overburden thickness is too great for economical surface or underground mining would be potential sites for geologic CO₂ sequestration (Stricker and Flores, 2002; White et al., 2003).

In the Powder River Basin, 500 ft (152 m) is the maximum overburden thickness limit for surface mining (Stricker and Flores, 2002). Most of the coal seams in the Wasatch Formation occur under less than 200 ft (61 m) of overburden (Choate et al., 1984). The shallow depths of the Wasatch Formation coal seams eliminate them as potential sites for geologic CO₂ sequestration.

The Wyodak–Anderson coal zone contains the largest coal resource in the Fort Union Formation and is the main target of surface mining and coalbed natural gas resource exploitation. The coal resources in the Wyodak–Anderson coal zone are estimated to total 550 billion short tons (0.5×10^{15} kg) (Ellis et al., 1999).

Figures 3 and 4 are isopach maps showing the areal distribution, overburden thickness, and net coal thickness of the Wyodak–Anderson coal zone (Ellis et al., 1999). The overburden thickness of the Wyodak–Anderson coal zone ranges from 0 ft to as much as 2500 ft (762 m). Figure 3 indicates that the overburden thickness is less than 500 ft (152 m) in almost all of the area in Montana that is underlain by the Wyodak–Anderson coal zone.

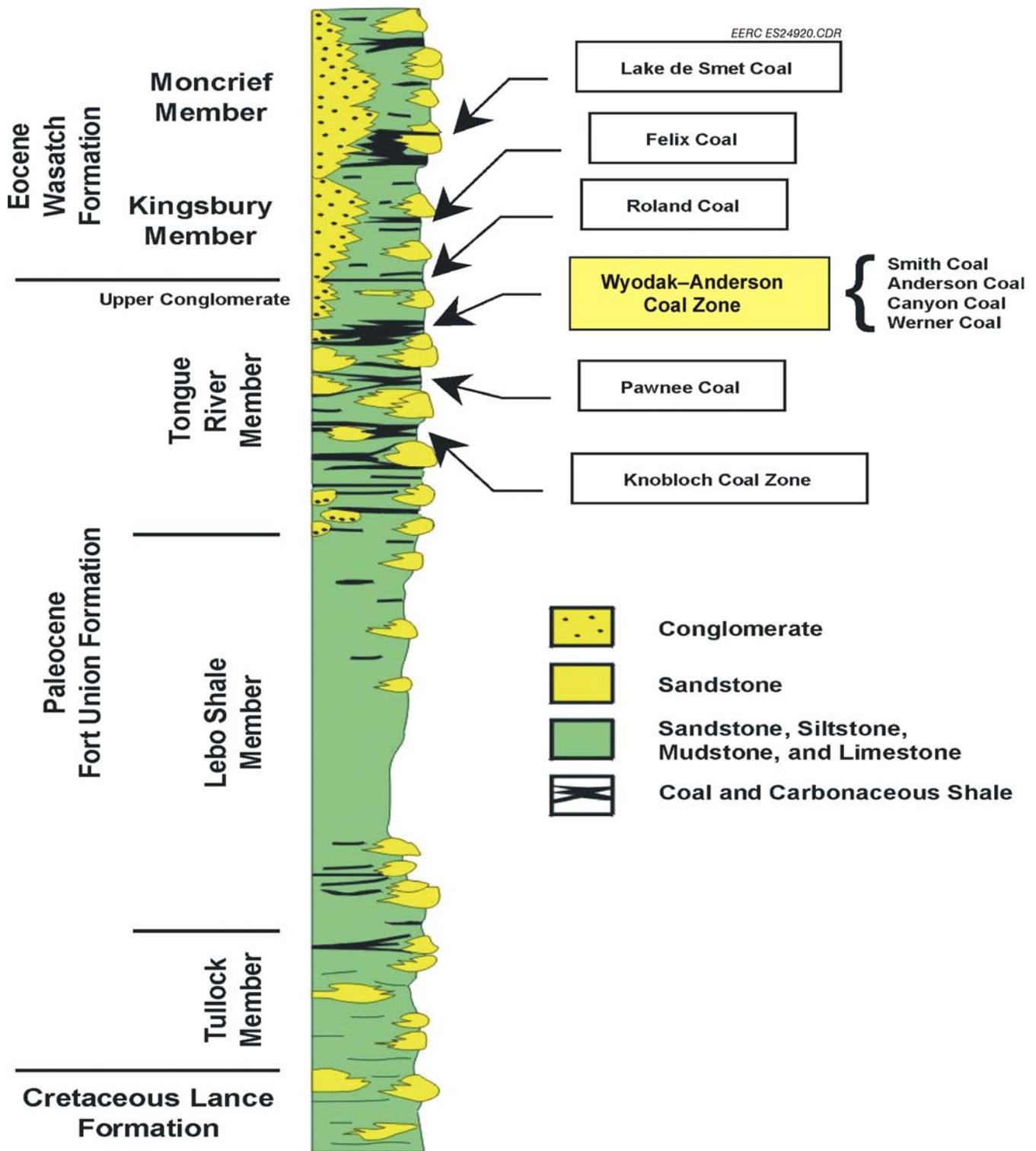


Figure 2. Representative stratigraphic column for the Fort Union and Wasatch Formations in the Powder River Basin (modified from Flores et al., 1999).

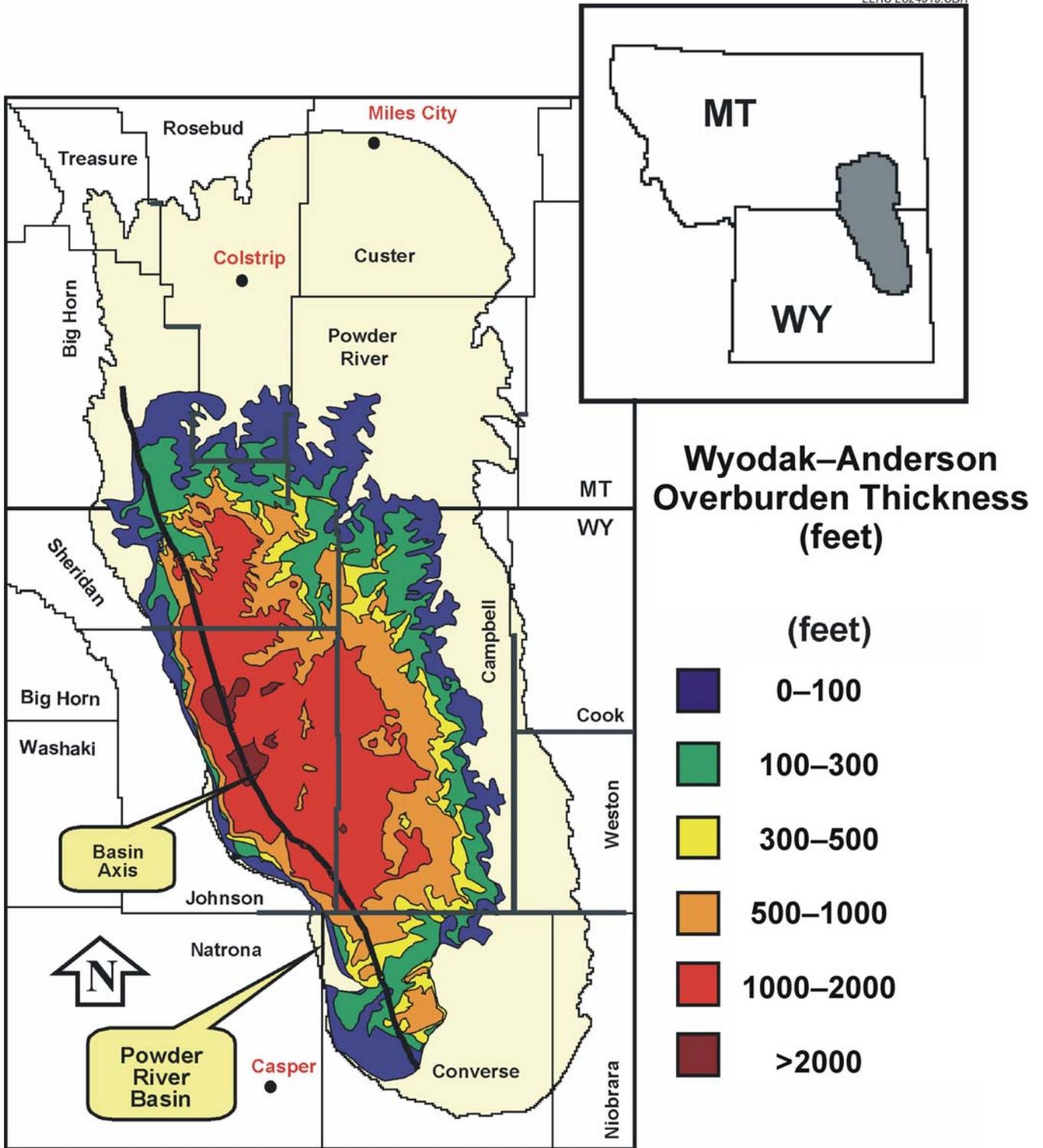


Figure 3. Net overburden thickness isopach map for the Wyodak-Anderson coal zone (modified from Ellis et al., 1999).

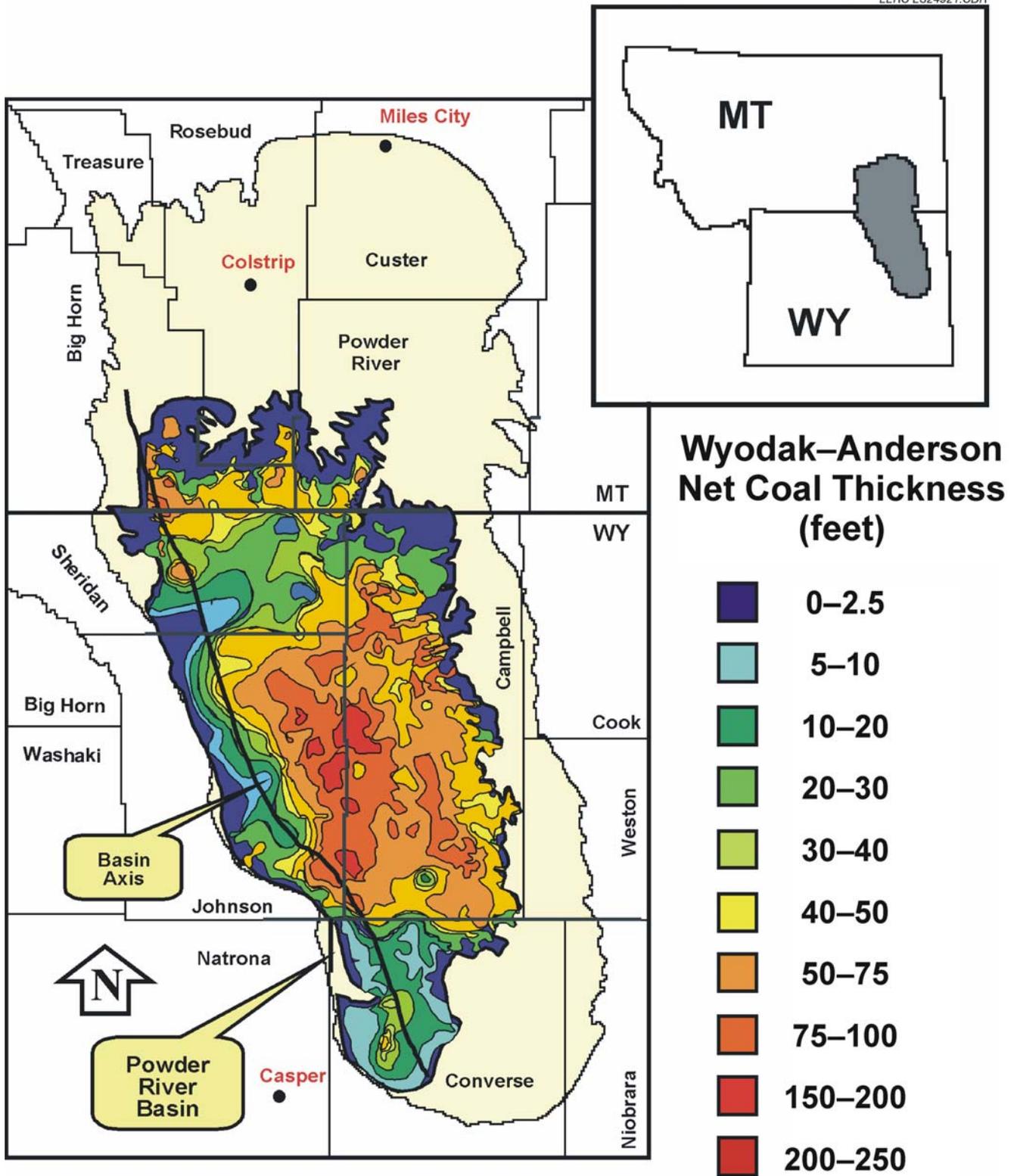


Figure 4. Net coal thickness isopach map for the Wyodak-Anderson coal zone (modified from Ellis et al., 1999).

COAL PRODUCTION DATA

Table 1 summarizes Powder River Basin coal production, which in 2002 totaled 396.7 million short tons (35.99×10^{10} kg), all of it from surface mines (see Figure 1). The Powder River Basin was the No. 1 coal-producing area in the United States, accounting for 36.2% of U.S. output in 2002 (Energy Information Agency, 2002).

Table 1. Powder River Basin Coal Production Data for 2002^a

State	County	Coal	
		Surface Mines	Production, short tons
MT	Big Horn	3	24,237,000
	Rosebud	2	12,820,000
WY	Campbell	12	332,796,000
	Converse	1	26,809,000

^a Data are from the EIA Annual Coal Report (2002).

MAJOR CO₂ EMISSION SOURCES

Eight coal-fired power plants are located in or within 60 miles (97 km) of the Powder River Basin. Table 2 shows their 2001 estimated CO₂ emissions (Stricker et al., 2002).

COALBED NATURAL GAS PRODUCTION

Table 3 summarizes data for the Powder River Basin coalbed natural gas play (Wyoming Oil & Gas Conservation Commission, 2005; Montana Board of Oil & Gas Conservation, 2005). The coalbed natural gas resources in the Wyodak–Anderson coal zone are estimated to total 20 Tcf (0.57×10^{12} m³) (Nelson, 2004).

Figure 5 is a map showing the locations of the Powder River Basin coalbed natural gas wells. The majority of all producing coalbed gas wells are located on the eastern flank of the basin, downdip from the large surface coal mines in Campbell

County, Wyoming (Wyoming Oil & Gas Conservation Commission, 2005; Montana Board of Oil & Gas Conservation, 2005; Nelson, 2004).

GAS STORAGE MECHANISM

The sequestration of CO₂ can occur by either a physical or chemical trapping process (White et al., 2003). In coalbed reservoirs, the gas molecules are immobilized or trapped by physical adsorption at near liquidlike densities on micropore wall surfaces. In coalbed reservoirs, the hydrostatic pressure in the formation controls the gas adsorption process (Mavor and Nelson, 1997; Nelson, 1999; Pashin et al., 2001).

The gas adsorption process is reversible. Thus the hydrostatic pressure must be maintained at or above the gas desorption pressure in order for sorbed-phase gas molecules to remain immobile (Mavor and Nelson, 1997).

In most areas of the Powder River Basin, the sorbed-phase gas content of the Wyodak–Anderson coal is less than the gas storage capacity. As a result, the natural gas is immobile. The hydrostatic pressure of the reservoirs must be reduced in order to initiate gas desorption from the coal (Crockett and Meyer, 2001; Nelson, 2003, 2004; Wyoming Bureau of Land Management, 2004).

Figure 6 shows hydrostatic and casing head gas pressure data for a water monitor well completed in a Wyodak–Anderson coalbed reservoir in Campbell County, Wyoming (Nelson, 2004; Wyoming Bureau of Land Management, 2004). The initiation of gas desorption is indicated by the abrupt increase in the casing head gas pressure. The data indicate that the hydrostatic pressure of the coalbed reservoir had to be reduced before gas desorption began.

Table 2. Estimated CO₂ Emissions for Powder River Basin Power Plants in 2001^a

Plant Name	Location	Estimated CO ₂ Emissions, short tons
Colstrip	Colstrip, Montana	18.58 × 10 ⁶
Laramie River	Wheatland, Wyoming	14.39 × 10 ⁶
Dave Johnston	Glenrock, Wyoming	6.76 × 10 ⁶
Wyodak	Gillette, Wyoming	3.69 × 10 ⁶
JE Corette	Billings, Montana	1.57 × 10 ⁶
Neil Simpson 2	Gillette, Wyoming	0.98 × 10 ⁶
Osage	Osage, Wyoming	0.43 × 10 ⁶
Neil Simpson 1	Gillette, Wyoming	0.22 × 10 ⁶

^a Data are from Stricker et al., 2002.

Table 3. Characteristics of Powder River Basin Coalbed Natural Gas Play^a

State	Number of Producing Gas Wells in 2004	Coalbed Natural Gas Production in 2004	Coproduced Water, vol. in 2004	Cumulative Coalbed Gas Production (1987–2004)	Cumulative Coproduced Water, vol. (1987–2004)
Montana	430	12.2 Bcf	15.6 MMbbl	41 Bcf	83.8 MMbbl
Wyoming	13,450	327.4 Bcf	527.7 MMbbl	1531 Bcf	2891.4 MMbbl
Total	13,880	339.6 Bcf	543.3 MMbbl	1572 Bcf	2975.2 MMbbl

^a Data are from Wyoming Oil & Gas Conservation Commission, 2005; Montana Board of Oil & Gas Conservation, 2005.

Data from water-level monitoring in wells completed in Wyodak–Anderson coalbed reservoirs at other Powder River Basin locations indicate that the initial gas desorption pressures vary from 40% to 92% of the original hydrostatic pressure. These data also indicate that in most areas of the basin the pressure gradient is less than normal hydrostatic, i.e., <0.43 psi/ft (Crockett and Meyer, 2001; Nelson, 2003, 2004; Wyoming Bureau of Land Management, 2004).

TEMPERATURE GRADIENT

Temperature affects the amount of gas that coal can adsorb. Gas sorption capacity decreases as temperature increases (Mavor and Nelson, 1997; Pashin et al., 2001; Pashin and McIntyre, 2003).

The temperatures of the coalbed reservoirs in the Wyodak–Anderson coal zone range from 60°F up to about 100°F (16°C to

38°C). The average temperature gradient in the Fort Union Formation in the southern Powder River Basin is 0.02°F/ft (0.019°C/m). The average ground surface temperature in the basin is 50°F (10°C). The relationship between temperature and depth in the Fort Union Formation is shown in Equation 1 (McPherson and Chapman, 1996):

$$T (^{\circ}\text{F}) = 0.02 \times \text{Depth (ft)} + 50 \quad [\text{Eq. 1}]$$

CO₂ SUPERCRITICAL PHASE WINDOW

Figure 7 shows the phase diagram for CO₂. Above the critical point temperature (88°F) and pressure (1074 psi), CO₂ is a supercritical fluid. Supercritical CO₂ may interact differently with coal than normal gaseous CO₂. Thus determining if supercritical CO₂ conditions could occur is important when areas are evaluated for CO₂ sequestration (Pashin and McIntyre,

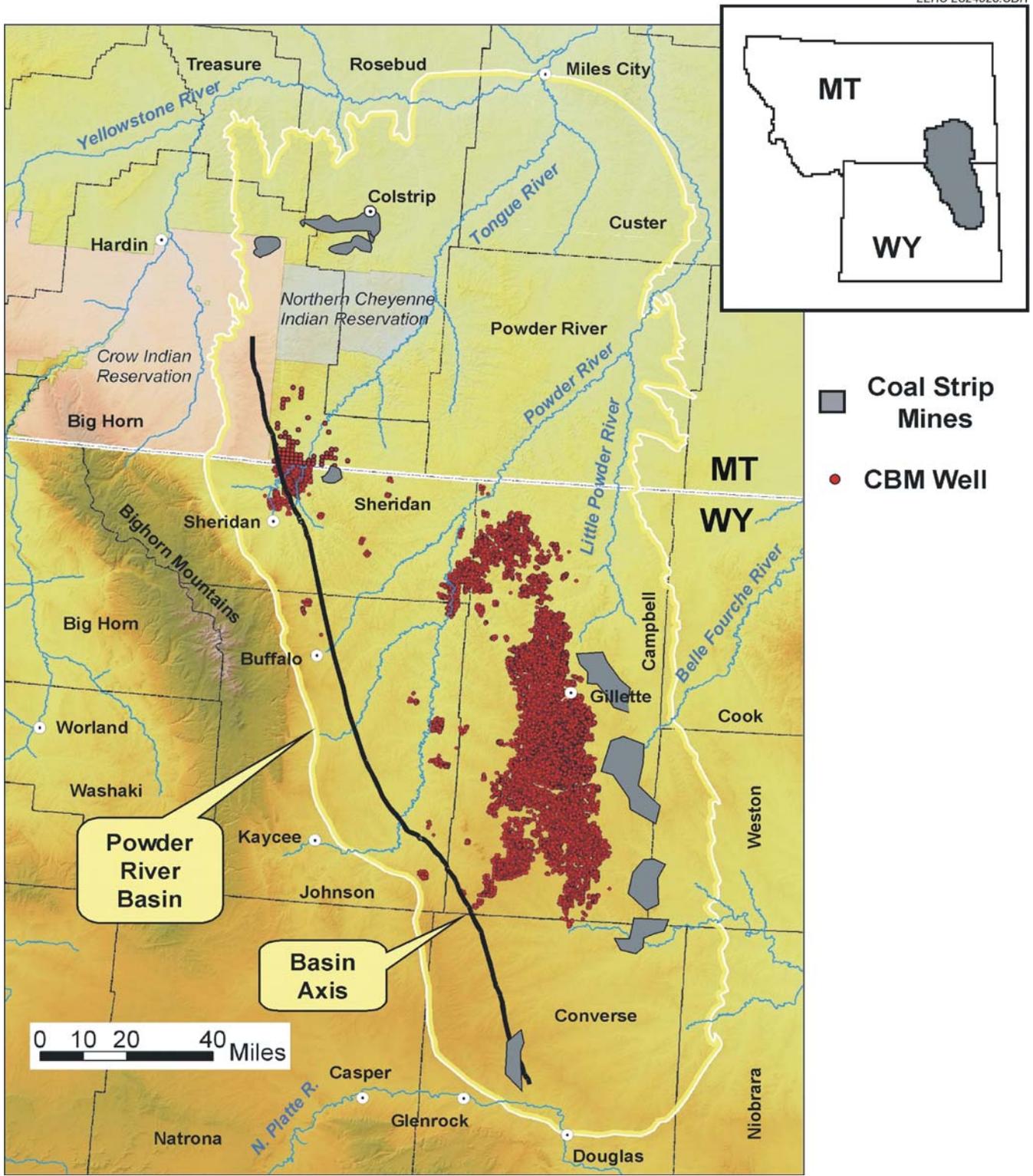


Figure 5. Map showing the locations of the coalbed natural gas wells in the Powder River Basin.

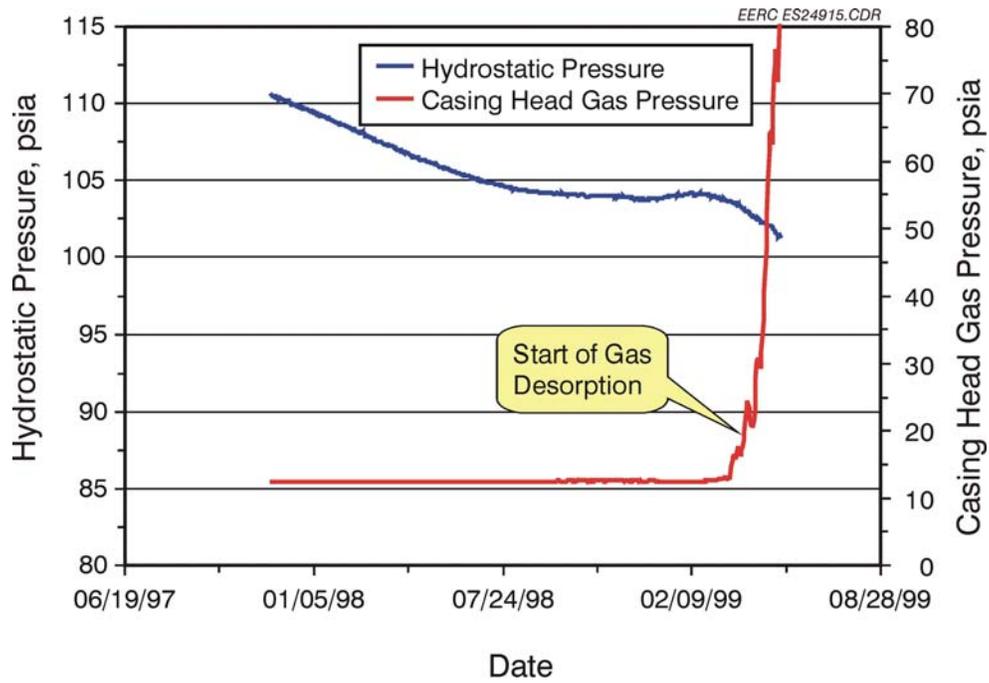


Figure 6. Hydrostatic and casing head gas pressure data for a water monitor well.

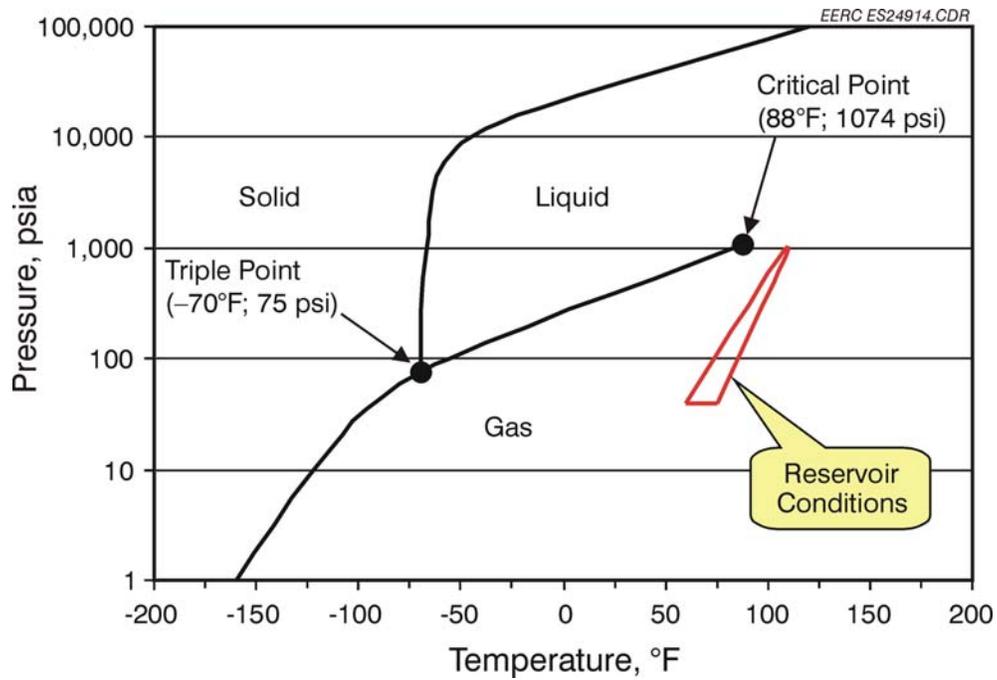


Figure 7. CO₂ phase diagram.

2003). Figure 7 also shows the expected range of temperature and pressure conditions in the Wyodak–Anderson coal zone. In most areas, conditions will not favor supercritical CO₂ formation.

PILOT CO₂ INJECTION PROJECT

In coalbed gas reservoirs, CH₄ and CO₂ compete for surface adsorption sites in the coal micropores, but the stoichiometry of the competitive adsorption process is not one-to-one. Coal can adsorb from two to ten times more CO₂ than CH₄. Lignite and subbituminous coals have higher CO₂ adsorption capacities than bituminous coals. The adsorption ratio decreases as the coal rank increases (Caroll and Pashin, 2003; Mavor and Nelson, 1997; Nelson, 2003, 2004; Stricker and Flores, 2002).

The attractive force between CO₂ and coal is greater than that between CH₄ and coal. Injecting CO₂ into a coalbed reservoir should promote CH₄ desorption, thereby accelerating the CH₄ recovery rate. The results from a pilot CO₂ injection project conducted by industry in a coalbed reservoir in the San Juan Basin support this model. After 5 years of CO₂ injection, there was very little increase in the CO₂ content of the gas stream recovered at the production wells, and there was a small increase in the total produced gas volume (Nelson, 2000; White et al., 2003).

This pilot project showed that CO₂ sequestration can be achieved by injecting CO₂ into a coalbed gas reservoir. The results of the pilot project also suggest that, at least initially, the injected CO₂ primarily fills unoccupied adsorption sites.

WATER RESOURCES PROTECTION

The data in Table 3 indicate that coalbed natural gas production in the Powder River Basin involves the coproduction of a significant volume of water. CO₂ is not considered a hazardous waste, but its

injection into coal seams could potentially impact regional water resource quality (Garduno et al., 2003; White et al., 2003).

The Wyodak–Anderson coal zone is a regional aquifer. The water quality ranges from fresh to slightly saline. The total dissolved solids (TDS) content is typically less than 2500 ppm, the dominant cation is sodium, and the dominant anion is bicarbonate. The relatively low TDS content permits beneficial uses of coproduced water, such as irrigation and livestock watering (De Bruin et al., 2004; Nelson, 2004; Rice et al., 2000).

When CO₂ dissolves in water, carbonic acid forms which lowers the pH of the solution (White et al., 2003). The increased acidity would result in the leaching of minerals. Powder River Basin subbituminous coal contains arsenic and lead (Stricker and Ellis, 1999). In some Powder River Basin areas, there is evidence of hydrologic communication between coalbeds and overlying sandstone aquifers (Frost et al., 2001; Wyoming Bureau of Land Management, 2004). Increases in the dissolved concentrations of arsenic and lead could potentially impact water quality in the sandstone aquifers as well as the suitability of coproduced water for beneficial uses.

KEY GEOLOGIC VARIABLES

The CO₂ sequestration capacity of a coal deposit depends on five key geologic variables: 1) the amount of coal, 2) the hydrostatic pressure of the coal zone, 3) the CO₂ storage capacity of the coal, 4) the coal's content of sorbed-phase natural gas, and 5) the composition of the sorbed-phase natural gas.

The first three geologic variables define the CO₂ storage capacity of the coal deposit. The third and fourth geologic variables account for factors that would reduce the

number of adsorption sites available for CO₂ uptake and storage.

Most subsurface coal deposits contain some sorbed-phase natural gas (Nelson, 2001). The sorbed-phase gas content and its composition affect the CO₂ sequestration potential of the coal deposit. In the Powder River Basin, the sorbed-phase gas in the Wyodak–Anderson coal zone is predominantly CH₄, but some CO₂ is commonly present (Boreck and Weaver, 1984; Hower et al., 2003; Nelson, 2003).

A sixth variable is an engineering safety factor. The injected CO₂ volume must be less than the CO₂ storage capacity of the coal because the hydrologic pressure in the formation could undergo natural variation over geologically long time periods (Pashin and McIntyre, 2003).

CO₂ SEQUESTRATION POTENTIAL

The amount of CO₂ that could potentially be sequestered in the Powder River Basin’s Wyodak–Anderson coal zone was evaluated with the procedure that is used for gas-in-place (GIP) analysis of coalbed reservoirs (Mavor and Nelson, 1997; Nelson, 1999, 2004). The CO₂ sequestration potential was calculated using Equation 2:

$$\text{CO}_2 \text{ SP} = [A \times h \times \rho \times \text{SC}_{\text{CO}_2}] \quad [\text{Eq. 2}]$$

Where:

A = Area

h = Net coal thickness

ρ = Density

SC_{CO₂} = CO₂ storage capacity

CO₂ SP = CO₂ sequestration potential

Two sets of CO₂ sequestration potential estimates were calculated for the Wyodak–Anderson coal zone. The first estimate was total CO₂ storage capacity. The second estimate was effective CO₂ storage capacity, which accounts for the impacts of sorbed-phase natural gas and its

composition on the total CO₂ storage capacity. The effective CO₂ sequestration potential was calculated using Equation 3:

$$\text{Effective CO}_2 \text{ SP} = \text{CO}_2 \text{ SP} - [A \times h \times \rho \times \text{GC}] \quad [\text{Eq. 3}]$$

Where:

GC = Sorbed-phase gas content

An engineering safety factor was included in both sets of calculations. The safety factor set the maximum sorbed-phase CO₂ volume at a value where CO₂ desorption would begin if there was a 20% reduction in the hydrostatic pressure.

These calculations were based on information obtained from analysis of three types of geologic and coal property data: overburden thickness and net coal thickness isopach maps (Ellis et al., 1999); hydrologic pressure and gas desorption pressure data (Crockett and Meyer, 2001; Nelson, 2003, 2004; Wyoming Bureau of Land Management, 2004); and coal density, gas content, gas composition, and storage capacity data (Boreck and Weaver, 1984; Choate et al., 1984; Holland and Kimmons, 1995; Hower et al., 2003; Nelson, 2003, 2004; Wyoming Bureau of Land Management, 2004).

The area underlain by the Wyodak–Anderson coal zone was subdivided into 36-mi² (93.2-km²) (township-sized) units. The CO₂ sequestration potential was evaluated for the 136 townships where the Wyodak–Anderson coal zone overburden thickness is at least 500 feet (152 m) and the net coal thickness is at least 10 feet (3 m). Ten feet net coal thickness was chosen as a minimum because this is a commonly used technical criterion for defining viable CBM play areas in lower-rank coals (site will be provided by Nelson–ARI 3003 report). Figure 3 indicates that only a very small area in Montana meets the overburden thickness criterion.

A geologic model of the average overburden thickness and average net coal thickness of the Wyodak–Anderson coal zone in each township was created using data obtained from the isopach maps shown in Figures 3 and 4. Equation 4 was used to calculate the coal-in-place resource estimate for each township. A value of 1810 tons/acre-ft (1.33 g/cm^3) was used for the in situ density of the subbituminous coal (Nelson, 2003, 2004).

$$\text{Coal-in-Place Resource} = [A \times h \times \rho] \text{ [Eq. 4]}$$

CO₂ storage capacity and gas content were estimated for each township using reservoir depth, initial reservoir pressure, initial gas desorption pressure, and gas storage capacity correlations. Figure 8 shows that in the Wyodak–Anderson coal zone, there is a linear relationship between the reservoir depth and the initial reservoir pressure. Figure 9 shows that there also is a linear relationship between the initial reservoir pressure and the initial gas desorption pressure (Crockett and Meyer, 2001; Nelson, 2004; Wyoming Bureau of Land Management, 2004).

Figure 10 shows CH₄ and CO₂ storage capacity isotherms for a Wyodak–Anderson coal sample. The gas storage capacity of the coal increases nonlinearly as pressure increases. At a pressure of 450 psia, the CO₂ storage capacity is ten times greater than the CH₄ storage capacity (Nelson, 2003).

The CO₂ and CH₄ storage capacity values were calculated based on the initial hydrostatic pressure and gas desorption pressure, respectively. The gas storage capacity calculations were made using the Langmuir isotherm model, which is a numerical model that describes the relationship between the gas storage capacity and pressure. This is the most commonly used isotherm model for coal (Mavor and Nelson, 1997).

The CO₂ and CH₄ isotherms of Wyodak–Anderson coal exhibit considerable variability (Hower et al., 2003; Nelson, 2003, 2004; Stricker and Flores, 2002; Wyoming Bureau of Land Management, 2004). To account for this variability, the Wyodak–Anderson coal zone was subdivided into two depth intervals, and a

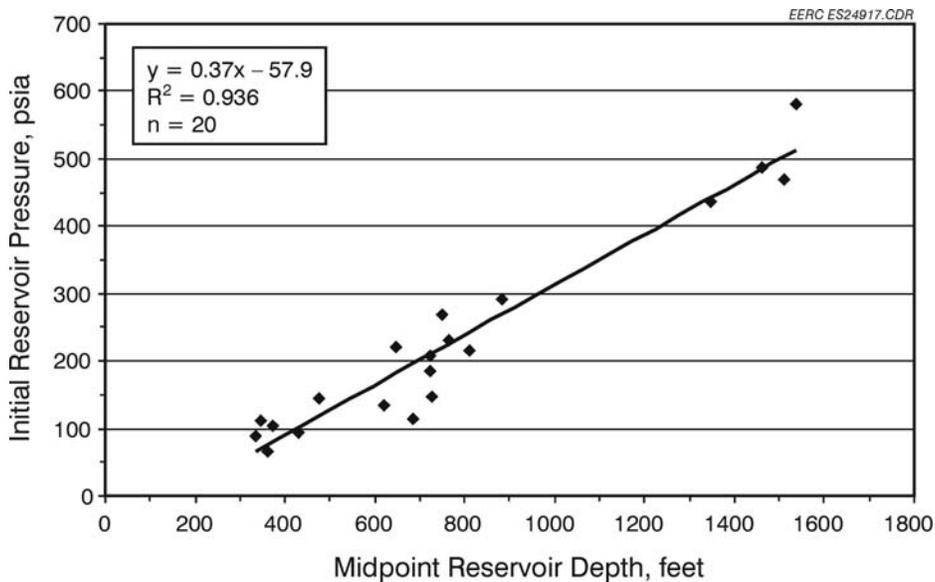


Figure 8. Variation of initial reservoir pressure as a function of coalbed reservoir depth.

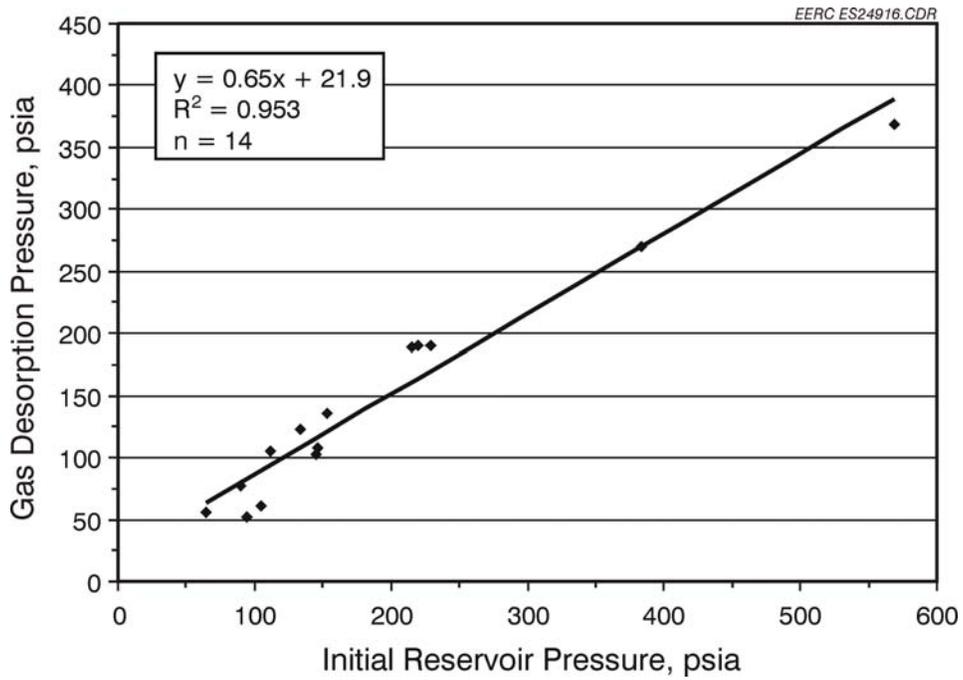


Figure 9. Variation of gas desorption pressure as a function of initial reservoir pressure.

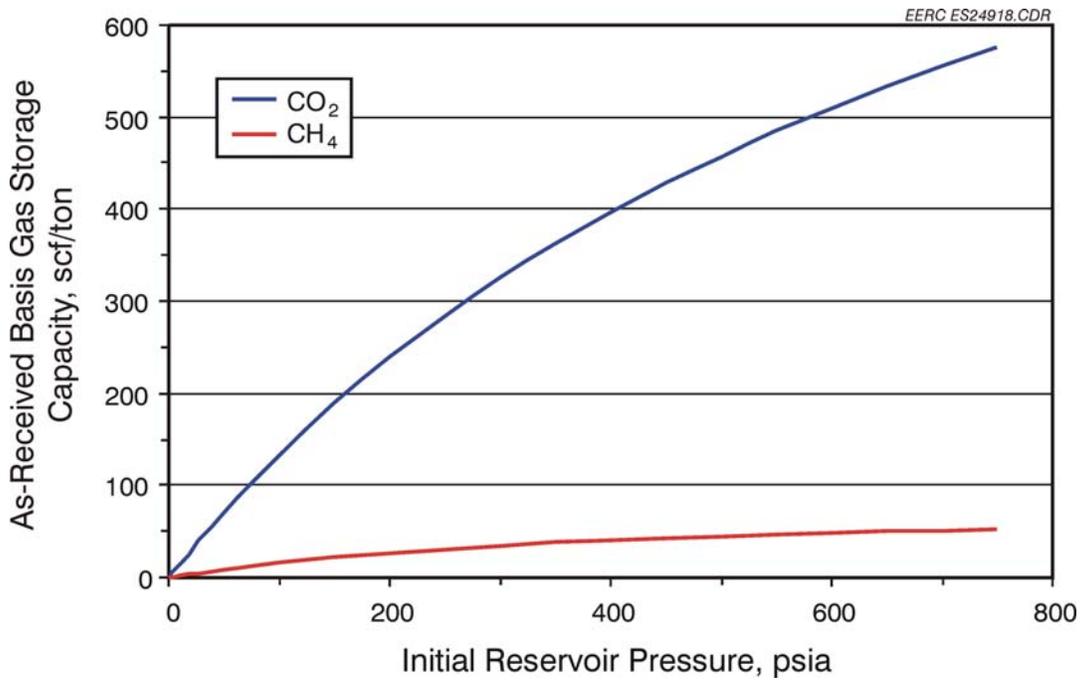


Figure 10. Isotherms for Wyodak-Anderson coal.

Table 4. CO₂ Langmuir Isotherm Equations for the Wyodak–Anderson Coal Zone

Depth Interval, ft	CO ₂ Storage Capacity Equations ^{a,b}
500–1200	$SC_{CO_2} = (1045 \times [P_h / \{P_h + 650\}])$
>1200	$SC_{CO_2} = (1100 \times [P_h / \{P_h + 620\}])$

^a P_h = Initial hydrostatic pressure.

^b SC_{CO₂} = scf/ton (in situ basis).

separate Langmuir isotherm equation was formulated for each interval. The two CO₂ Langmuir isotherm equations are shown in Table 4. Initial hydrostatic pressure for each township was estimated using the correlation shown in Figure 8. The CO₂ storage capacity for each township was estimated using the isotherm equations shown in Table 4. The CO₂ sequestration potential for each township was calculated using Equation 2.

Table 5 shows the Langmuir isotherm equations used for estimating gas storage capacity. Powder River Basin coalbed reservoirs are not gas-saturated, so the gas content was calculated by using the estimated gas desorption pressure, not the initial hydrostatic pressure (Crockett and Meyer, 2001; Nelson, 2004; Wyoming Bureau of Land Management, 2004).

Table 5. Gas Storage Capacity Equations for the Wyodak–Anderson Coal Zone^a

Depth Interval, ft	Gas Content Equations ^{a,b}
500–1200	$GC = (95 \times [P_d / \{P_d + 330\}])$
>1200	$GC = (150 \times [P_d / \{P_d + 450\}])$

^a P_d = Gas desorption pressure.

^b GC = scf/ton (in situ basis).

The isotherm equations in Table 5 account for the CH₄ and CO₂ composition of the sorbed-phase gas in the coal. For the shallower depth interval, the sorbed-phase gas was considered to be 95% CH₄ and 5% CO₂. For the deeper interval, the sorbed-phase gas was considered to be 90% CH₄ and 10% CO₂ (Boreck and Weaver, 1984; Hower et al., 2003; Nelson, 2003).

The correlations shown in Figures 8 and 9 and the gas storage capacity equations shown in Table 5 were then used to estimate gas content values for each township. The effective CO₂ sequestration potential for each township was calculated using Equation 3.

An internally consistent set of coal seam thicknesses, densities, and gas content values were used for the calculations. The coal seam thickness obtained from the isopach map shown in Figure 4 reflected the in situ bulk compositional properties of the coal. Thus in situ basis density and gas content values were used for the resource calculations. The GIP resource estimate for each township was calculated using Equation 5:

$$GIP = [A \times h \times \rho \times GC] \quad [\text{Eq. 5}]$$

EVALUATION RESULTS

Table 6 and Figure 11 show the CO₂ sequestration potential estimates for the Powder River Basin Wyodak–Anderson coal zone. The total CO₂ sequestration potential is 137.6 Tcf (3.9 × 10¹² m³). The effective CO₂ sequestration potential estimate is 118.6 Tcf (3.4 × 10¹² m³). Approximately 85% of the total CO₂ sequestration capacity is in areas where the overburden thickness is >1000 ft (305 m).

The CO₂ sequestration potential estimates shown in Table 6 and Figure 11 are only for areas in Wyoming. Figure 3 indicates

Table 6. CO₂ Sequestration Potential Estimates for the Wyodak–Anderson Coal Zone^a

Depth Interval, ft	Total CO ₂ Capacity ^b		Effective CO ₂ Capacity ^b	
	Tcf	10 ⁶ short ton (st)	Tcf	10 ⁶ st
500–1000	20.3	1178	17.4	1007
>1000	117.3	6805	101.2	5874
Total	137.6	7983	118.6	6881

^a Estimates are for areas where the net coal thickness is 10+ ft.

^b 20% pressure decrease required before start of gas desorption.

that only a very small area in Montana meets the 500+ ft (152+ m) overburden thickness criterion. Therefore, no CO₂ sequestration potential estimates were calculated for areas in Montana underlain by the Wyodak–Anderson coal zone.

NATURAL GAS RESOURCE POTENTIAL

CO₂ emissions to the atmosphere are not regulated, and there is little to no market value associated with geologic CO₂ sequestration. An economically viable approach would be to sequester CO₂ in unminable coal seams in conjunction with natural gas recovery. The natural gas would provide a revenue stream to partially offset the costs of CO₂ capture and sequestration (Garduno et al., 2003; Pashin et al., 2001; White et al., 2003; Wong et al., 2000).

Table 7 shows the coal and coalbed natural gas resource estimates for the Wyodak–Anderson coal zone. The coal resources total 395 billion short tons (0.36×10^{15} kg). The coalbed natural gas resources total 18.9 Tcf (0.54×10^{12} m³).

The coal and coalbed natural gas resource estimates shown in Table 7 are only for areas in Wyoming. Figure 3 indicates that only a very small area in Montana meets the 500+ ft (152+ m) overburden thickness criterion. Therefore, no coal or coalbed natural gas resource estimates were calculated for any areas in Montana underlain by the Wyodak–Anderson coal zone.

Table 7. Coal and Gas Resource Estimates for the Wyodak–Anderson Coal Zone^a

Depth Interval, ft	Coal 10 ⁹ st	Recoverable Coalbed	
		Gas Tcf	Gas ^b Tcf
500–1000	178	6.2	5.3
>1000	217	12.7	10.8
Total	395	18.9	16.1

^a Estimates are for areas where the net coal thickness is 10+ ft.

^b Based on a recovery factor value of 85%.

Large-scale reservoir simulation indicates that a primary gas recovery factor of 85% can be expected for the Powder River Basin Wyodak–Anderson coalbed reservoirs (Hower et al., 2003). If the 85% recovery factor is achieved, the potentially recoverable coalbed natural gas resource base in areas where the Wyodak–Anderson coal zone is suitable for CO₂ sequestration totals 16.1 Tcf (0.46×10^{12} m³) through primary recovery. In turn, up to 2.8 TCF of incremental coalbed natural gas could be potentially recovered through CO₂ sequestration.

Figure 10 shows that the CO₂ storage capacity of the Wyodak–Anderson subbituminous coal is ten times greater than the CH₄ storage capacity. Ten moles of CO₂ would need to be injected to liberate 1 mole of CH₄. The high CO₂-to-CH₄ ratio would strongly impact the economics of using CO₂ injection to enhance the CH₄

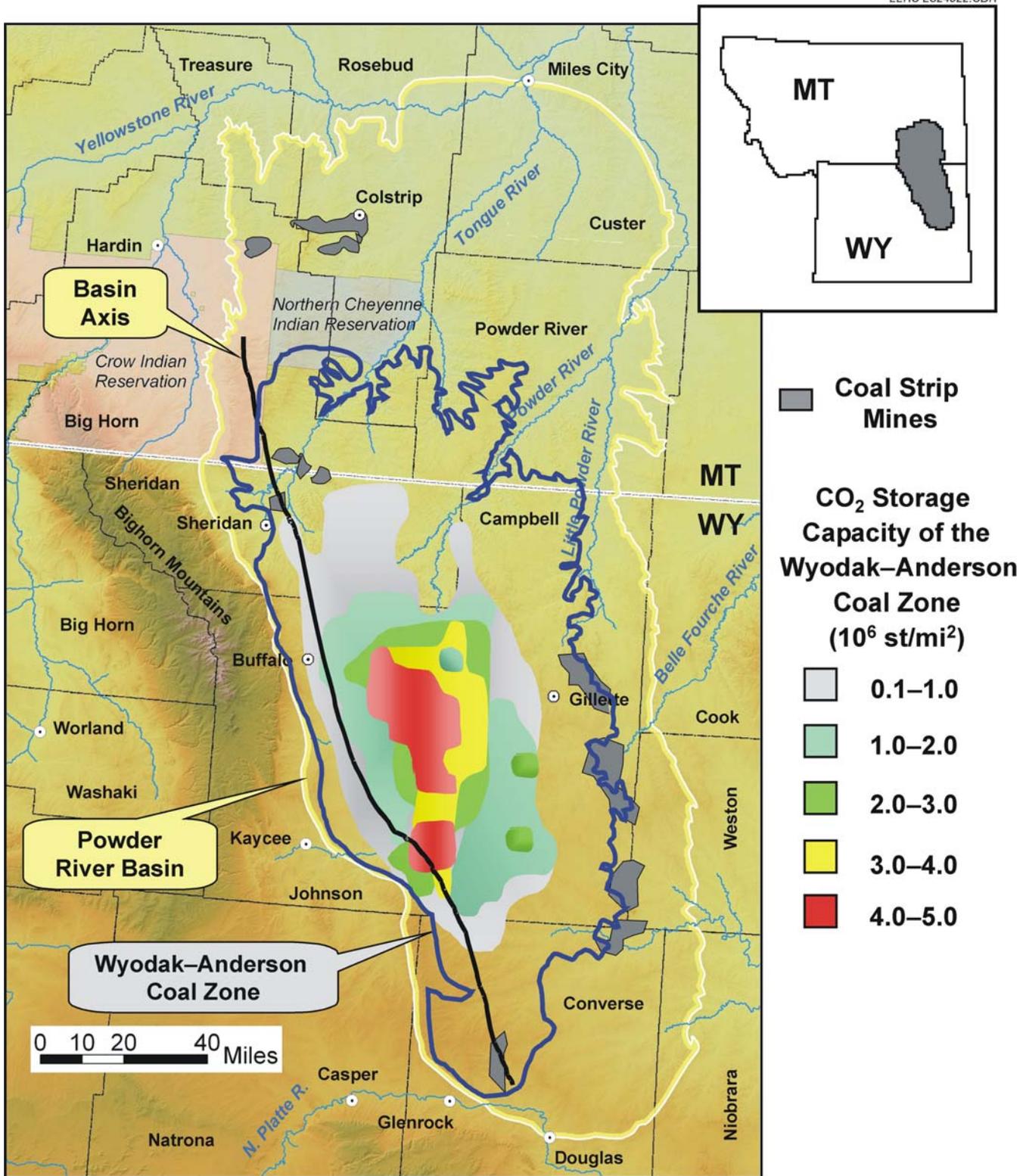


Figure 11. Isopach map showing the CO₂ sequestration potential of the Wyodak-Anderson coal zone in the Powder River Basin.

recovery rate (Wong et al., 2000). Nonetheless, the use of CO₂ injection to enhance the rate of CH₄ recovery could potentially represent a large market for CO₂ in the western PCOR Partnership region.

SUMMARY

Coal-fired power plants in southeastern Montana and northeastern Wyoming generate an estimated 43.6 million short tons (39.6×10^9 kg) of CO₂ annually. Currently, this CO₂ is emitted directly to the atmosphere. All of these power plants overlie or are proximal to significant subbituminous coal deposits in the Powder River Basin. This basin is the No. 1 coal-producing area and the second most prolific coalbed natural gas-producing area in the United States.

The geologic factors that control coalbed natural gas accumulation are similar to those that would control the CO₂ sequestration potential of a coal seam. A geologic model was constructed and used to evaluate the CO₂ sequestration potential of the areas underlain by non-surface-minable portions of the Powder River Basin Wyoming-Anderson coal zone. The CO₂ sequestration potential estimate for the areas where the coal overburden thickness is estimated at >1000 ft (305 m) is 6.8 billion short tons (6.2×10^{12} kg). The coal resources that underlie these deep areas could sequester all the current annual CO₂ emissions from nearby power plants for the next 156 years.

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