Chapter 2

Coalbed Methane in the Powder River Basin, Wyoming and Montana: An Assessment of the Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System

By Romeo M. Flores

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Chapter 2 *of*

Total Petroleum System and Assessment of Coalbed Gas
in the Powder River Basin Province, Wyoming and Montana

By USGS Powder River Basin Province Assessment Team

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Coalbed Methane in the Powder River Basin, Wyoming and Montana: An Assessment of the Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System

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Introduction

The Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System in the Powder River Basin, Wyoming and Montana (fig. 1), produces coalbed methane that was mainly generated within the coalbeds of the Paleocene Fort Union Formation. The Total Petroleum System covers that part of the Powder River Basin that is overlain by the Upper Cretaceous and Tertiary rocks (fig. 2). The Total Petroleum System reaches a maximum thickness of about 8,940 ft of rocks (fig. 3).

Since 1957, coalbed methane (CBM) was known to occur in flowing artesian wells from coal-bed aquifers in the Fort Union Formation in the Powder River Basin. Northern Campbell County, Wyoming, contained an anomalously large number of these artesian wells, and in 1978 the U.S. Geological Survey (USGS) drilled 15 holes there to measure gas contents from the Anderson and Canyon coalbeds of the Wyodak-Anderson coal zone in the Tongue River Member of the Fort Union Formation (Flores, 1999). This investigation reported gas flow for individual wells of more than 1,000,000 cubic ft per day (MMCF). However, it was not until 1981 that coalbed methane production was reported from two wells in Campbell County, which were completed in the Wyodak-Anderson coal zone. A cumulative total of 46,080 thousand cubic feet (MCF) of gas was produced from these two wells during the 1981–89 period before they were abandoned. In 1989 sandstone gas production was reported from four wells in Campbell County, which produced from fluvial-channel sandstones interbedded with the Wyodak-Anderson coal zone. The pay zones in these sandstone reservoirs range from 372 to 436 ft deep and yielded total cumulative gas of about 416,043 MCF from 1989 to 1992 before they were abandoned. The purpose of this resource assessment is to estimate the potential for additions to gas reserves in the next 30 years from these and related reservoirs in the Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System of the Powder River Basin.

General Geology

The Powder River Basin is in southeast Montana and northeast Wyoming (fig. 1). The basin is an asymmetrical syncline with the deep axis (northwest to southeast orientation) along the westernmost margin. The Upper Cretaceous and Tertiary coal-bearing rocks dip more than 20 degrees along the western margin of the basin and 2–5 degrees along the eastern margin. The basin is flanked by the Bighorn Mountains on the west, the Casper Arch-Laramie Range on the southwest and south, the Hartville Uplift on the southeast, the Black Hills on the east, and the Miles City Arch on the northeast, all formed during the Late Cretaceous to Tertiary Laramide Orogeny.

Barrier shoreface-marine deposits of the Upper Cretaceous Fox Hills Sandstone and Lewis Shale underlie the Upper Cretaceous and Tertiary coal-bearing rocks. A subsiding depocenter formed in the basin, particularly in the southern part, during early Maastrichtian time as indicated by thickening of these barrier shoreface-marine deposits. This structural downwarp probably marked the onset of the Laramide Orogeny in the basin and surrounding areas (Curry, 1971). The barrier shoreface-marine environments were succeeded by terrestrial settings.

The coalbeds of the overlying Upper Cretaceous Lance Formation and Tertiary Fort Union and Wasatch Formations (fig. 3) were deposited in mires associated with fluvial systems that drained coastal and intermontane plains, respectively (figs. 4 and 5). West-to-east flow-through fluvial systems (fig. 4) developed during the Late Cretaceous deposition of the Lance Formation. These depositional systems evolved into intermontane fluvial systems as mountain building related to the Laramide Orogeny reshaped the Powder River Basin depocenter during the Paleocene (fig. 5). Crustal loading and thrust faulting along the western margin of the Powder River Basin promoted accumulation of a thick succession of fluvial sediments in the western part of the basin. Orogeny continued to reshape the landscape of the Powder River Basin by continued downwarping of the basin accompanied by upwarping of the surrounding mountain ranges. The basin developed coal-forming mires between northeast-flowing river systems bounded by these uplifts. Rivers established long-term drainage patterns confined by long-standing domed mires where the thick Fort Union and Wasatch coalbeds accumulated, sustained by an

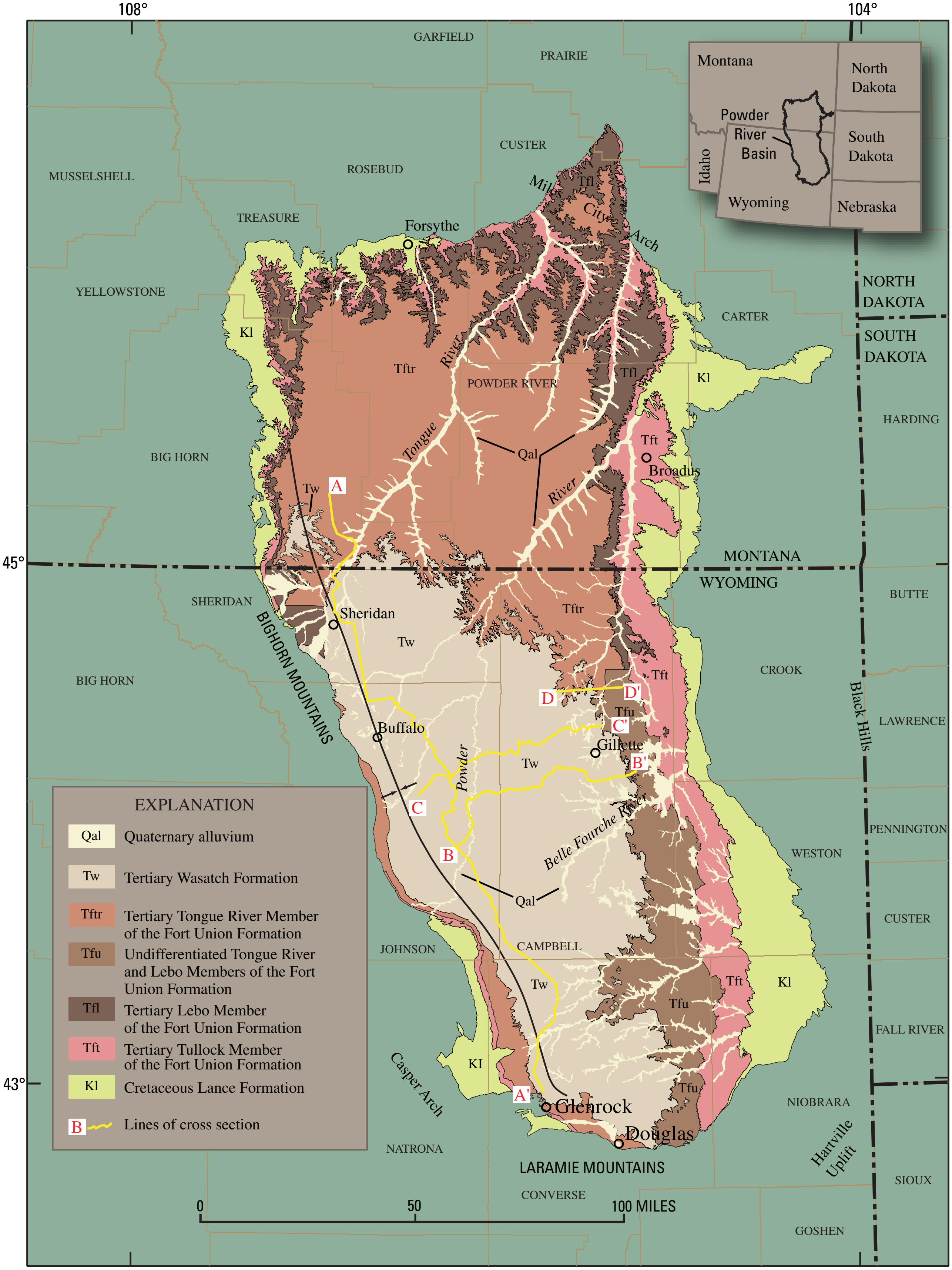


Figure 1. Generalized geologic map of the Powder River Basin in Montana and Wyoming. Cross sections A–A′, B–B′, C–C′, and D–D′ shown in figures 13, 14, 15, and 18.

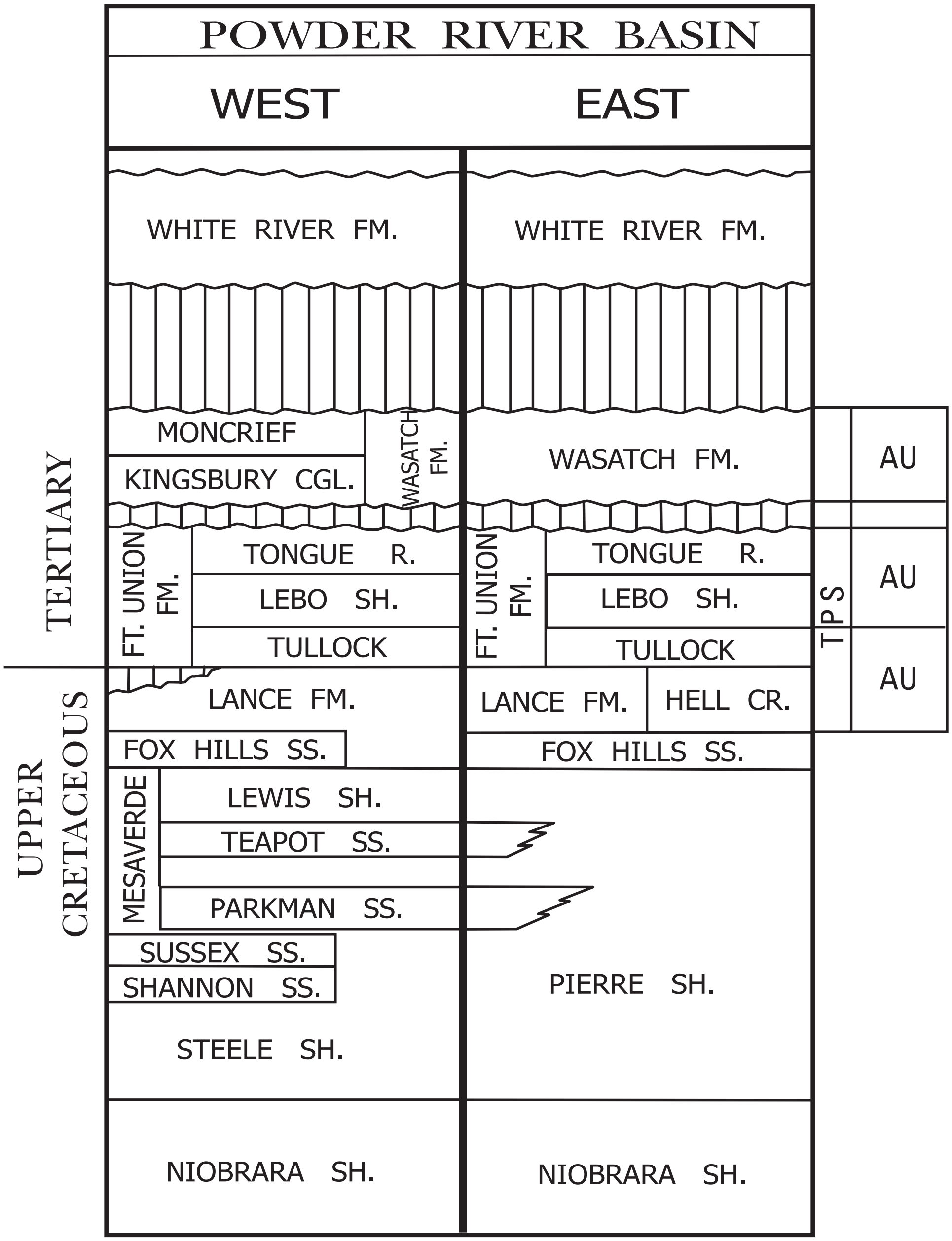


Figure 2. Generalized stratigraphic column of the Upper Cretaceous and Tertiary rock units in the Powder River Basin, Wyoming and Montana, including the Total Petroleum System and assessment units. Modified from Laudon and others (1976).

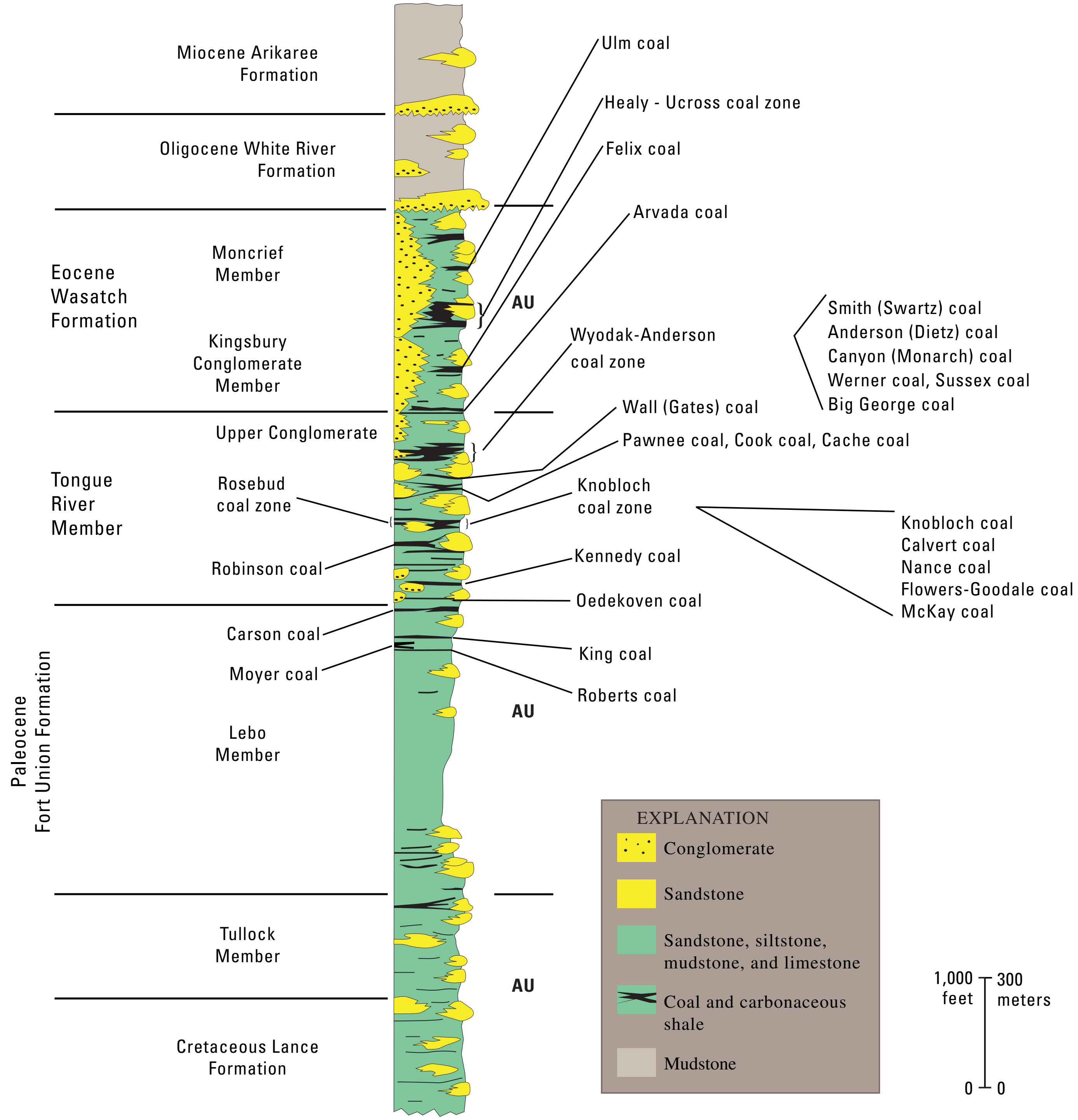
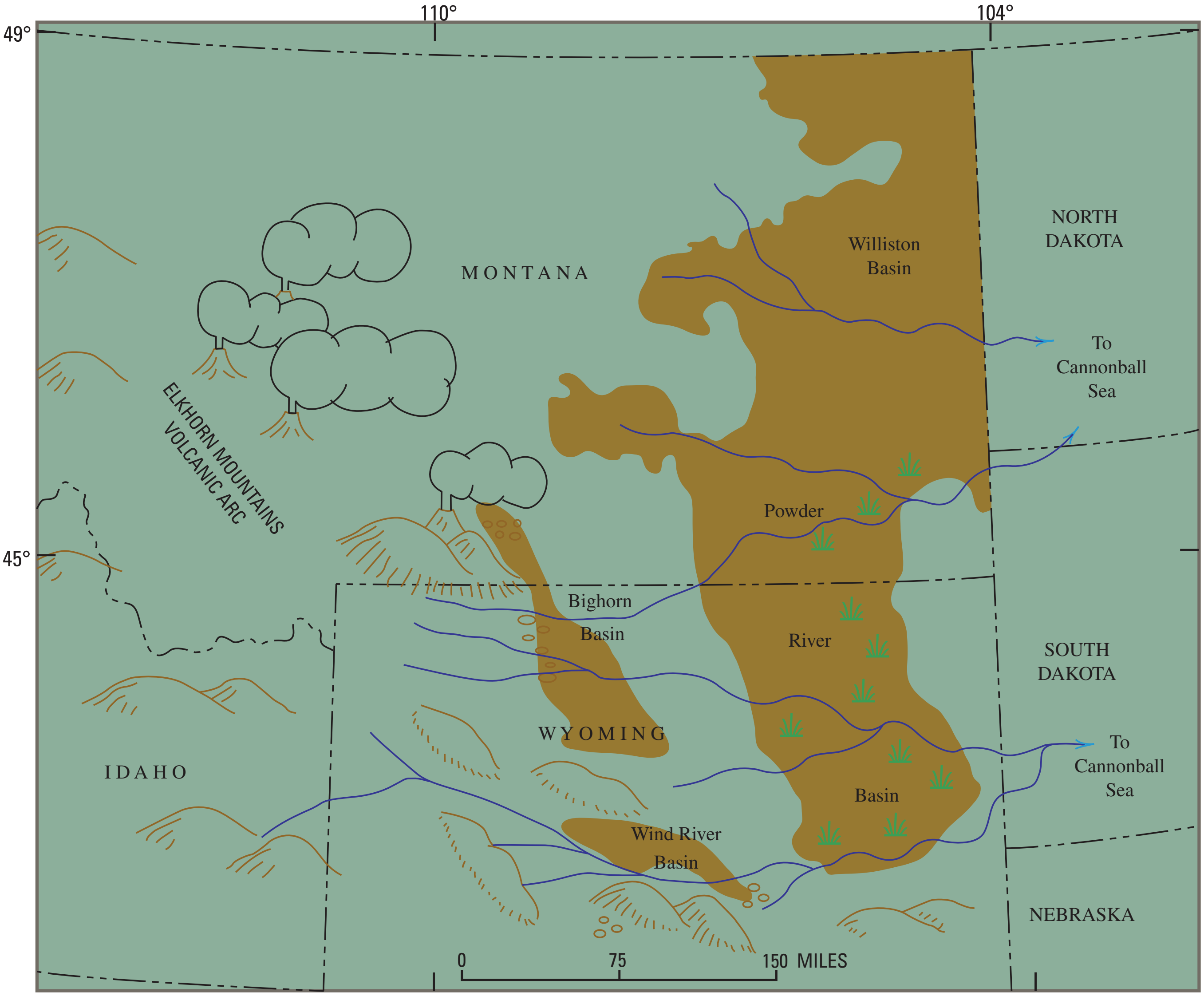


Figure 3. Generalized stratigraphic column showing general lithology, coals, and coal zones of the Upper Cretaceous and Tertiary rocks in the Powder River Basin, Wyoming and Montana. TPS, Total Petroleum System; AU, assessment unit.



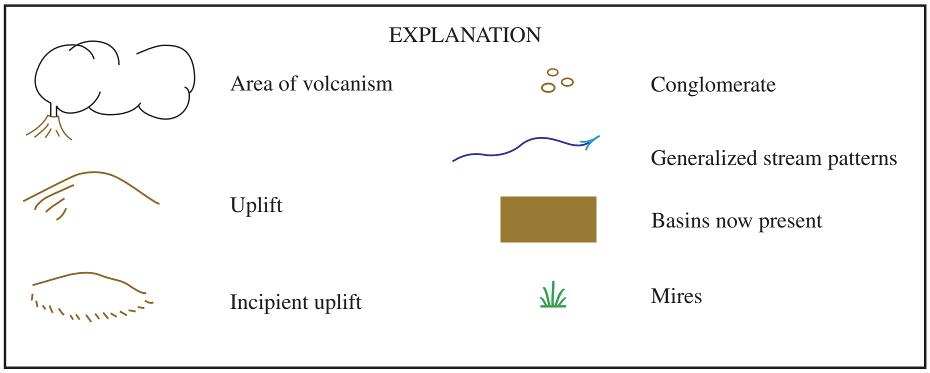


Figure 4. Paleogeography of the Powder River Basin and adjoining areas during deposition of the Upper Cretaceous Lance Formation. Modified from Connor (1991).

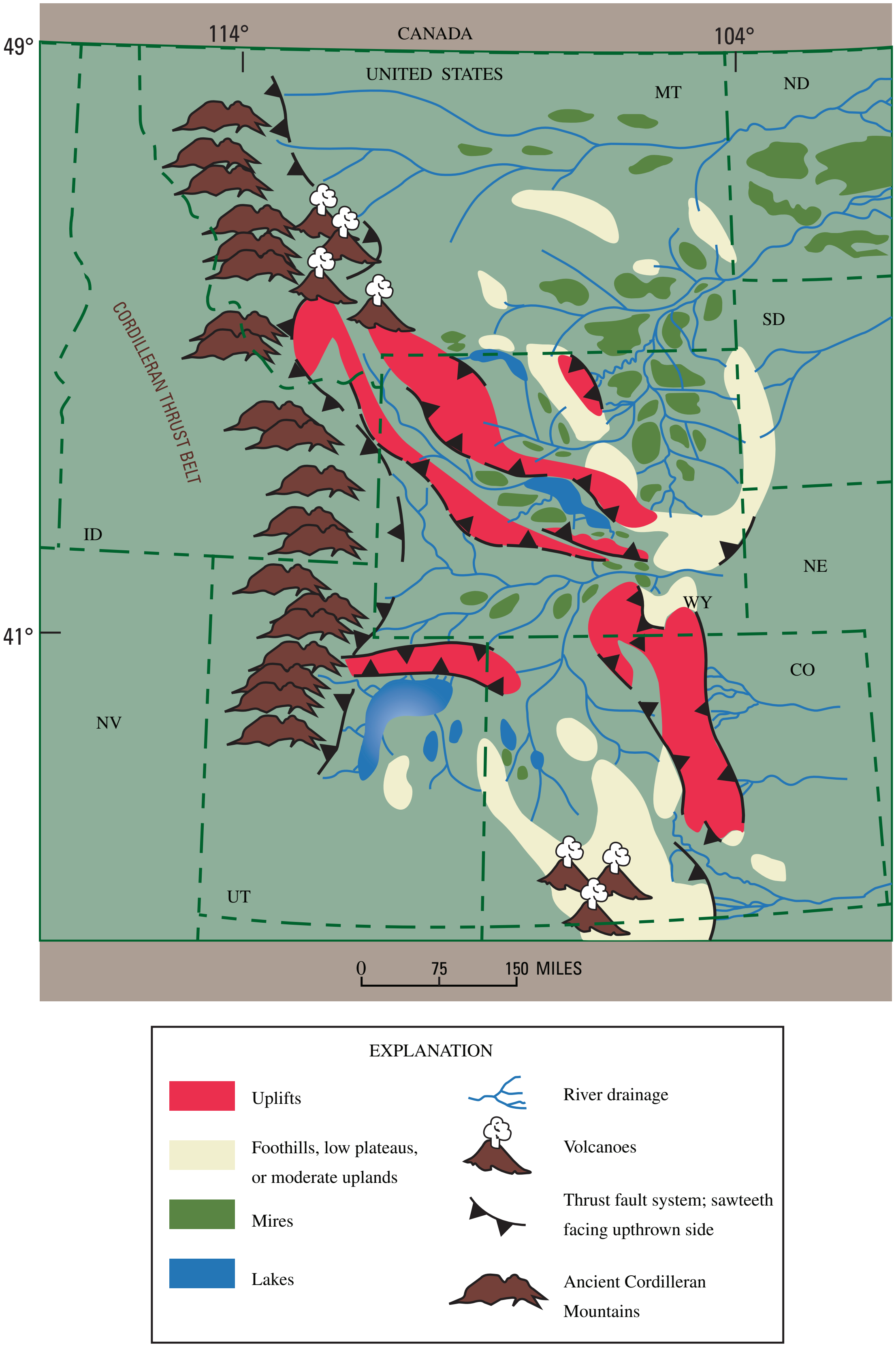


Figure 5. Paleogeography of the Powder River Basin and adjoining areas during deposition of the Paleocene Tongue River Member of the Fort Union Formation.

ever-wet, subtropical climate very similar to modern mires in Borneo (Flores and Moore, 2004).

Intermontane fluvial sedimentation in the Powder River Basin was terminated in the late Eocene time near the end of the Laramide Orogeny. As much as 1,000 ft of Oligocene-age volcaniclastics of the White River Formation unconformably overlie the Wasatch in the basin (fig. 3). The White River Formation, in turn, is overlain unconformably by volcaniclastics of the Miocene Arikaree Formation (fig. 3), which has been estimated by Nuccio (1990) to have once been as much as 1,000 ft thick in the basin. Regional uplift and erosion, which began about 10 Ma ago, removed all of the Arikaree volcaniclastics and most of the White River volcaniclastics and exposed the Eocene, Paleocene, and Cretaceous rocks in the Powder River Basin.

Hydrogeology

Two of the most important factors related to generation and production of CBM from the coalbeds of the Wasatch, Fort Union, and Lance Formations in the Powder River Basin are hydrogeology and coproduced water, respectively. To produce CBM, the coalbeds must be dewatered to the point at which gas is desorbed from internal coal surfaces, diffuses through the matrix and pores, and flows through the network of natural fractures or cleats to the well bore. The water in coalbeds may be either inherent moisture from the peatification and coalification processes or recharge water from outcrops and adjacent aquifers. Inherent moisture is derived from the peat precursor, which contains as much as 90 percent water. During coalification the moisture content decreases with increasing rank. For example lignite (R_o=0.3) contains moisture of about 60 percent (dry and ash-free basis), subbituminous A (R_o=0.6) about 44 percent (dry and ash-free basis), and low volatile bituminous (R_o=1.8) about 16 percent.

Most water in the coalbeds is introduced after coalification. Coalbeds in the Wasatch, Fort Union, and Lance Formations serve as important aquifers. For example, the Wyodak-Anderson coal zone (see fig. 3) of the Fort Union Formation is reported as the most continuous hydrogeologic unit in the Powder River Basin (Bureau of Land Management, 2003). Splitting of a thick coalbed into multiple coalbeds and merging of these beds into one bed or two beds, however, affect the water flow in this coal zone. The water in the Wyodak-Anderson coal zone and related coalbeds flows away from the outcrops and is confined by impermeable underlying and overlying mudstones and carbonaceous shales (Martin and others, 1988). Daddow (1986) reported that recharge of the Wyodak-Anderson coal zone occurs in the outcrops along the eastern margin of the Powder River Basin. Here and along the northern margin of the basin, outcrops of permeable clinkers (orange-colored rocks baked and melted by burning of coalbeds due to spontaneous combustion and lightning strikes; fig. 6) of the Wyodak-Anderson coal and other coalbeds that store water from rainfall and snowmelt are common (Heffern and Coates, 1999). In these areas, clinkers and coalbeds both act as aquifers with vertical recharge occurring from precipitation and lateral recharge from streams. Based on isotope composition, Martin and others (1988) reported that the ground water in the outcrops is meteoric.

Heffern and Coates (1999) indicated that clinker areas cover about 290 mi^2 in the eastern and northern parts of the Powder River Basin where the Tongue River Member of the Fort Union Formation crops out and another 170 mi^2 of Wasatch Formation outcrops. Coates and Heffern (1999) indicated that the coalbeds in the Tongue River Member have burned to form clinkers for the past 4 million years. Thus, the clinkers played a major role in recharge of the ground water, which must have been an important hydrologic process during pre- and post-Pleistocene time along the eastern and northern parts of the Powder River Basin. Recharge of the ground water by rainfall and conduction of large amounts of water downdip from the clinkers to laterally equivalent coalbeds may have varied during glacial and interglacial periods. During these periods of variable ground-water levels, reservoir pressure differences allowed gas to desorb from coalbeds and migrate into adjoining sandstone reservoir rocks. Also, the clinkers provided a frequent influx of oxygenated water allowing renewed bacterial activity in the coalbeds for methane generation. Coalbeds that pinched out before reaching the outcrops did not receive oxygenated water through recharge and failed to generate methane by bacterial activity. Thus, not all coalbeds in the Powder River Basin hold CBM.

In the eastern part of the basin the regional flow of the ground water in the coalbeds is toward the northwest and into the central part of the basin (Daddow, 1986; Martin and others, 1988). In the southeastern part of the basin, regional water flow is to the north; local flow patterns may vary from this overall pattern (Bureau of Land Management, 2003). In the central part of the basin, where the coalbeds are deep, the CBM reservoirs have coproduced as much as 4,800 barrels of water per day from one well. During the 10-year period from January 1990 to January 2000 (fig. 7), the rate of water production has varied from 30 to 480 barrels per day per well (Flores and others, 2001). As of October 30, 2000, the total coproduced water was about 37 million barrels per month at a rate of about 370 barrels per day per well. Coproduced water from Federal leases is less due to fewer producing wells.

In addition to coalbed aquifers, sandstone beds interbedded with mudstone, siltstone, and carbonaceous shale beds serve as aquifers in the Wasatch, Fort Union, and Lance Formations but are not as continuous as the coalbed aquifers. For example, regional ground-water flow in Wasatch sandstone aquifers, which is toward the north, is extremely slow because of the discontinuity of the sandstone beds. The storage capacity of, and water movement in, sandstone aquifers vary with the grain size, texture, internal structures, and cementation of the sandstone. Artesian conditions are common in sandstone aquifers, particularly from deeper, isolated beds away from the outcrops.

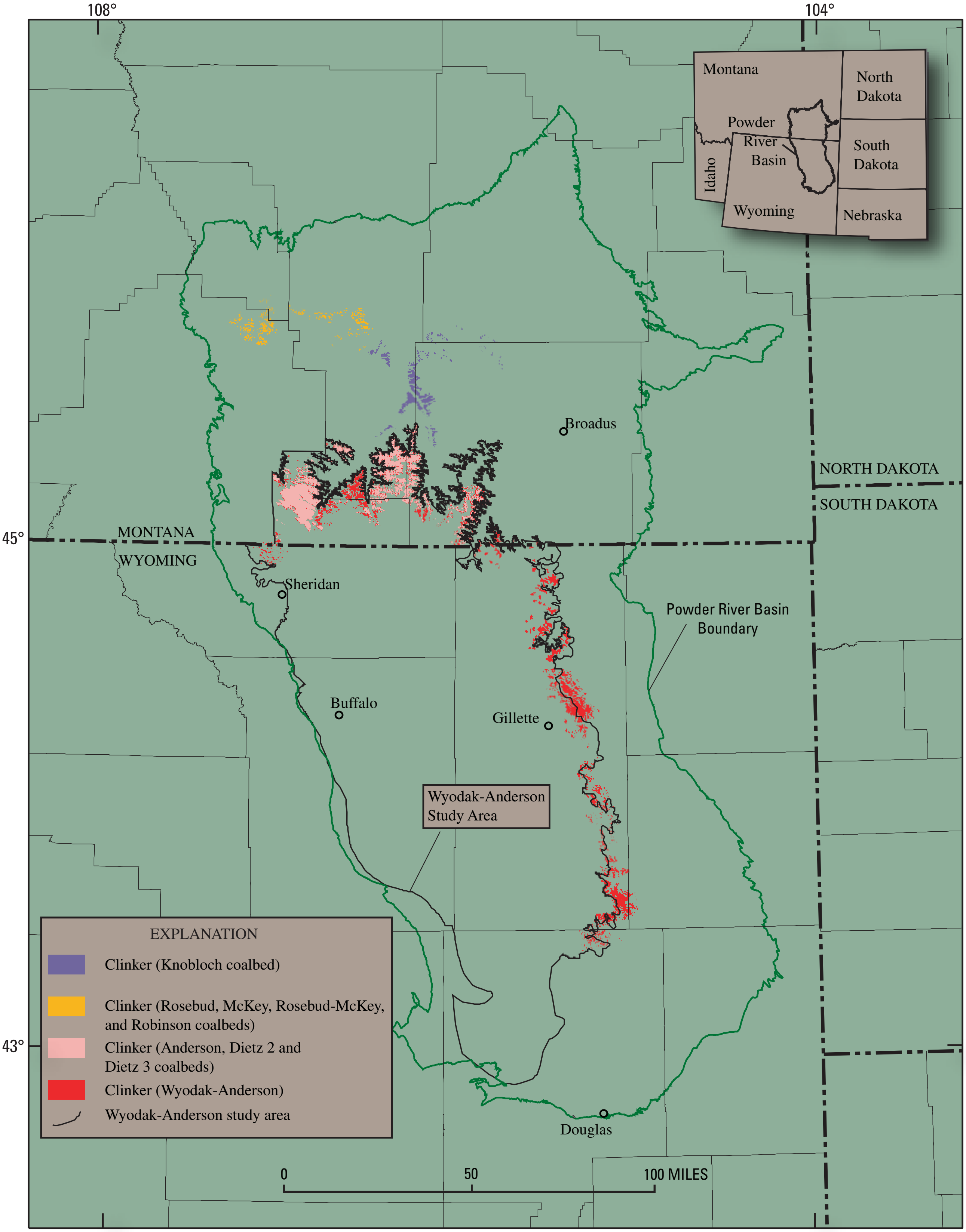


Figure 6. Map showing the areal distribution of the clinkers of coalbeds of the Wyodak-Anderson, Knobloch, and Rosebud-Robinson coal zones in the eastern and northern Powder River Basin in Wyoming and Montana.

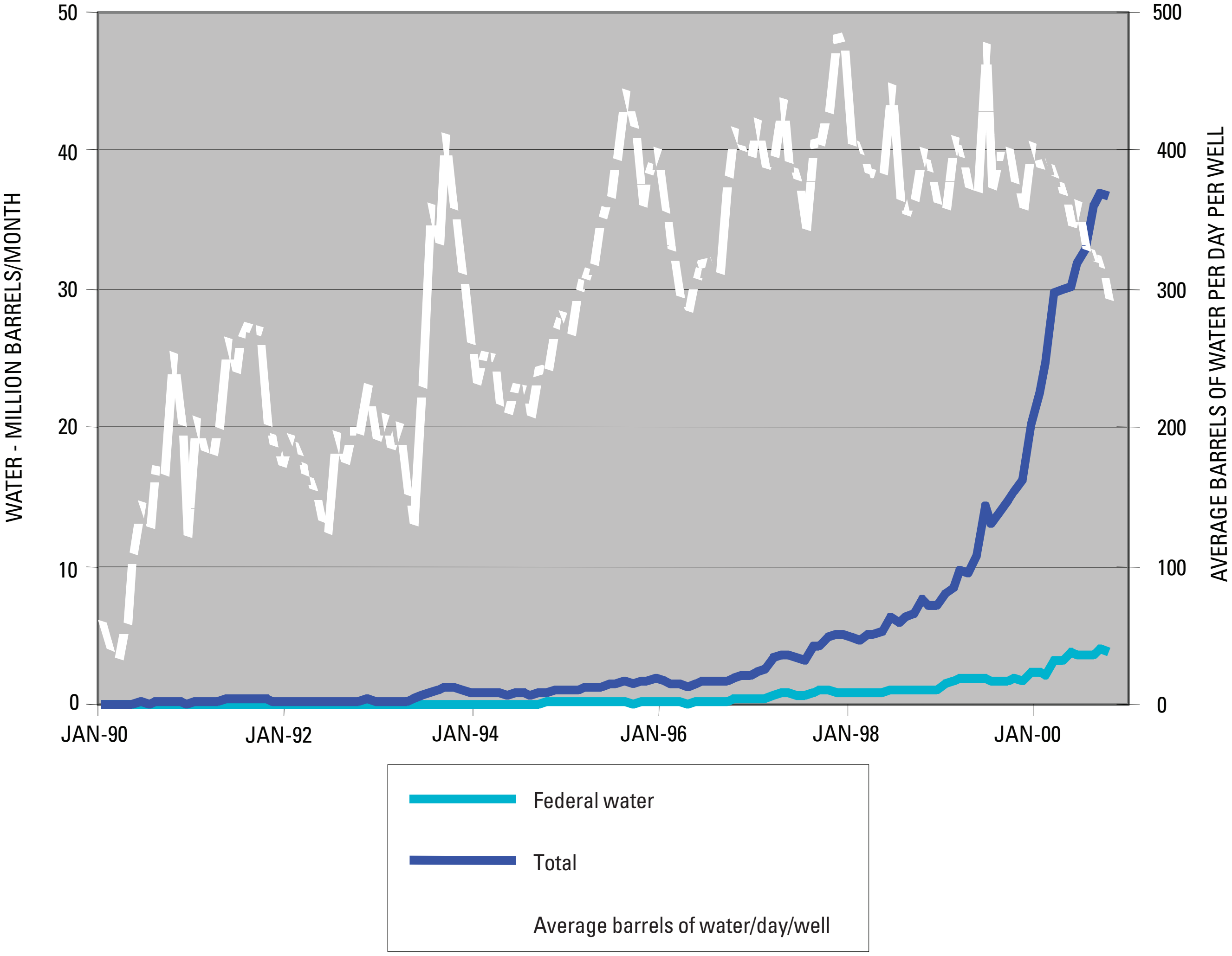


Figure 7. Graph showing the monthly rate of water coproduced from coalbed methane wells from January 1990 to October 2000 in the Powder River Basin, Wyoming. The average number of barrels of water per day per well is also shown. During the 10-year period the rate of water production ranged from an average of 30 to 480 barrels per day per well. Total coproduced water includes that from Federal, State, and private leases. Adopted from Flores and others (2001). Data from Wyoming Oil and Gas Conservation Commission (Wyoming Oil and Gas Conservation Commission, 2002).

In the Powder River Basin, water coproduced with the CBM is fresh and contains mainly sodium and bicarbonate ($Na\text{-}HCO_3$; 290–2,320 mg/L), with total dissolved solids (TDS) between 370 and 1,940 mg/L and trace metals generally less than 1 ppm (Rice and others, 2000, 2002). High sulfate concentrations may be found in the water of the Fort Union Formation in Campbell County (Larson and Daddow, 1984). The TDS in coproduced water from the Wyodak-Anderson coal zone increase toward the central part of the Powder River Basin or from east to west and south to north. The concentrations of TDS are mainly within the national drinking-water standards (Rice and others, 2000). The recommendation for TDS concentrations in national drinking-water standards is a maximum of 500 mg/L for potable water (seawater is about 35,000 mg/L).

Total Petroleum System

The Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System (TPS) (Magoon and Schmoker, 2000) in the Powder River Basin comprises the Upper Cretaceous Lance, Paleocene Fort Union, and Eocene Wasatch Formations (fig. 8). The Lance Formation is as much as 2,695 ft thick, the Fort Union Formation is as much as 5,845 ft thick, and the Wasatch is as much as 1,400 ft thick. The TPS contains abundant thin to thick, subbituminous coalbeds that are presently commercially producing biogenic gas with potential for future CBM discoveries. The coal-bearing intervals of the TPS, particularly the Fort Union Formation, are interbedded with fluvial-channel sandstones that may serve as reservoirs for bacteria-generated gas liberated from adjoining coalbeds (Flores, 1986; Rice and Flores, 1990; Law and others, 1991, Oldham 1997).

The Tertiary-Upper Cretaceous Coalbed Methane TPS consists of four assessment units (AUs) that are discussed in detail in the following sections. Three AUs are continuous gas accumulations and the fourth a conventional gas accumulation. These AUs are based on the thickness and distribution of the coalbeds and the characteristics and distribution of the fluvial-channel sandstones. The first AU is the Wasatch Formation AU (fig. 8) with its associated coalbeds and related CBM. The second AU, the Upper Fort Union Formation AU, is the coal-rich upper part of the Fort Union Formation and consists of the Lebo and Tongue River Members (fig. 8). The third AU, the Lower Fort Union–Lance Formations AU, consists of the lower part of the Fort Union Formation (the Tullock Member) and the Lance Formation (fig. 8) and contains less coal and related CBM than the second AU. The fourth AU, Eastern Basin Margin Upper Fort Union Sandstone AU, is a conventional accumulation consisting of the fluvial-channel sandstones in the upper part of the Fort Union Formation. The coalbeds in the first three AUs serve both as source and reservoir rocks for CBM, whereas in the fourth AU, coalbeds serve as a source for gas that has migrated into the sandstone reservoirs.

Source Rock

The coalbeds of the Tertiary-Upper Cretaceous Coalbed Methane TPS are the source of gas both in the coal and in the sandstones. The coal source rocks vary from a few inches to as much as 250 ft thick. The average thickness of the Wasatch coalbeds is about 25 ft, the upper Fort Union coalbeds about 50 ft, and the lower Fort Union and the Lance coalbeds about 2 ft. The net coal-thickness isopach of the Wasatch coalbeds shows that the thickest coalbeds are in the west-central part of the Powder River Basin, where the net thickness is as much as 200 ft and the beds have an elongate shape in plan view. The overburden above the Wasatch Formation is as much as 1,500 ft in the west-central part of the basin.

The upper Fort Union net coal thickness is best displayed by two isopach maps, the first for the Wyodak-Anderson coal zone (uppermost part of the upper Fort Union) (fig. 9) and the second for undifferentiated coal zones below the Wyodak-Anderson coal zone (lower part of the upper Fort Union (fig. 10). The net coal-thickness isopach map of the Wyodak-Anderson coal zone (fig. 10) shows thickening to as much as 250 ft toward the central part of the basin. Here the overburden is as much as 2,000 ft thick and the isopach map displays ovoid to elongate thick areas. The net coal thickness for coals of the undifferentiated coal zones below the Wyodak-Anderson coal zone is as much as 150 ft in the central part of the basin where the overburden is as much as 3,000 ft.

The coalbeds of the Tertiary-Upper Cretaceous Coalbed Methane TPS are low rank, ranging from lignite to subbituminous. The Wasatch coal ranges from lignite to subbituminous B (7,990–9,200 Btu; as-received basis). The rank of the upper Fort Union coal ranges from lignite to subbituminous B and C with vitrinite reflectance varying from R_o 0.31 to 0.47 percent (Pontolillo and Stanton, 1994). However, Stricker and Flores (2002) reported apparent rank of the Fort Union coals to be subbituminous A, B, and C. The apparent rank of the Fort Union coals is important, especially with methane-undersaturated coalbed reservoirs; coalbed undersaturation varies from 66 percent for subbituminous C coal to 23 percent for subbituminous A coal (Stricker and Flores, 2002). Law and others (1991) reported vitrinite reflectance of 0.28–0.30 percent for the Wyodak-Anderson coal in the mines north of Gillette, Wyoming. In that report, the vitrinite reflectance values probably were suppressed either by weathering from prolonged exposure of the coal in the mine highwall/outcrop or due to lowering of the ground-water table below the coalbed. The coal rank of the lower Fort Union (Tullock Member) and Lance Formations is mainly subbituminous (7,700–9,200 Btu; as-received basis).

The CBM generated by the upper Fort Union coalbeds is biogenic, as indicated by enrichment in the light isotope 12C (methane $\delta^{13}C$ values range from –56.5 to 53.8 permil) (Rice, 1993). The biogenic gas is derived by bacterial reduction of CO2 in which the methanogens, strictly anaerobic bacteria, use available H2 to convert acetate and CO2 to methane as a

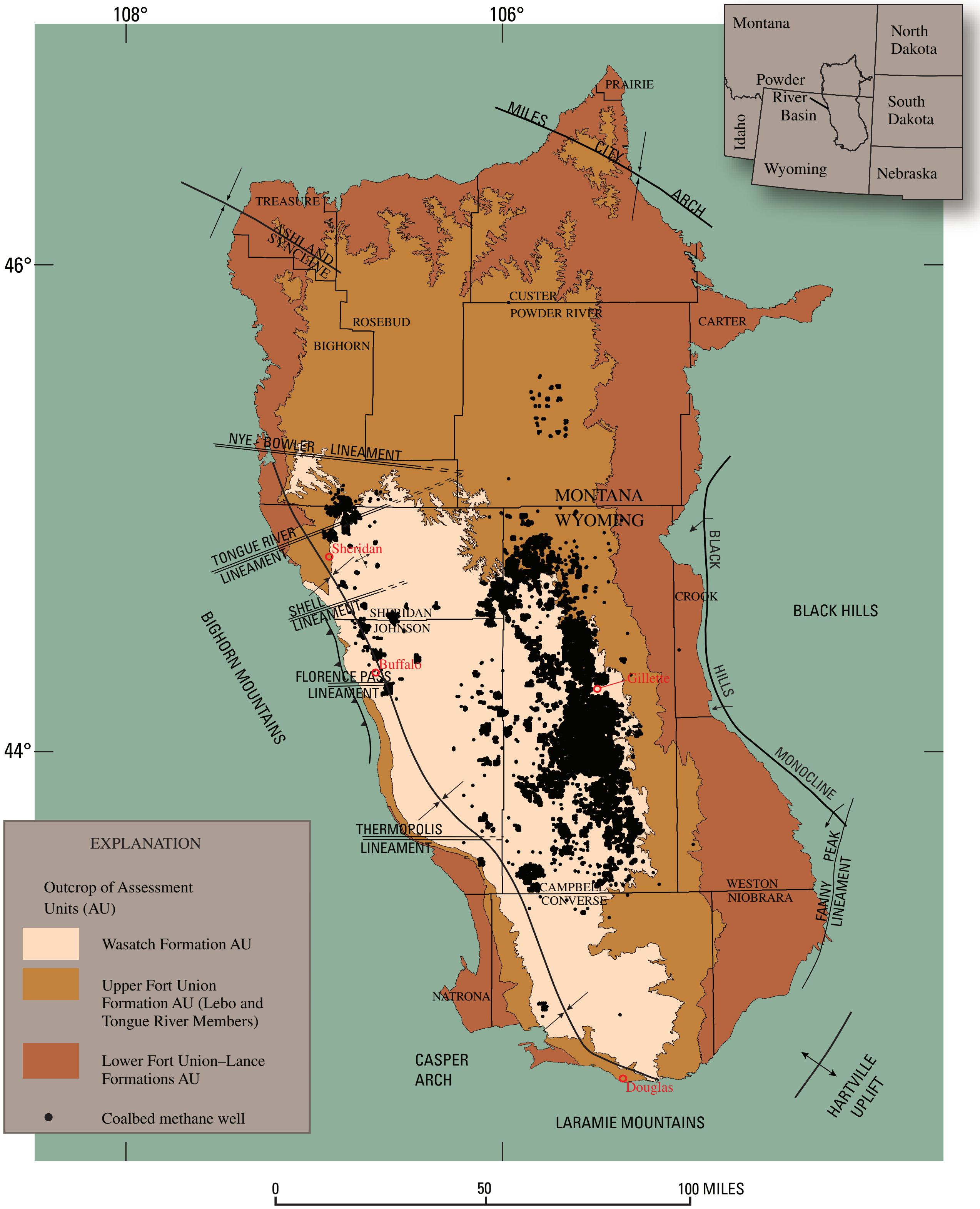


Figure 8. Map showing the assessment units of the Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System, major structural elements, and distribution of coalbed methane wells in the Powder River Basin and adjoining areas in Wyoming and Montana.

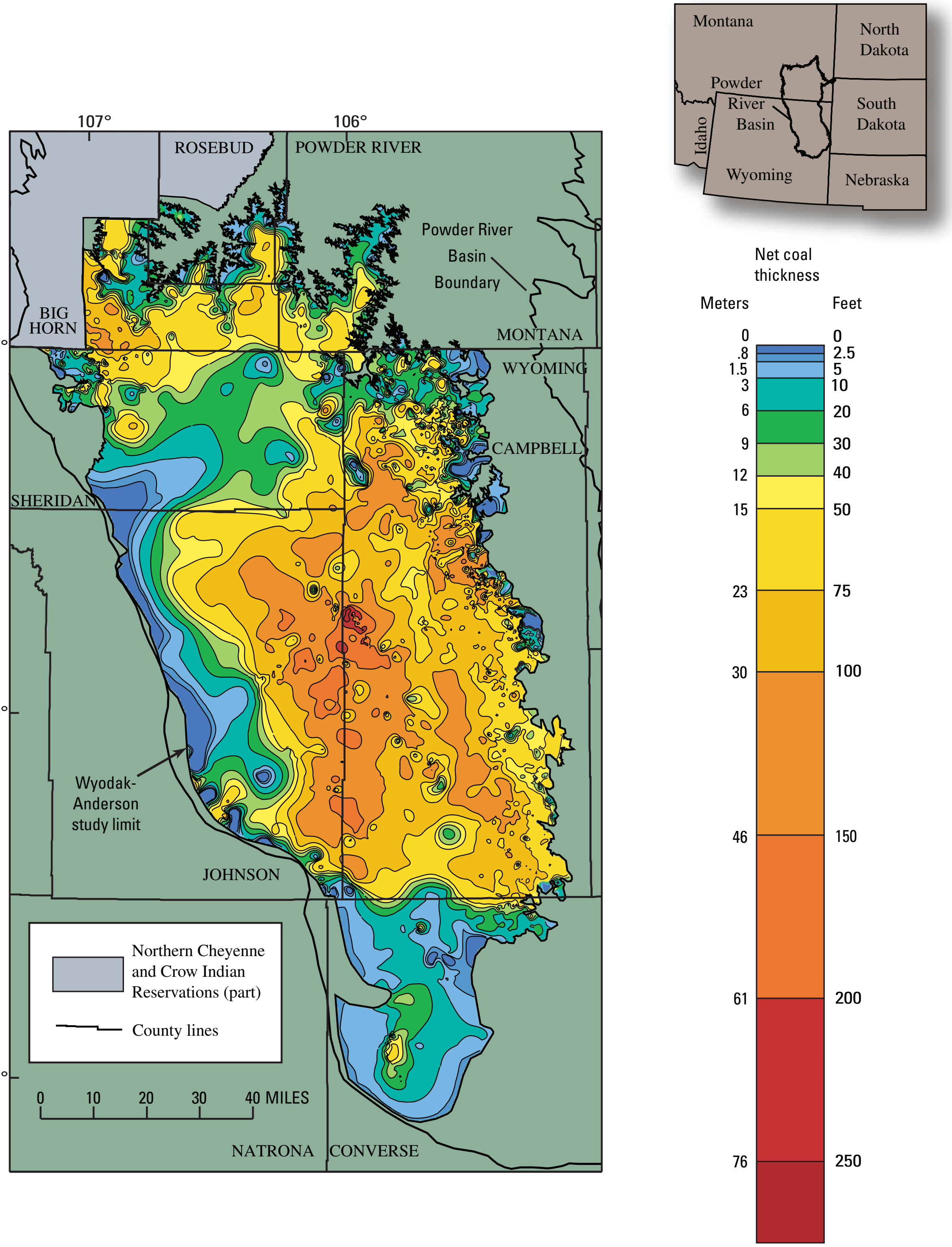


Figure 9. Net coal-thickness map of the Wyodak-Anderson coal zone in the Upper Fort Union Formation Assessment Unit, Powder River Basin, Wyoming and Montana.

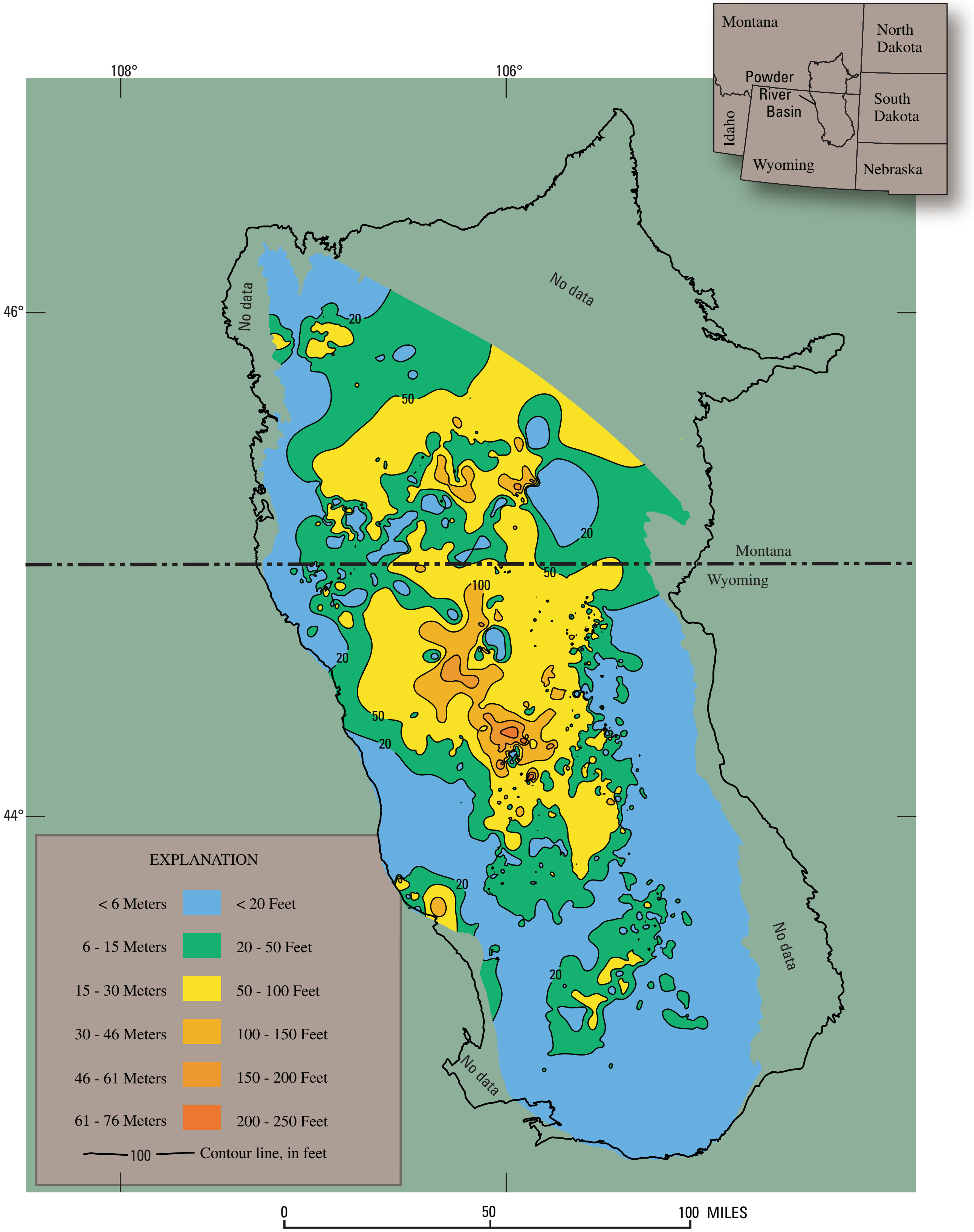


Figure 10. Net coal-thickness map of the coalbeds and zones below the Wyodak-Anderson coal zone in the Upper Fort Union Formation Assessment Unit, Powder River Basin, Wyoming and Montana.

byproduct of their metabolism. However, certain methanogens utilize amines, sulfides, and methanol to produce methane. The chemical composition (air-free basis) of the biogenic gas of the Big George coalbed in the Powder River Basin consists of CH4 of 87 to 94 percent, CO2 of 4 to 12 percent, N2 of 0 percent, and trace amounts (0.005 to 0.97 parts per million) of hydrocarbons (for example, propane, isobutane, butane, isopentane, and pentane) (Boreck and Weaver, 1984). However, recent analysis of gas from various Fort Union coalbeds in the basin by Stricker and others (2001) indicates average chemical composition of CH4 of 73 percent, CO2 of 5 percent, N2 of 22 percent, and a trace of ethane.

Maturation

The lignite to subbituminous rank (6,595 to 9,850 Btu; as-received basis) of the Wasatch and Fort Union coalbeds indicates that these beds are the lowest rank from which commercial gas is produced in the United States. The rank of the Lance coal is also low (subbituminous) and varies from 7,695 to 9,270 Btu (as-received basis; Dorf, 1940). Reconstruction of the burial and thermal history of the Upper Cretaceous Steele Member of the Cody Shale in the Powder River Basin in Wyoming by Nuccio (1990) indicates that as much as 2,000 ft of overburden was eroded over much of the basin during the past 10 Ma. Thus, the Fort Union and Wasatch coalbeds have never been buried deeper than 4,500 ft. However, various depths of burial of the coalbeds may be indicated by the different ranks of the Wyodak-Anderson coal mined in the eastern part of the basin. Here the Wyodak-Anderson coal mined north of Gillette averages less than 8,400 Btu (as-received basis), between Gillette and Wright 8,600 Btu (as-received basis), and southeast of Wright more than 8,800 Btu (as-received basis). Furthermore, investigation of the gas content of Fort Union coalbeds indicates a direct relationship of apparent coal rank and desorbed gas with depth (Stricker and Flores, 2002). Subbituminous C coal (8,300–9,500 moist, mineral-matter-free Btu basis) is distributed at depths from 150 to 1,100 ft; subbituminous B coal (9,500–10,500 moist, mineral-matter-free Btu basis) is distributed at depths from 200 to 1,800 ft; and subbituminous A coal (10,500–11,500 moist, mineral-matter-free Btu basis) is distributed at depths from 1,100 to 1,500 ft.

Nuccio (1990) reported that vitrinite reflectance of the Steele Member of the Cody Shale varies from R_o 0.49 to 0.66 percent. Nuccio noted that vitrinite reflectance does not increase systematically with depth, as indicated by one sample showing R_o of 0.61 percent at a depth of 8,606 ft and another sample with R_o of 0.56 percent at a depth of 11,750 ft. The area of vitrinite reflectance values greater than R_o 0.60 percent is located along the axis and west-central part of the Powder River Basin (fig. 11). The burial and thermal histories of the Wasatch Formation, Upper Fort Union Formation, and Lower Fort Union–Lance Formations AUs in the Powder River Basin are shown in figure 12. Isotherms suggest that during the burial history of these AUs the coal was exposed to maximum temperatures of only 20 to 100 degrees C. These low temperatures substantiate the low rank and low vitrinite reflectance values of the coalbeds in the AUs.

Pontolillo and Stanton (1994) found that vitrinite reflectance of the Fort Union coals (for example, Anderson-Wyodak and Rosebud-Robinson coal zones) increased from R_o 0.31 to 0.49 percent to the northwest part of the basin. However, recent vitrinite reflectance data provided by R.W. Stanton (oral commun., 2000) as shown in figure 11 shows R_o increasing from 0.31 percent in the central part of the basin in Wyoming to R_o 0.47 percent in the northwest margin in Montana. In addition, these new data show areas with R_o more than 0.40 percent in the northwest (Montana) and southeast (Wyoming) parts of the basin. Pontolillo and Stanton (1994) interpreted their pattern of increasing vitrinite reflectance to the northwest to be a function of depth of burial rather than a function of emplacement of the Laramide deformational front of thrust faulting and crustal loading along the western margin of the basin (Perry and Flores, 1997). However, Flores (2003) suggests that the high vitrinite reflectances (R_o) in Tertiary coal basins in the northern Rocky Mountains and Great Plains region are related to the southwest-to-northeast migration of the Laramide deformation fronts. Within each basin this deformation led to (1) successive partitioning, (2) variable subsidence or downwarping, (3) unequal burial depths, (4) differential compaction and sediment loading, (5) diverse time of maximum thrust-fault-related subsidence, and (6) different amounts of folding.

Maturation studies by Nuccio (1990) and Pontolillo and Stanton (1994) in the Powder River Basin indicated that vitrinite reflectance in the Upper Cretaceous Steele Shale Member attains a maximum of R_o 0.66 percent and the overlying Tertiary Fort Union coal attains a maximum of R_o 0.49 percent. Although the Steele Shale Member was buried deeper than the Fort Union Formation, the vitrinite reflectance values do not increase much in maturation with depth. The most significant observation of these studies is that the area of greatest vitrinite reflectance values is in the west-northwest part of the basin in Bighorn County, Montana, juxtaposed to the Bighorn Mountains (figs. 8 and 11). This observation indicates that maturation may be related to tectonic deformation of the basin influenced by thrust-faulting and crustal loading of the Bighorn uplift on the western margin of the basin. In addition, the highest vitrinite values for the Fort Union coalbeds in the northwest part of the Powder River Basin (R_o 0.41 to 0.47 percent) may have been influenced by the intersecting Nye-Bowler and Tongue River lineaments (fig. 8). This area of lineament intersection may have served as a “hot spot” of increased pressure and temperature. The area of high vitrinite reflectance values (R_o 0.31 to 0.49 percent) in the southeast part of the basin may be due either to depth of burial and/or tectonism along the southwestern extent of the Fanny Peak lineament and Black Hills monocline (fig. 8).

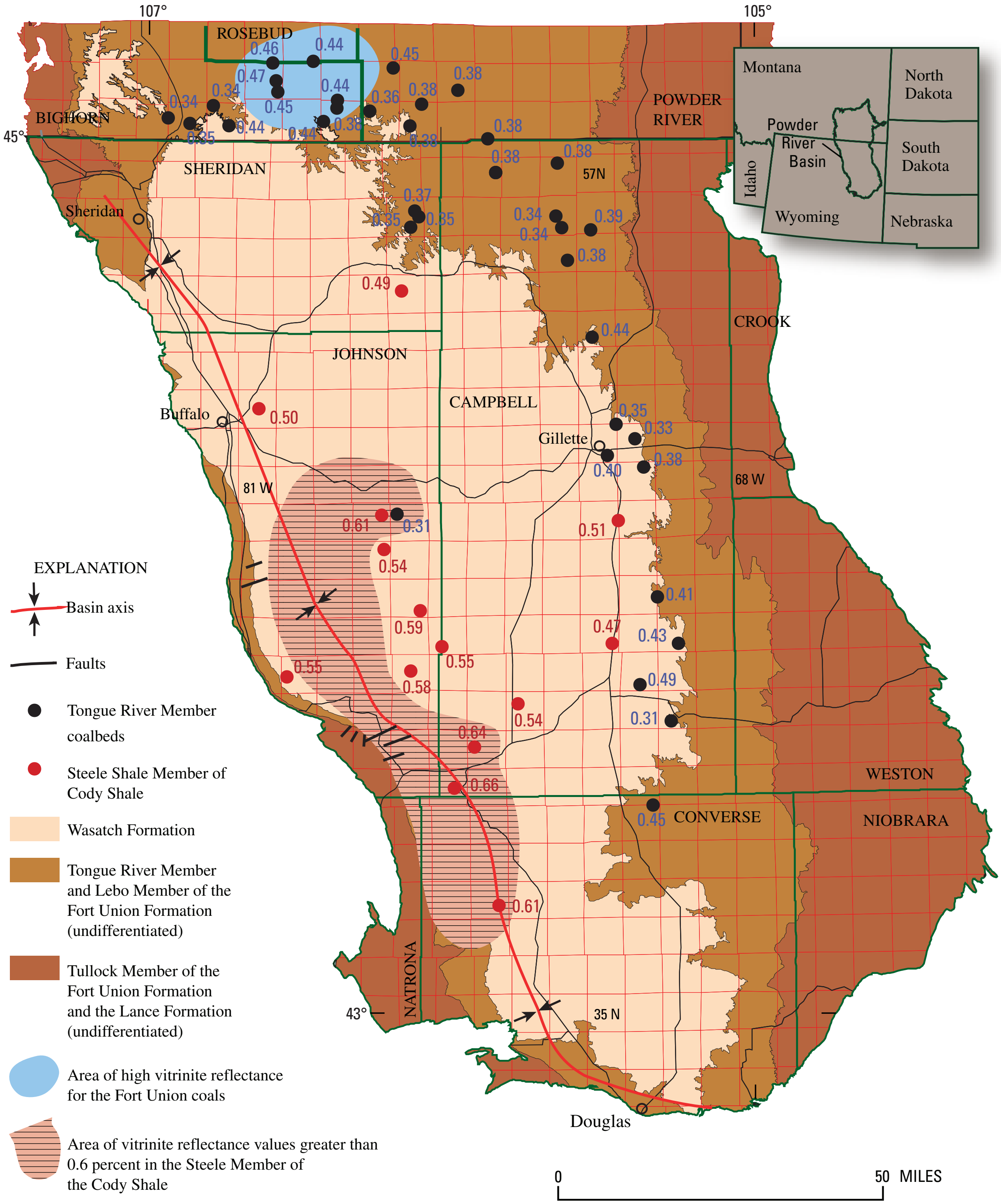


Figure 11. Map showing vitrinite reflectance values from the Upper Cretaceous Steele Shale Member of the Cody Shale and Paleocene Fort Union Formation. The vitrinite reflectance data for the Fort Union coal is from Ronald Stanton (oral commun., 2000). The vitrinite reflectance data for the Steele Shale Member are from Nuccio (1990). Modified from Nuccio (1990).

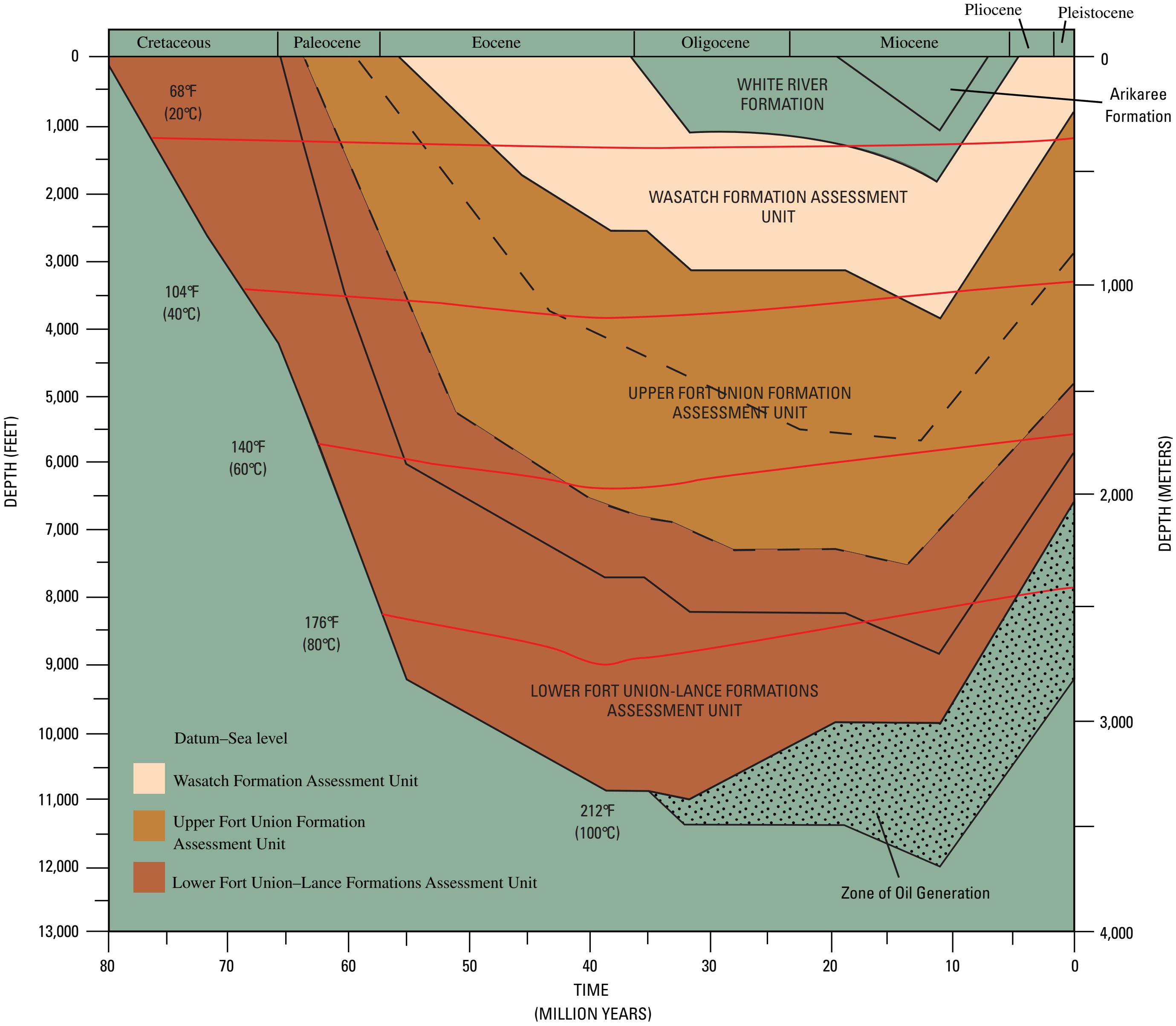


Figure 12. Thermal and burial history model of the assessment units in the Powder River Basin. Modified from Nuccio (1990).

Migration Summary

Rice (1993) speculated that the early-formed gas probably was degassed from low-rank coal following regional uplift and erosion about 10 Ma ago. This uplift and erosion led to the establishment of the aquifer systems in the coalbeds, some of which have produced as much as 4,800 barrels of water per day. Ground-water flow, in turn, led to renewed bacterial activity resulting in the generation of late-stage biogenic gas (Rice 1993; Gorody, 1999).

Methane in the coalbeds and adjacent sandstones is isotopically identical (Gorody, 1999) indicating that the coalbeds are the source for the gas. The methane formed largely by CO_2 reduction and is in equilibrium with CO_2 present in the coalbeds today (Rice 1993; Gorody, 1999), implying a close relationship between the methane and the aquifer water. Gorody (1999) indicates that during maximum burial, which occurred between 10 and 30 Ma ago, the maximum temperature in the coals was between 40° and 90°C, which would have been within the range ideal for bacterial methane generation. These studies strongly suggest that the methane was largely generated after the present-day ground-water systems were established.

Given this premise of methane generation in the Powder River Basin, I hypothesize that migration pathways of the biogenic gas during the Pleistocene may have been significant along the shallow margins of the basin, particularly along the eastern and northern margins. Here, with the lowering of ground-water levels during Pleistocene glacial times, the biogenic gas was released from coalbed source rocks into adjoining, updip, fluvial-channel sandstones. Lowering of the ground-water levels, especially during glacial times, was a mechanism to dewater the coalbeds, which resulted in decreasing the reservoir pressure and in turn releasing CBM into sandstone reservoirs (Upper Fort Union Formation AU). A corollary of this process is the regeneration of biogenic gas during interglacial times when either the ground-water levels rose or the coalbeds were flushed with surface water, thus indicating that CBM is a renewable resource. Gorody (1999) suggested a close spatial relationship between aquifer water and the source of methane; he further suggested, on the basis of deuterium data, that a significant amount of methane might have been generated during the Pleistocene. If this relationship existed, methane regeneration may have occurred during Pleistocene interglacial times after repeated emplacements of regional artesian ground-water systems enhanced by recharge along the basin margins.

Reservoir Rocks

The coalbeds serve as both source and reservoir rocks. That is, the CBM is produced in situ and is adsorbed along surfaces in the fractures (cleats), mesopores, and micropores. These surfaces attract gas molecules, which pack closely together in the process called sorption. Gas is stored in the natural fracture and pore systems in the coal until dewatering changes the pressure in the reservoir, at which point the gas is desorbed. Desorbed gas then diffuses through the coal matrix and finally flows through fracture systems into well bores (Kuuskraa and Brandenberg, 1989). Coalbed methane can also migrate vertically and laterally into adjoining rocks such as sandstones. Migration from the coalbed source rock to the sandstone reservoirs can occur along faults and fractures and through direct contact when the sandstone adjoins the coalbed. Thus, sandstones serve as a conventional reservoir rock for CBM that has migrated from the coal source rocks.

Coalbed Reservoirs

Coalbeds laterally merge, split, and pinch out as shown in figures 13, 14, and 15. Individual coalbeds vary from lenticular to elongate in shape, from a few inches to 250 ft thick, and from several hundred feet to several tens of miles in lateral extent. A single thick coalbed reservoir can split into as many as 11 beds. Thus, the reservoirs are interconnected in zigzagging and en echelon or offset patterns.

Internally coalbed reservoirs are heterogeneous and comprise seven major lithologic types: (1) hard, woody textured, (2) woody textured, (3) finely laminated, (4) coarsely laminated, (5) very coarsely laminated, (6) attritus-rich, and (7) clay or impure coal (Stanton and others, 2001). Lamellae can consist of (a) stem and predominantly root tissues that are well preserved, (b) attritus which to the unaided eye appears as granular coal, and (c) less commonly, fusain or charred wood resulting from forest fires in the peat. The major differentiation between types (a) through (c) is the thickness of the woody lamellae or vitrain. In cases where vitrain is not separated by layers of attritus, these sections are described as woody textured. Two types of woody-textured layers have been observed—soft and hard— possibly the result of differing types of plants or different plant parts.

The coalbed reservoir has two sets of natural fracture systems developed perpendicular to each other and perpendicular to bedding surfaces. The fracture systems consist of the through-going face cleat or primary fracture that formed first and a butt cleat or secondary fracture that formed second (see, for example Laubach and others, 1998). The cleats are cross cutting, planar, and curvilinear in plan view and as much as 0.79 inch of aperture size (Gamson and others, 1993). Cleat spacing, which increases with coal rank, is in the order of a few inches (Ammosov and Erimen, 1963). The cleat network, particularly in the face cleats, serves as a significant pathway for gas. Cleats are the major contributor to permeability and porosity of the coalbed reservoir, with pores accounting for a minor part (fig. 16). Cleat (fracture) permeability based on interference tests ranges from 1.5 darcies to 325 millidarcies. Coal matrix permeability based on effective-stress tests of vertical and horizontal core specimens (2.05 inches in diameter)

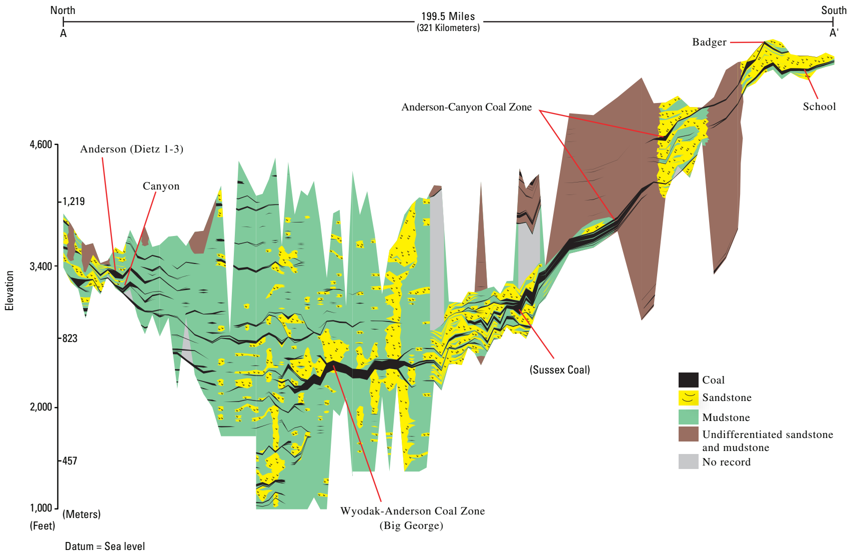


Figure 13. North-south cross section (A–A′) of the upper part of the Fort Union Formation across the west-central part of the Powder River Basin from Montana to Glenrock, Wyoming. For location see figure 1.

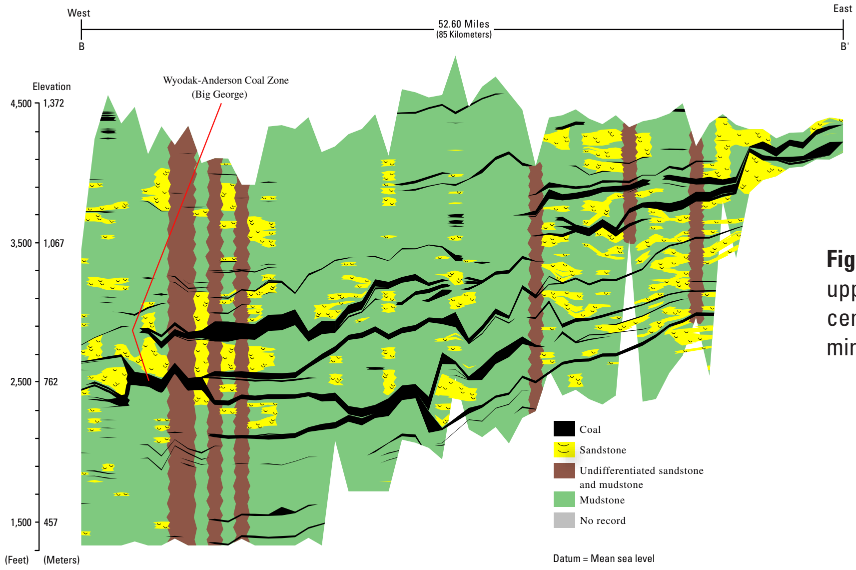


Figure 14. West-east cross section (B–B′) of the upper part of the Fort Union Formation across the central part of the Powder River Basin in Wyoming. For location see figure 1.

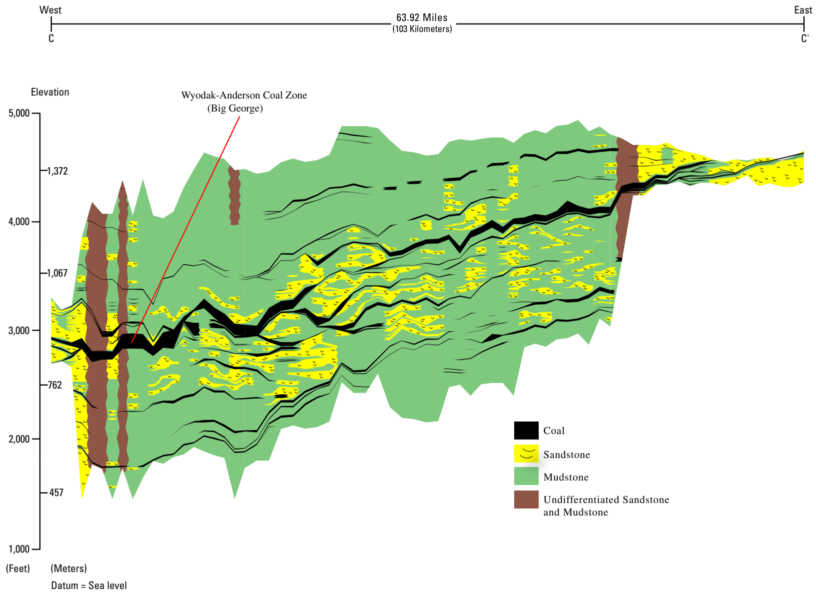


Figure 15. West-east cross section (C–C′) of the upper part of the Fort Union Formation across the south-central part of the Powder River Basin in Wyoming. For location see figure 1.

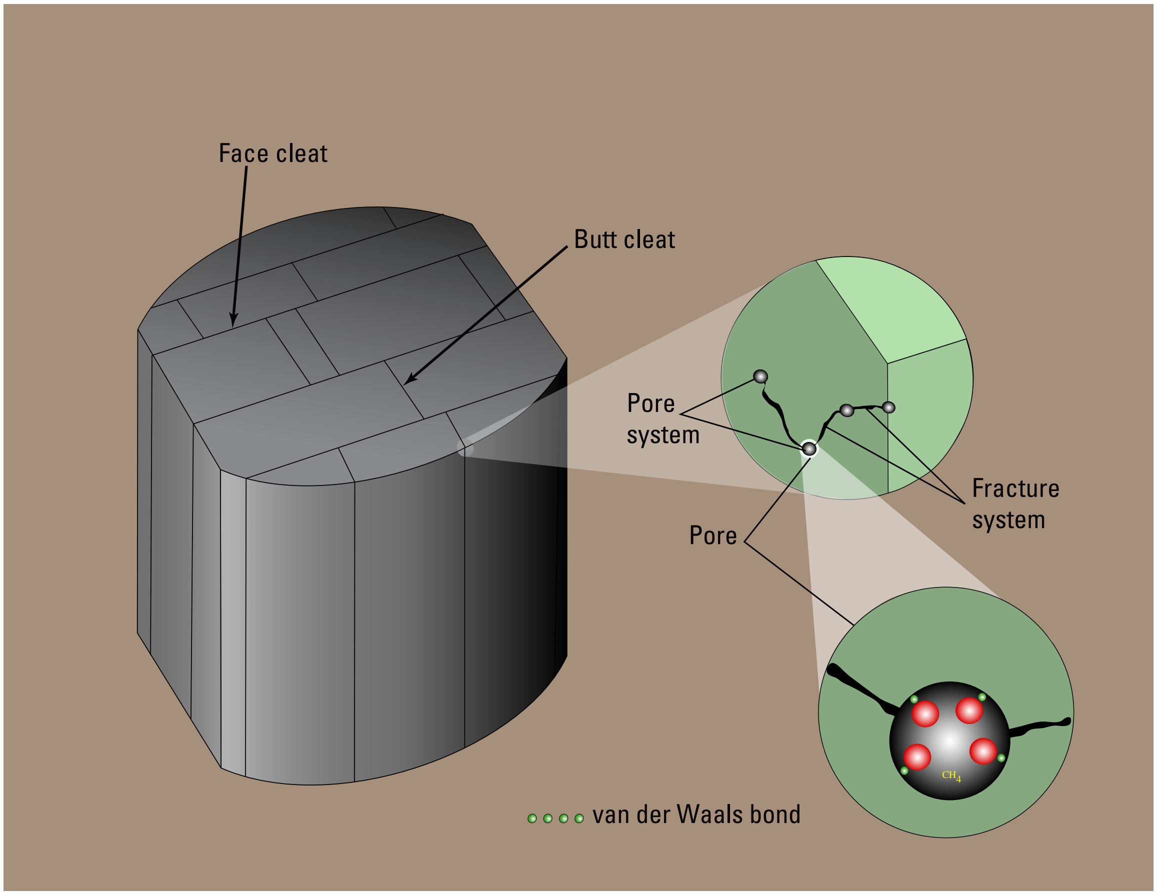


Figure 16. Diagram showing cleat, fracture, and pore systems and cleat spacing in a coalbed. Face and butt cleat systems are the primary and secondary permeability fractures, respectively, used by gas and water flows in the coal. The pore system in coal is an aperture-cavity type system where methane (CH_4) molecules are adsorbed along its surface by a weak chemical bond. Hurlbut (1959) indicated that this "weak bond, which ties neutral molecules and essentially uncharged structure units into a lattice by virtue of small residual changes on their surfaces, is called the *van der Waals bond.*"

ranges from 0.04 to 0.70 millidarcy. The ratio of vertical to horizontal coal matrix permeability ranges from 1:4 to 2:1.

In the Powder River Basin the cleat spacing (fig. 16) is described from cores of >3-inch diameter and coal mine highwalls. Cleat spacing ranges from 0.04 to more than 3.94 inches with wider spaced cleats in coalbeds with thicker vitrain lamellae (Ronald Stanton, U.S. Geological Survey, 1999, oral commun.). Law and others (1991) reported that cleat spacing in the Wyodak-Anderson coal measured in the Eagle Butte mine ranges from 3 to 5 inches with the wider spaced cleats occurring in the lower part of the coal, possibly because of a higher vitrain (woody) content in that part of the bed (Warwick and Stanton, 1988). The face cleats in that coal mine strike east-northeast; the face cleats of the same coal near Gillette strike northwest with the butt cleats northeast (Henkle and others, 1978). In contrast, face cleats in the Wyodak-Anderson coal measured by Glass (1975) in the Wyodak mine east of Gillette strike northeast-southeast. These limited cleat measurements suggest that the strike varies widely and locally. The northeast and northwest orientation of the face cleats corresponds to the tectonic stress fields expressed by southwest-northeast and northwest-southeast lineaments in the Bighorn Mountains (fig. 8) (Hoppin and Jennings, 1971; Maughan and Perry, 1986). The face cleat orientation and permeability could affect regional migration pathways of CBM. Face and butt cleats both could enhance well performance.

Sandstone Reservoirs

The sandstone reservoirs (fig. 17), which commonly split the coalbeds, are 10 to 350 ft thick, as much as 10 mi wide, and as much as 20 mi long. The cross sections shown in figures 13, 14, and 15 display contemporaneous and en-echelon or offset distribution of the sandstones between the coalbeds. The sandstones frequently intertongue with coalbeds that merge into a single bed, as shown in the central part of figure 13. Also, the sandstone beds form a "want area," which is an area where the channel sandstone has eroded the coalbed of the Wyodak-Anderson coal zone, as shown in figure 18. A total net isopach map of the sandstone within the Anderson-Wyodak coal zone in the Wyoming part of the basin shows east and north-northeast trends in sandstone thickness (fig. 19).

Figure 17. A fluvial-channel sandstone overlying the Wyodak-Anderson coal exposed in the highwall of a mine in the eastern part of the Powder River Basin.

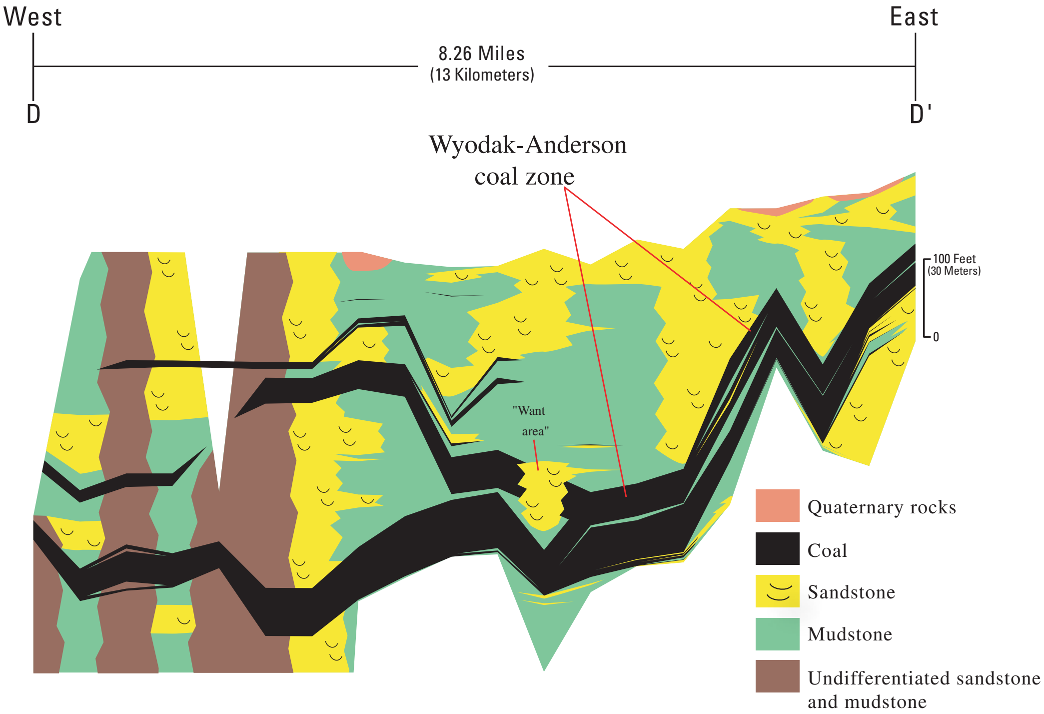


Figure 18. A west-east cross section (D–D’) in the eastern part of the Powder River Basin, Wyoming, showing a “want area” composed of a fluvial-channel sandstone between a coalbed of the Wyodak-Anderson coal zone. “Want area” represents a cutout of the coalbed by the fluvial channel. Location of this cross section, D–D’, is shown in figure 1.

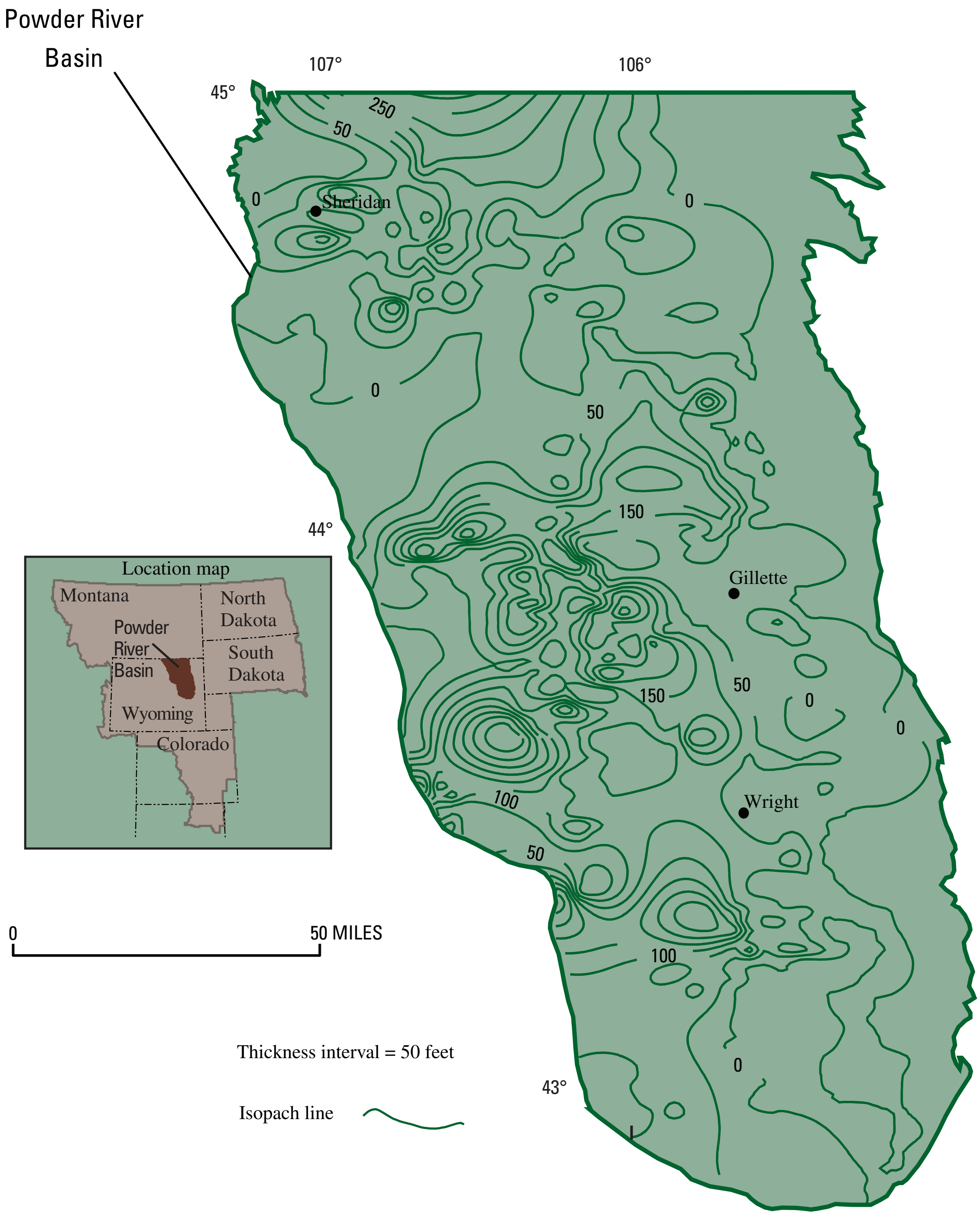


Figure 19. Net sandstone thickness map of sandstone beds greater than 10 feet thick in the Wyodak-Anderson coal zone in the Powder River Basin, Wyoming. These sandstone beds represent fluvial channel deposits between coalbeds. The map shows a southwest-northeast thickening trend of thick fluvial-channel sandstones in the area west of Gillette and Wright and in the Sheridan area in Wyoming. No data for Montana.

The sandstone reservoirs are lenticular and elongate and consist of either single or multistory bodies. The sandstones are typically trough- to planar-crossbedded in the lower part and ripple-laminated and rooted in the upper part, exhibit an erosion base marked by lag conglomerates, and coarsen upward from fine- to medium-grained. The mean grain size of the sandstone is fine grained. The sandstones are commonly composed of multistacked bodies separated by erosional surfaces marked by ironstone conglomerates. The internal structures, grain size or texture, and multistory nature of the sandstone indicate internal compartmentalization of the reservoir. The sandstones in the lower and upper parts of the Fort Union Formation vary from calclithite to chert arenite, and the sandstones in the Wasatch Formation vary from subarkose to arkose (Whipkey, 1988). These immature sandstones contain as much as 33 percent clay-mineral matrix, are calcite cemented, and are moderately well sorted. Oldham (1997) described an atypical sandstone reservoir above the Canyon coalbed (within the Wyodak–Anderson coal zone), which exhibits very high porosity (35 to 40 percent) resulting from the absence of cement.

Sedimentology of Reservoir Rocks

Environments of deposition may be defined by studying the sedimentology of the reservoir rocks. Flores (1981, 1986) interpreted the depositional environments of the coalbed and sandstone reservoirs as deposits of intermontane trunk-tributary fluvial systems (fig. 5). The coalbeds were interpreted as deposits in domed mires between fluvial channels. These domed mires are similar to the tropical rain-fed ombrotrophic mires of Indonesia, particularly those in Sumatra and Borneo (Flores and Moore, 2004). The fluvial channels were deposited mainly by meandering and anastomosed streams. Minor deposits of braided streams and alluvial fans (Flores and others, 1989) occur particularly along the west-central part of the basin. These fluvial systems and associated domed mires were interpreted to be identical to the Batang Hari fluvial system and mires in west-central Sumatra (Flores and Moore, 2004). These fluvial systems flowed to the northeast and drained into the Paleocene coastal plain and Cannonball Sea of the Williston Basin in eastern Montana and western North Dakota.

Traps and Seals

Coalbed methane accumulations in the coalbed and sandstone reservoirs are within stratigraphic and structural traps (fig. 20). Stratigraphic traps are formed by vertical change in the lithology and lateral pinch-out of a coalbed into carbonaceous shale and mudstone. The mudstone is a smectite-rich (mixed layer montmorillonite-illite; Thorez and others, 1993) impermeable rock, which acted as an ideal seal. Entrapment of gas in coalbeds is directly related to the position of ground-water levels. Normally, ground-water level is well above the coalbeds and holds the gas in the beds. Mining can lower the ground-water table by decreasing reservoir pressure and consequently releases CBM. Significant water drawdown near coal mines in the Wyodak-Anderson coal north of Gillette may have contributed to the loss of gas (fig. 21). A regional drawdown assessment of the Wyodak-Anderson coal zone by Meyer (1999) is shown in figure 22 and attests to the lowering of ground-water levels related to mining between Gillette and Wright, Wyoming.

Structural traps occur in both coalbed and sandstone reservoirs. Differential compaction over sandstone lenses can create folds and closures into which CBM can migrate and become trapped by overlying impermeable mudstone seal rock (fig. 19) (Law, 1976; Oldham 1997). Coalbed methane accumulates in structural highs early in the burial history as the sand, which compacts less than the stratigraphically equivalent mud, is differentially compacted, and forms lithologically induced, high-relief anticlines at the thickest parts of the sand. Continued differential compaction of coarse- and fine-grained sediments with prolonged burial amplifies differential compaction and closure. The closure is capped by impermeable mudstone, which seals CBM that has migrated from adjacent coalbeds. This mechanism of entrapment is not analogous to a fold or fault trap created by structural movements.

Assessment Units

The Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System includes four gas (coalbed methane) assessment units (AU). Three AUs were assessed as continuous type accumulations (50330181, 50330182, and 50330183) and one AU was assessed as a conventional accumulation (50330101). As defined by the U.S. Geological Survey (1995), the continuous type accumulation in coalbeds is a widespread accumulation of coalbed gas or methane. The conventional type accumulation is less pervasive, occurring in lenticular to elongate sandstone reservoirs interbedded with the coalbed reservoirs. The methane in the sandstone reservoirs accumulated in structural and stratigraphic traps.

Wasatch Formation Assessment Unit, 50330181

Assessment Unit 50330181 is a CBM continuous accumulation in coalbeds of the Eocene Wasatch Formation. It is bounded stratigraphically by the underlying Paleocene Fort Union Formation and the overlying Oligocene White River Formation (fig. 2). The Wasatch Formation is as much as 1,400 ft thick along the basin axis and consists of interbedded coal, carbonaceous shale, mudstone, siltstone, sandstone, conglomerate, and limestone beds. The coalbeds, which vary from a few inches to 200 ft thick, are the least common rock type of

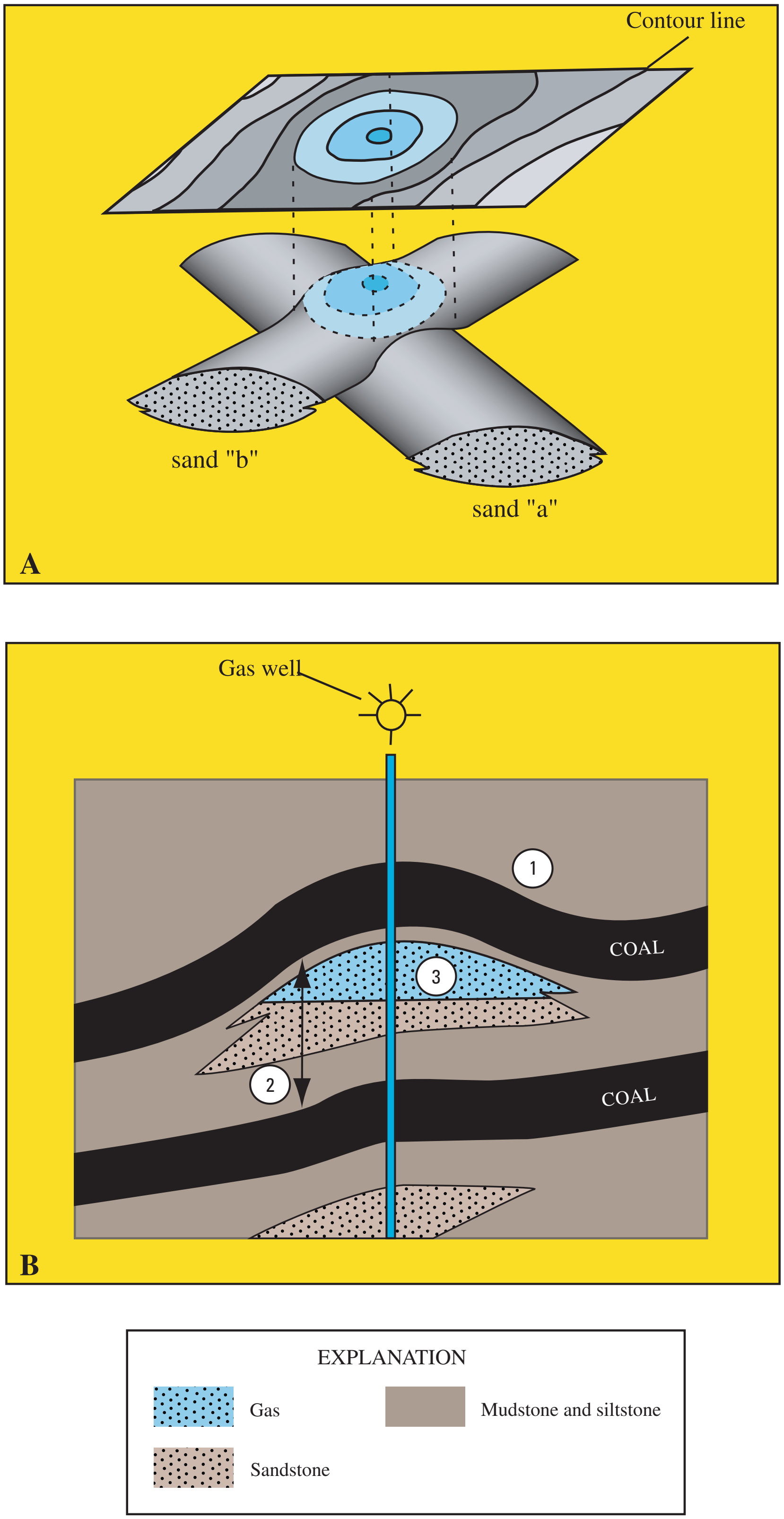


Figure 20. Diagrams A and B showing sandstone reservoirs "a" and "b" and compaction structure above the sandstone reservoirs in the Eastern Basin Margin Upper Fort Union Sandstone Assessment Unit. Diagram A shows enhancement of closure on a compactional trap in stacked sandstone reservoirs. Not shown between the sandstone reservoirs is interbedded coal and fine-grained sediments. Diagram B shows (1) a compaction model with a structural closure, (2) increased noncoal interval (arrow) below the upper coalbed, and (3) gas-saturated top of the sandstone. Modified from Oldham (1997).

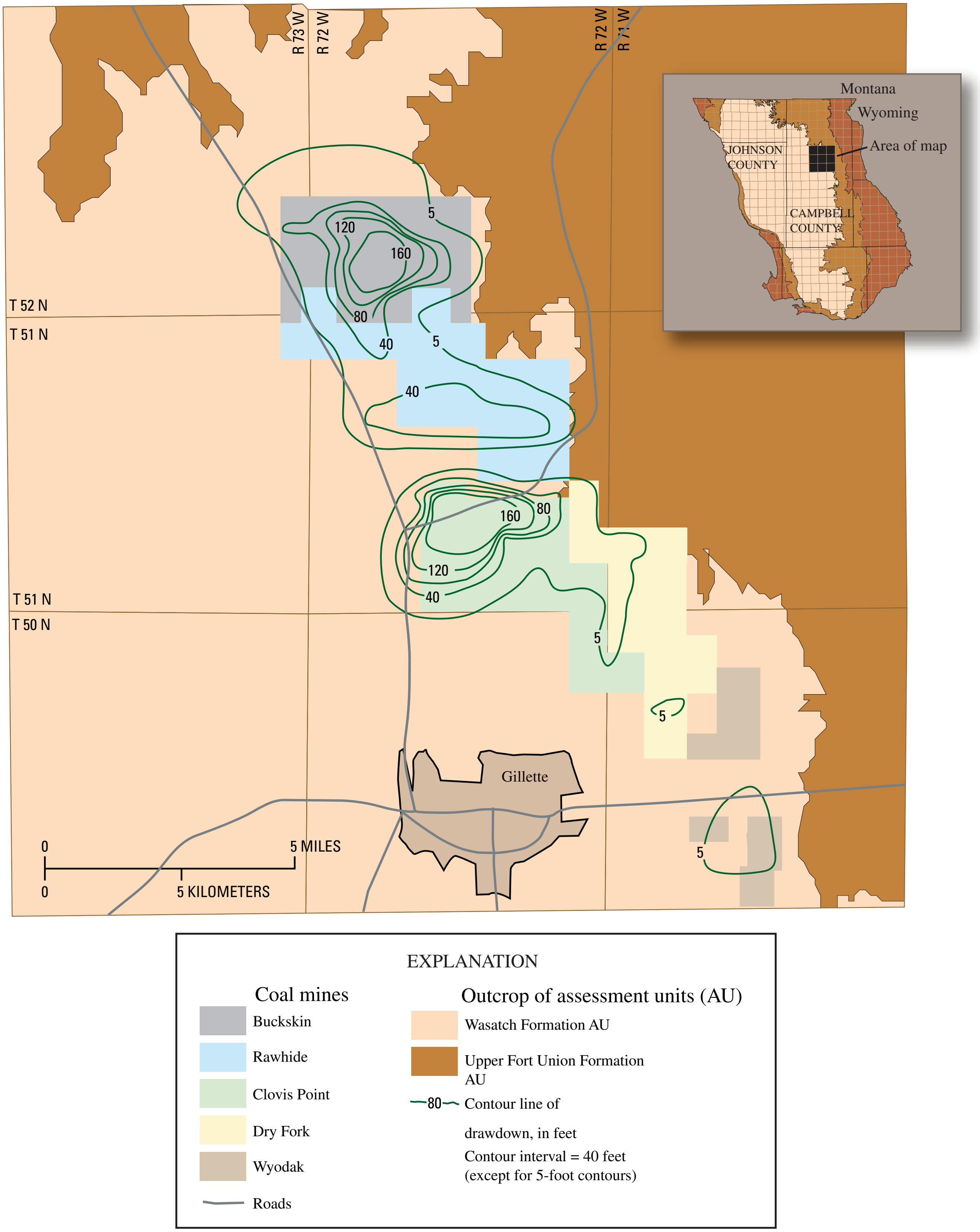


Figure 21. Map showing the cumulative drop in water level, or drawdown, for the past 15 years in the Wyodak-Anderson coal-mined area north of Gillette, Wyoming. Data from Gillette Area Groundwater Monitoring Organization (GAGMO). Modified from Bureau of Land Management (2003).

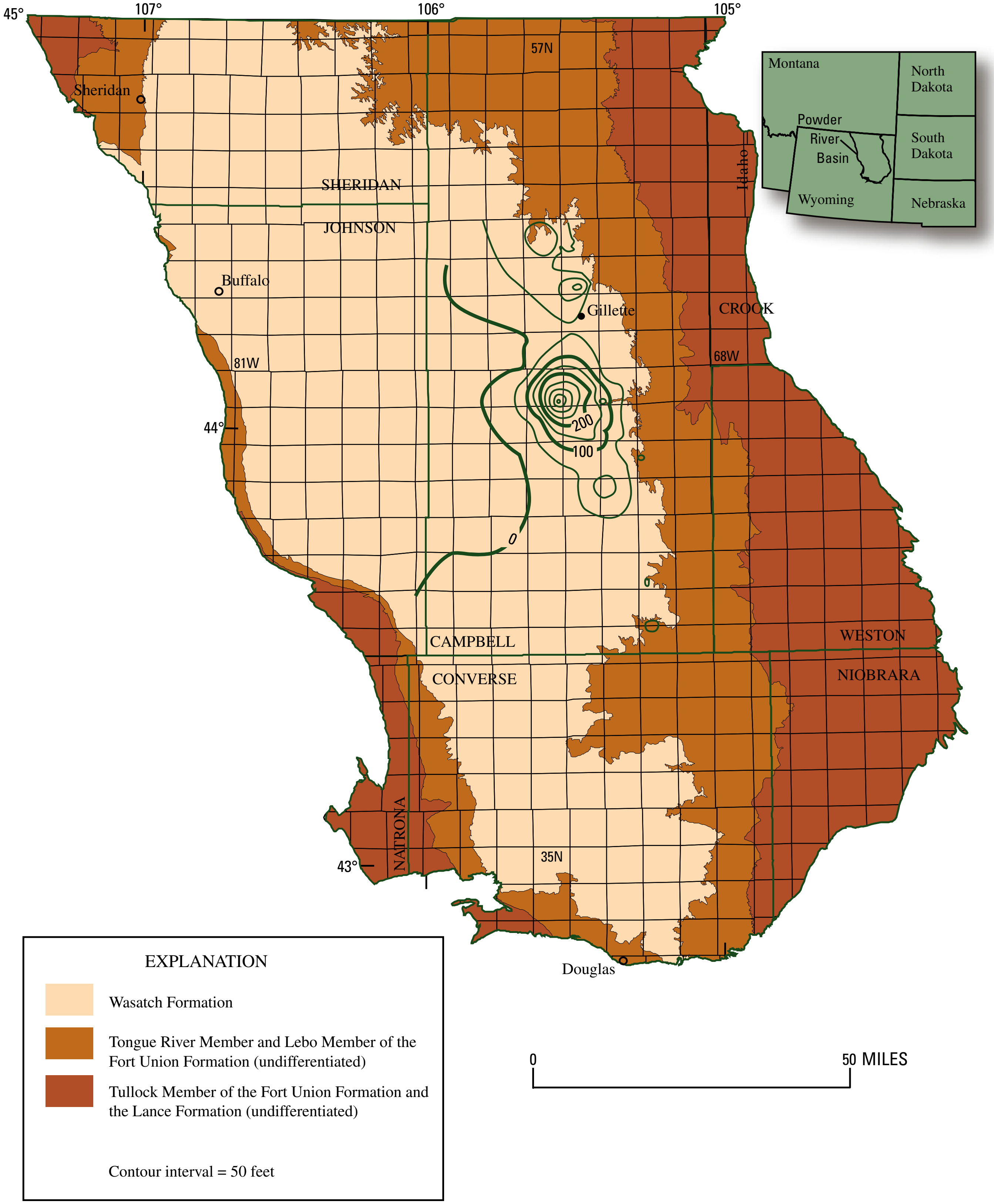


Figure 22. A generalized regional drawdown map of the Wyodak-Anderson coal zone for the period 1980–98 along the eastern part of the Powder River Basin. Modified from Meyer (1999).

the Wasatch Formation; mudstone and sandstone are the most abundant rock types. Conglomerate deposits are present in the Wasatch Formation mainly along the western margin of the basin and along the eastern flank of the Bighorn Mountains where they are mapped, from bottom to top, as the Kingsbury Conglomerate Member and the Moncrief Member of the Wasatch Formation. These very coarse grained sediments were deposited in alluvial fans that debouched into the basin margin and joined braided tributaries of northerly flowing meandering and anastomosed systems that drained the basin center. Finer grained sediments were deposited in these fluvial systems on flood plains away from fluvial channels, and the coal and carbonaceous shale beds accumulated in low-lying and raised mires between river channels (Flores and Warwick, 1984).

The boundary of the Wasatch Formation AU is shown in figure 8 and is defined by the outcrop contact of the base of the Wasatch Formation. This AU covers an estimated area of about 4,902,000 acres and contains coalbeds, mainly of subbituminous C rank with some lignite rank (as-received Btu), which range from a few inches to 200 ft thick. Thick coalbeds, with net thickness from 20 to 200 ft, are concentrated in the west-central part of the AU (fig. 23). This area contains about 130 billion short tons of Wasatch coal resources out of a total 167 billion short tons of Wasatch coal (greater than 2.5 ft thick) basinwide. The potentially productive coal-bearing interval is as much as 1,400 ft deep (fig. 24) and consists of as many as six coalbeds (Arvada, Felix, Ucross, Healy, Ulm 1 and 2; see fig. 3) targeted for CBM exploration and development. These coalbed reservoirs are ideally sealed by thick, impermeable mudstones.

The general lack of wells testing the Wasatch Formation AU makes it a hypothetical AU, and for the assessment, this necessitated the use of analogue CBM production data from one of the tested coalbeds in the Upper Fort Union Formation AU (see fig. 8). For this assessment, a test well is one that has penetrated and tested the AU. In the Powder River Basin, many wells were drilled through the Wasatch Formation and into the underlying Fort Union Formation at the time (end of 1999) of this assessment, but these wells are not considered to be tests of the Wasatch Formation AU because they tested only the Fort Union coalbeds. In order to estimate possible additions to reserves in the next 30 years, the Anderson coal of the Fort Union Formation was selected as the production analogue for the Wasatch coalbeds. The Anderson coal has the same rank and possesses coal-quality characteristics similar to coalbeds in the overlying lower part of the Wasatch Formation.

The Wasatch Formation AU had to have a minimum estimated ultimate recovery (EUR) per cell of 0.02 billion cubic feet (BCF) of methane to be considered in this assessment (table 1). About 164 cells are estimated to have EURs greater than 0.02 BCF. The assessment area ranges from an estimated minimum of 4,435,000 acres, median of 4,669,000 acres, and a maximum of 4,902,000 acres (table 1). The drainage area per cell of untested cells having potential for additions to reserves is estimated at a minimum of 40 acres, a median of 80 acres, and a maximum of 140 acres (table 1). The drainage areas are similar to those estimated for the analogue used from the Upper Fort Union Formation AU. Percentage of total AU area that is untested is 100 percent (table 1). The percentage of total assessment unit area that has potential for additions to reserves in the next 30 years was estimated at a minimum of 1 percent, a median of 13 percent, and a maximum of 24 percent (table 1). This is based on the occurrence of thick Wasatch coalbeds that are as deep as 1,400 ft in the west-central part of the Powder River Basin in Wyoming. The maximum area was estimated by drawing a boundary at the net coal thickness isopach of >50 ft. The total recovery per cell for untested cells having potential for addition to reserves in the next 30 years was estimated at a minimum of 0.02 BCF, median of 0.18 BCF, and a maximum of 3 BCF (table 1).

Upper Fort Union Formation Assessment Unit, 50330182

Assessment unit 5330182 is a continuous CBM accumulation sourced by coalbeds of the upper part of the Fort Union Formation. This AU includes, from bottom to top, the Lebo and Tongue River Members of the Paleocene Fort Union Formation (see fig. 3). The upper Fort Union Formation is as much as 3,900 ft thick along the basin axis where the Lebo Member is about 2,000 ft and the Tongue River Member about 1,900 ft thick. The Lebo Member contains abundant drab gray mudstone, minor siltstone and sandstone, and sparse coal and carbonaceous shale beds. The Tongue River Member consists of interbedded sandstone, conglomerate, siltstone, mudstone, limestone, coal, and carbonaceous shale beds. The sandstone and mudstone beds are the most abundant rock types within which conglomerates and siltstone beds are most common and coal, carbonaceous shale, and limestone beds least common. The coalbeds of the Tongue River Member are anomalously thick, as much as 202 ft, and average about 50 ft thick. These beds are extensively mined along the southern, eastern, and northwestern parts of the basin.

The upper part of the Fort Union Formation is interpreted to have been deposited in braided, meandering, and anastomosed streams (Flores, 1986; Flores and Bader, 1999; figures 25 and 26). These streams comprised a northeast-flowing trunk-tributary fluvial system in the central part of the basin, which merged into an alluvial fan system along the western basin margin. The coalbeds formed primarily in rain-fed raised mires, which were confined by river channels. Thick deposits of peat, a coal precursor, accumulated in the raised mires and developed a widespread distribution controlled by the accommodation space created by tectonic basin subsidence.

The AU covers 10,884,000 acres with the boundary of the unit drawn at the contact, an outcrop (see fig. 1) of the base of the Lebo Member (or top of the Tullock Member) of the Fort Union Formation (fig. 8). The upper boundary of the unit is the top of the Tongue River Member of the Fort Union Forma-

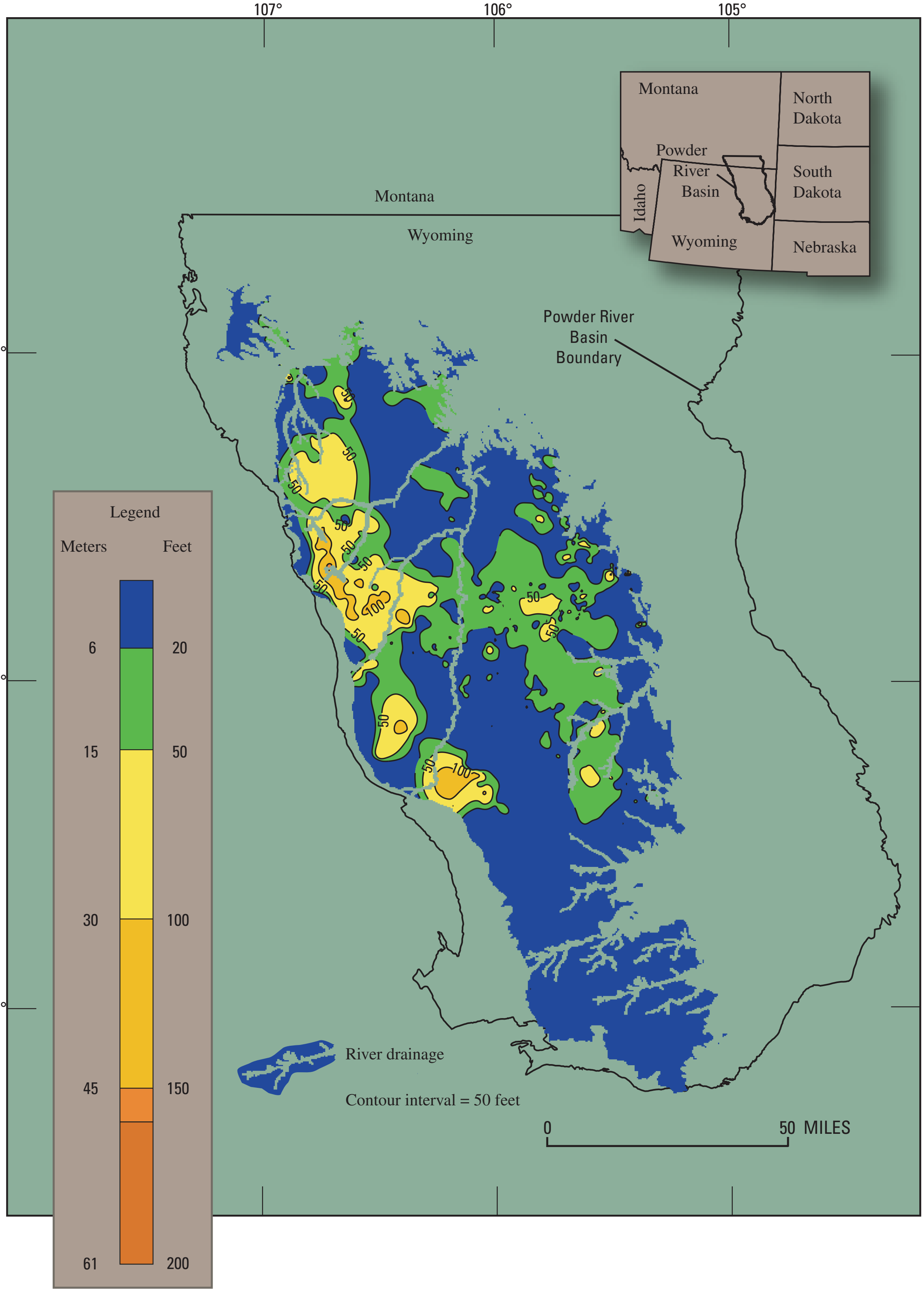


Figure 23. Net coal thickness map of the Wasatch Formation Assessment Unit in the Wyoming part of the Powder River Basin.

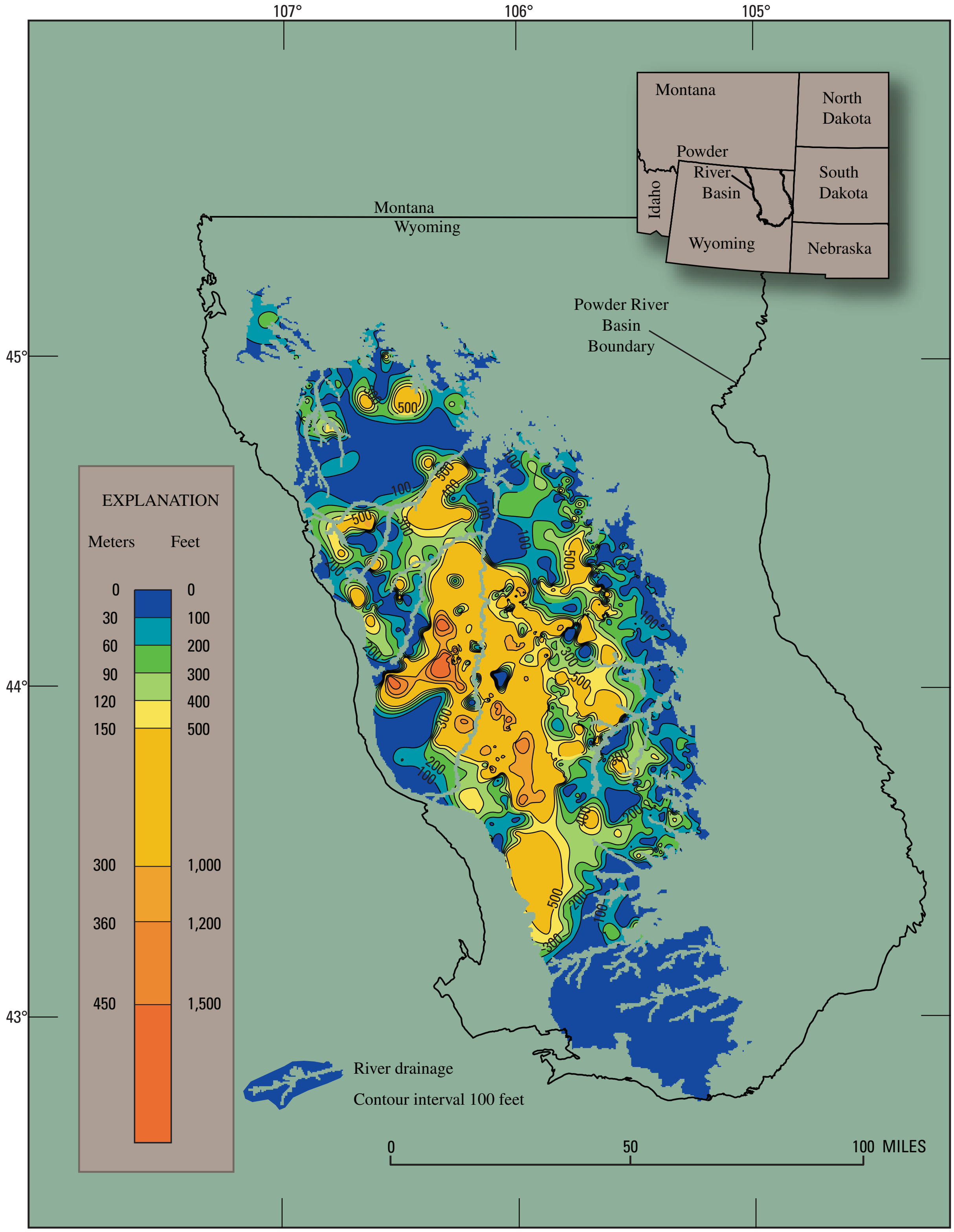


Figure 24. Total thickness map of the Wasatch Formation Assessment Unit in the Wyoming part of the Powder River Basin.

Table 1. Basic input data form for the Wasatch Formation Assessment Unit (50330181) of the Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System, Powder River Basin Montana and Wyoming.

FORSPAN ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 7, 6-30-00)

IDENTIFICATION INFORMATION

Assessment Geologist:…	Romeo M. Flores	Date:	10/17/00
Region:……………………	North America	Number:	5
Province:…………………	Powder River Basin	Number:	5033
Total Petroleum System:.	Tertiary-Upper Cretaceous Coalbed Methane	Number:	503301
Assessment Unit:……….	Wasatch Formation	Number:	50330181
Based on Data as of:……	PI production data current through third quarter 1999		
Notes from Assessor…..	Gas is biogenic. Anderson coal of the Fort Union Formation as an analogue.		

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-Unit type: **Oil** (<20,000 cfg/bo) **or** **Gas** (≥20,000 cfg/bo) Gas
What is the minimum total recovery per cell?… 0.02 (mmbo for oil A.U.; bcfg for gas A.U.)
Number of tested cells:………… 0
Number of tested cells with total recovery per cell ≥ minimum: …….... 0
Established (>24 cells ≥ min.) Frontier (1-24 cells) Hypothetical (no cells) x
Median total recovery per cell (for cells ≥ min.): (mmbo for oil A.U.; bcfg for gas A.U.)
1st 3rd discovered 2nd 3rd 3rd 3rd

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an untested cell with total recovery ≥ minimum ……	1.0
2. **ROCKS:** Adequate reservoirs, traps, seals for an untested cell with total recovery ≥ minimum.	1.0
3. **TIMING:** Favorable geologic timing for an untested cell with total recovery ≥ minimum………..	1.0

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3):……............…… 1.0

4. **ACCESS:** Adequate location for necessary petroleum-related activities for an untested cell with total recovery ≥ minimum ……………………………………………………………… 1.0

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES IN THE NEXT 30 YEARS

1.	Total assessment-unit area (acres): (uncertainty of a fixed value)	minimum 4,435,000	median 4,669,000	maximum 4,902,000
2.	Area per cell of untested cells having potential for additions to reserves in next 30 years (acres): (values are inherently variable)	minimum 40	median 80	maximum 140
3.	Percentage of total assessment-unit area that is untested (%): (uncertainty of a fixed value)	minimum 100	median 100	maximum 100
4.	Percentage of untested assessment-unit area that has potential for additions to reserves in next 30 years (%): (a necessary criterion is that total recovery per cell ≥ minimum) (uncertainty of a fixed value)	minimum 1	median 13	maximum 24

Table 1 — **Continued.** Basic input data form for the Wasatch Formation Assessment Unit (50330181) of the Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System, Powder River Basin Montana and Wyoming.

TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves in next 30 years:
(values are inherently variable)
(mmbo for oil A.U.; bcfg for gas A.U.) minimum 0.02 median 0.18 maximum 3

AVERAGE COPRODUCT RATIOS FOR UNTESTED CELLS, TO ASSESS COPRODUCTS

(uncertainty of fixed but unknown values)

Oil assessment unit:	minimum	median	maximum
Gas/oil ratio (cfg/bo)…………………………….			
NGL/gas ratio (bngl/mmcfg)…………………….….			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)….…………..……	0	0	0

SELECTED ANCILLARY DATA FOR UNTESTED CELLS

(values are inherently variable)

Oil assessment unit:	minimum	median	maximum
API gravity of oil (degrees)…………….………….			
Sulfur content of oil (%)……………………….….			
Drilling depth (m) ……………...………………..….			
Depth (m) of water (if applicable)……………….			
Gas assessment unit:			
Inert-gas content (%)……………………….....…..	2.00	3.00	4.00
CO_2 content (%)……………………………….……..	3.00	5.00	8.00
Hydrogen-sulfide content (%)……………...…….	0.00	0.00	0.00
Drilling depth (m)…………………………………	60	260	450
Depth (m) of water (if applicable)……………….			

Figure 25. Modern meandering river and associated mires. Such an environment is an analogue for the depositional environment in which the Tertiary coalbeds in the Powder River Basin were deposited.

Figure 26. Modern anastomosed river and associated mires. Such an environment is an analogue for the depositional environment in which the Tertiary coalbeds in the Powder River Basin were deposited.

tion. The Wyoming part of the AU area contains coal mainly of subbituminous C, B, and A ranks (moist, mineral-matter-free Btu basis), whereas mainly subbituminous B (moisture-free Btu basis) coal is present in the northwest part of the AU in Montana. Although coalbeds vary from a few inches to 200 ft thick basinwide, the thickness of coals in the AU averages about 40 ft in Wyoming and about 20 ft in Montana. Coalbeds ranging from 20 to 140 ft thick are mined in the northwest part of the AU in Montana and in the eastern part of the unit in Wyoming.

There are two intervals in the Upper Fort Union Formation AU that contain coalbeds and zones presently targeted for CBM production. The first is the Wyodak-Anderson coal zone in the upper part of the upper Fort Union, and the second is the coals beneath the Wyodak-Anderson. The Wyodak-Anderson contains as many as 11 coalbeds in an interval as much as 850 ft thick, that merge, split and pinch out. These coalbeds include the Smith, Swartz, Anderson, Dietz, Canyon, Monarch, Sussex, Big George, and Werner coal (see fig. 3). The Wyodak-Anderson coal zone includes merged coalbeds that vary from 50 to 200 ft thick. The net coal-thickness isopach map (see fig. 9) of the Wyodak-Anderson coal zone shows a concentration of coal more than 100 ft thick in the eastern and central part of the AU in Wyoming and in the northwest part of the AU in Montana. The coal resources of the Wyodak-Anderson coal zone in the AU were estimated by the Fort Union Coal Assessment Team (1999) to be as much as 550 billion short tons. Most of these coal resources are found in the deeper part (1,000 to 2,000 ft overburden; fig. 27) of the AU. The coalbed reservoirs are sealed by thick, impermeable mudstones.

The second interval in the Upper Fort Union Formation AU consists of coalbeds and coal zones in the lower part of the Fort Union Formation below the interval of the Wyodak-Anderson coal zone. This second interval is as much as 1,400 ft thick. The coalbeds in the Wyoming part of the AU include the Cook (Carney), Wall, Pawnee, Kennedy, Carson, Oedekoven, King, Moyer, and Roberts (see fig. 3). Coal in the Montana part includes beds in the Knobloch coal zone, which contains the Nance, Calvert, Flowers, and Goodale coalbeds, and beds in the Rosebud-Robinson coal zone, which consists of the Rosebud and Robinson coalbeds, which partly merge with the Knobloch coal zone (see fig. 3). These coalbeds and zones vary from 20 to 50 ft thick. The net coal-thickness map (see fig. 10) of these coalbeds and zones shows thickness greater than 10 ft in the central part of the AU area in Wyoming. Here, the coal resources (for greater than 100 ft in net coal thickness) are about 290 billion short tons out of a total of 460 billion short tons basinwide. These coal resources are in the deeper part of the AU area (1,000 to 3,000 ft overburden; fig. 28). The coalbed reservoirs are sealed by thick, impermeable mudstones.

Coalbed methane in the Upper Fort Union Formation AU is now being actively developed and produced. The fast pace of drilling activity in the Powder River Basin is best illustrated by the rapid rise in the total number of wells (nonproducing and producing), which was about 6,000 at the end of 2000 and about 22,000 as of February 22, 2002 (Wyoming Oil and Gas Conservation Commission, oral commun., 2002). The nonproducing wells include those that have been permitted but not yet drilled, wells that have been scudded, abandoned, shut in (for example, waiting to be connected to gas-gathering system), wells that are dormant, and dry holes. As of February 22, 2002, of the approximately 22,000 total wells, about 6,100 wells were in production in the AU in Wyoming and Montana (see fig. 8). The Wyoming Oil and Gas Conservation Commission (WOGCC) reports that more than a dozen coalbed reservoirs, mainly in the Wyodak-Anderson coal zone in the upper part of the Fort Union Formation, are producing CBM (Richard Marvel, Wyoming Oil and Gas Conservation Commission, oral commun., 2000). Total CBM production in both States as of the end of May 2002 totaled about 600 BCF.

The number of evaluated (tested) cells in the Upper Fort Union Formation AU is 3,090 (tested as of April 2000) of which 2,449 is the number of evaluated cells with EUR (table 2). However, the EURs from these cells are based on the total of 1,179 CBM-producing wells that were completed as of the end of 1999. Of these CBM-producing wells, there were only 638 wells that have sufficient production history to calculate EURs. The 638 wells were divided into three equal groups based on the start of CBM production in 1980 to the time of this assessment in 1999. The first one-third comprised the longest producing and oldest (1980–99) group of CBM wells. The last one-third comprised the shortest producing and newest (01/1999–11/1999) group of CBM wells. The second one-third comprised the group of CBM-producing wells between the first one-third and last one-third developed from 1998 to January 1999. Thus, the EUR of all the wells greater than the minimum size (0.02 BCF) assessed was grouped by thirds and analyzed (fig. 29; table 2) (see chapter by Troy Cook in this CD-Rom for more information on the methodology). The estimated median total recovery per cell by thirds of wells drilled is 0.19 BCF for the first one-third, 0.24 BCF for the second one-third, and 0.21 BCF for the last one-third drilled. The increase in EURs with time suggests that operators are using improved technology for well completions and prolonged dewatering of the coal reservoirs. Also, this may be explained by widespread gas drainage from outlying undeveloped leases (Dwain McGarry, oral commun., 2002).

The total area of the AU is estimated at a minimum of 8,447,000 acres, a median of 8,892,000 acres, and a maximum of 9,337,00 acres (table 2). Estimated area (drainage area) per cell having potential for additions to reserves in the next 30 years is a minimum of 40 acres, median of 80 acres, and a maximum of 140 acres (table 2). Figure 30 shows the density of wells in the Sasquatch unit in the central part of the Powder River Basin. Here, the developed areas (for example, State, Federal, and private leases) have as many as 16 wells per square mile based on 40-acre well spacing. However, the WOGCC later changed the spacing to 80 acres (8 wells per square mile) due to increased water production. The large volume of water in the Powder River Basin coproduced with

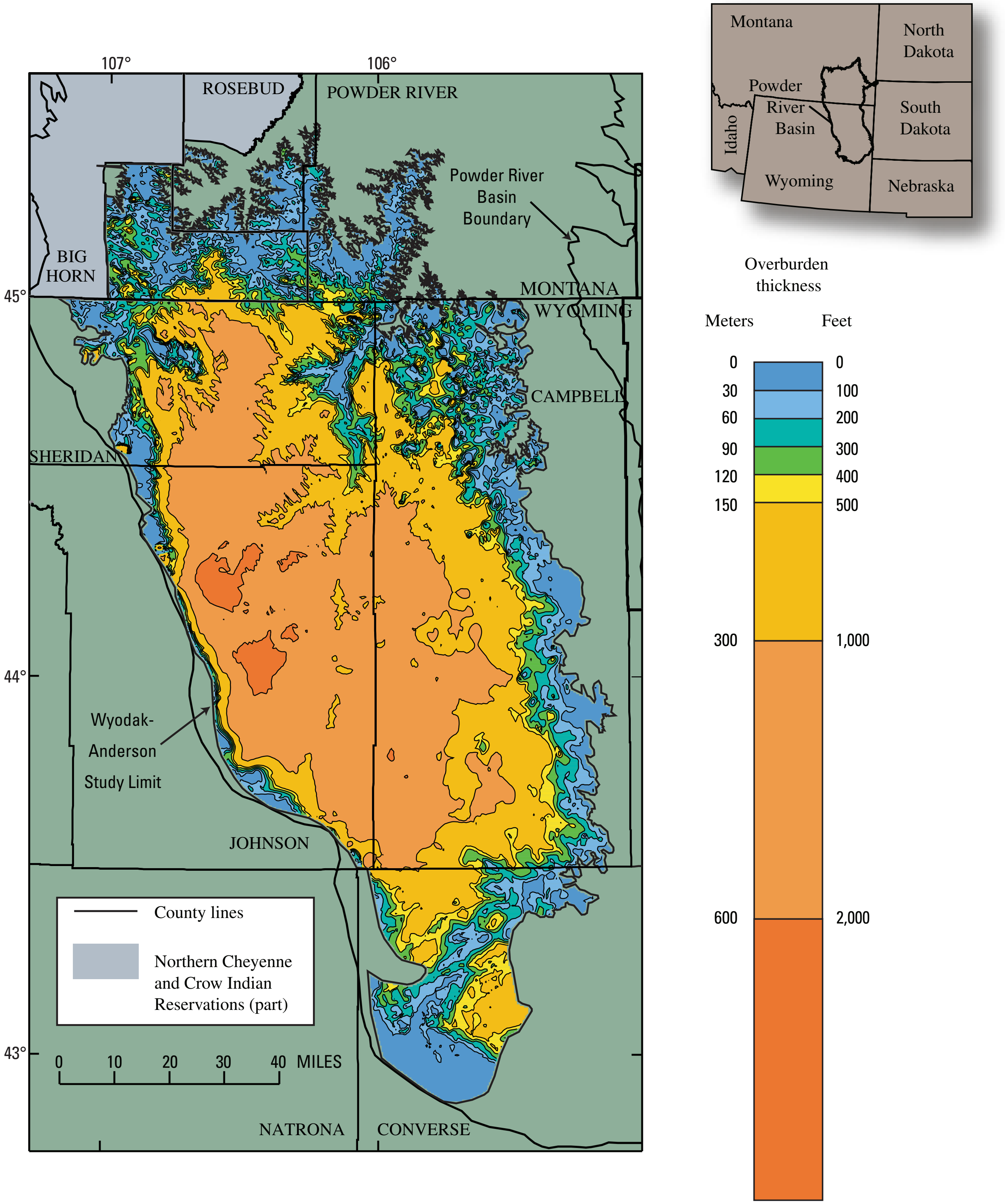


Figure 27. Map showing thickness of the strata above the Wyodak-Anderson coal zone in the Upper Fort Union Formation Assessment Unit, Powder River Basin, Wyoming and Montana.

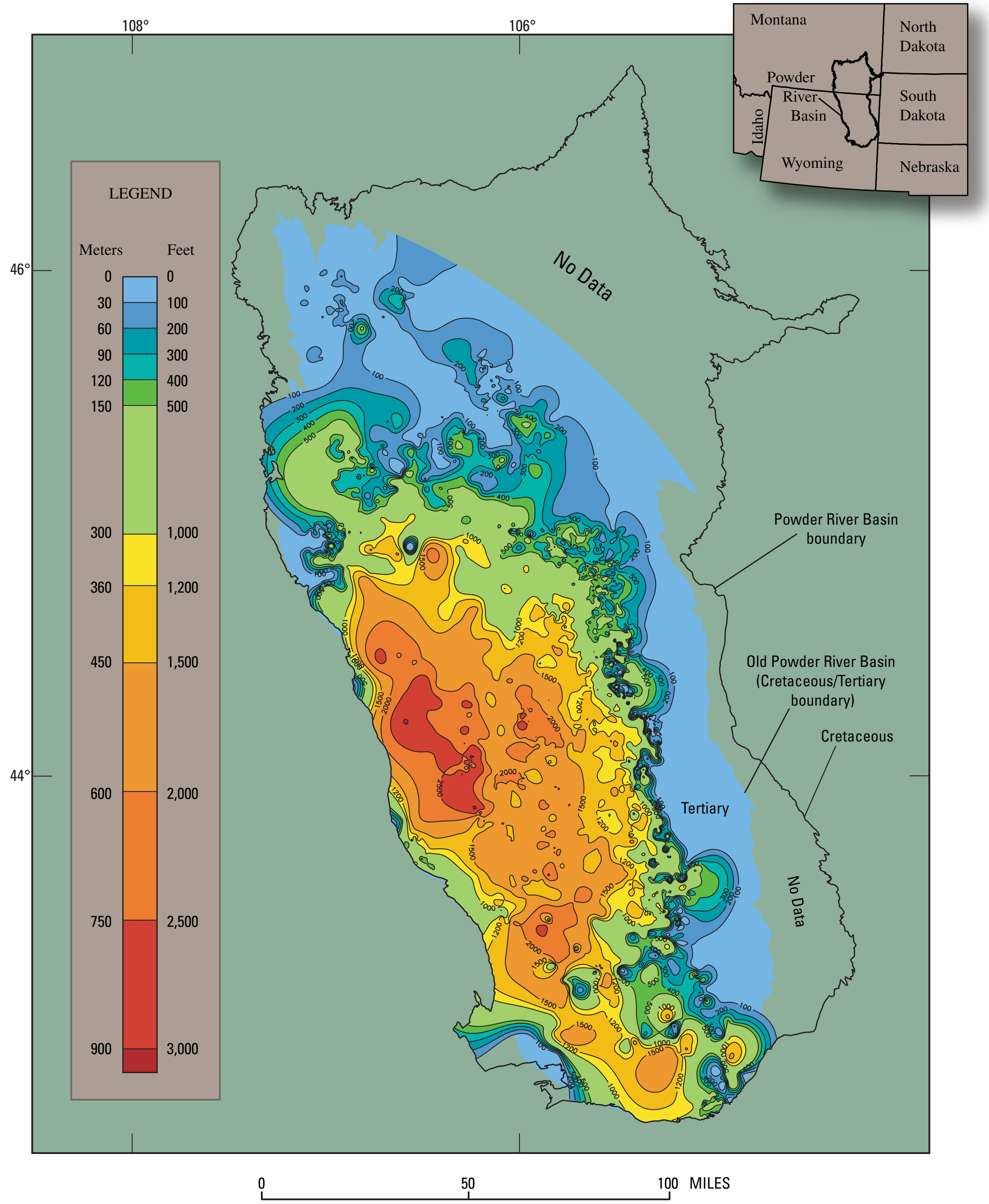


Figure 28. Map showing thickness of strata below the Wyodak-Anderson coal zone from base of the coal zone to the base of the Lebo Shale Member in the Upper Fort Union Formation Assessment Unit, Powder River Basin.

Table 2. Basic input data form for the Upper Fort Union Formation Assessment Unit (50330182) of the Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System, Powder River Basin Montana and Wyoming.

FORSPAN ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 7, 6-30-00)

IDENTIFICATION INFORMATION

Assessment Geologist:…	Romeo M. Flores	Date:	10/17/00
Region:……………………	North America	Number:	5
Province:…………………	Powder River Basin	Number:	5033
Total Petroleum System:.	Tertiary-Upper Cretaceous Coalbed Methane	Number:	503301
Assessment Unit:……….	Upper Fort Union Formation	Number:	50330182
Based on Data as of:……	PI production data current through third quarter 1999		
Notes from Assessor…..	Gas is biogenic. Very active and recent coalbed methane drilling and development		

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-Unit type: Oil (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo) Gas

What is the minimum total recovery per cell?… 0.02 BCF (mmbo for oil A.U.; bcfg for gas A.U.)

Number of tested cells:………… 3,090

Number of tested cells with total recovery per cell ≥ minimum: ……... 2,449

Established (>24 cells ≥ min.) x Frontier (1-24 cells) ____ Hypothetical (no cells) ____

Median total recovery per cell (for cells ≥ min.): (mmbo for oil A.U.; bcfg for gas A.U.)

1st 3rd discovered 0.19 2nd 3rd 0.23 3rd 3rd 0.21

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an untested cell with total recovery ≥ minimum ……	1
2. **ROCKS:** Adequate reservoirs, traps, seals for an untested cell with total recovery ≥ minimum.	1
3. **TIMING:** Favorable geologic timing for an untested cell with total recovery ≥ minimum………..	1

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3):……….......……. 1.0

4. **ACCESS:** Adequate location for necessary petroleum-related activities for an untested cell with total recovery ≥ minimum ……………………………………………………………… 1.0

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES IN THE NEXT 30 YEARS

	minimum	median	maximum
1. Total assessment-unit area (acres): (uncertainty of a fixed value)	8,447,000	8,892,000	9,337,000
2. Area per cell of untested cells having potential for additions to reserves in next 30 years (acres): (values are inherently variable)	40	80	140
3. Percentage of total assessment-unit area that is untested (%): (uncertainty of a fixed value)	97	98	99
4. Percentage of untested assessment-unit area that has potential for additions to reserves in next 30 years (%): (a necessary criterion is that total recovery per cell ≥ minimum) (uncertainty of a fixed value)	10	33	58

Table 2 —Continued. Basic input data form for the Upper Fort Union Formation Assessment Unit (50330182) of the Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System, Powder River Basin Montana and Wyoming

TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves in next 30 years:
(values are inherently variable)
(mmbo for oil A.U.; bcfg for gas A.U.) minimum 0.02 median 0.23 maximum 4

AVERAGE COPRODUCT RATIOS FOR UNTESTED CELLS, TO ASSESS COPRODUCTS

(uncertainty of fixed but unknown values)

Oil assessment unit:	minimum	median	maximum
Gas/oil ratio (cfg/bo)………………………..…….			
NGL/gas ratio (bngl/mmcfg)…………………..…..			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)….……………..……	0	0	0

SELECTED ANCILLARY DATA FOR UNTESTED CELLS

(values are inherently variable)

Oil assessment unit:	minimum	median	maximum
API gravity of oil (degrees)…………….………….			
Sulfur content of oil (%)………………………...…			
Drilling depth (m) ……………...……………..……			
Depth (m) of water (if applicable)……………….			
Gas assessment unit:			
Inert-gas content (%)……………………….....…..	2.00	3.00	4.00
CO_2 content (%)……………………………….....….	3.00	5.00	8.00
Hydrogen-sulfide content (%)………….....…….	0.00	0.00	0.00
Drilling depth (m)………………………………….	60	365	800
Depth (m) of water (if applicable)……………….			

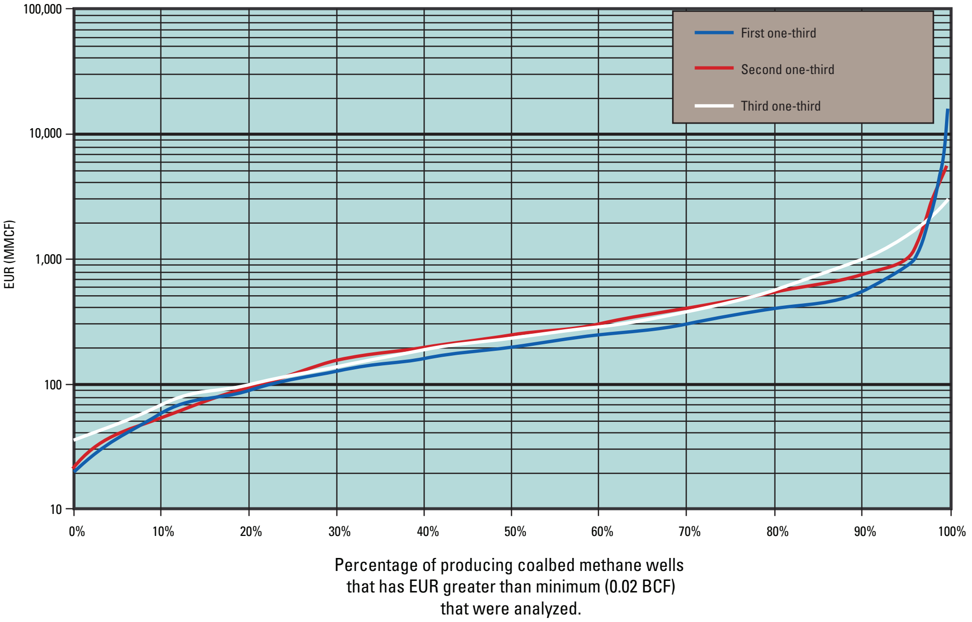


Figure 29. Estimated ultimate recovery distributions for coalbed methane wells in the first, second, and third one-thirds analyzed in the Upper Fort Union Formation Assessment Unit in the Powder River Basin, Wyoming (EUR, estimated ultimate recovery; MMCF, million cubic feet; BCF, billion cubic feet).

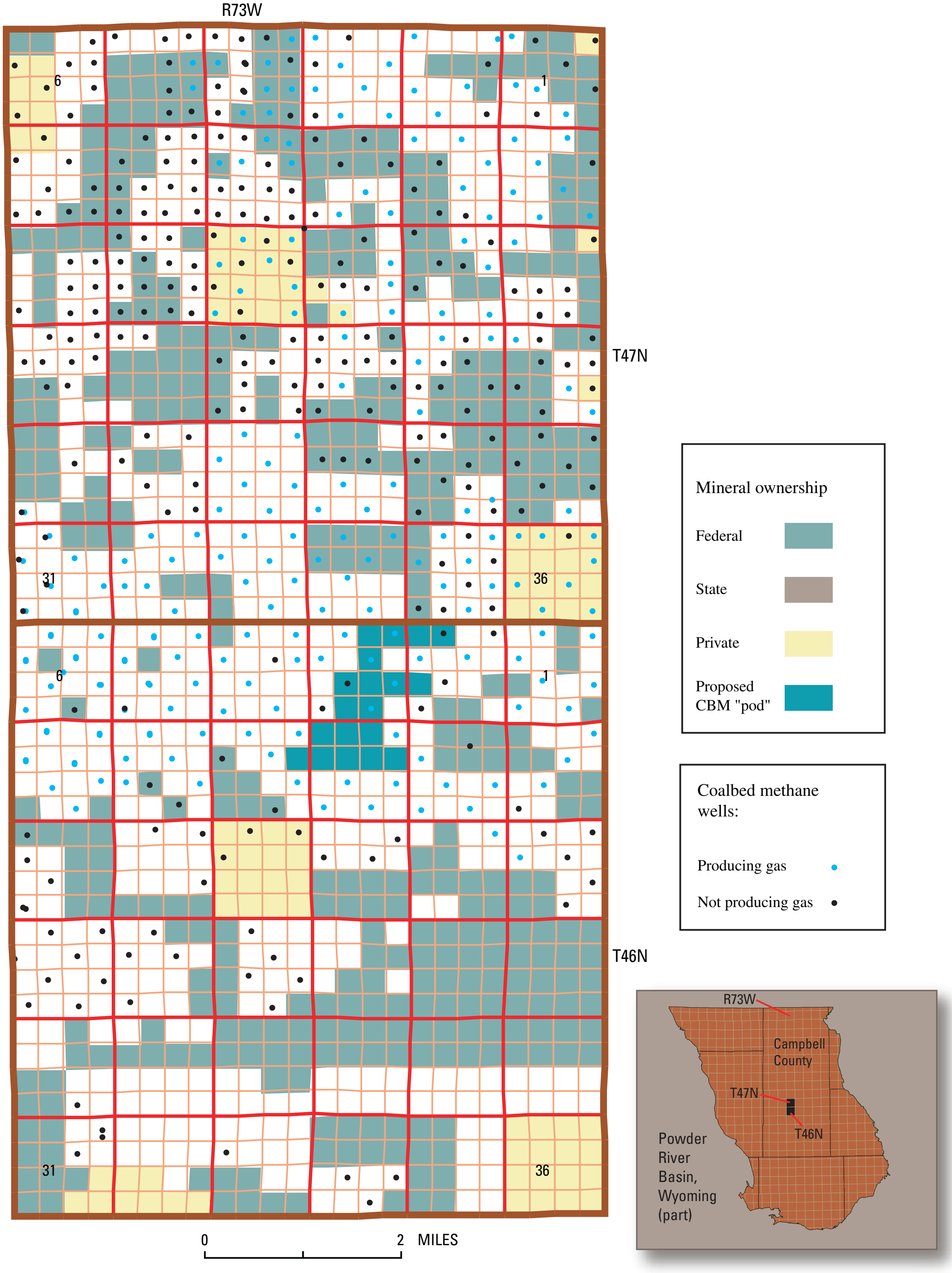


Figure 30. Map showing mineral ownership and well density in the Sasquatch unit in the Upper Fort Union Formation in the central part of the Powder River Basin, Wyoming.

CBM has led to problems related to surface disposal. As drilling proceeds toward the central part of the basin, the volume of coproduced water will eventually control the size of the drainage area. To date, the surface disposal problem has forced the WOGCC to require a maximum of 80-acre spacing throughout the basin. In addition, a 140-acre spacing may be imposed along the boundaries of the coal mines where the gas content is low as a result of water drawdown due to mining (see fig. 21). Similar drainage areas are estimated for the Wasatch Formation AU.

The area of the Upper Fort Union Formation AU that is untested is estimated at a minimum of 97 percent, a median of 98 percent, and a maximum of 99 percent. The minimum area that will add to reserves in the next 30 years was determined by tightly "shrink wrapping" the area around the majority of the producing wells in the eastern part of the basin. In this scenario, it is assumed that only in-fill drilling will be performed here in the next 30 years. More specifically, in-fill drilling will proceed in the northwest part of the basin where thick and shallow coalbeds are similar to those generating CBM in the eastern part of the basin. In-fill drilling will be followed with development in the deep central part of the basin where the thickest (maximum of 205 ft) coalbeds of the Fort Union Formation are concentrated.

The percentage of untested area in this AU that has potential for additions to reserves in the next 30 years is estimated at a minimum of 10 percent, a median of 33 percent, and to a maximum of 58 percent (table 2). Although production "sweet spots" may be found, especially in the central part of the basin, the high volume of water coproduced with methane here leads to more time for the methane to desorb, which may present more risk to production. The total recovery per cell for untested cells having potential for additions in the next 30 years is estimated at a minimum of 0.02 BCF, a median of 0.23 BCF, and a maximum of 4.0 BCF (table 2). The maximum assumes that the operators have not found the best accumulation or sweet spot in the AU; this may be found in the central part of the basin where individual coalbeds are as much as 202 ft thick and the net coal thickness is greater than 350 ft.

Lower Fort Union–Lance Formations Assessment Unit, 50330183

Assessment Unit 50330183 is a continuous accumulation of CBM from coalbeds of the Paleocene Tullock Member of the Fort Union Formation and the underlying Upper Cretaceous Lance Formation (see fig. 2). The composite thickness of these stratigraphic units is as much as 4,640 ft. The Tullock Member is as much as 1,945 ft thick, and the Lance Formation is as much as 2,695 ft thick (Curry, 1971). The thickest interval of the Tullock and Lance is along the basin axis in the southernmost part of the Powder River Basin (figs. 31 and 32). The Tullock Member of the Fort Union Formation consists of sandstone, siltstone, and sparse coal and carbonaceous shale. The Lance Formation consists of interbedded sandstone, siltstone, mudstone, limestone, coal, and carbonaceous shale beds. Sandstone, siltstone, and mudstone are the most abundant rock types and coal and carbonaceous shale the least common. The thickness of coalbeds in the Tullock Member ranges from a few inches to 7.5 ft, and beds in the Lance Formation range from a few inches to 6.6 ft (Wegemann, 1912).

The Tullock and Lance deposits are interpreted to be deposited in fluvial environments (Flores and Ethridge, 1985; Brown, 1993; Connor, 1991). Brown (1993) reported that anastomosed streams, which flowed in east and northeast directions, deposited the Tullock. Flores and Ethridge (1985) interpreted the coal deposits to have formed in poorly drained backswamps. The Lance detrital rocks were deposited by eastward-flowing fluvial systems, and the coalbeds formed in associated backswamps (Connor, 1991).

The AU covers as much as 4,965,000 acres with the lower boundary of the unit drawn at the contact, an outcrop (see fig. 1) of the base of the Cretaceous Lance Formation (fig. 8). The upper boundary of the unit is the top of the Tullock Member of the Fort Union Formation. Coalbeds are best developed and thickest (maximum of 7.5 ft) in the southern and eastern parts of the AU (fig. 33) where the coal ranks are mainly subbituminous C and B (7,700–9,300 Btu, as-received basis; Wegemann, 1912). The low-rank nature of the Tullock and Lance coal is confirmed by the vitrinite reflectance analysis of the underlying Steele Member of the Cody Shale by Nuccio (1990). The Steele Member is about 2,800 ft below the Lance Formation. The vitrinite reflectance of the Steele Member ranges from Ro 0.39 to 0.61 percent. These vitrinite reflectance values coincide with subbituminous A, B, and C coal rank as defined by Stach and others (1982). The area of vitrinite reflectance values of greater than Ro 0.60 percent lies along the basin axis in the southwestern part of the Powder River Basin. The deep southern Powder River Basin contains the thickest strata of the Tullock Member and Lance Formation as indicated by their isopach maps in figures 31 and 32.

The Lower Fort Union–Lance Formations AU is hypothetical because of the lack of drilling data and development of CBM (fig. 33). To assess this AU, the EURs from a CBM field (Mill-Gillette field) producing from the Upper Fort Union Formation AU were used as an analogue for production. The Mill-Gillette field produces from coalbeds with characteristics similar to the Tullock and Lance coalbeds of the Lower Fort Union–Lance Formations AU; the field also has a poor production record, which was assumed to resemble that of the Lower Fort Union–Lance Formations AU because of the thin nature and low-rank properties of the coalbeds. Thus, based on the Mill-Gillette production analogue, only 13 wells are estimated to have EURs greater than the minimum of 0.02 BCF.

The area of the AU was estimated at a minimum of 4,063,000 acres, a median of 4,514,000 acres, and a maximum of 4,965,000 acres (table 3). The minimum area is calculated by drawing a boundary around all existing thick coalbeds in the AU in the eastern and southern parts of the Powder River Basin. The coalbeds of the AU are thickest in the deepest part

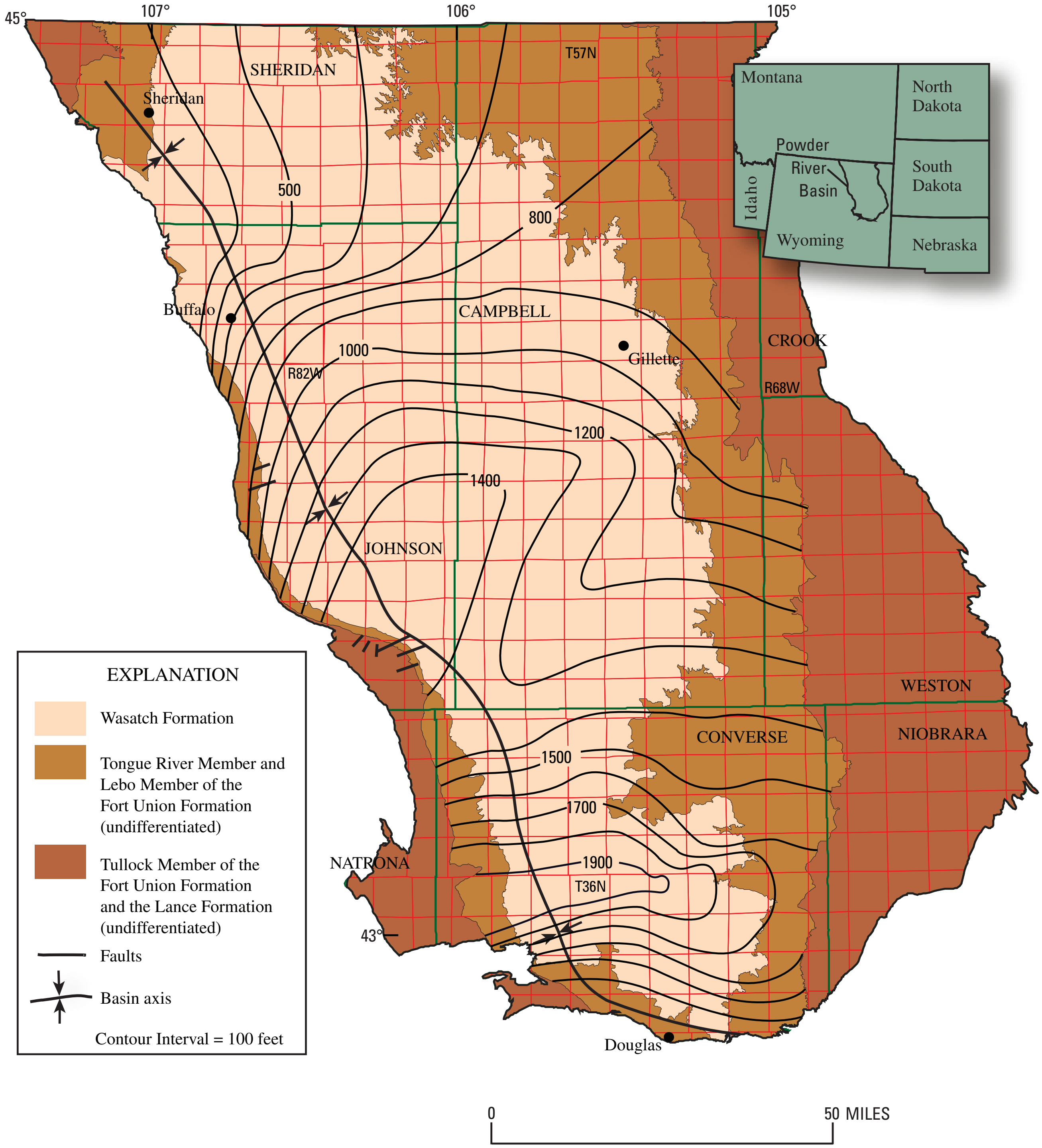


Figure 31. Isopach map of the Tullock Member of the Fort Union Formation superimposed on the generalized geological map, in the Powder River Basin, Wyoming. Modified from Curry (1971).

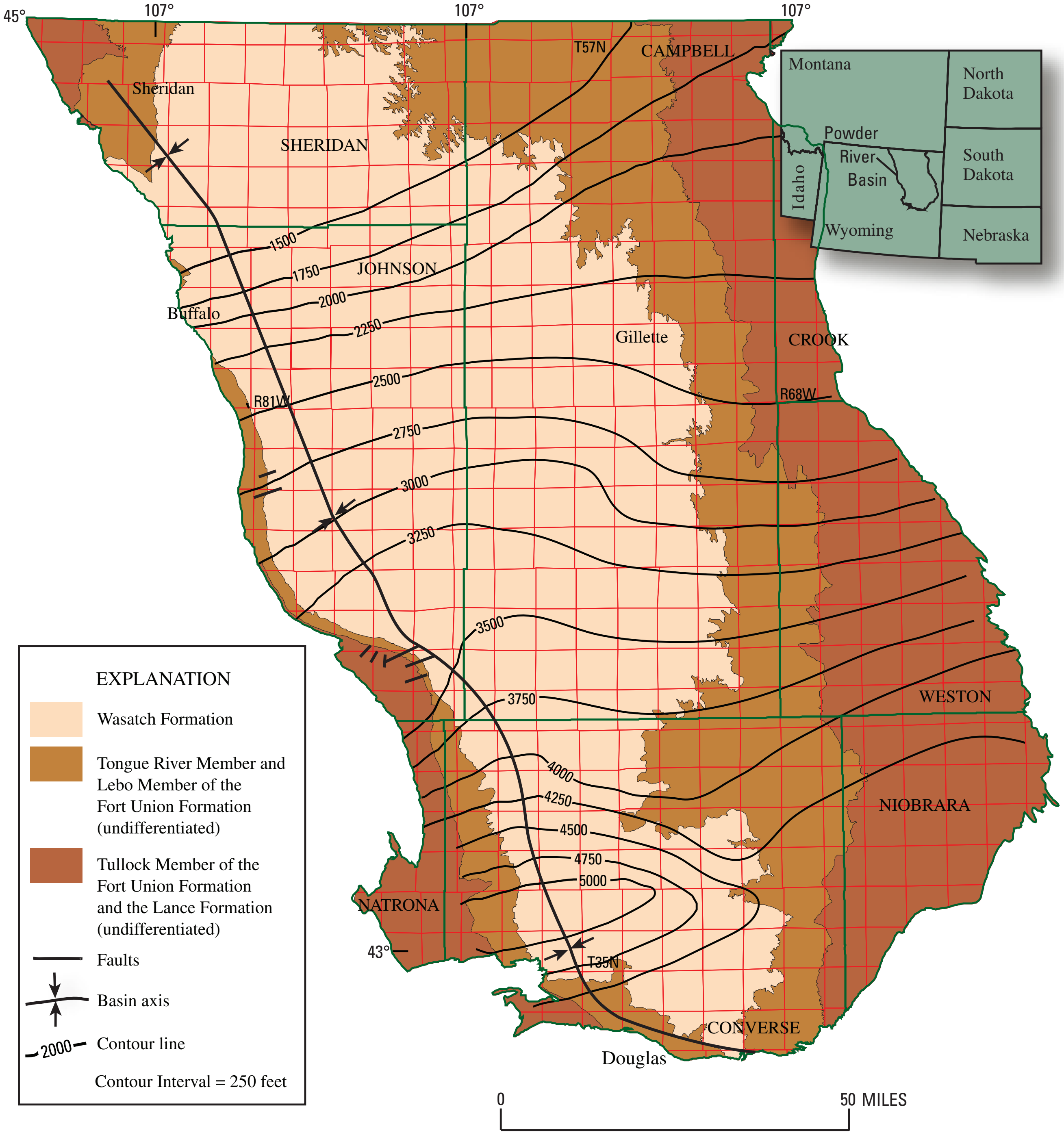


Figure 32. Isopach map of the Lance Formation and Fox Hills Sandstone superimposed on the generalized geologic map, Powder River Basin, Wyoming. Modified from Curry (1971).

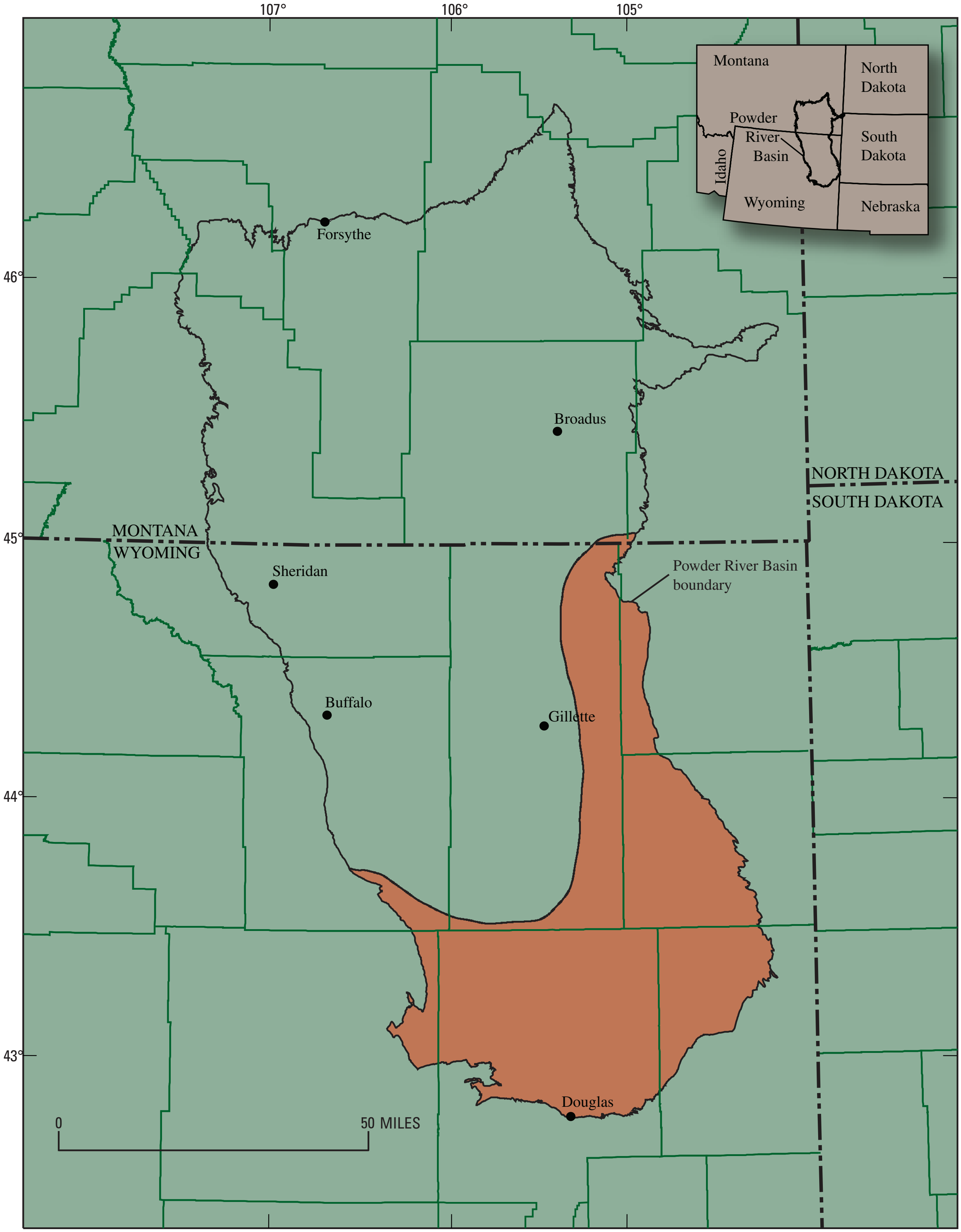


Figure 33. Map showing area in the southern Powder River Basin of Wyoming and Montana where coalbeds are as much as 7.5 feet thick in the Lower Fort Union–Lance Formations Assessment Unit.

Table 3. Basic input data form for the Lower Fort Union–Lance Formations Assessment Unit (50330183) of the Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System, Powder River Basin Montana and Wyoming.

FORSPAN ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 7, 6-30-00)

IDENTIFICATION INFORMATION

Assessment Geologist:… Romeo M. Flores Date: 10/18/00
Region:…………………… North America Number: 5
Province:………………… Powder River Basin Number: 5033
Total Petroleum System:. Tertiary-Upper Cretaceous Coalbed Methane Number: 503301
Assessment Unit:………. Lower Fort Union-Lance Formations Number: 50330183
Based on Data as of:…… PI production data current through third quarter 1999
Notes from Assessor….. Gas is biogenic. Mill-Gillette Field, because of similar coal rank, as an analogue.

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-Unit type: **Oil** (<20,000 cfg/bo) **or** **Gas** ($\geq$20,000 cfg/bo) Gas
What is the minimum total recovery per cell?… 0.02 BCF (mmbo for oil A.U.; bcfg for gas A.U.)
Number of tested cells:………… 0
Number of tested cells with total recovery per cell $\geq$ minimum: ……... 0
Established (>24 cells $\geq$ min.) Frontier (1-24 cells) Hypothetical (no cells) x
Median total recovery per cell (for cells $\geq$ min.): (mmbo for oil A.U.; bcfg for gas A.U.)
1st 3rd discovered ______ 2nd 3rd ______ 3rd 3rd ______

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an untested cell with total recovery $\geq$ minimum ……	1
2. **ROCKS:** Adequate reservoirs, traps, seals for an untested cell with total recovery $\geq$ minimum.	0.95
3. **TIMING:** Favorable geologic timing for an untested cell with total recovery $\geq$ minimum………..	1

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3):……….......……. 1.0

4. **ACCESS:** Adequate location for necessary petroleum-related activities for an untested cell with total recovery $\geq$ minimum ……………………………………………………………… 1.0

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES IN THE NEXT 30 YEARS

1. Total assessment-unit area (acres): (uncertainty of a fixed value)
minimum 4,063,000 median 4,514,000 maximum 4,965,000

2. Area per cell of untested cells having potential for additions to reserves in next 30 years (acres):
(values are inherently variable) minimum 40 median 80 maximum 140

3. Percentage of total assessment-unit area that is untested (%): (uncertainty of a fixed value)
minimum 100 median 100 maximum 100

4. Percentage of untested assessment-unit area that has potential for additions to reserves in next 30 years (%): (a necessary criterion is that total recovery per cell $\geq$ minimum)
(uncertainty of a fixed value) minimum 0.002 median 3 maximum 9

Table 3—Continued. Basic input data form for the Lower Fort Union-Lance Formations Assessment Unit (50330183) of the Tertiary- Upper Cretaceous Coalbed Methane Total Petroleum System, Powder River Basin Montana and Wyoming.

TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves in next 30 years:

	minimum	median	maximum
(values are inherently variable) (mmbo for oil A.U.; bcfg for gas A.U.)	0.02	0.085	1

AVERAGE COPRODUCT RATIOS FOR UNTESTED CELLS, TO ASSESS COPRODUCTS

(uncertainty of fixed but unknown values)

Oil assessment unit:	minimum	median	maximum
Gas/oil ratio (cfg/bo)………………………...……..			
NGL/gas ratio (bngl/mmcfg)……………………..….			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)….…………..……	0	0	0

SELECTED ANCILLARY DATA FOR UNTESTED CELLS

(values are inherently variable)

Oil assessment unit:	minimum	median	maximum
API gravity of oil (degrees)…………….………….			
Sulfur content of oil (%)………………………...…			
Drilling depth (m) ……………...…………….……			
Depth (m) of water (if applicable)……………….			
Gas assessment unit:			
Inert-gas content (%)……………………….....…..	2.00	3.00	4.00
CO_2 content (%)………………………………..…..	3.00	5.00	8.00
Hydrogen-sulfide content (%)……………...…….	0.00	0.00	0.00
Drilling depth (m)………………………………….	460	1400	2500
Depth (m) of water (if applicable)……………….			

of the basin. Area per cell of untested cells having potential for additions to reserves in the next 30 years is estimated at a minimum of 40 acres, a median of 80 acres, and a maximum of 140 acres (table 3). The drainage areas are the same as those for Wasatch Formation AU and the Upper Fort Union Formation AU because of their similarity lithologically to the Lower Fort Union-Lance Formations AU. The percentage of total AU area that is untested is 100 percent. The percentage of untested AU area that has potential for additions to reserves in the next 30 years is estimated at a minimum of 0.002 percent, a median of 3 percent, and a maximum of 9 percent (table 3). This is predicated by coalbeds in the AU, which are not as thick and common as those in the Upper Fort Union Formation AU. The total recovery per cell for untested cells having potential for additions to reserves in the next 30 years is estimated at a minimum of 0.02 BCF, a median of 0.085 BCF, and a maximum of 1 BCF (table 3). The thin and low-rank coalbeds of the Lower Fort Union–Lance Formations AU do not add significantly to reserves in the next 30 years. In addition, the position of these coalbeds in the deeper southern part of the Powder River Basin, particularly at depths more than 6,000 ft, decreases their permeability and potential for gas production (McKee and others, 1986).

Eastern Basin Margin Upper Fort Union Sandstone Assessment Unit, 50330101

Assessment Unit 50330101 is a conventional accumulation of CBM contained in sandstones interbedded with coalbeds in the upper part of the Fort Union Formation (see fig. 2). The fluvial-channel sandstones, which are as much as 300 ft thick, are mainly found in the Tongue River Member of the Fort Union Formation. The sandstone reservoirs were deposited largely in meandering and anastomosed streams flanked by flood plains and raised mires. The fluvial-channel sandstones, which make up more than one-third of the total volume of the upper part of the Fort Union, commonly pinch out against and are bounded by mudstones. The coalbeds directly underlie and overlie the fluvial-channel sandstones, indicating communication between the sandstone reservoir beds and the CBM source rocks along erosional contacts and through fractures and faults. Early formed biogenic gas from the coal or its precursors may have migrated into adjoining sandstones during burial and differential compaction of detrital sediments. Gas may have been trapped early by surrounding impermeable mudstones and later during erosion and uplift when the ground-water system was recharged and late-stage CBM was generated. As ground-water levels were lowered during glacial periods, pressure in the coalbeds was decreased, permitting desorption of the gas from the coal and its migration into and entrapment in the sandstones.

The area of this conventional AU (fig. 34) is defined by the outcrop contact at the top of the Tongue River Member of the Fort Union Formation on the east and the 750-ft-depth isoline in the central part of the Powder River Basin. In addition, the AU is limited by the areal distribution of the clinkers of coalbeds in the Tongue River Member (see fig. 6). The geographic location of the clinkers defines the area of groundwater recharge, storage, and flow downdip to coalbeds in proximity to potential sandstone reservoirs in the upper part of the Fort Union Formation.

The sandstones in the Eastern Basin Margin Upper Fort Union Sandstone AU display maximum net total thickness from 250 to 300 ft (figs. 35 and 36). Single fluvial-channel sandstone bodies can be as much as 50 ft thick, while multistacked bodies can be as much as 200 ft thick, more than 4 mi wide, and more than 40 mi long. A typical multistacked body is the northerly oriented complex in the interval between the Pawnee and Cache coalbeds (figs. 3 and 37) (Flores, 1981, 1986). The cross section in figure 37 shows that this Pawnee-Cache fluvial-channel sandstone complex is, in turn, laterally offset or en echelon to the fluvial-channel sandstone complex in the interval between the Wall and Cook coalbeds. That is, the thickest part of the successive fluvial-channel sandstone complexes do not directly overlie one another but are slightly displaced, with the thickest part of the youngest fluvial-channel sandstone complex overlying the coal and fine-grained sediments that are lateral equivalents of the underlying older fluvial-channel sandstone complex. In addition, where the younger complex pinches out, the Wall and Cook coalbeds are merged. The en-echelon arrangement of the fluvial-channel sandstone complexes may serve as a model to predict stratigraphic and areal distributions of sandstone reservoirs for CBM exploration and development.

The en-echelon patterns of the fluvial-channel sandstone complexes are typical of autocyclic shifts or avulsion of fluvial channels into an adjoining, topographically low area such as that created by dewatering and compaction of the original peat represented by the more than 40-ft-thick Pawnee coalbed and fine-grained flood-plain sediments (Flores, 1981, 1986). Fluvial-channel aggradation on one part of the alluvial plain was accompanied by deposition of peat and flood-plain sediments on another part where the lower gradient influenced diversion and abandonment of the former fluvial channel. Peat-forming mires, expanding from surrounding areas, gradually covered the abandoned fluvial channel sands. Repetition through time of fluvial-channel aggradation and peat-flood-plain sedimentation eventually caused the coalbeds to be split by the fluvial-channel sandstones. Crossbed measurements of the fluvial-channel sandstone beds indicate an east-northeast flow direction (see fig. 37)

Commercial quantities of gas have been produced from shallow (200–400 ft below the surface) fluvial-channel sandstone reservoirs since 1987. Oldham (1997) reported a large gas accumulation (CH_4 = 94.1 percent; N_2=5.8 percent; CO_2=0.1 percent) and cumulative production (1.8 BCF) at a depth of 340 ft from fluvial-channel sandstones between the Anderson, Canyon, and Cook coalbeds in the Oedekoven field in the Recluse area (fig. 38). In the same area, the Chan field also produced about 1.5 BCF of gas from fluvial-channel sand-

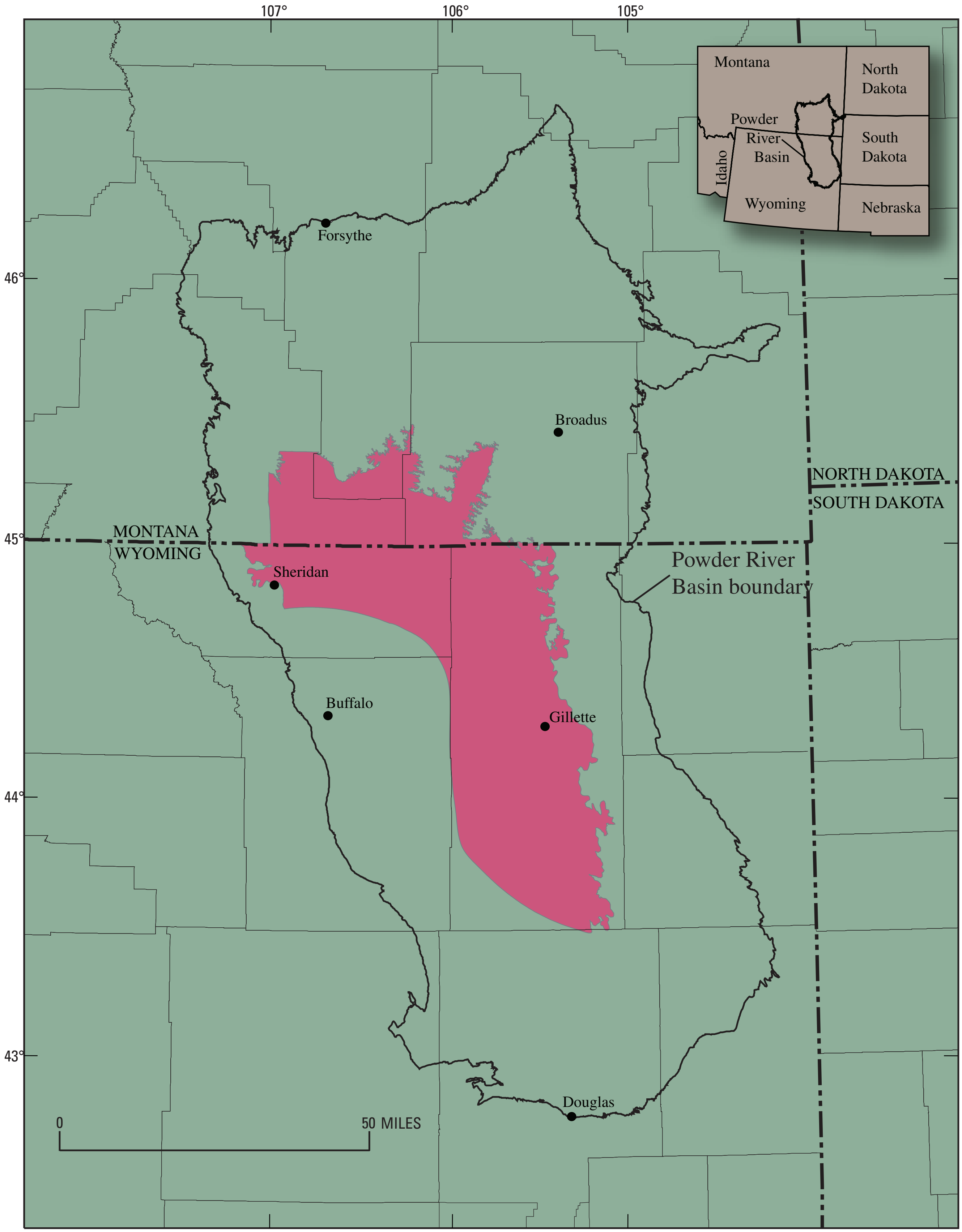


Figure 34. Map showing the extent of the Eastern Basin Margin Upper Fort Union Sandstone Assessment Unit, Powder River Basin, Wyoming and Montana.

Figure 35. Map showing net sandstone thickness above the Wyodak-Anderson coal zone of the Fort Union Formation in Wyoming. Only those sandstone beds greater than 10 feet thick are included in the isopach map.

Figure 36. Map showing net sandstone thickness of the Fort Union Formation below the Wyodak-Anderson coal zone of the Fort Union Formation in Wyoming. Only those sandstone beds greater than 10 feet thick are included in the isopach map.

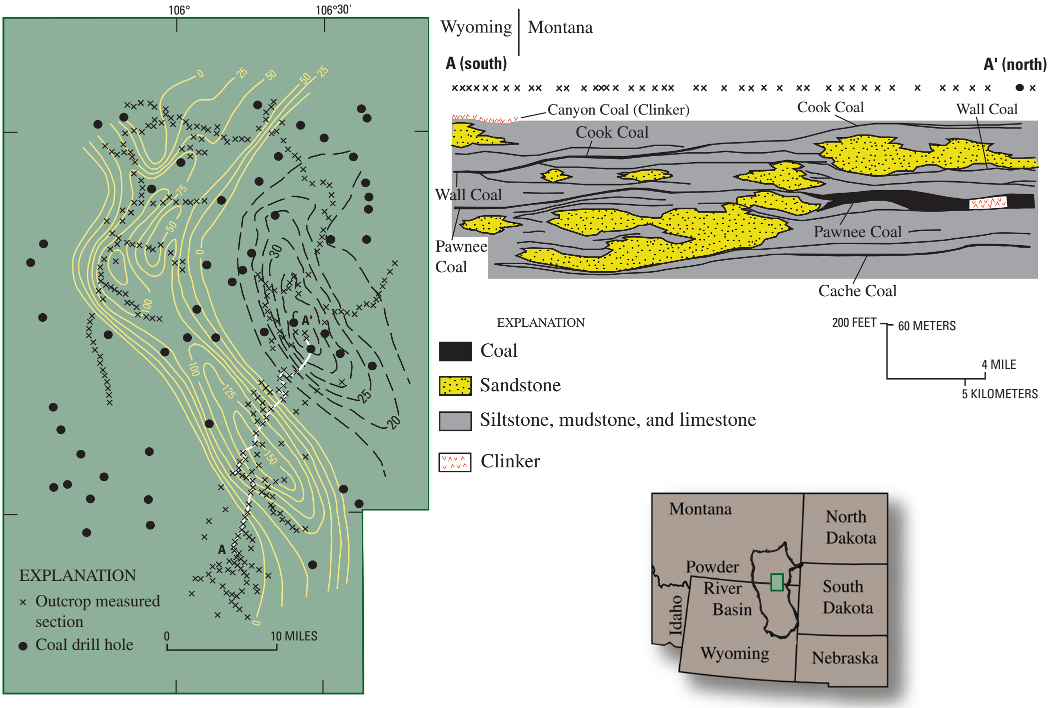


Figure 37. In this two-part diagram, the isopach map shows thickness of the fluvial-channel sandstone complex between the Pawnee and Cache coalbeds. On the isopach map, yellow lines are isopachs of the channel sandstone complex and dashed black lines are isopachs of Pawnee coal, in feet. The white line on the isopach map shows the location of the cross section which, in turn, shows the stratigraphic variations of the fluvial-channel sandstone complexes between the Cache, Pawnee, and Canyon coalbeds. Modified from Flores (1981, 1986).

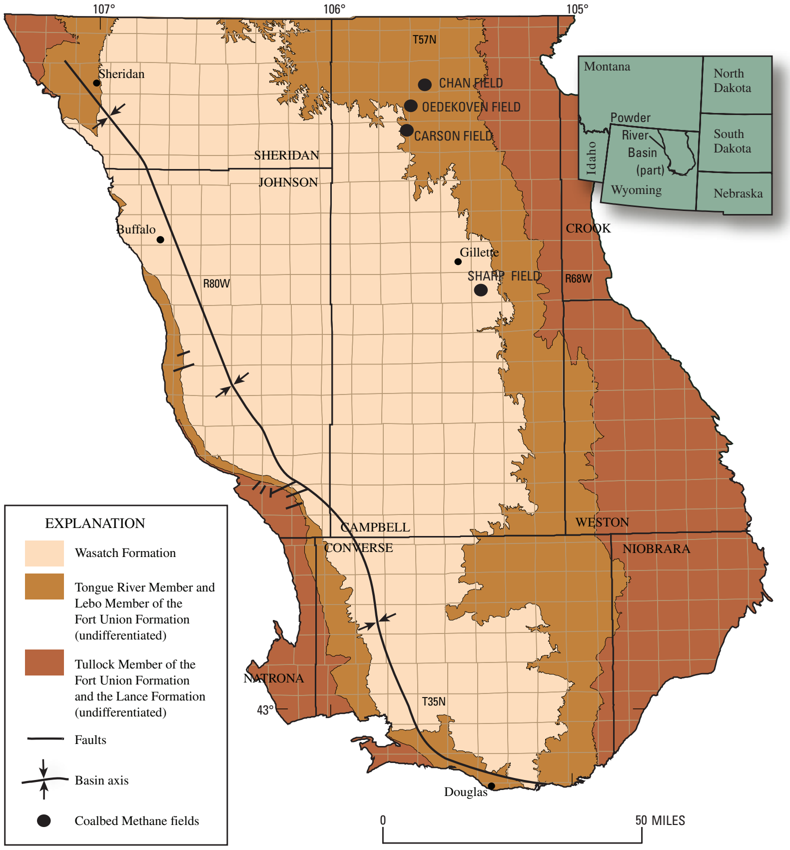


Figure 38. Map showing locations of gas fields producing coalbed methane from the fluvial-channel sandstone reservoirs of the upper part of the Fort Union Formation in the eastern part of the Powder River Basin in Wyoming.

stones 300 to 500 ft deep interbedded with Canyon, Cook, and Wall coalbeds. Gas saturation in the upper parts of these sandstone reservoirs is recognized by upward increasing resistivity and unchanged gamma ray response (Oldham, 1997).

Randall (1989) reported a direct relationship between thicker sandstone reservoirs and increased cumulative gas production in the Oedekoven and Chan fields. Randall (1989) also indicated that productive sandstone reservoirs have high self potential and very little water production, although some sandstone reservoirs with gas/water contacts are present in the Oedekoven field (fig. 39). The best producing wells in the Oedekoven and Chan fields have the thickest sandstone pays and are present at the crests of anticlines and in structural lows. The anticlines, which overlie coalbeds where CBM is trapped, resemble compaction folds described by Law (1976) and Law and others (1991) (see fig. 39). In addition, normal faults, which may have been propagated as compaction faults, may act as traps for gas in sandstones (Henderson, 1991; Law and others, 1991).

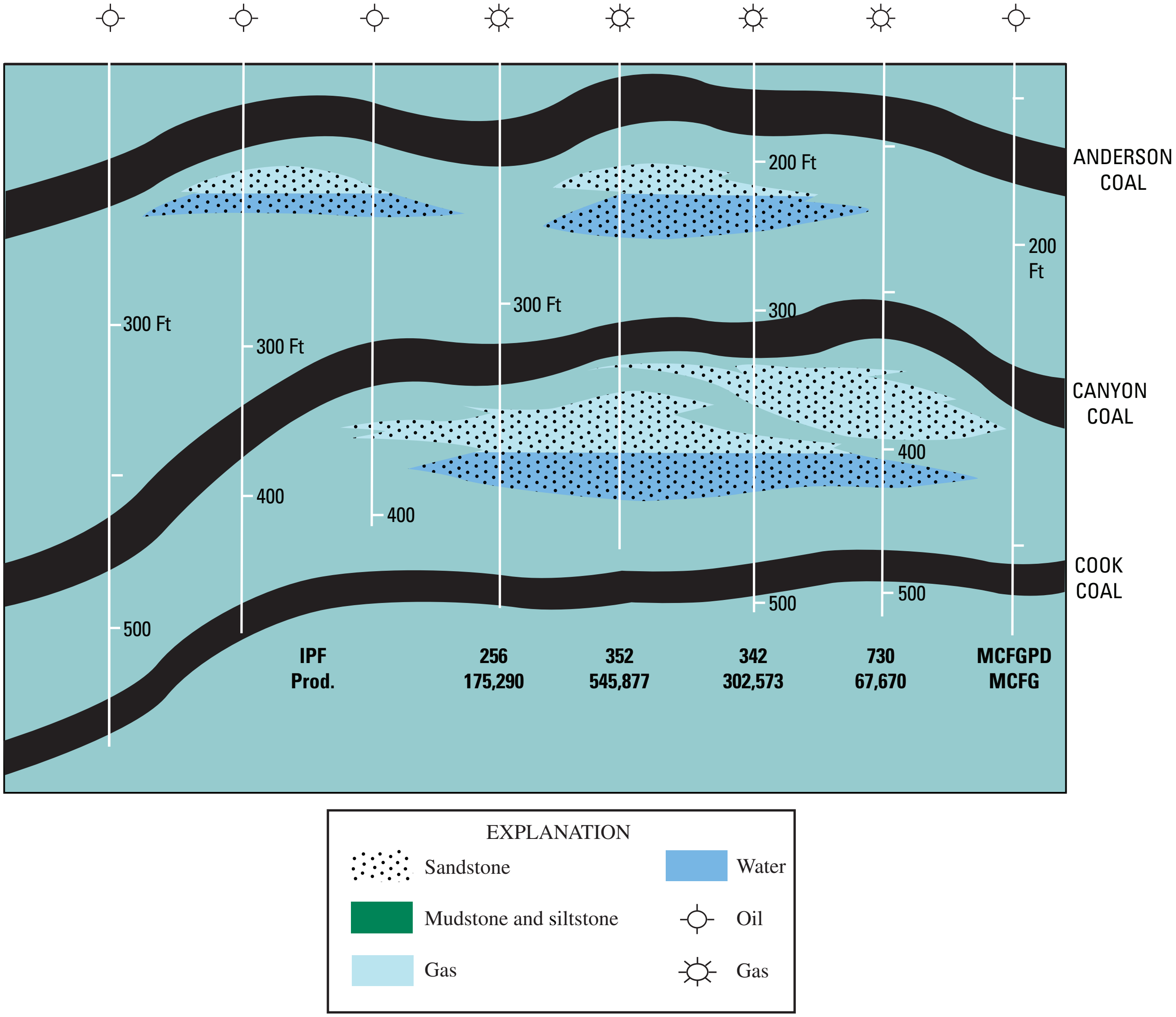


Figure 39. Generalized cross section showing the upper Fort Union Formation fluvial-channel sandstone reservoirs and associated water and coalbeds in the Oedekoven gas field in Campbell County, Powder River Basin, Wyoming. Modified from Oldham (1997). IPF = initial production flow. MMCFG = million cubic feet of gas. MMCFGPD = million cubic feet of gas per day. Vertical scale at sea level. No horizontal scale.

Thus, discovery and development of sandstone gas from these fields demonstrate the potential of other upper Fort Union sandstone reservoirs, which Rice and Flores (1990) reported, particularly in the shallow eastern and northern parts of the Powder River Basin. The shallow depths (250–2,500 ft) of the sandstone reservoirs and the ability to delineate these reservoirs from the abundant well control, particularly from CBM-producing wells, make them attractive targets for exploration and continued development.

The Oedekoven and Chan fields that produce CBM within the Eastern Basin Margin Upper Fort Union Sandstone AU do not have EURs above the minimum of 0.5 BCF. The number of undiscovered gas accumulations above the minimum size (0.5 BCF) that can be found in the next 30 years are a minimum of 1, a median of 6, and a maximum of 15 (table 4). The size of undiscovered gas fields is estimated at a minimum of 3 BCF, a median of 5 BCF, and a maximum of 200 BCF (table 4).

Results of Coalbed Methane Assessment in the Powder River Basin

The tabulated estimates of undiscovered CBM resources in the Powder Basin for AUs in the Tertiary-Upper Cretaceous Coalbed Methane TPS are listed in table 5. The resource estimates are summarized for each accumulation type (continuous and conventional) and for each AU (Wasatch Formation, Upper Fort Union Formation, and Lower Fort Union-Lance Formations under continuous type; and Eastern Basin Margin Upper Fort Union Sandstone under conventional type). The tabulated results represent estimates of undiscovered CBM resources from the coal and sandstone reservoirs in the Tertiary-Upper Cretaceous Coalbed Methane TPS that have the potential to contribute to gas reserves in the next 30 years.

The mean estimate for undiscovered CBM resources in the Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System is about 14.26 trillion cubic feet (TCF). Of this total, the vast majority of the CBM resources is in the coal-bed reservoirs in the Wasatch, Fort Union, and Lance Formations. A subordinate amount, about 0.027 TCF, is in the sandstone reservoirs of the upper part of the Fort Union Formation. Thus, more than 99 percent of the estimated CBM resources in the Powder River Basin are associated with continuous-type accumulations.

A summary of the mean estimates for undiscovered CBM resources in individual AUs includes: (1) 1.9 TCF for the Wasatch Formation AU, (2) 12.1 TCF for the Upper Fort Union Formation AU, (3) 0.2 TCF for the Lower Fort Union-Lance Formations AU, and (4) 0.03 for the Eastern Basin Margin Upper Fort Union Sandstone AU. The statistical chances (F95, F50, and F5) of at least the amount of estimated CBM resources are also shown in table 5.

These CBM resource estimates differ from those of Rice and Finn (1996) who used a different methodology to estimate a mean of 1.1 TCF of potential additions to reserves from two CBM plays: (1) Powder River Basin – Shallow Mining-Related play (3350) and (2) Powder River Basin – Central Basin play (3351). Rice and Finn (1996) estimated the first CBM play to have a mean of 681 BCF potential additions to reserves and the second CBM play to have a mean of 425 BCF potential additions to reserves.

Summary

The Tertiary-Upper Cretaceous Coalbed Methane TPS in the Powder River Basin consists of about 8,940 ft of Lance, Fort Union, and Wasatch Formations. These rock units contain thin to thick coalbeds, which produce bacteria-generated methane particularly in the Upper Fort Union Formation AU (50330182). In this continuous assessment unit the coalbed methane is coproduced with a high volume of freshwater that is released on the surface. As much as 57 BCF of methane was produced from about 1,500 wells as of December 31, 1999. Presently, the well density ranges from 8 to 16 wells per section, with the WOGCC determining an average of 80-acre well spacing basinwide to alleviate the high volume of water being disposed of on the surface. Currently, CBM development is in the eastern part and moving toward the center of the basin. The Bureau of Land Management (2003) projects about 50,000 completed wells in the basin.

The Wasatch Formation AU (50330181) and Lower Fort Union–Lance Formations AU (50330183) are hypothetical assessment units in which potential for additions to reserves in the next 30 years is best defined along the west-central and southern parts of the Powder River Basin where the coals are thick and deep. Although the coalbeds in these hypothetical units are neither as thick nor as high in rank as those in the Upper Fort Union Formation AU, analogues from the Upper Fort Union Formation AU were used to determine potential for additions to reserves in the next 30 years. The Wasatch Formation AU has better potential than the Lower Fort Union–Lance Formations AU based on more coal resources and shallower distribution.

Figure 40 is a summary of the timing of geologic events for the continuous AUs in this TPS. This geologic events chart shows the onset of the biogenic gas and its generation, accumulation, migration, maturation, and trapping/sealing processes. In addition, the chart shows the relationship between these processes and the deformation of the basin by the Laramide Orogeny and by depositional settings in the basin.

The Eastern Basin Margin Upper Fort Union Sandstone AU (50330101) is contained within the Upper Fort Union Formation AU (50330182) and is presently being developed for CBM that migrated from adjoining coalbeds into the sandstones. However, CBM is not as extensively developed in these sandstone beds as in the Upper Fort Union coalbeds. The AU area is directly related to the proximity of the sandstone reservoirs to clinker areas where large amounts of

Table 4. Basic input data form for the Eastern Basin Margin Upper Fort Union Sandstone Assessment Unit (50330101) of the Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System, Powder River Basin Montana and Wyoming.

SEVENTH APPROXIMATION
DATA FORM FOR CONVENTIONAL ASSESSMENT UNITS (NOGA, Version 5, 6-30-01)

IDENTIFICATION INFORMATION

Assessment Geologist:……..	Romeo M. Flores	Date:	10/18/00
Region:………………………..	North America	Number:	5
Province:………………………	Powder River Basin	Number:	5033
Total Petroleum System:……	Tertiary-Upper Cretaceous Coalbed Methane	Number:	503301
Assessment Unit:……………	Eastern Basin Margin Upper Fort Union Sandstone	Number:	50330101
Based on Data as of:……….	Data from BLM and Wyoming Oil and Gas Commission, both first quarter 2000		
Notes from Assessor……….	Degassing of coalbed gas into adjacent sandstones during lowering of water. channel sandstones		

CHARACTERISTICS OF ASSESSMENT UNIT

Oil (<20,000 cfg/bo overall) **or** Gas (≥20,000 cfg/bo overall):… Gas

What is the minimum accumulation size?………. 0.5 mmboe grown
(the smallest accumulation that has potential to be added to reserves in the next 30 years)

No. of discovered accumulations exceeding minimum size:………… Oil: 0 Gas: 0
Established (>13 accums.) ______ Frontier (1-13 accums.) ______ Hypothetical (no accums.) x

Median size (grown) of discovered oil accumulation (mmbo):
1st 3rd ______ 2nd 3rd ______ 3rd 3rd ______
Median size (grown) of discovered gas accumulations (bcfg):
1st 3rd ______ 2nd 3rd ______ 3rd 3rd ______

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an undiscovered accum. ≥ minimum size………………	0.7
2. **ROCKS:** Adequate reservoirs, traps, and seals for an undiscovered accum. ≥ minimum size……	1.0
3. **TIMING OF GEOLOGIC EVENTS:** Favorable timing for an undiscovered accum. ≥ minimum size	0.7

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3):……..……....…. 0.49

4. **ACCESSIBILITY:** Adequate location to allow exploration for an undiscovered accumulation ≥ minimum size………………………………………………..………………..……..………… 1.0

UNDISCOVERED ACCUMULATIONS

No. of Undiscovered Accumulations: How many undiscovered accums. exist that are ≥ min. size?:
(uncertainty of fixed but unknown values)

Oil Accumulations:…………………min. no. (>0)	0	med. no.	0	max. no.	0
Gas Accumulations:………………min. no. (>0)	1	med. no.	6	max. no.	15

Sizes of Undiscovered Accumulations: What are the sizes (**grown**) of the above accums?:
(variations in the sizes of undiscovered accumulations)

Oil in Oil Accumulations (mmbo):…...…min. size		med. size			max. size
Gas in Gas Accumulations (bcfg):…..…min. size	3	med. size	5	max. size	200

Table 4 — Continued. Basic input data form for the Eastern Basin Margin Upper Fort Union Sandstone Assessment Unit (50330101) of the Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System, Powder River Basin Montana and Wyoming.

AVERAGE RATIOS FOR UNDISCOVERED ACCUMS., TO ASSESS COPRODUCTS

(uncertainty of fixed but unknown values)

Oil Accumulations:	minimum	median	maximum
Gas/oil ratio (cfg/bo)			
NGL/gas ratio (bngl/mmcfg)			

Gas Accumulations:	minimum	median	maximum
Liquids/gas ratio (bliq/mmcfg)	0	0	0
Oil/gas ratio (bo/mmcfg)			

SELECTED ANCILLARY DATA FOR UNDISCOVERED ACCUMULATIONS

(variations in the properties of undiscovered accumulations)

Oil Accumulations:	minimum	median	maximum
API gravity (degrees)			
Sulfur content of oil (%)			
Drilling Depth (m)			
Depth (m) of water (if applicable)			

Gas Accumulations:	minimum	median	maximum
Inert gas content (%)	2	3	4
CO_2 content (%)	3	5	8
Hydrogen-sulfide content (%)	0	0	0
Drilling Depth (m)	80	460	770
Depth (m) of water (if applicable)			

Table 5. Coalbed methane, Powder River Basin province, assessment unit results summary.

[MMBO, million barrels of oi
is the minimum field siz
probability (including both geologic and accessibility probabilities) of at least one field (or for continuous-type resources, cell) equal to or greater than the minimum. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 represents a 95- percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable]

Code and Field Type	Minimum	Prob. (0-1)	Undiscovered Resources											
			Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
503301	**Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System—Continuous Resource Assessment Unit Summary**													
50330181	Wasatch Formation Assessment Unit													
Gas	0.02	1.00	▨	▨	▨	▨	1,011.94	1,815.71	3,257.89	1,934.09	0.00	0.00	0.00	0.00
50330182	Upper Fort Union Formation Assessment Unit													
Gas	0.02	1.00	▨	▨	▨	▨	7,232.13	11,635.87	18,721.10	12,132.50	0.00	0.00	0.00	0.00
50330183	Lower Fort Union-Lance Formations Assessment Unit													
Gas	0.02	1.00	▨	▨	▨	▨	0.00	171.67	440.89	197.89	0.00	0.00	0.00	0.00
503301	**Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System—Conventional Resource Assessment Unit Summary**													
50330101	Eastern Basin Margin Upper Fort Union Sandstone Assessment Unit													
Oil Fields	0.5		0	0	0	0	0	0	0	0	0	0	0	0
Gas Fields	3	0.49					0	0	107.43	27.37	0	0	0	

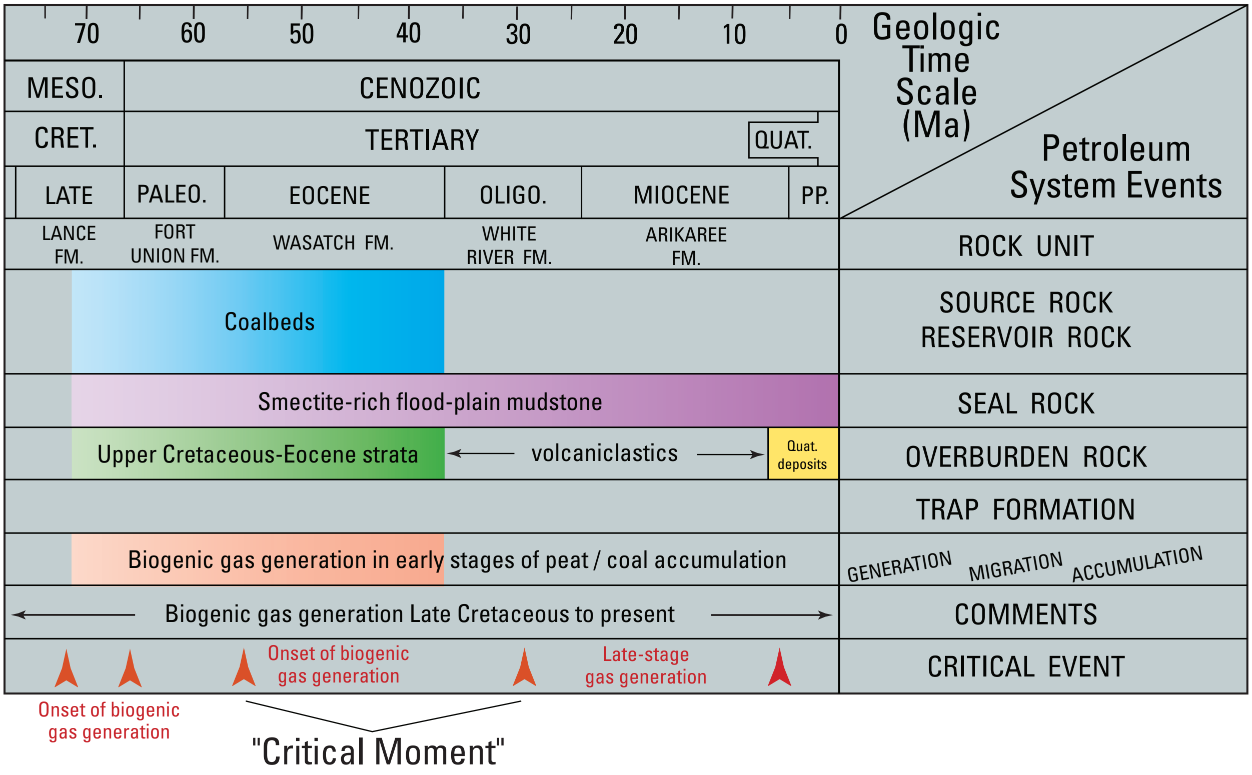


Figure 40. Events chart showing timing of elements and processes related to coalbed methane generation and accumulation in the Wasatch Formation, Upper Fort Union Formation, and Lower Fort Union-Lance Formations Assessment Units of the Powder River Basin, Wyoming and Montana. PP. = Pliocene-Pleistocene; FM. = Formation; Ma = million years. Arrows show onset of gas generation.

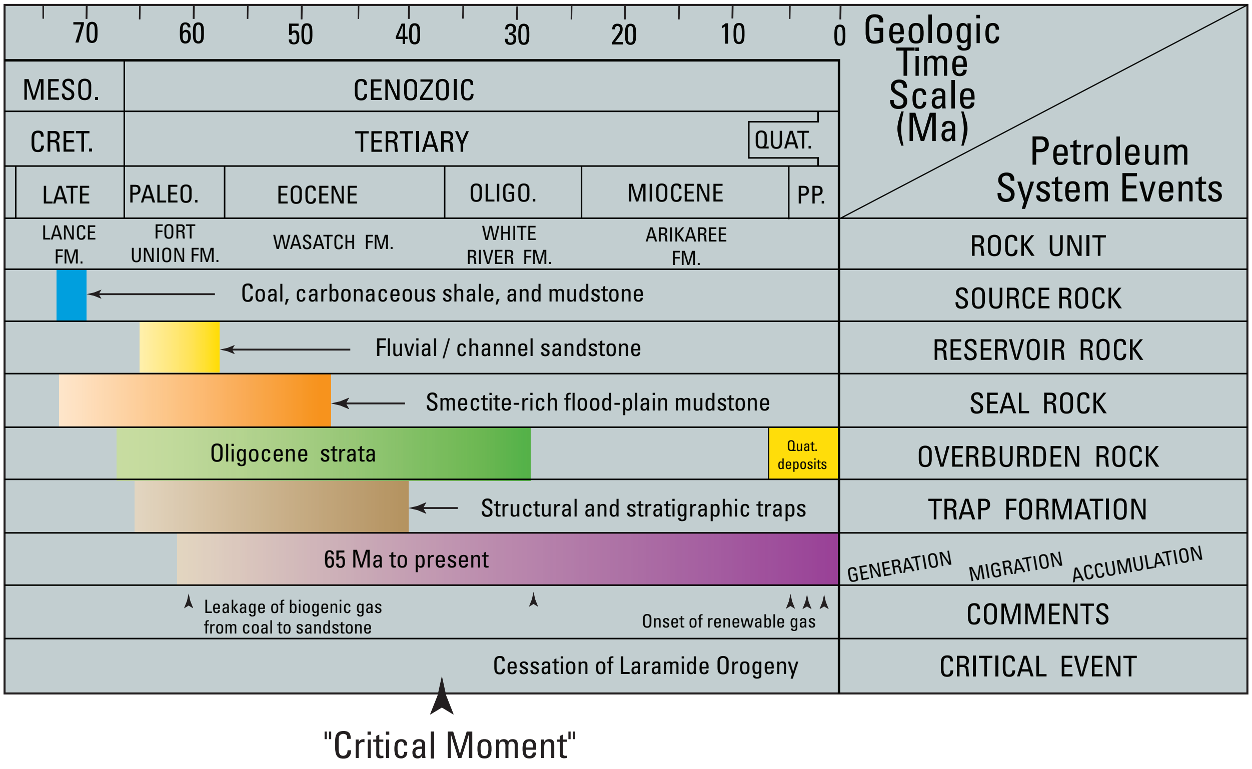


Figure 41. Events chart showing timing of elements and processes related to coalbed methane generation, migration, accumulation, and entrapment in the Eastern Basin Margin Upper Fort Union Sandstone Assessment Unit of the Powder River Basin, Wyoming and Montana. PP. = Pliocene-Pleistocene; FM. = Formation; Ma = million years.

water are stored and conducted to interbedded coalbeds. In these sandstones, minor CBM fields (less than 0.5 BCF) produce from structural and stratigraphic traps. The estimate of potential for additions to reserves in the next 30 years assumes discovery of bigger fields in the part of the basin where the net total thickness of the sandstones is as much as 300 ft and the lateral extent more than 3 mi wide and 40 mi long.

The timing of geologic events related to the conventional Eastern Basin Margin Upper Fort Union Sandstones AU is summarized in figure 41. The events chart shows the time of evolution and generation of the biogenic gas, its leakage from the coalbeds, and its migration, accumulation, and trapping/sealing mechanisms. Also, the chart shows the relationship between these mechanisms and the timing of basin deformation, as controlled by the Laramide Orogeny. Finally, it shows the regeneration of the biogenic gas, particularly in relation to recharge and changes in ground-water levels during Pleistocene time.

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