Attachment 5
The Powder River Basin

The Powder River Basin is located in northeastern Wyoming and southern Montana. The basin covers an area of approximately 25,800 square miles (Larsen, 1989), approximately 75 percent of which is within Wyoming (Figure A5-1). Fifty percent of the basin (Figure A5-2) is believed to have the potential for production of coalbed methane (Powder River Coalbed Methane Information Council, 2000). Much of the coalbed methane-related activity has been north and south of Gillette in northeastern Wyoming (Figure A5-2). The majority of the potentially productive coal zones range from about 450 feet to over 6,500 feet below ground surface (Montgomery, 1999). In addition to being an important resource for coalbed methane, the basin has also produced coal, petroleum, conventional natural gas, and uranium oxide (Law et al., 1991; Randall, 1991). Recent estimates of coalbed methane reserves in the Powder River Basin have been as much as 40 trillion cubic feet (Tcf) (PRCMIC, 2000) but more conservative estimates range from 7 to 12 Tcf (Montgomery, 1999). Annual production volume was estimated at 147 billion cubic feet (Bcf) in 2000 (GTI, 2002). In 2002, wells in the Powder River Basin produced about 823 million cubic feet (Mcf) per day of coalbed methane (DOE, 2002).

The information available indicates that hydraulic fracturing currently is not widely used in this region due to concerns about the potential for increased groundwater flow into the coalbed methane production wells and collapse of open hole wells in coal upon dewatering. According to the available literature, where hydraulic fracturing has been used in this basin, it has not been an effective method for extracting methane.

5.1 Basin Geology

The Powder River Basin is a thick sequence of sedimentary rock formed in a large downwarp within the Precambrian basement. The basin is bounded on the east by the Black Hills uplift, on the west by the Big Horn uplift and Casper Arch, on the south by the Laramie and Hartville uplifts and, on the north, it is separated from the Williston Basin by the Miles City Arch and the Cedar Creek Anticline (Larsen, 1989) (Figure A5-1). The long axis of the basin is aligned in a generally southeast to northwest direction, and it is as much as 18,000 feet deep (Randall, 1991) (Figures A5-1 and A5-3). Sediments range from Paleozoic at the bottom through Mesozoic to Tertiary at the top (DeBruin et al., 2000). The basin is a large asymmetrical syncline with its axis (deepest part) near the west side of the basin (Figure A5-3). From outcrops along the eastern edge of the basin, the sediments slope gently (1.5^o, about 100 feet per mile) downward to the southwest and then bend steeply upward (10 to 45^o) to outcrop in a monocline along the western edge of the basin.

Several periods of deposition by marine and fluvial-deltaic processes have occurred within the basin during the Cretaceous and Tertiary periods. These Cretaceous and lower

Tertiary rocks have a total thickness of up to 15,000 feet (Montgomery, 1999). Coal is found in the Paleocene Fort Union and Eocene Wasatch Formations (Figure A5-4). The Wasatch Formation occurs at land surface in the central part of the basin and is covered by alluvium or White River Formation in some places (Figure A5-4). Most of the coalbeds in the Wasatch Formation are continuous and thin (six feet or less) although, locally, thicker deposits have been found (DeBruin et al., 2000). The Fort Union Formation lies directly below the Wasatch Formation and can be as much as 6,200 feet thick (Law et al. 1991). The Fort Union Formation outcrops at the ground surface on the eastern side of the basin, east of the City of Gillette and on the western side of the basin, north and south of Buffalo. The coalbeds in this formation are typically most abundant in the upper Tongue River Member (Figure A5-4). This member is typically 1,500 to 1,800 feet thick, of which up to a composite total of 350 feet of coal can be found in various beds. The thickest of the individual coalbeds is over 200 feet (Flores and Bader, 1999). The coalbeds are interspersed with sandstone, conglomerate, siltstone, mudstone and limestone (Montgomery, 1999).

Most coalbed methane wells in the Powder River Basin are in the Tongue River Member of the Fort Union Formation, in the Wyodak-Anderson coal zone, which contains up to 32 different coalbeds according to some authors (Ayers, 1986), including the Big George in the central part of the basin (Flores and Bader, 1999). The Wyodak is one of the thick coalbeds that are targeted for coalbed methane development. This coalbed is also called the Wyodak-Anderson or the Anderson, and it can be subdivided further into several other coalbeds. These coalbeds are the Canyon, Monarch, and Cook. All of these coalbeds are coalbed methane targets. Most coalbeds are found within 2,500 feet of the ground surface.

The Wyodak or Wyodak-Anderson coalbed in the Wyodak-Anderson coal zone is prominent in the eastern portion of the Powder River Basin near the City of Gillette (Figures A5-3, A5-5 and A5-6). The Wyodak has been identified as the largest single coalbed in the country (Montgomery, 1999). The coal is close to the ground surface and mining of the coal is common. The Wyodak coalbed gets progressively deeper and thicker toward the west. This bed ranges from 42 to 184 feet thick. Most of the coalbed methane wells in the Powder River Basin are within the Wyodak coal zone near the City of Gillette.

The Big George Coalbed is located in the central and western portion of the Powder River Basin (Figure A5-7). Although the Big George is stratigraphically higher than the Wyodak, owing to the structure of the basin, the Big George, in the center portion of the basin, is deeper than the Wyodak at the eastern margin of the basin (Tyler, et al., 1995). To date, the Big George has not been developed for coalbed methane production to the same extent as the Wyodak-Anderson coal zone. This is due to a combination of factors including greater depth to coal, more groundwater, and longer distances to available transmission pipelines. However, as of December 2001, there were about 850 coalbed methane wells drilled into the Big George with a large number of wells planned for the future (Osborne, 2002).

A third significant coal zone, the Lake De Smet coal zone in the Wasatch Formation, is up to 200 feet thick and is located in the Lake De Smet area (Figure A5-8), 55 miles southwest of Recluse on the western side of the basin (Larsen, 1989). It has not yet been widely used for coalbed methane production.

Most of the coal in the Powder River Basin is subbituminous in rank, which is indicative of a low level of maturity. Some lignite, lower in rank, has also been identified. The thermal content of the coals found in the Powder River Basin is typically 8,300 British thermal units per pound (Randall, 1991). Coal in the Powder River Basin was formed at relatively shallow depths and relatively low temperatures. Most of the methane generated under these conditions is biogenic, which means that it was formed by bacterial decomposition of organic matter. Thermogenic formation (formed under high temperature) was not significant in most locations within the Powder River Basin. Consequently, coal in the Powder River Basin contains less methane per unit volume than many other coal deposits in other parts of the country. Coal in the Powder River Basin has been found to contain 30 to 40 standard cubic feet of methane per ton of coal compared to 350 standard cubic feet of methane per ton in other areas (DeBruin et al., 2000). The gas is typically more than 95 percent methane, the remainder being mostly nitrogen and carbon dioxide. This resource was overlooked for many years because it was thought to be too shallow for the production of significant amounts of methane (Petzet, 1997). However, the relatively low gas content of Powder River Basin coal is compensated by the thickness of the coal deposits. Because of the thickness of the deposits and their accessibility, commercial development of the coalbed methane has been found to be economical.

The Powder River Basin contains approximately 60 percent of the coalbed methane reserves in the State of Wyoming (DeBruin et al., 2000). Recent estimates of coalbed methane reserves in the Powder River Basin have been as much as 40 Tcf (PRCMIC, 2000) but more conservative estimates range from 7 to 12 Tcf (Montgomery, 1999). As of December 1999, monthly production exceeded 7 Bcf from 1,657 wells (DeBruin et al., 2000). Wells typically produce 160,000 cubic feet of gas per day (DeBruin et al., 2000). Annual production volume was estimated at 147 Bcf in 2000 (GTI, 2002). In 2002, wells in the Powder River Basin produced about 823 Mcf per day of coalbed methane (DOE, 2002). Coalbed methane has been developed along both the east and west flanks of the basin where the coalbeds are buried but relatively shallow. Many existing wells are awaiting connection to the distribution system and still more wells are being drilled. The estimated lifetime production from these wells is 300 to 400 Mcf per well (Petzet, 1997).

The amount of coalbed methane produced from each well is highly variable, and the volume of gas depends on the quality and thickness of the coal, the frequency of natural cleats in the coal, and the amount of water present. Other factors, such as well completion techniques and well stimulation techniques, also control the amount of gas produced from a well. Maximum coalbed methane flow from a well is typically achieved after one to six months of dewatering (Montgomery, 1999). Stable production is usually experienced for one to two years before production begins to decline (Montgomery, 1999). Production often declines at a rate of 20 percent per year until the well is no longer economically useful (Montgomery, 1999). Several options exist at that point, including re-fracturing the well, completing the well in a deeper coal formation, converting the well to a water supply well, or abandoning the well.

5.2 Basin Hydrology and USDW Identification

A report prepared by the United States Geological Survey (USGS) showed that samples of water co-produced from 47 coalbed methane wells in the Powder River Basin all had total dissolved solids (TDS) levels of less than 10,000 milligrams per liter (mg/L) (Rice et al., 2000). Based on the water quality component of the underground source of drinking water (USDW) definition, which specifies that a USDW contain less than 10,000 mg/L of TDS, the Fort Union Formation coalbeds are within a USDW. The water produced by coalbed methane wells in the Powder River Coal Field commonly meets drinking water standards, and production waters such as these have been proposed as a separate or supplemental source for municipal drinking water in some areas (DeBruin et al., 2000). Sandstones in the sediments both above and below the coalbeds are also aquifers.

In 1990, Wyoming withdrew an average of 384 million gallons per day of groundwater for a variety of purposes, the majority of which was agriculture. Approximately 13 percent was used for potable water supplies. Approximately 22 percent was withdrawn by industry and mining (Brooks, 2001). The proportion of this 22 percent attributable to coalbed methane production is increasing rapidly, and a concern exists that such good quality water in a semiarid region should be conserved (Quarterly Review, 1993). In 1990, before the rapid expansion of coalbed methane extraction in the region, Campbell County was identified by the USGS as an area of major groundwater withdrawal.

Approximately 80 percent of Wyoming residents rely on groundwater as their drinking water source (Powder River Basin Resource Council, 2001). Few public water supply systems exist in the Powder River Basin due to relatively low population densities. The City of Gillette, the largest in the major coalbed methane development area (Figure A5-2), uses groundwater from two sources identified as “in-town wells”, and the “Madison Well Field”. The city has experienced considerable drawdown and reduced production from their in-town wells that are completed in the Fort Union and Lance/Fox Hills aquifers (Brooks, 2001). It is unclear how much of the drawdown is attributable to withdrawals for water supply as a consequence of population growth and how much is attributable to nearby coalbed methane production. Between 1995 and 1998, the city restored and/or replaced several of its wells. The Madison Well Field produces water from the Madison Formation and is approximately 60 miles east of the city. There are no coalbed methane wells in the vicinity of the Madison Well Field (Brooks, 2001).

Regional groundwater flow in the basin is reported to be toward the northwest (Martin et al., 1988 in Law, 1991), with recharge occurring in the east along the Rochelle Hills.

Cleats and other fractures within the coalbeds create high hydraulic conductivities and facilitate the flow of groundwater and high water production within the coalbeds (Montgomery, 1999). The coalbeds are largely hydraulically confined by underlying shale and by basinward pinch-out. Surficial water and rainwater can enter the Fort Union coals from land surface at the eastern edge of the basin and at the Black Hills uplift. This flow inward from outcrop areas at higher elevations on the edge of the basin may have created artesian conditions in the deeper central portions of the basin. However, this view may not be entirely correct. For example, coalbed research (Law et al., 1991) hypothesizes that the sodium bicarbonate water in the Fort Union coal near the central part of the basin may not be derived from meteoric recharge, but rather from interstitial waters of the original peat deposits. Furthermore, Martin et al. (1988, as cited in Law et al., 1991) concluded on the basis of isotopic composition of water samples that only part of the water near outcrops was of meteoric origin. Although artesian pressure in the center of the basin has been thought to be evidence that the center of the basin is fed from meteoric recharge at the basin margins, the apparent artesian pressure (flowing wells) could be explained by the airlift effect of methane coming out of solution within the rising well water column.

Because the coalbeds are productive aquifers, they also require more dewatering of coalbed methane wells for methane production. Groundwater production, in terms of volume of water produced, was a major factor considered in the selection of sites for early coalbed methane wells and may still guide development of sites in some parts of the Powder River Basin. Wells in the eastern portion of the basin have been found to contain less water due to their location above the water table within the eastern anticlinal updip of the formation and, in some areas, due to the presence of nearby mines that dewater the aquifer. Drawdowns of up to 80 feet have been measured in wells near active mines; however, water levels have been reported to be unaffected at distances of more than three miles from mines (Randall, 1991). The Bureau of Land Management in conjunction with the State Engineer's Office has been conducting ongoing research on the effects of coalbed methane production on drawdown (Wyoming Geological Association, 1999).

5.3 Coalbed Methane Production Activity

Coalbed methane activity in Wyoming occurs predominantly in Campbell, Sheridan and Johnson Counties (DeBruin, 2001). Wells are spaced from 40 to 80 acres per well, as determined by the State. Permits are required under both state water well regulations and state gas well regulations before drilling can commence. A discharge permit from the Wyoming Department of Environmental Quality is also required for the water that is removed from the well. Coalbed methane production wells in the Powder River Basin are typically 400 to 1,500 feet deep and can be as shallow as 150 feet (PRCMIC, 2000). By comparison, conventional gas and oil wells installed in the area are typically 4,000 to 12,000 feet deep (PRCMIC, 2000). Plans for construction of approximately 4,000 new coalbed methane production wells in the Montana portion of the Powder River Basin await completion of an in-depth environmental study (DeBruin, 2001).

Commercial development of methane directly from the coal seams began approximately in 1986. There were only 18 wells producing coalbed methane in the Powder River Basin by 1989. The number grew slowly through the early 1990s with 171 wells producing approximately 8 Bcf of gas per year. The rate of development of the resource accelerated greatly from 1997 to 1999. In 1999, there were 1,657 coalbed methane wells operating in the Powder River Basin, producing approximately 58 Bcf per year (Figure A5-9) of coalbed methane. As of November 2000, there were about 4,270 wells in Wyoming producing 15 Bcf of coalbed methane in that month alone (Osborne, 2002). By November 2001, monthly coalbed methane production had climbed to 23.5 Bcf from 7,870 producing wells in Wyoming (Osborne, 2002). In Montana, 246 active wells produced 872,008 Mcf of coalbed methane in December, 2001 (Osborne, 2002). The Powder River Basin has become the most active coalbed methane exploration and production area in the country (DeBruin et al., 2000). Despite all of the activity, less than 5 percent of the land underlain by coal in the Powder River Basin had been explored for the presence of coalbed methane as of the year 2000 (PRCMIC, 2000).

During the early years of coalbed methane development in the Powder River Basin (1980s to early 1990s), gas exploration and development companies completed wells with and without hydraulic fracture techniques. Larsen (1989) indicated that early wells were completed without fracturing treatments, particularly wells targeting gas reserves in coals interspersed between sandstone layers. However, the Quarterly Review (1989) reported that in one well, Rawhide 15-17, located north of Gillette, Wyoming, an "open frac" hydraulic fracturing was performed using 13,000 lbs of 12/20-mesh sand in 3,500 gallons of gelled water. Several wells installed in the early 1990s by Betop, Inc. were fractured using 4,000 to 15,000 gallons of a solution with 2 percent potassium chloride (KCl) in water. Sand was used to prop the fractures open in five of these wells (Quarterly Review, 1993). However, hydraulic fracturing experienced little success in this basin. Fractured wells produced poorly because the permeable, shallow subbituminous coals collapsed under the pressure of the overburden after they were dewatered (Lyman, 2001).

The Powder River Basin contains coals of high permeability. The permeability is so high in many areas that drilling fluid (typically water) is lost when drilling the coalbeds. Many times drilling mud is substituted to prevent loss of circulation (DeBruin, 2001). Because of this high permeability, most coalbed wells in the Fort Union Formation can be drilled and completed without the use of hydraulic fracturing (DeBruin, 2001; Quarterly Review, 1993). This has been confirmed by USGS officials in Wyoming (Brooks, 2001). Hydraulic fracturing is also avoided to prevent fracturing of impermeable formations adjacent to the coal, such as shales, that prevent the migration of groundwater. It is thought that fracturing the shale would increase the amount of water flowing into the wells. When fracturing has been done, it has been with water or sand/water mixtures. Unspecified "modest" improvements in coalbed methane gas flow have been observed (Quarterly Review, 1993).

In the Powder River Basin, two different coalbed methane sources are commonly developed: (1) gas extraction from methane-charged dry sand layers overlying or interbedded with the coals, and (2) conventional methane extraction from the water saturated coal seams. In the eastern (up dip) portion of the basin, the coals in the Wyodak-Anderson seam are relatively shallow and interbedded with sands (Montgomery, 1999) (Figure A5-6). In up dip areas above the water table, wells require minimal dewatering for coalbed methane production because there is little to no water in the sands (Quarterly Review, 1989; Montgomery, 1999). Coal mining operations near Gillette have lowered the water table in the vicinity of the mines, thereby dewatering nearby coalbeds and allowing desorption of methane gas from the coal. The sands are penetrated using open-hole techniques, generally without any fracture treatments (Quarterly Review, 1989). Further west, down dip (Figure A5-6), the coalbed methane producing sands and coals of the Fort Union Formation are separated from the overlying Wasatch Formation by a poorly permeable shale of limited areal extent (Quarterly Review, 1989; Quarterly Review, 1993). Further west, down dip (Figure A5-6) in this more water-saturated part of the basin, coalbed methane wells are also completed as open-hole wells.

The practice of open-hole drilling is commonly used in this region. In this practice, a portion of the borehole in the coal is drilled without any casing or well screen. Most other regions of the country where coalbed methane is recovered use a perforated casing throughout the target coal interval. The open coal zone is then cleaned out with water, and the surrounding coal formation is sometimes fractured to improve recovery of the methane. A submersible pump is set at the bottom of the target zone with tubing to the ground surface to remove groundwater from the well. The methane gas travels up the space between the water tubing and the casing. The well is capped to control the flow of methane gas. Wells are often dewatered for several months before producing optimal quantities of methane gas.

Side jetting has also been performed with some success; however, dynamic open-hole cavitation had not been attempted as of 1993. Side jetting is the process by which water and air are injected at high pressure to enlarge the boring in the coal seam. The cavitation process uses dynamic pressure changes to break apart the coal and to widen the boring within in the coal seam (Quarterly Review, 1993).

Production of coalbed methane from water-saturated coalbeds below the water table first requires partial dewatering of the coal to allow desorption of methane from the coal. Production from water-bearing coal seams can yield significant volumes of water; enough to make it difficult or infeasible to dewater the formation sufficiently to initiate coalbed methane flow (Montgomery, 1999). Tests on 11 wells reported by Crockett (2000) indicate that coalbed methane is desorbed from coal as a consequence of decreased hydrostatic pressure caused by pumping groundwater. One well started desorbing at 92 percent of the original reservoir pressure. "Most drilling to date has attempted to remain near or above the existing water table to minimize water production" (Montgomery, 1999). Modifications to well spacing and pumping configuration have been cited by Montgomery (1999) as showing some promise for allowing greater production from the water-saturated coal seams in the future. Because the water in the deeper coal seams may be original interstitial water, and recharge from meteoric water might not be an important factor (Montgomery, 1999), dewatering of these coals for the purposes of coalbed methane production might become economically feasible.

Disposal of water produced by coalbed methane wells is an issue at many well locations. Coalbed methane wells are generally pumped constantly, removing as much as 168,000 gallons per day of water from deeper formations (Randall, 1991). Averages of 17,000 gallons per day per well are more common (Powder River Basin Resource Council, 2001). Water produced during the dewatering of coalbed wells is generally discharged to stock ponds, water impoundments (reservoirs), drainages with ephemeral and intermittent streams, and surface waters. A National Pollution Discharge Elimination System permit is required for surface discharge of production water. The water is generally of potable quality in the center of the basin, becoming more saline to the north and south. It is sometimes used for irrigation and watering livestock (DeBruin, 2001). TDS levels are typically less than 5,000 parts per million. The water's salt content is primarily sodium bicarbonate (Quarterly Review, 1993). Average analytical results from 47 USGS water quality analyses of untreated, co-produced water from coalbed methane wells in the Powder River Basin are displayed in Table A5-1 below.

Table A5-1. Average Water Quality Results from Produced Waters (Rice et al., 2000)

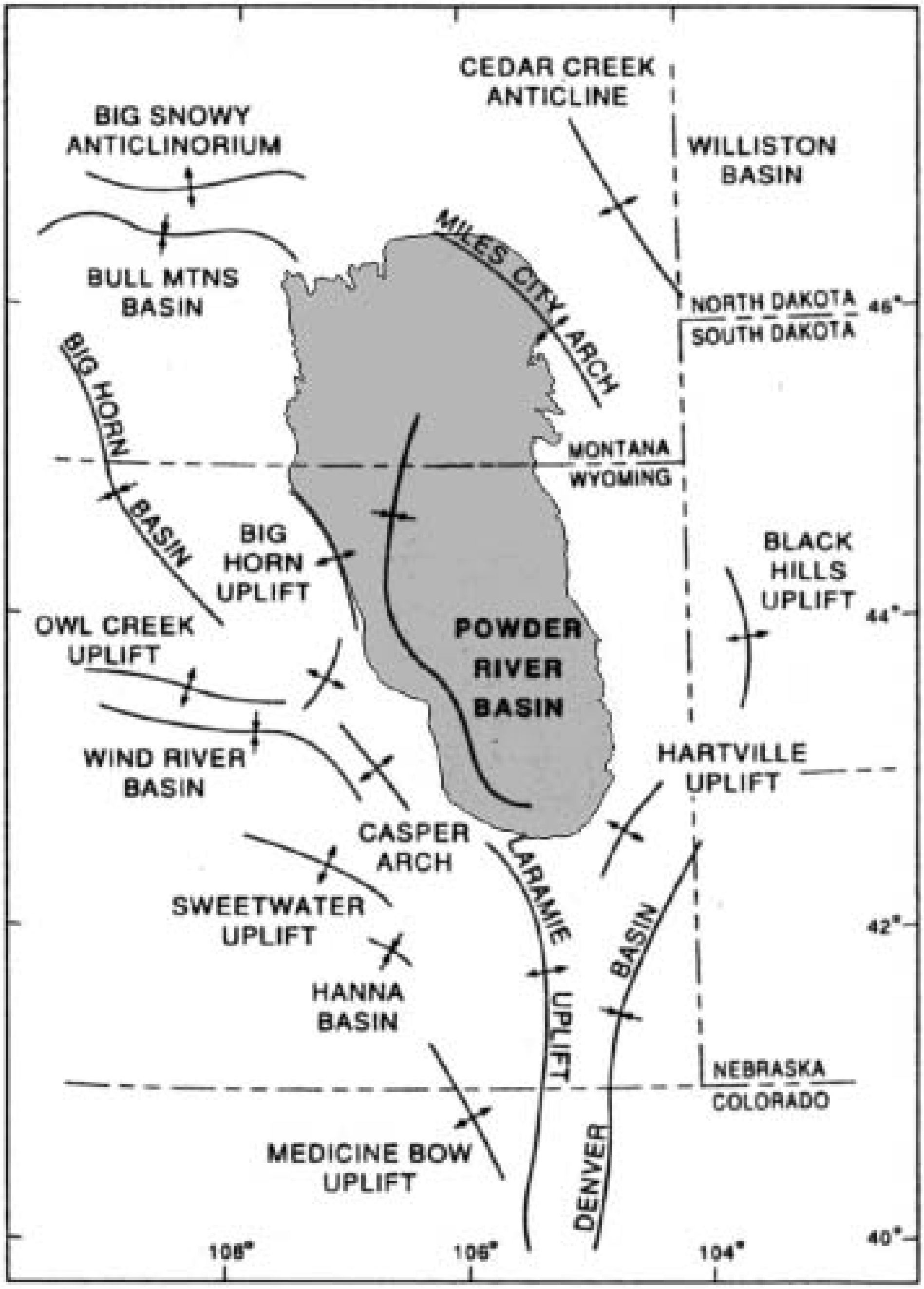
Parameter	Result	Units
pH	7.3	N/A
temperature	19.6	^oC
specific conductance	1,300	microsiemens
TDS	850	mg/L
fluoride	0.92	mg/L
chloride	13.0	mg/L
sulfate	2.4	mg/L
bromide	0.12	mg/L
alkalinity (as HCO_3)	950	mg/L
ammonium	2.4	mg/L
calcium	32	mg/L
potassium	8.4	mg/L
magnesium	16	mg/L
sodium	300	mg/L
barium	0.62	mg/L
iron	0.8	mg/L

As a result of the rapid growth in the coalbed methane industry, the Wyoming State Engineer's Office (SEO) requested funding for drilling, equipping, and monitoring of observation wells, and the installation of surface water measuring devices to be located in coalbed methane production areas. These monitoring facilities would become part of the SEO statewide observation well network to monitor changes in groundwater levels and stream flow over time. As of 1999, work was underway, but no report of results had yet been made available.

5.4 Summary

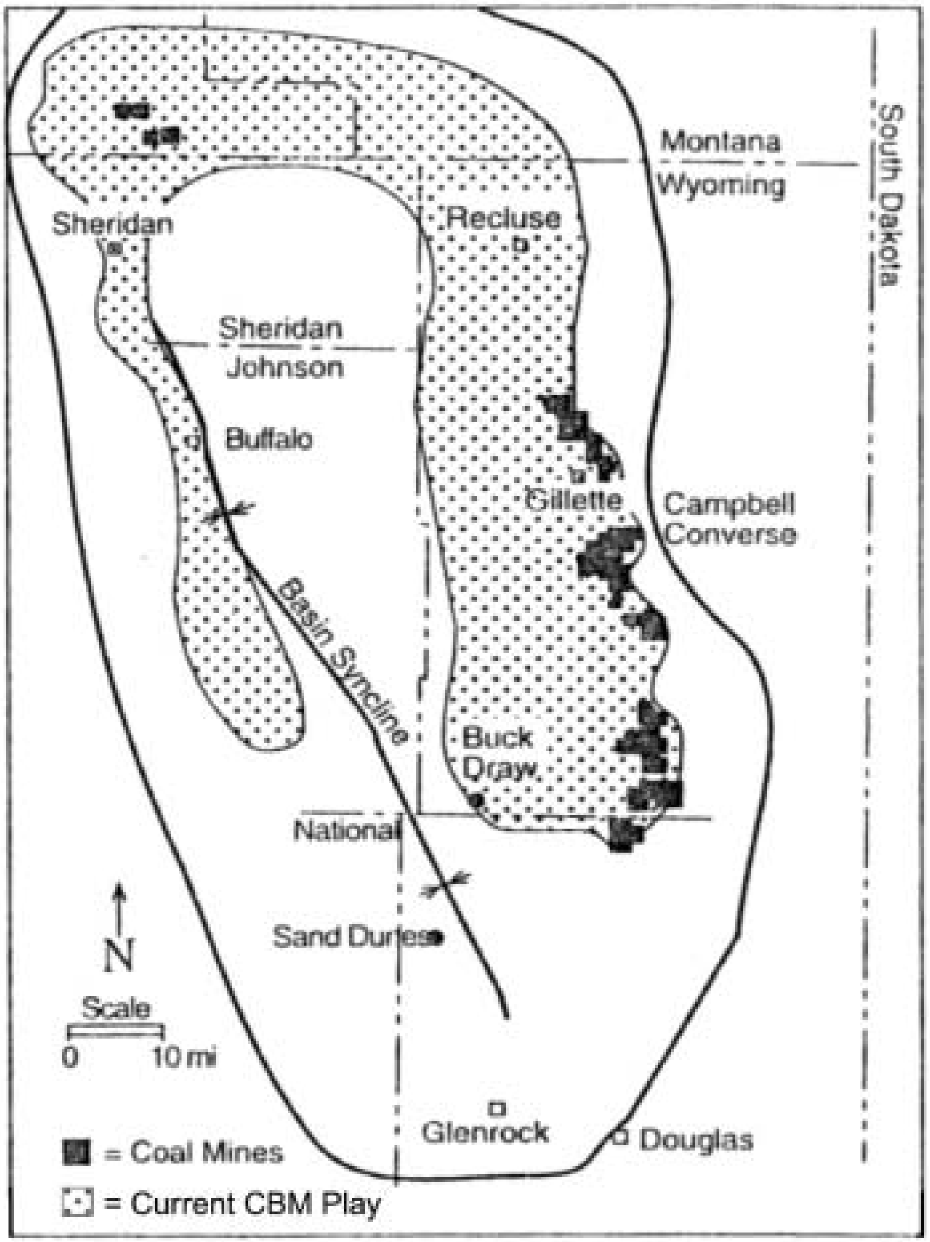
Based on the information for the Powder River Basin, the coalbeds that are being developed, or which may be developed, for coalbed methane in the Powder River Basin are also USDWs. Coalbeds in this basin are interspersed with sandstone and shale at varying depths. The Fort Union Formation that supplies municipal water to the City of Gillette is the same formation that contains the coals that are developed for coalbed methane. The coalbeds contain and transmit more water than the sandstones. The sandstones and coalbeds have been used for both the production of water and the production of coalbed methane. TDS levels in the water produced from coalbeds meet the water quality criteria for USDWs.

The information available indicates that currently hydraulic fracturing is not widely used in this region due to concerns about the potential for increased groundwater flow into the coalbed methane production wells and the consequent collapse of open hole wells in coal upon dewatering. According to the available literature, where hydraulic fracturing has been used in this basin, it has not been an effective method for extracting methane. Hydraulic fracturing has been conducted primarily with water, or gelled water and sand, although the recorded use of a solution of KCl was identified in the literature.



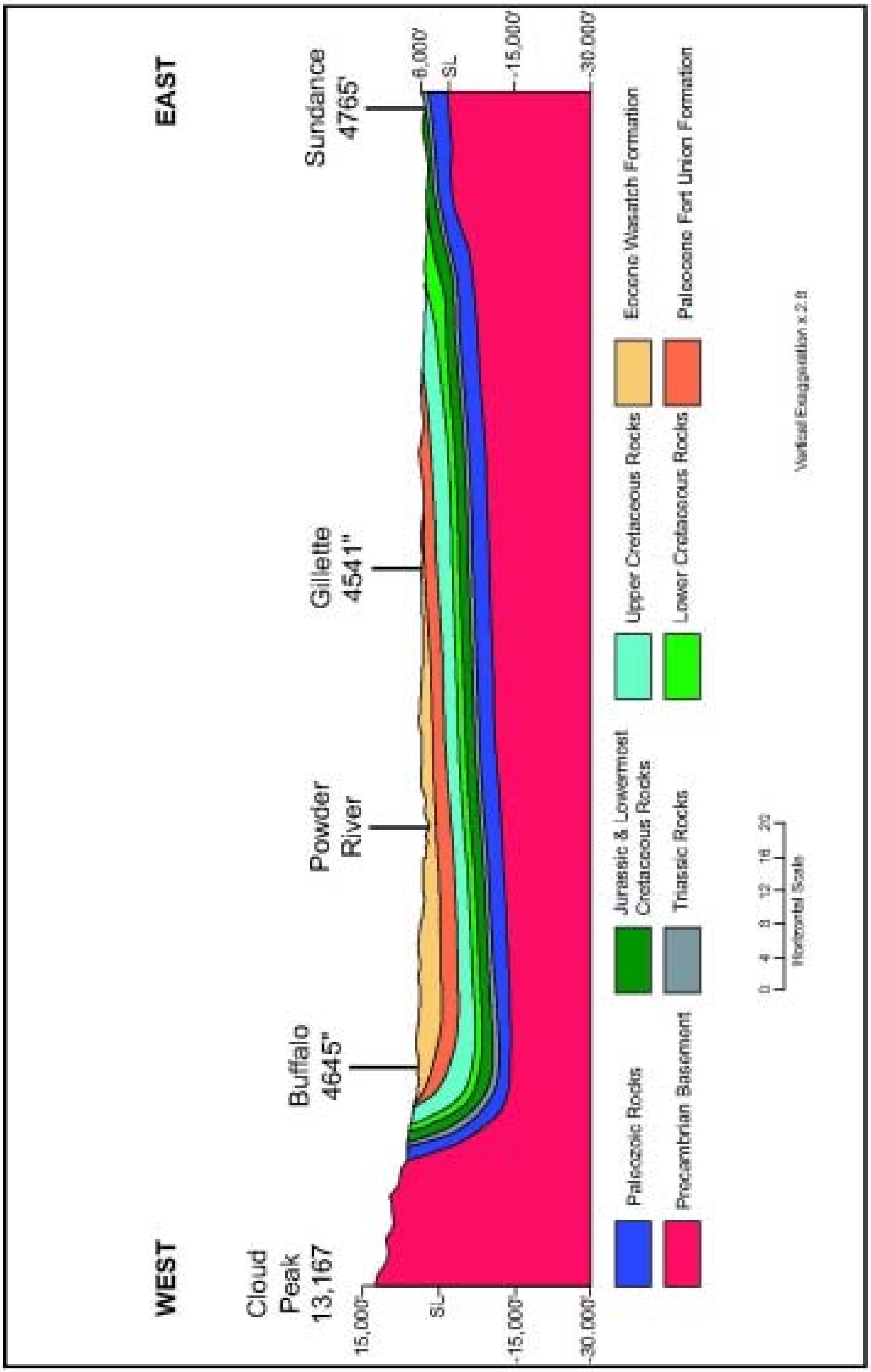
Location of the Powder River Basin of Wyoming and Montana
(Larsen, 1989 and Rice et al, 2000)

Figure A5-1



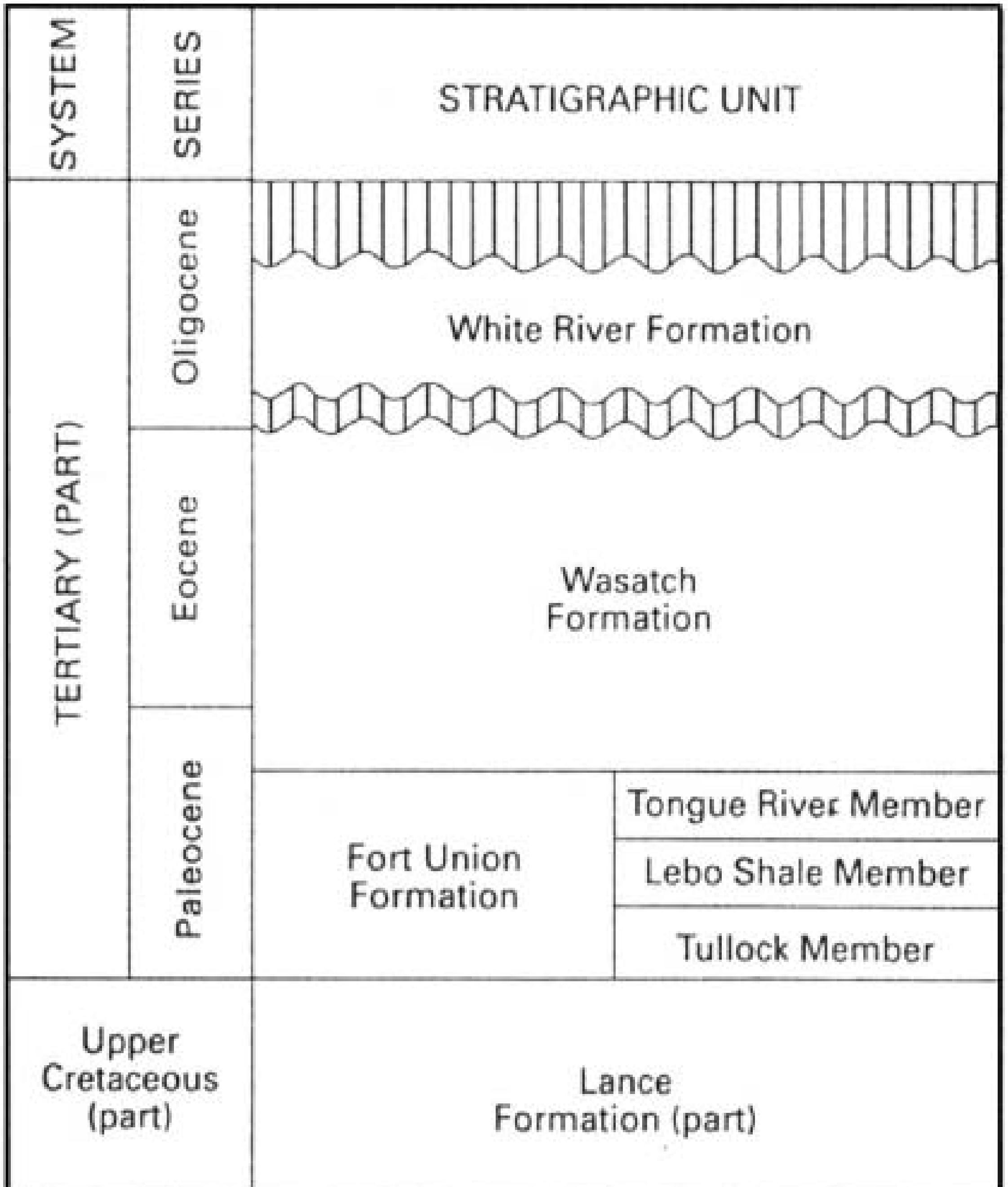
Map of the development of Coalbed Methane in the Powder River Basin
(Montgomery, 1999)

Figure A5-2



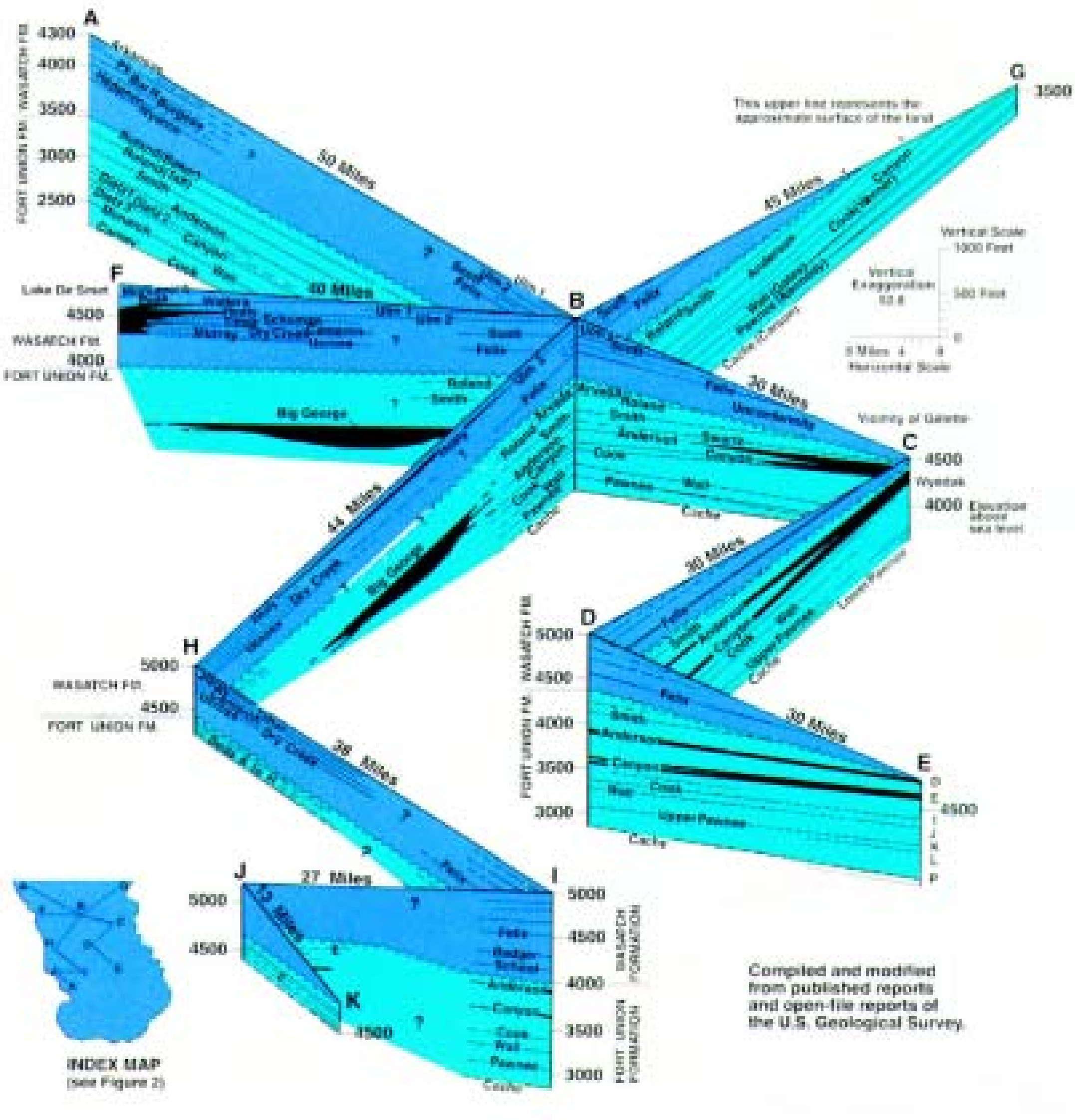
Conceptual Cross Section of the Powder River Basin (West-East) (DeBruin et al., 2000)

Figure A5-3



Stratigraphic Diagram of Geology in the Powder River Basin
(Law et al., 1991)

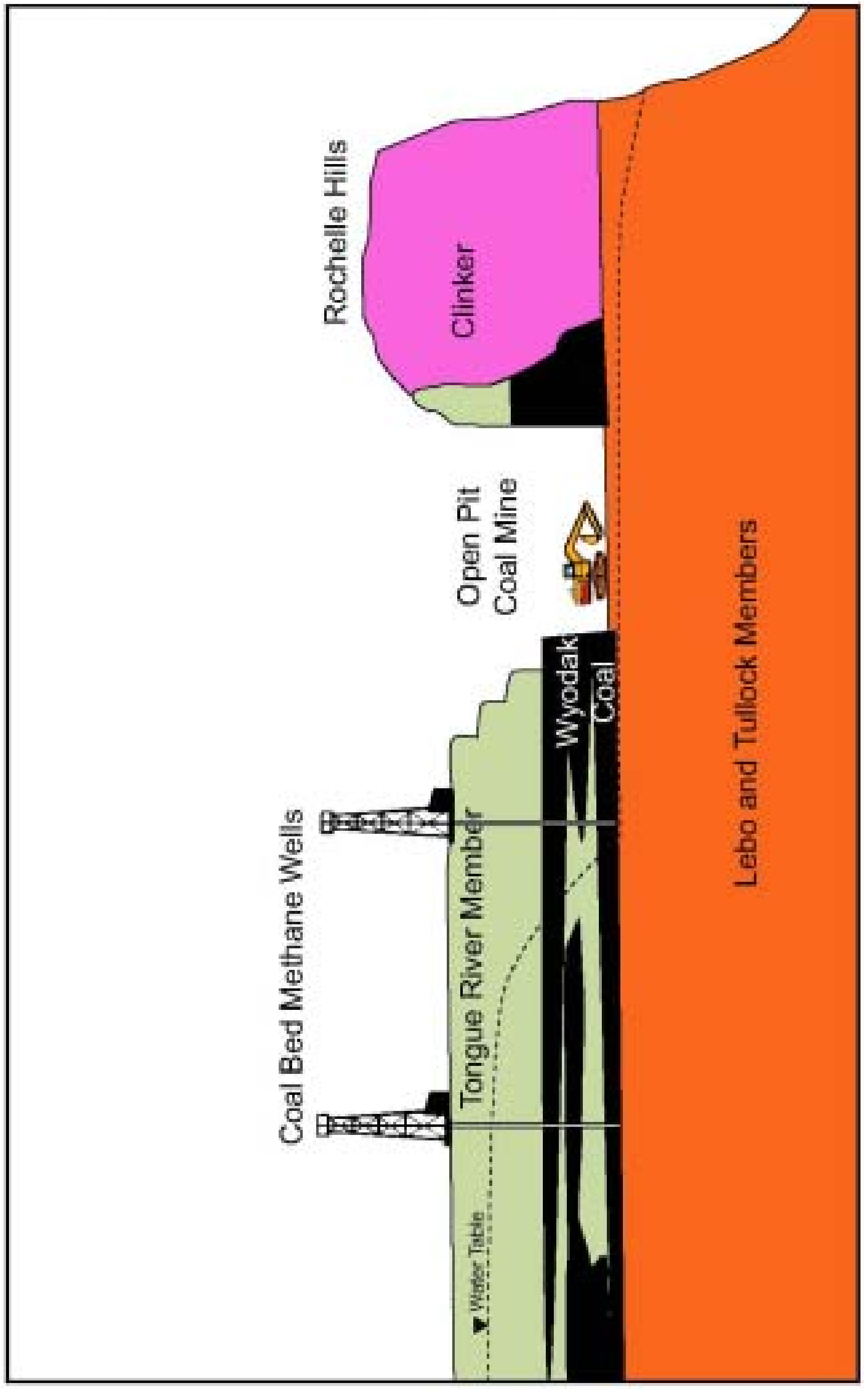
Figure A5-4



Detailed Cross Section of the Wasatch and Fort Union Formations in the Powder River Basin (DeBruin et al., 2000)

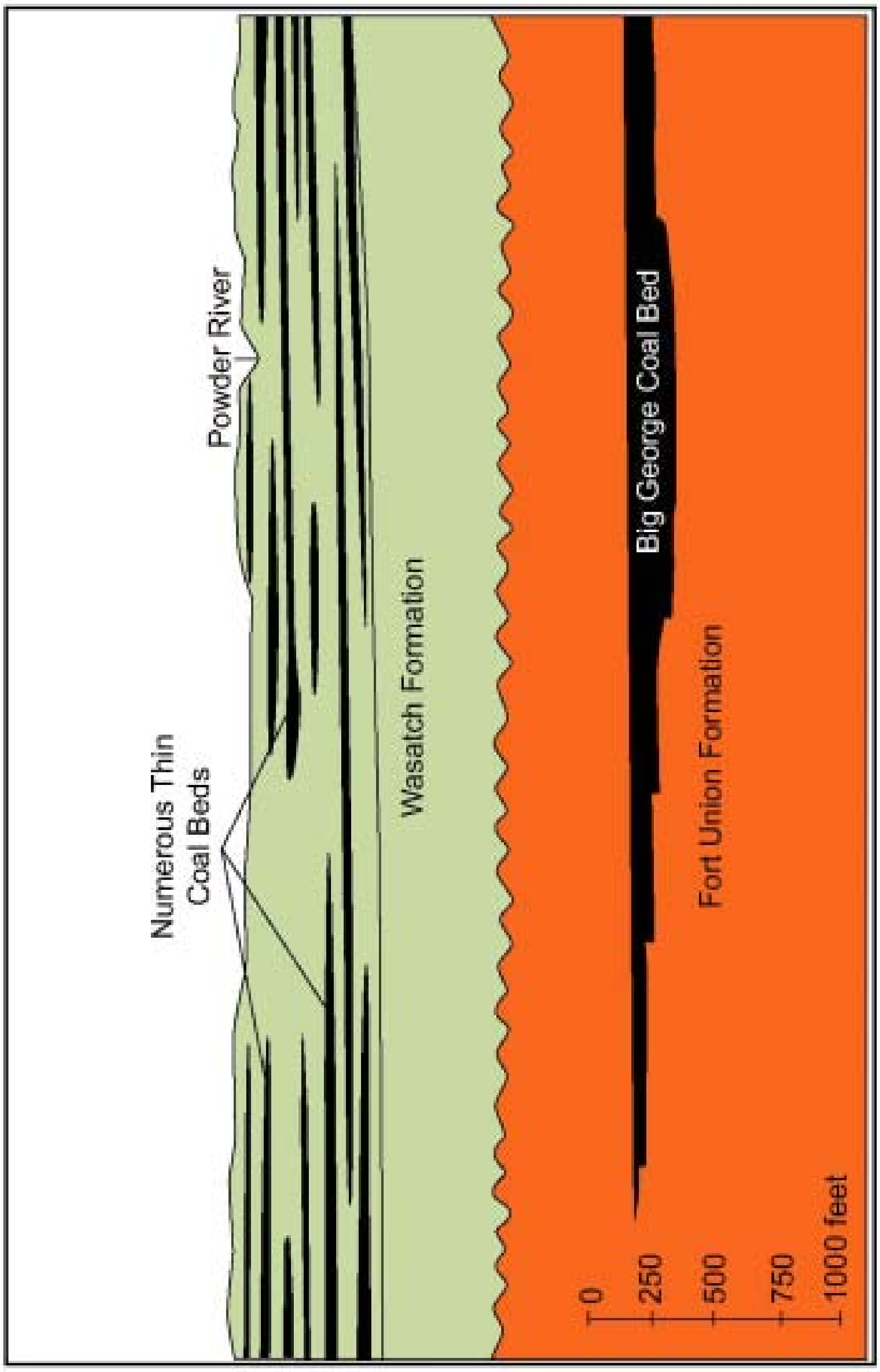
7/14/2001 1027-HF-PR-5

Figure A5-5



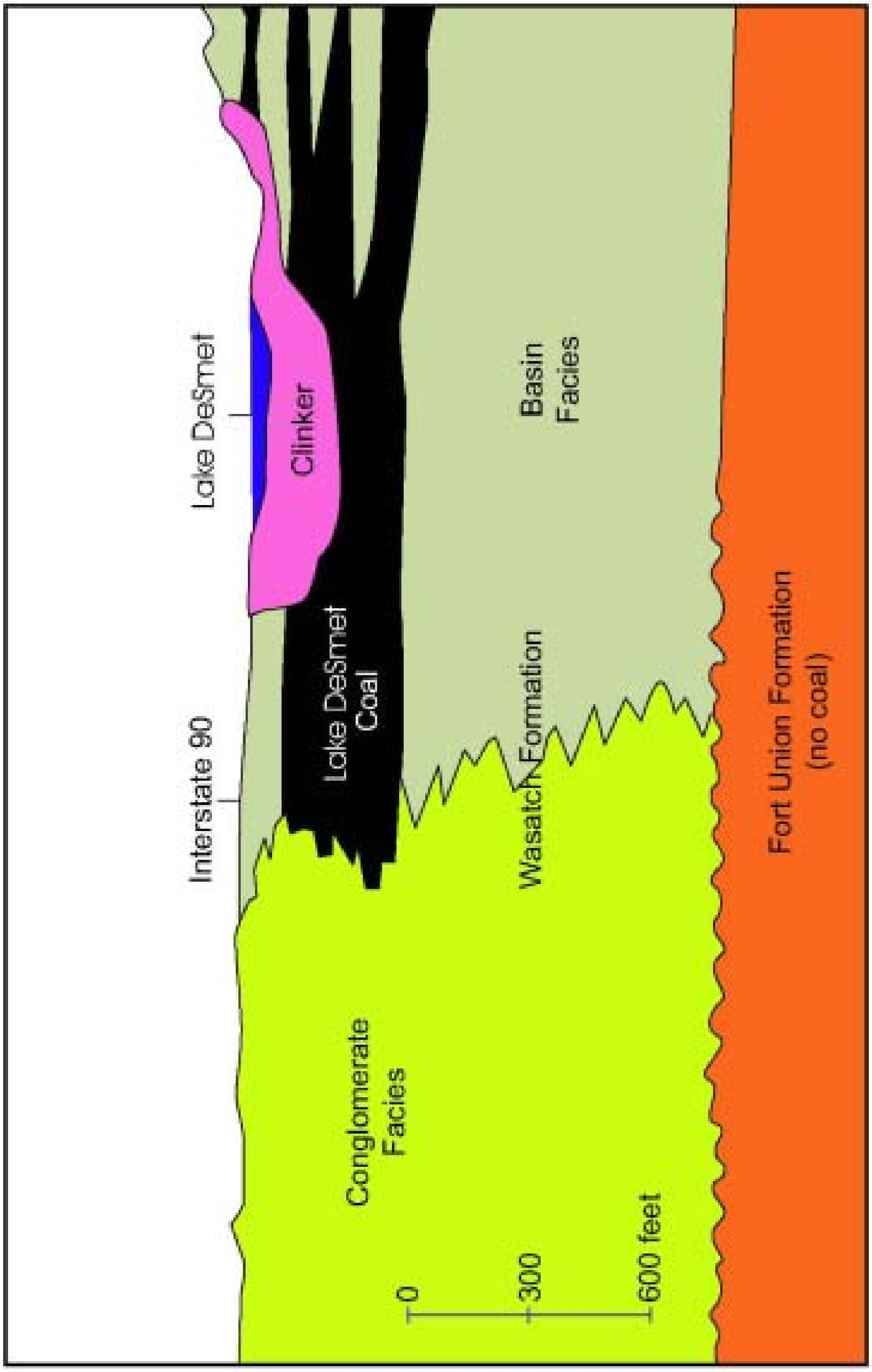
Conceptual Cross Section (West-East) of the Fort Union Formation in the Eastern Powder River Basin Near Gillette, Wyoming (DeBruin et al., 2000)

Figure A5-6



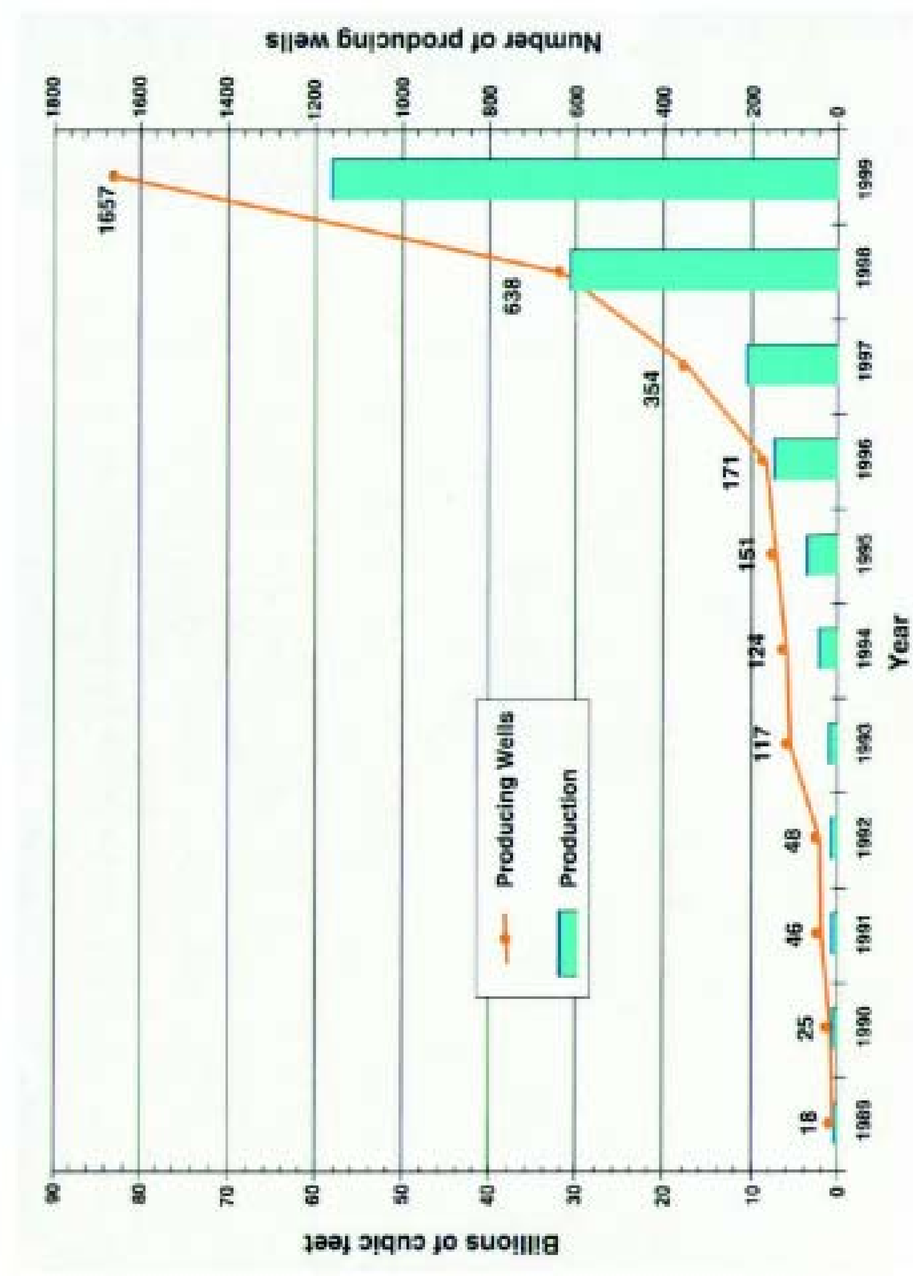
Conceptual Cross Section Near the Center of the Powder River Basin (Debruin et al., 2000)

Figure A5-7



Conceptual Cross Section in the Western Powder River Basin Near Lake DeSmet (DeBruin et al., 2000)

Figure A5-8



Graph of Coalbed Methane Production and Wells in Service in the Powder River Basin, 1989 to 1999
(DeBruin et al., 2000)

Figure A5-9

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