Chapter PS

FORT UNION COAL IN THE POWDER RIVER BASIN, WYOMING AND MONTANA: A SYNTHESIS

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Click here or on this symbol
in the toolbar to return.

Contents

Figures

Click here or on this symbol
in the toolbar to return.

PS-5. Variegated and mottled siltstone and mudstone (lower part of picture) are capped by partly oxidized, rooted carbonaceous mudstone (central part of picture) representing a paleosol formed in the interfan environment.

PS-6. Pebble conglomerate of the Tongue River Member exposed north of Kaycee; represents braided stream deposits.

PS-7. Floodplain mudstone, siltstone, and silty sandstone underlain by fluvial channel sandstone beds (lower part of photo).

PS-8. Coarsening-upward mudstone, siltstone, and silty sandstone crevasse splay deposits. These rocks are exposed along the Powder River in northeastern Wyoming.

PS-9. Vertically stacked fluvial channel sandstone deposits interbedded with floodplain and crevasse splay deposits. These deposits are below along the "Sussex" coal zone, which is exposed north of Linch, Wyoming.

PS-10. Fluvial channel deposit consisting of multi-erosional, crossbedded sandstone intercalated with basally erosional mudstone deposits that are abandoned "clay plugs." These deposits are below along the "Sussex" coal zone, which is exposed north of Linch, Wyoming.

PS-11. Wyodak-Anderson coal, which is more than 100 ft thick, in the Eagle Butte coal mine in the Gillette coalfield in Wyoming. Coal train is on horizon in background.

PS-12. Diagrammatic cross section of a raised bog between two river estuaries in Sumatra, Indonesia.

PS-13. Peat exposed along a drainage ditch cut near the margin of a raised bog in central Kalimantan, Borneo, Indonesia.

PS-14. Wyodak-Anderson coal (Anderson-Dietz coal), showing a thin, carbonaceous, coaly mudstone parting in the Spring Creek coal mine in Montana.

Click here or on this symbol
in the toolbar to return.

PS-15. The split Wyodak-Anderson coal zone (upper bed is Anderson or Dietz 1 coal and the lower bed is Dietz 2 coal) in the Decker coal mine in Montana.

PS-16. The merged Wyodak-Anderson coal, which is more than 80 ft thick, in the Spring Creek coal mine in Montana.

PS-17. Distribution of the number of coal beds in the Wyodak-Anderson coal zone in the Powder River Basin.

PS-18. Biozones of the Wyodak-Anderson coal zone indicate early late Paleocene (P5) to latest Paleocene (P6) from the center to the margins of the basin. P5–P6 biozone is between these Paleocene ages.

PS-19. Clinker (orange-red) of the Anderson coal bed (upper clinker) and Canyon coal bed (lower clinker) of the Wyodak-Anderson coal zone along the valley wall of the Powder River in Wyoming. Here, the coal beds are susceptible to burning, which progresses downdip (to the left of photo).

PS-20. A closer view of the clinker consisting of black, vesicular, cryptocrystalline to glassy fused rock, range-red baked mudstone, siltstone, and sandstone, and breccia composed of angular unfused to slightly fused rock fragments (Coates, 1980).

PS-21. Clinker (orange-red on the left of the picture) of the Anderson or Dietz 1 coal bed (on the right of the picture) on the highwall of the Decker coal mine in Montana. Burning has reduced the reserve of the Anderson coal bed.

PS-22. An outcrop (north of Linch, Wyoming) of the “Sussex” coal zone consisting of a more than 20-ft- thick coal bed (upper part of picture) and three underlying thin coal beds that are interbedded with silty sandstone, siltstone, and mudstone representing floodplain deposits. The “Sussex” coal zone is overlain by a fluvial channel sandstone.

Click here or on this symbol
in the toolbar to return.

INTRODUCTION

Major coal resources of subbituminous rank exist in the Fort Union Formation (Paleocene) in the Powder River Basin in Wyoming and Montana (fig. PS-1). Fort Union strata make up the surface bedrock along the margins of the Powder River Basin. These strata (fig. PS-2) are conformably underlain by the Lance Formation (Upper Cretaceous) and conformably (in the basin center) and unconformably (at the basin margins) overlain by the Wasatch Formation (Eocene). The coaly nature of the Fort Union strata was first documented in mid-1850's by Kemble Warren in eastern Montana (Bryans, 1987). In 1859 and 1860 Ferdinand V. Hayden, a member of Capt. W. F. Raynolds' expedition exploring the Lower Yellowstone, reported extensive lignite in an area between the Platte River and Pumpkin Buttes (Bryans, 1987). In 1865, James A. Sawyer received a commission from the Department of the Interior to survey the Montana gold fields. Traveling through the Powder River country, he observed several sizeable coal deposits south of Gillette, Wyoming (Gardner and Flores, 1989). Sawyer indicated that these coal deposits were the best he had seen in the west, and an inexhaustible coal resource seemed to be present, judging from the amount of outcrops he had observed (Bryans, 1987). These coal deposits in the Powder River Basin remained undeveloped prior to 1877 because the coal was within tribal lands belonging to the Sioux, Cheyenne, and Arapahoe (Gardner and Flores, 1989). Lands north of the North Platte River and east of the Bighorn Mountains were designated as unceded Indian territory by the Fort Laramie Treaty of 1868. However, reports of gold in the Black Hills in 1874 encouraged trespassers to the territory, and hostilities began between the U.S. Army and the Sioux and Cheyenne that led to the Rosebud and Little Bighorn battles. After the surrender of Crazy Horse in the spring of 1877, the Powder River Basin was opened to development by settlers.

Click here or on this symbol
in the toolbar to return.

Hayden (1861) first named the lignite beds between the Platte River and Pumpkin Buttes as the Great Lignite Group, which was renamed the Fort Union Group by Meek and Hayden (1862). The upper part of this group was dated by Newberry (1868) as Tertiary, based on plant fossils. Later, the lower part of this group was dated by Stanton and Knowlton (1897) as Cretaceous, based on dinosaur fossils, and these workers identified this part as the Lance Formation. Brown (1907) named the Hell Creek Formation in Montana, which is correlative to the Lance Formation in Wyoming. However, Knowlton (1909) divided the Fort Union Group above the Cretaceous Lance into the upper and lower Fort Union, with the lower part including the Hell Creek Formation. The position of the Cretaceous-Paleocene boundary between the Hell Creek Formation and the overlying Fort Union Group was resolved by discovery of mammalian fossils and confirmed by plant fossils (Simpson, 1937; Dorf, 1940, 1942; Brown, 1958, 1962). The paleobotanical studies of Dorf (1940; 1942) resolved the position of the Cretaceous-Paleocene (Lance-Fort Union) boundary in the Powder River Basin. The dated Fort Union Group was divided into the Fort Union Formation in the lower part and the Wasatch Formation in the upper part. Traditionally, the Fort Union is dated as Paleocene and the Wasatch is dated as Eocene. The actual position of the Paleocene-Eocene boundary between these formations remains controversial. The time boundary and formation contact, often considered to be coincident, have been recognized on the basis of: (1) the change in the lithology of mappable units (Taff, 1909; Wegemann, 1910, 1917, 1929; Davis 1912; Thom and Dobbin, 1924; Dobbin and Barnett, 1928; Baker, 1929; Bass, 1932; Bryson, 1952; Olive, 1957; Mapel, 1959; Bryson and Bass, 1973; Culbertson and Mapel, 1976); (2) erosion or a regional unconformity (Glass, 1976; Kent 1986); (3) a change in the heavy-mineral suite (Denson and Chisholm, 1971; Denson and Horn, 1975; Denson and

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in the toolbar to return.

others, 1989a, 1989b); (4) mammalian fossils (Simpson, 1928; 1929; 1937); and (5) plant microfossils (Tschudy, 1976; Pocknall, 1987). These differing criteria placed the Fort Union-Wasatch formations contact and the Paleocene-Eocene boundary at various positions within an interval of 175 to 725 ft between the top of the Wyodak-Anderson coal zone and the base of the Felix coal bed (fig. PS-2). The contact of the formations is generally placed above the Roland coal (see fig. PS-2).

The Fort Union Formation exists over 22,000 square miles in the Powder River Basin in Wyoming and Montana. Over a large part of its extent in the central part of the basin, it is overlain by the Wasatch Formation (fig. PS-1). Our study investigates only the Fort Union Formation in the Powder River Basin in Wyoming and Montana because coal (for example, Wyodak-Anderson and equivalent and Rosebud coal zones) is mined from this formation and a large part of the coal resource is strippable along the basin margin. More importantly, the Fort Union coal contributed more than 340 million short tons or about 34 percent of the U.S. total coal production in 1998 (Resource Data International, Inc., 1998). The coal produced from 25 coal strip mines (see fig. PS-1) in the Wyodak-Anderson and Rosebud coal zones supplies energy fuel to 144 power plants in 25 states of the conterminous U.S. and also to Canada, France, and Spain (Resource Data International, Inc., 1998). These coal zones are expected to produce an additional 150 million short tons by the year 2016 (Energy Information Administration, 1996). In addition, in this study the Knobloch coal zone is assessed as a potentially minable deposit. The Fort Union coal deposits in the basin will be the focus of development during the next several decades due to their clean and compliant characteristics (low sulfur and ash contents).

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in the toolbar to return.

From the 1950's through the 1980's a number of subsurface data points became available from petroleum exploration and exploration for uranium-enriched strata (including coal beds) for the Fort Union Formation in the Powder River Basin. In the 1970's increased demand for low-sulfur Fort Union coal led to shallow drilling by coal companies and by U.S. Geological Survey-Montana Bureau of Mines and Geology cooperative drilling projects. These projects provided subsurface stratigraphic information on the Fort Union Formation for coal assessments. In the 1980's, drilling in association with coal leasing by the U.S. Bureau of Land Management and various coal companies contributed additional stratigraphic information. Log reports of these drilling activities are archived by the U.S. Geological Survey and Wyoming State Geological Survey. These log reports were converted into digital files by using spreadsheet software. A total of 6,909 proprietary and non-proprietary drill holes (coal, oil, and gas) was used for the study. A database of these drill holes is stored and managed in the U.S. Geological Survey's National Coal Resources Data System in Reston, Virginia (e-mail: mdcarter@usgs.gov).

HISTORY OF COAL MINING

Building of new railroads through northeastern Wyoming from 1886 to 1887 created growth in underground coal mining in the Powder River Basin. Mining of Fort Union coal in the basin began in 1883 near Glenrock and Douglas, Wyoming. The Inez mine near Douglas produced 12,986 tons of coal in 1888 (Gardner and Flores, 1989). About the same year, the Deer Creek mine near Glenrock produced 13,000 tons of coal (Gardner and Flores, 1989). Converse County was producing a total of 31,000 tons from these two mines by the end of 1888 (Trumbull, 1905). In 1904, Cole Creek Coal Company in Big Muddy, Wyoming, was mining multiple coal beds as much as 5.5 ft thick and annually produced 15,708 tons (Trumbull, 1905). The Glenrock Coal Company operating at Glenrock, Wyoming, a few miles east of Big Muddy, produced as much as 60,440 tons in 1905 (Trumbull, 1905). The total annual production in Converse County was about 80,000 tons (Trumbull, 1905).

In addition, in 1888 the Buffalo Fuel Company No. 1 mine opened near Buffalo, Wyoming, and wagon mines opened near Sheridan (Gardner and Flores, 1989). These mine openings were followed by opening of the Dietz mine northwest of Sheridan in 1890. The Dietz mine, which produced from 9- to 12-ft-thick coal beds, expanded with the demand for coal, and by 1892 the mines in Sheridan County had reached total production of 2,000 tons per year (Trumbull, 1905; Gardner and Flores, 1989). These five mining districts produced the majority of coal in the Powder River Basin in Wyoming before the turn of the century. Underground coal mines in Sheridan County increased by 17 mines (for example, Dietz Nos. 4, 6, 8; Old Monarch; Carney; Black Diamond, Acme, Kooi, Storm King, Minersville, Hotchkiss Nos. 1 and 2; Schreibeis) from 1903 to 1925 (Dunrud and Osterwald, 1980). The total coal produced from these mines by September 30, 1904, was 429,153 tons (Trumbull, 1905). At the Carney mine, production was from coal beds as much as 15 ft thick. At the Monarch mine, coal was produced from a 25- to 30-ft-thick bed, and as much as 200,000 tons was produced by 1905. In 1905, Sheridan County was producing 550,000 tons annually (Trumbull, 1905). Seven more mines were added from the mid-1920’s to the mid-1950’s. The increased production in these mines was due to the onset of mechanization in underground mines.

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in the toolbar to return.

While mechanization increased in underground mines in the early 1900's, the U.S. Geological Survey reported the first strip mining at the Peerless mine east of Gillette in 1924 (Gardner and Flores, 1989). The overburden, which was 25 ft thick, was stripped to expose a coal bed as much as 90 ft thick. A horse-drawn scraper known as a fresno was used to peel back the overburden (Gardner and Flores, 1989). The fresno was later replaced by full-revolving steam shovels, motorized graders, and bulldozers to remove the surface cover. Thus, the Peerless mine was a harbinger of more profitable mining methods in the Powder River Basin. The first large strip mine in the Powder River Basin was opened near Gillette by the Wyodak Coal and Manufacturing Company. This newly opened strip mine produced about 33,579 tons in 1925; the coal was extracted by 15 men, yielding about 2,239 tons of coal per person per year. This mine was the only strip mine listed in the Wyoming state coal mine inspector's report in 1925. The Wyodak strip mine produced about 1,778 tons per man per year from 1925 to 1935.

In 1939 there were four strip mines in Wyoming and three were in the Powder River Basin in Campbell, Sheridan, and Converse Counties (Gardner and Flores, 1989). These strip mines, with the exception of the Wyodak strip mine, were small operations, which produced a total of 107,923 tons in 1939, as indicated in the Wyoming state coal inspector's report. In the 1940's and 1950's, mechanization continued to increase in surface mines with improvements in mining equipment that provided the opportunity for more efficient and profitable production. Strip mines, such as the Big Horn mine northwest of Sheridan, eventually proved to be too efficient for the competing underground mines, which were gradually put out of business. Underground coal mining companies that were not put out of business became part of stripping ventures, such as the Monarch and Storm King Coal companies north of Sheridan. In 1955 the strip mines in Campbell County (for

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in the toolbar to return.

example, the Wyodak mine) produced a total of 349,566 short tons, in Sheridan County (for example, the Big Horn mine) 437,222 short tons, and in Converse and Johnson Counties (for example, the Dave Johnston mine) 9,433 short tons (Young and others, 1957). These strip mines contained overburden that varied from 10 to 130 ft thick.

Coal production in the Powder River Basin from 1865 to 1949 was about 51 million short tons according to Berryhill and others (1950). More than 45 million short tons was produced from mines in the Sheridan coalfield, approximately 3 million short tons in the Gillette coalfield, and about 1.5 million short tons in the Glenrock area. These amounts represent about 15 percent of the total coal produced in Wyoming during that 84-year period. The coal produced during this period was used mainly for locomotive fuel on the Chicago, Burlington, and Quincy Railroad, and a subordinate amount was used to fuel power plants, sugar factories, cement plants, and for local heating (Mapel, 1958).

In the mid-1960's the Powder River Basin coal industry expanded in response to the demand for more electricity from newly built, coal-fired power plants (for example, the Dave Johnston plant in Glenrock and the Wyodak plant in Gillette). Power plants were built near the coal reserves in the Powder River Basin in Wyoming and Montana where cheap coal could be obtained by strip mining. In addition, the demand for clean coal to be used in these power plants, as mandated by the Air Quality Act of 1967, which required emission reductions, was met by the compliant coal of the Powder River Basin. During the early 1970's, strip mines were opened in Montana (for example, the Decker and Sarpy Creek mines) and Wyoming (for example, the Bighorn and Belle Ayr mines). Additional mines were opened in the Powder River Basin in the late 1970's and 1980's as public utility companies

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in the toolbar to return.

increased their consumption of Powder River Basin coal for generating electricity. Initially, the utility companies gave the coal companies in the basin long-term contracts (as long as 30 years), which helped to stabilize the coal industry. Presently, the Gillette coalfield in the Wyoming part of the basin includes 19 mines (Resource Data International, Inc., 1998). The Powder River Basin, in general, and the Gillette coalfield, in particular, hold the distinction of being the number one coal-producing area in the United States.

GEOLOGICAL SETTING

The Powder River Basin is a structural and sedimentary basin located in the northeastern part of Wyoming and southeastern part of Montana. It contains more than 8,000 ft of Upper Cretaceous and Tertiary rocks along the axis in the western part of the basin (Curry, 1971). The basin is asymmetrical with rocks dipping an average of 20-25 degrees along the western margin of the basin and 2-5 degrees along the eastern margin. The Miles City arch separates the northernmost Powder River Basin in Montana from the Williston Basin in Montana and North Dakota (fig. PS-1). Paleocene Laramide positive structures representing basement-block uplifts (Curry, 1971; Perry and Flores, 1994) include the Bighorn uplift on the west, the Casper arch-Laramie range-Hartville uplift on the south, and the Black Hills uplift on the east (fig. PS-1). These ancestral uplifts reflect northeastward migration of Laramide deformation because the uplift on the west (the Bighorn Mountains) is older than that on the east (the Black Hills) (Perry and Flores, 1994).

Although the basin is structural in origin and was formed during the late Laramide tectonic movements, accumulation of the Fort Union sediments was controlled primarily by subsidence of the basin and accompanying depositional settings.

Click here or on this symbol
in the toolbar to return.

Tectonic uplifts of surrounding areas influenced the nature of the Fort Union sediments, which comprised mainly reworked Cretaceous fine- and coarse-grained rocks (Whipkey and others, 1991) and subordinate Jurassic to Paleozoic rocks (Obernyer, 1978). Tectonism may have played a significant control in accumulation of thick Fort Union coal (Flores, 1983; Ayers and Kaiser, 1984; Kent, 1986).

The Fort Union Formation is more than 5,200 ft thick along the basin axis in the western part of the Powder River Basin in Wyoming (Curry, 1971; Lewis and Hotchkiss, 1981). The Fort Union Formation is divided, in ascending stratigraphic order, into the Tullock, Lebo, and Tongue River Members (fig. PS-2; the Lebo Member of Wyoming is known as the Lebo Shale Member in Montana). The Tullock Member is as much as 740 ft thick, the Lebo Member is as much as 2,600 ft thick, and the Tongue River Member is as much as 1,860 ft thick. Subdivision of Fort Union Formation is based on the color, dominant lithology, and thickness variation of the rock units (Mapel, 1958; Tudor, 1975; Denson and others, 1989a, 1989b). For example, the Tullock and Tongue River Members include abundant weathered, drab yellow and light-gray sandstone beds. The Tongue River Member includes common light-gray to tan mudstone in contrast to the Lebo Member, which contains abundant drab-gray mudstone. The coal beds of the Tullock Member are thin to thick compared to the coal beds of the Tongue River Member, which are mainly thick; the Lebo Member includes very thin and sparse coal beds and carbonaceous mudstone.

DEPOSITIONAL SETTING

The lithological variations of the Fort Union Formation in the Powder River Basin were controlled by tectonics and depositional environment (Brown, 1958; 1962;

Click here or on this symbol
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Mapel, 1958; Denson and Chisholm, 1971; Obernyer, 1978; Ayers and Kaiser, 1984; Flores, 1980, 1986; Kent, 1986; Culbertson, 1987). Brown (1958, p. 111) reported that the “similarity of the lithology of the Fort Union Formation at correlative stratigraphic levels over a large part of the terrain it occupies indicates that relatively the same environmental and depositional conditions can be inferred as having prevailed simultaneously at those levels.” Brown suggested that the Fort Union sediments were deposited in floodplains, estuaries, sloughs, and swamps sometimes considerably inland from the Cannonball sea, which was located east and northeast of the Powder River Basin. He further reported that the presence of plant fossils of palms and birches suggested warm temperate to temperate paleoclimate. This paleoclimatic interpretation was modified by Wolfe and Upchurch (1986; 1987) and Nichols and others (1989) as warm tropical-subtropical paleoclimate, based on characteristics of fossil leaves (for example, leaf size, leaf margins). These workers suggested that the annual temperature was about 20°C (68°F) but reached to as much as 23°C (73.4°F) and that annual precipitation was as much as 90.6 in. (2,300 mm) during the late Paleocene. According to Brown (1958, p. 111), periods of static basin deposition influenced accumulation of “materials that were to become a coal seam,” and basin subsidence “changed stream flow and direction that caused incipient coal to be buried by sand and silt.” These environmental and depositional settings, unlike the modern alluvial valley of the lower Mississippi River (Fisk, 1944), were accompanied, according to Brown (1958, p. 111), by “orogenic movements to the west of the basin from Late Cretaceous through Paleocene and into Eocene.” Brown’s model of the environmental, depositional, and tectonic settings of the Powder River Basin is an advanced interpretation that has withstood the test of time.

Click here or on this symbol
in the toolbar to return.

Modification of Brown’s model by succeeding workers included identification of the types of stream or fluvial systems that drained the Powder River Basin and flowed into the Cannonball sea in the Williston Basin (Flores, 1980, 1981, 1983, 1986; Flores and Ethridge, 1985; Ethridge and others, 1981; Flores and others, 1989; Warwick and others, 1997, 1998). Internal drainage of the basin was interpreted by Ayers and Kaiser (1984) to include a lake in which the Lebo Member was deposited. Perhaps the most controversial issue pertaining to the deposition of the Fort Union sediments is the origin of the coal, particularly the accumulation of very thick coal (that is, beds more than 200 ft thick). Kent (1986) proposed a seesaw effect of tectonic subsidence and uplift in which coal accumulated in swamps developed on paleoslopes affected by uplift; eastern uplift caused a westward tilt of these paleoslopes and western uplift caused an eastward tilt. In contrast, Ayers and Kaiser (1984) envisioned a rapidly subsiding basin infilled by lacustrine deltas in which swamps formed thick peat. These workers assumed that the presence of abundant mudstone in the central part of the basin, which bypassed coarse sediments during deposition, represented lake deposits. However, Flores and co-workers suggested that the mudstone was derived mainly from Cretaceous marine shales exposed in surrounding uplifts and deposited in the basin by alluvial fans and braided, meandering, and anastomosed streams. Intense uplift of surrounding ancestral mountains (for example, Big Horn Mountains) is indicated by deposition of conglomerates in alluvial fans (figs. PS-3, PS-4, and PS-5) and braided streams (fig. PS-6).

The traditional interpretation of the origin of coal in the fluvial system, following Brown’s model, is deposition in swamps formed on distal floodplains, abandoned crevasse splays, and abandoned belts of rivers, as described by Flores (1980, 1981, 1983) and Flores and Hanley (1984). Examples of clastic deposits in floodplain,

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in the toolbar to return.

crevasse splay, and fluvial channel environments are shown in figures PS-7, PS-8, PS-9, and PS-10. Very thick organic deposits (fig. PS-11) of these fluvial swamps were interpreted by Flores (1980; 1981; 1986) and Flores and Ethridge (1985) as ombrotrophic or rain-fed, raised bogs typically formed in wet, tropical-subtropical climate as described by Wolfe and Upchurch (1986; 1987) and Nichols and others (1989). Flores further suggested that the Fort Union raised bogs in the Powder River Basin are exemplified by similar modern environmental, depositional, and tectonic settings in the Kutai Basin drained by the Mahakam River in southeast Kalimantan, Indonesia. These modern raised bogs are similar to those described by Cecil and others (1993) and Neuzil and others (1993) in Borneo and Sumatra (figs. PS-12 and PS-13). However, in order to accumulate very thick peat or coal precursors, these raised bogs must be influenced by either local subsidence (for example, peat autocompaction, sediment compaction) or basin subsidence. Thickening of peat deposits, hence the resulting thickening of coal beds, may be explained by stacking of peat deposits separated by organic or inorganic partings (Moore, 1994). These partings (fig. PS-14) represent a demise of the swamp by oxidation and degradation of organic matter yielding a deflated peat surface prone to flooding events. Evidence of rapid flooding events over these peat surfaces were discussed by Sholes and Cole (1981), Sholes and Daniel (1992), and Flores and Moore (1994). The Fort Union peat swamps were mainly vegetated by conifers related to the living bald cypress and also by ancestors of other living plant families, including broad-leaved evergreens (Spindel, 1975; Rich, 1980; Satchell, 1985; Pocknall and Flores, 1987; Wolfe and Upchurch, 1986, 1987; Nichols and others, 1989; Nichols, 1995).

The importance of tectonic control in the development of the Powder River Basin and related coal deposits has been discussed by Curry (1971), Obernyer (1978),

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in the toolbar to return.

Jenkins (1986), Whipkey and others (1991), and Perry and Flores (1994). Curry (1971) suggested that Laramide structural movements are evidenced in the Powder River Basin during deposition of the Lebo Member, which thickens from 370 to 2,600 ft from east to west across the basin. He indicated that rapid subsidence provided a space to accommodate Lebo sediments, particularly in the western part of the basin. Also, he noted that when the Laramide movements were active in the basin, only mudstones were derived from the uplifts. Flores and others (1994) suggested that the fine-grained Lebo sediments were derived primarily from Cretaceous marine shale. This interpretation is supported by the presence of glauconite in the Lebo Member that was derived from marine rocks from the Bighorn uplift (Whipkey and others, 1991). Faulting may be characterized in part by normal faulting according to Obernyer (1978) and thrust faulting according to Jenkins (1986) along the western basin margin. Obernyer proposed that the very thick and linear (north-south orientation) Lake de Smet coal of the Wasatch Formation (fig. PS-2) in the western part of the basin was formed on the subsiding downthrown side of a fault. Effects of Laramide deformation of the Powder River Basin and surrounding uplifts were discussed by Perry and Flores (1994). These workers suggested that a northeastward younging and migrating Laramide deformation front prompted evolution of the Powder River Basin from a foreland basin into an intermontane basin in early to late Paleocene time. The basin was a well-developed intermontane basin by the late Paleocene; it was surrounded by uplifts on the west, south, and east. These surrounding uplifts may have contributed to the orographically wet paleoclimate that promoted development of rain-fed, raised bogs in the basin (Flores, 1998).

COAL GEOLOGY

The coal geology of the Fort Union Formation in the Powder River Basin reflects the tripartite subdivision of the formation, with the Tullock Member in the lower part, the Lebo Member in the middle part, and the Tongue River Member in the upper part (see fig. PS-2). This subdivision parallels differences in stratigraphy, sedimentology or depositional settings, biostratigraphy, and coal geology, including the thickness and areal distribution of coal and associated rocks in the members of the Fort Union Formation.

The coal geology and stratigraphy of the Fort Union Formation differ in the vertical and lateral patterns of coal beds and zones and associated clastic rocks. The vertical stratigraphic pattern in the Tullock Member consists of abundant thick sandstone interbedded with siltstone and mudstone and less abundant, thin (a few inches to several feet) coal and carbonaceous beds. The Lebo Member consists of abundant mudstone, subordinate siltstone and sandstone, and sparse coal and carbonaceous mudstone. The Tongue River Member contains abundant sandstone, siltstone, mudstone, and sparse limestone and carbonaceous shale. Coal beds are abundant and range from thin (a few inches) to very thick (more than 200 ft).

Although the members of the Fort Union Formation were deposited in fluvial environments, the depositional setting of the Tullock is different from that of the Lebo and Tongue River Members. The Tullock Member was deposited primarily by braided to meandering fluvial systems (Flores and others, 1994). The Lebo Member was deposited in fine-grained fluvial systems, as proposed by Flores and Ethridge (1985), although Ayers and Kaiser (1984) interpreted the deposition of the Lebo sediments to have been in a lacustrine environment. The Tongue River

Member was interpreted as fluvial deposits by Flores (1980; 1981; 1983; 1986), Flores and Hanley (1984), Flores and Ethridge (1985), Warwick and Stanton (1986, 1988), but as deltaic deposits by Ayers and Kaiser (1984). The fluvial deposits accumulated in meandering and anastomosed fluvial systems in the central part of the basin and alluvial fans and braided streams in the basin margins. These fluvial styles developed in response to accommodation space created by tectonic uplift, basin subsidence, and base-level changes.

Biostratigraphy based on palynology (analysis of fossil spores and pollen) of the Fort Union Formation in the northern Rocky Mountains and Great Plains region was developed by Nichols and Ott (1978). Pocknall (1987) proposed zones for the upper part of the Fort Union Formation in the central part of the Powder River Basin; his zonation is mostly equivalent to part of that of Nichols (1994; 1996). Using his zonation, Nichols subdivided the Fort Union Formation into six Zones, P1-P6 (see fig. PS-2 and Chapter PB, the biostratigraphy section for the Powder River Basin, in this CD-ROM). For the most part, the Tullock Member is within Zones P1 and P2, the Lebo Member is within Zones P3 and P4, and the Tongue River Member is within the Zones P4 through P6. Variations in occurrence of certain groups of fossil pollen within the Wyodak-Anderson coal are depicted graphically in Chapter PB, the biostratigraphy section of this CD-ROM, and some of the biostratigraphically important species are illustrated. Detailed descriptions and illustrations of the fossil spores and pollen of the Fort Union Formation in the Powder River Basin can be found in Nichols and Brown (1992) and Pocknall and Nichols (1996).

Our investigation focused on the coal geology and stratigraphy in the Tongue River Member (fig. PS-2), which has been the subject of detailed studies by numerous

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workers in the U.S. Geological Survey. The publications of Dobbin (1929), Bass (1932), Bryson (1952), Brown and others (1954), Olive (1957), Bryson and Bass (1973), and Keefer and Schmidt (1973) focused on detailed areal mapping of coal beds and description of coal-bearing stratigraphic sections in the Tongue River Member. The publications of Mapel (1958; 1976), Culbertson and others (1979), Law and others (1979), Kent and others (1980), Hardie and Van Gosen (1986), Culbertson (1987), McLellan and Biewick (1988), McLellan and others (1990), Hardie (1991), Pierce and others (1990), and Molnia and Pierce (1992) focused on investigation of the coal stratigraphy or lateral and vertical variations of the coal beds. Publications of Flores (1979), Flores and Canavello (1979), Weaver and Flores (1985; 1987), Pierce and Johnson (1991), and Johnson and Pierce (1991) concentrated on relating the variations of the rock types and their depositional environments to the stratigraphic variations of the Tongue River Member.

There has been an evolution in the interpretation of the coal stratigraphy of the Tongue River Member from coal existing as tabular, laterally continuous beds more than 50 miles in extent (Mapel, 1958) to the existence of complex, laterally merging and splitting beds and zones (Flores, 1979; Flores and Canavello 1979). Early mapping suggests areal distribution of the coal as continuous mappable units. Later, as more subsurface stratigraphic data and/or outcrop sections became available, coal beds of the Tongue River Member were found to be more variable in lateral extent. The work of Flores and his co-workers (Canavello, 1980; Lynn, 1980; Pait 1981; Toth, 1982; Coss; 1985; Warwick, 1985; Moore, 1986; Whipkey, 1988) exhibited that lateral continuity of the coal beds of the Tongue River Member of the Fort Union Formation and the Wasatch Formation, which vary from a few hundred feet to several miles in extent, was controlled by the depositional environments of related rocks. For example, the splitting of coal beds caused by incursion of crevasse-splay sediments into the mires was demonstrated by Moore (1986) and Flores and Moore (1994) in the Decker coalfield, Montana. The characteristic of the lateral continuity of coal beds is revealed by the stratigraphic control points utilized for correlation.

Complex correlation is displayed by splitting (fig. PS-15) and merging (fig. PS-16) of the Wyodak-Anderson, Rosebud, and Knobloch coal zones. The Wyodak-Anderson coal zone is distributed basinwide in Wyoming and Montana, and the Rosebud-Robinson and Knobloch coal zones are distributed in the northern part of the basin in Montana. The Wyodak-Anderson coal zone (Glass, 1980) is also known as the Wyodak coal (Mapel, 1973) and Wyodak-Anderson coal, which is coalesced Anderson, Canyon, and related coal beds (Denson and Keefer, 1974). Splitting of the coal beds of the Wyodak-Anderson coal zone has generated 2 beds (lower Wyodak bed comprising the merged Canyon and Werner coal, and upper Wyodak bed comprising the merged Smith, Swartz, and Anderson coal; Mapel 1973; Kent and others, 1980), 3 beds (Anderson or Dietz 1, Dietz 2, and Dietz 3; Sholes and Coles, 1981; Moore, 1986; Flores and Moore, 1994), 5 beds (lower and upper Anderson and lower, middle, and upper Canyon beds; Molnia and Pierce, 1992), 6 beds (Smith, Swartz, Anderson, upper and lower Canyon, and Werner beds; Kent and others, 1980), or as many as 11 beds (Sussex beds; Hardie and Van Gosen, 1986). The local distribution of the split coal beds of the Wyodak-Anderson coal zone is shown on figure PS-17. Split coal beds merge to form a single bed; later splitting and remerging of this bed basinwide show overlapping, offsetting, zigzagging, and shingling segments of the coal zone indicating older Wyodak-Anderson coal (for example, Big George coal) in the west-central part of the basin than in the basin margins (for example, Smith, Anderson, Dietz, Canyon, School, and Badger coal; see fig. PS-18). Splitting of the Knobloch coal zone created as many as four beds that include the Knobloch, Calvert, Nance, and Flowers-Goodale

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(Culbertson 1987; Culbertson and Saperstone, 1987), which may be equivalent to the Sawyer, Lay Creek, and King coal beds (Sholes and Daniel, 1992). Splitting of the Rosebud-Robinson coal zone generated as many as 3 beds (Rosebud, McKay, and Robinson). Various interpretations of coal splitting and merging led to confused correlation of the different named coal beds of these coal zones. For example, Sholes and Daniel (1992) correlated the Knobloch coal zone to the Rosebud coal bed.

The sedimentology of the clastic rocks interbedded with the coal provides an understanding of the depositional environments and the dynamic processes that formed these rocks. These environments and accompanying processes controlled the lateral and vertical variability of the coal beds. For example, the process of autocyclicity or lateral shifting common in fluvial-channel and floodplain aggradation caused associated swamps to shift with fluvial aggradation. Rapid successions of avulsion or shift and abandonment of the fluvial depositional systems along the width of the alluvial plain caused splitting and merging of the coal beds and zones. In addition, the vast expanse of abandoned alluvial platforms on which swamps developed promoted accumulation of laterally extensive coal-forming peat deposits. This accounts for the variable distribution of coal deposits, from local to widespread, in the Tongue River Member of the Fort Union Formation.

COAL RESOURCES AND COAL QUALITY

Early estimates of the coal resources in the Powder River Basin were based mainly on outcrop data from shallow coal beds in the Tongue River Member. The strippability (from less than 50 to as much as 129 ft of overburden) of the Tongue River coal yielded coal resources estimated as strippable resources. An attempt to estimate strippable resources of Tongue River Member coal in the Rosebud coalfield in Rosebud and Custer Counties of Montana with 60 ft or less of overburden was made by Pierce (1936). The Terret and Burley beds of the Tongue River Member (see fig. PS-2), which vary from 5 to 8 ft thick with 50 to 60 ft of overburden, were estimated to contain resources of as much as 817 million short tons. Kepferle (1954) estimated strippable coal (with 120 ft of overburden) in central Rosebud County at about 604 million short tons; this included nine strippable beds as much as 20 ft thick (for example, Terret, Rosebud, Sawyer, Wall, Brewster-Arnold; see fig. PS-2). In the adjoining areas of Custer and Powder River Counties, Brown and others (1954) estimated strippable resources (with as much as 120 ft overburden) at 1,551 million short tons.

In the Powder River Basin in Wyoming, Berryhill and others (1950) estimated original resources of the greater-than-3-ft-thick Roland and Smith coal beds (partly equivalent to the Wyodak-Anderson coal zone) to include more than 45 billion short tons. In the Powder River Basin in Montana, Combo and others (1949) estimated original coal resources of coal beds more than 2.5 ft thick (for example, Wyodak-Anderson, Rosebud, and Knobloch coal zones; see fig. PS-2) in Bighorn and Powder River Counties to be 86.9 billion short tons. Mapel (1958) revised the original coal resources in the Lakota and Lance (Cretaceous), Fort Union (Paleocene), and Wasatch (Eocene) Formations in the Powder River Basin in Wyoming and Montana to be 200 billion short tons in coal beds more than 2.5 ft thick. He estimated the original coal resources in the Fort Union in the Powder River Basin in Wyoming to be about 82 billion short tons. Glass (1976) estimated the coal resources in four formations in the Cretaceous, Paleocene, and Eocene

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rocks in the Powder River Basin in Wyoming to be 600-700 billion short tons. Trent (1986) estimated resources of greater-than-5-ft-thick coal down to 3,000 ft depth to be 775 billion short tons for non-leased Federally-owned coal in 243 quadrangles in the Powder River Basin.

Coal resource estimates for the past 25 years have focused on the important, productive, and strippable Wyodak-Anderson coal zone (Averitt, 1975). Some of the coal and associated rocks of this zone were burned by spontaneous combustion resulting in a red-orange rock called "clinker" (figs. PS-19 and PS-20); burning of coal beds has reduced the coal resource of the coal zone along the outcrop (see fig. PS-21; Heffern and others, 1993; Boyd and Ver Ploeg, 1997; Heffern and Coates, 1997). Mapping by Denson and Keefer (1974) defined the Wyodak-Anderson coal zone as formed from coalesced beds and equivalent to the Anderson and Canyon coal beds. Mapping by Kent and Munson (1978) indicated the interval containing the Swartz (upper) and Werner (lower) coal beds as coalescing with the Wyodak-Anderson coal zone (see fig. PS-2). Glass (1976) correlated the Dietz 1, 2, and 3 (Anderson) and Monarch (Canyon) beds in the Sheridan coalfield to the Wyodak-Anderson coal zone of Denson and Keefer (1974). Coal beds (Anderson and Canyon) of the Wyodak-Anderson coal zone in the eastern part of the Powder River Basin in Wyoming range from 10 to 65 ft thick and coalesce into beds 70-125 ft thick (Glass, 1976; Culbertson and others, 1979). Smith and others (1972) estimated the strippable resource base of the Wyodak-Anderson coal zone south and north of Gillette, Wyoming, to be about 19 billion short tons. Averitt (1975) estimated the resource of the Wyodak-Anderson coal zone to be 100 billion short tons.

The equivalent Dietz coal beds (Anderson coal of the Wyodak-Anderson coal zone; see fig. PS-2) in the Sheridan coalfield, which average 10-25 ft thick and coalesce into beds as much as 75 ft thick, and the Monarch coal (Canyon coal of the

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Wyodak-Anderson coal zone; see fig. PS-2), which is as much as 60 ft thick, were collectively estimated to contain a strippable resource base of more than 39 million short tons (Glass, 1978). Smith and others (1972) estimated the strippable resource base of the Monarch coal bed, which locally coalesces with the Dietz 3 coal bed, to be 32 million short tons.

The Wyodak-Anderson coal zone in the Decker coalfield in the Powder River Basin in Montana includes the Dietz 1, 2, and 3 coal beds (Dietz 1 is correlated with the Anderson coal) and the Canyon coal bed (Matson and Blumer, 1973; Matson and Pinchock, 1977). The Dietz coal beds (Dietz 2 and 3) and the Monarch or equivalent to the Canyon coal bed occur in the Sheridan coalfield (Law and others, 1979). Matson and Blumer (1973) described the Dietz 1, Dietz 2, and Dietz 3 coal beds (Anderson coal; see fig. PS-2) in the Powder River Basin in Montana as varying from 4 to 18 ft thick and as coalescing to as much as 80 ft thick. According to Matson and Blumer (1973) the Canyon coal bed in the basin in Montana ranges from 4 to 25 ft thick; they estimated strippable coal resources (with less than 300 ft of overburden) of the Dietz and Anderson coal beds to be greater than 8.6 billion short tons. In addition, Matson and Blumer (1973) estimated the strippable coal resources of the Canyon coal in the same area to be more than 1.7 billion short tons. They described additional strippable coal beds in the Powder River Basin in Montana to include the Knobloch coal, which is as much as 66 ft thick, and the Rosebud coal, which averages 25 ft thick (fig. PS-2). Matson and Pinchock (1977) estimated the strippable coal resources (with less than 300 ft of overburden) for the Knobloch coal as more than 7.5 billion short tons and the Rosebud coal as more than 1.5 billion short tons.

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In the central part of the Powder River Basin in Wyoming, the Wyodak-Anderson coal zone coalesces from five coal beds of the Anderson and Canyon coal into a bed as much as 202 ft thick known as “Big George” coal (Kent and others, 1980; Pierce and others, 1982; Kent, 1986; Molnia and Pierce, 1992). This coal is a single bed varying from 46 to 202 ft thick within a 950-square-mile area at a depth of 1,100 ft below the surface (Pierce and others, 1982). The coal resource of this bed was estimated by Pierce and others (1982) and Kent (1986) to be as much as 113 billion short tons. This coal and laterally equivalent “Sussex” coal, which is as thick as 138 ft (a merged bed from as many as eleven beds; fig. PS-22), probably represent the largest deposit (about 194 billion short tons) of the Wyodak-Anderson in a single area (more than 1,000 square miles) in the Powder River Basin, but it is not economically strippable. Basinwide, (see Chapter PN of this CD-ROM) the resource of the Wyodak-Anderson coal zone is estimated to be as much as 550 billion short tons (Ellis and others, 1999). Volumes calculations of the Wyodak-Anderson coal zone, at a 90 percent confidence limit, range from 459 (lower limit) to 642 billion short tons (upper limit) (Ellis and others, 1999; Schuenemeyer and Power, in press).

The Fort Union coal in the Powder River Basin in Wyoming and Montana is mainly subbituminous B, and coal in the northeastern part of the basin tends to be slightly lower in rank, according to Fieldner and others (1931). These authors reported sulfur content to be mostly between 0.4 and 1.0 percent and ash yield to be between 5 and 10 percent on a moisture-free basis. Berryhill and others (1950) demonstrated the local variations in coal quality in the basin by reporting that the Sheridan coalfield contains Fort Union coal (Dietz and Monarch coal beds) averaging 0.54 percent sulfur, 4.3 percent ash, and 9,366 Btu/lb (subbituminous A and B) on an as-received basis, whereas other Fort Union coal (Roland/Anderson coal beds) averages 0.5

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percent sulfur, 6.8 percent ash, and 7,868 Btu/lb (subbituminous C) on an as-received basis. These analyses were performed for coal beds without partings. Mapel (1958) reported that the calorific values of Fort Union coal (Dietz, Monarch, and Rosebud coal beds) in the Powder River Basin in Montana range from 8,300 to 10,100 Btu/lb on a moist, mineral-matter-free basis.

Analyses of nine cores of the Anderson and Canyon coal beds (Wyodak-Anderson coal zone) in Campbell County in the Powder River Basin, as reported by the U.S. Geological Survey and Montana Bureau of Mines and Geology (1973) and the U.S. Geological Survey (1974), yielded averages of 29.5 percent moisture, 30.1 percent volatile matter, 33.9 percent fixed carbon, 6.5 percent ash, 0.52 percent sulfur, and a calorific value of 7,979 Btu/lb for the Anderson coal. The same publications reported averages of 29.6 percent moisture, 30.7 percent volatile matter, 34.6 percent fixed carbon, 5.1 percent ash, 0.34 percent sulfur, and a calorific value of 8,286 Btu/lb for the Canyon coal in Campbell County.

Based on five analyses of mine samples in the Sheridan coalfield, Glass (1980) reported 21.7-23.8 percent moisture, 33.6 percent volatile matter, 38.5 percent fixed carbon, 5.6-6.6 percent ash, 0.74-1.02 percent sulfur, and a calorific value of 9,220-9,387 Btu/lb (as-received basis) for the Dietz 2 coal bed. The Dietz 3 coal bed in the same Sheridan mines contains 19.1 percent moisture, 34.8 percent volatile matter, 41.7 percent fixed carbon, 4.4 percent ash, 0.5 percent sulfur, and a calorific value of 9,710 Btu/lb (as-received basis). The Monarch or Canyon coal bed was reported by Glass (1980) to contain averages of 21.5 percent moisture, 34.5 percent volatile matter, 39.6 percent fixed carbon, 4.4 percent ash, 0.4 percent sulfur, and a calorific value of 9,600 Btu/lb (as-received basis).

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In the Decker coalfield, north of the Sheridan coalfield in Montana, Matson and Blumer (1973) reported 17.3-23.8 percent moisture, 29.4-34.9 percent volatile matter, 26.6-42.8 percent fixed carbon, 2.9-34.8 percent ash, 0.2-0.6 percent sulfur, and a calorific value of 8,609-9,850 Btu/lb (as-received basis) for the Anderson and Dietz coal beds. These investigators reported 20.9-23.8 percent moisture, 26.3-32.5 percent volatile matter, 35.8-42.9 percent fixed carbon, 2.4-16.9 percent ash, 0.1-0.7 percent sulfur, and a calorific value of 8,081-9,691 Btu/lb (as-received basis) for the Canyon coal in the Decker coalfield. They reported 23.7-36.4 percent moisture, 25.7-36.5 percent volatile matter, 28.1-40.4 percent fixed carbon, 2.9-10.6 percent ash, 0.1-5.3 percent sulfur, and a calorific value of 7,458-9,314 Btu/lb (as-received basis) for the Knobloch coal. These investigators reported 21.3-23.8 percent moisture, 27.5-30.2 percent volatile matter, 34.7-41.2 percent fixed carbon, 7.7-12.5 percent ash, 0.5-7.2 percent sulfur, and a calorific value of 7,810-9,090 Btu/lb (as-received basis) for the Rosebud coal.

The coal quality of the Wyodak-Anderson coal in the Powder River Basin in Wyoming and Montana was studied by Ellis and others (1998), Flores and others (1998), and Stricker and others (1998). Ellis and others (1998) and Flores and others (1998) indicated a mean moisture of 28 percent, volatile matter of 30.1 percent, fixed carbon of 36 percent, ash yield of 6.4 percent, sulfur of 0.47 percent, and calorific value of 8,220 Btu/lb. Stricker and others (1998) reported that the Wyodak-Anderson coal contains lower concentrations of trace elements of environmental concern (formerly known as hazardous air pollutants—antimony, arsenic, beryllium, cadmium, chromium, cobalt, lead, manganese, mercury, nickel, selenium, uranium) than other Fort Union coal. This was supported by a study of trace elements in Fort Union coal in the Powder River Basin and elsewhere in the Fort Union region by Hatch and Swanson (1977). Crowley and others (1993;

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1994) found that high concentrations of these trace elements are directly related to high ash contents of the coal. Groundwater is also known to elevate concentrations of trace elements, particularly sodium (Hildebrand, 1988). Flores and others (1994) suggested that debris derived from uplifts adjoining the Powder River Basin also contributed to the kind and concentrations of the trace elements. Additional information on the coal quality and geochemistry of the Fort Union coal, particularly the Wyodak-Anderson coal in the Powder River Basin in Wyoming and Montana, are presented in Chapter PQ of this CD-ROM.

COAL-BED METHANE RESOURCE

The presence of methane in Fort Union coal was reported by U.S. Geological Survey investigators (Olive, 1957; Lowry and Cummings, 1966; Whitcomb and others, 1966; Hobbs, 1978; Boreck and Weaver, 1984). A number of flowing artesian wells at shallow depths (245 to 415 ft) contained substantial amounts of methane as reported by Olive (1957), Lowry and Cummings (1966), and Whitcomb and others (1966). Hobbs (1978) identified methane in 15 shallow drill holes in the Recluse area of northeastern Campbell County and south of Gillette, Wyoming. Drill holes for coal-bed methane were drilled to depths of no more than 500 ft and penetrated the Wyodak-Anderson zone in the Recluse area, which includes the Anderson and Canyon coal beds. Methane has been encountered in the coal beds as well as in overlying sandstone and interbedded sandstone and shale beds. Gas flow rates varying from a trace in shale interbeds to more than 1,000,000 cubic ft/day in coal have been recorded. Hobbs (1978) suggested that there could be potential methane production from the Anderson and Canyon coal beds and from the fluvial channel sandstone between the coal beds and possibly below the Canyon coal.

Coal-bed methane exploration and development in the Powder River Basin has rapidly accelerated in the past two to three years. Several hundred wells have been drilled and recent operator forecasts projected more than 5,000 additional wells to be drilled over the next few years. Development of shallow (less than 1,000 ft deep) Fort Union coal-bed methane is confined to Campbell and Sheridan Counties, Wyoming, and Big Horn County, Montana. The major lease area in Wyoming is in 43.39 to 45 degrees and 105.32 to 105.88 degrees (see fig. PS-1). Here the targeted coal beds are mainly the Anderson and Canyon of the Wyodak-Anderson coal zone.

Perhaps the most promising methane play for the deep (more than 1,000 ft) Wyodak-Anderson (or Big George and Sussex) coal bed and zone in the southwestern part of the basin in Wyoming is in 43.50 to 44.63 degrees and 105.93 to 106.38 degrees (see fig. PS-1). The Wyodak-Anderson coal bed in this area is as much as 202 ft thick and the Wyodak-Anderson coal zone is as much as 550 thick; it contains as many as 11 coal beds that average 25 ft thick (Boreck and Weaver, 1984; Hardie and Van Gosen, 1986). The isopach map of the Wyodak-Anderson coal zone (see Chapter PN of this CD-ROM) in this area exhibits a series of discontinuous, ovoid (8- to 22-square-mile areas) coal bodies that have from 150 to more than 200 ft of net coal thickness. These ovoid coal bodies, in turn, are surrounded by an elongate (more than 1,000 square-mile area) coal body that has from 100 to 150 ft of net coal thickness. These ovoid and elongate coal bodies are generally oriented in a north-south direction and contain a coal resource of about 194 billion short tons. The coal beds and zone generally range from 1,000 to 2,000 ft deep (see net coal thickness and overburden maps in Chapter PN of this CD-ROM). The stratigraphic variation in this play (see Chapter PF of this CD-ROM) shows that the northern part of the area includes merged beds of the Big George coal reaching

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as much as 202 ft thick; they split southward and merge with the Sussex coal, which is as much as 138 ft thick. Where the coal beds are split, they are interbedded, overlain, and underlain by fluvial channel sandstone (see stratigraphic cross sections in Chapter PF of this CD-ROM). Where the coal beds are merged they are overlain and underlain by similar rock types. The clastic rocks, particularly the sandstone, potentially contain recoverable methane that has migrated from the coal.

Boreck and Weaver (1984) reported methane from a U.S. Geological Survey test drill hole in the Wyodak-Anderson (or Big George coal bed) in the central part of the basin in Johnson County, Wyoming (see fig. PS-1). Desorption data from seven coal core samples from this test hole ranged from 56 to 74 standard cubic ft/ton (scf/t). Methane recovered from these coal core samples indicated biogenic origin. Core analysis (three samples) of the Wyodak-Anderson or Big George coal bed at the Betop Incorporated Dead Horse Creek 8-32 well in Campbell County, Wyoming (see fig. PS-1), indicated a gas content from 26 to 44 scf/t and an average of 39 scf/t (summarized from a Core Laboratories report in BLM files).

Utilizing the minimum (26 scf/t) and maximum (74 scf/t) desorption data from the U.S. Geological Survey drill hole and the Betop well and the coal resource estimate (550 billion short tons) by Ellis and others (1999) (also see Chapter PN of this CD-ROM) provide an estimate of the methane resource for the Wyodak-Anderson coal bed and zone basinwide. Other coal beds and zones above and below the Anderson-Wyodak coal bed and zone in the Fort Union Formation (for example, Wall, as much as 25 ft thick; Pawnee, as much as 60 ft thick; Knobloch, as much as 70 ft thick; Rosebud, as much as 20 ft thick; Broadus, as much as 30 ft thick; see fig. PS-2) and in the Wasatch Formation (for example, Felix, as much as 40 ft thick and Lake de Smet coal, as much as 250 ft thick; see fig. PS-2) are possible targets for

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coal-bed methane. The coal-bed methane play in the Powder River Basin was reported by Rice and Finn (1995).

CONCLUSIONS

Fort Union coal, which represents a significant energy resource in the Powder River Basin in Wyoming and Montana, has been mined and developed since 1886. The most important use of this coal resource is energy fuel for mine-mouth power plants and many other electric power generating plants outside the basin. Currently, open-pit mines develop the Wyodak-Anderson and equivalent coal beds and the Rosebud coal beds and zones. Production from these mines supports 144 electric power plants in 26 states of the conterminous United States and three foreign countries. The electric power plants are located in the western, midwestern, southern, and southeastern parts of the United States. Coal production in 1998 from 25 mines in the Powder River Basin attained more than 305 million short tons.

With the likelihood of this coal continuing to support electric power plants during the next century, our assessment of the clean and compliant Fort Union coal in the Powder River Basin focused on the Wyodak-Anderson, Rosebud, and Knobloch coal beds and zones. The Wyodak-Anderson coal is as much as 202 ft thick, mainly subbituminous, and contains resources of as much as 550 billion short tons (in coal beds more than 2.5 ft thick, Ellis and others, 1999). The thick coal beds were deposited mainly in raised swamps related to fluvial environments. The extensive to limited areal distribution of these coal beds and zones reflects accumulation in raised swamps on abandoned alluvial platforms as well as depositional processes that affected the fluvial environments in late Paleocene time.

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The thickness, areal distribution, high quality, and trace-element chemistry of this coal and associated coal-bed methane make it a clean and compliant energy resource.

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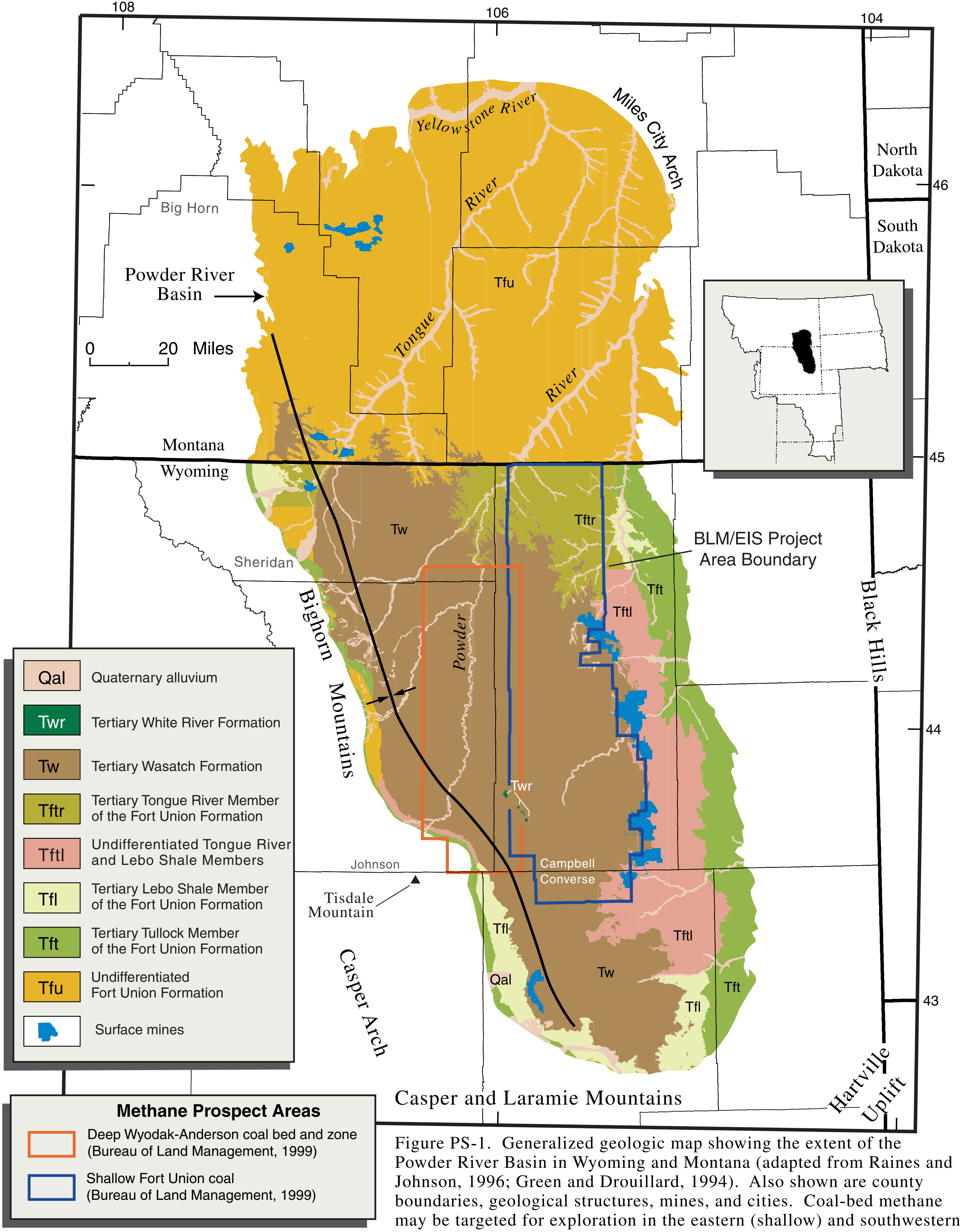

Figure PS-1. Generalized geologic map showing the extent of the Powder River Basin in Wyoming and Montana (adapted from Raines and Johnson, 1996; Green and Drouillard, 1994). Also shown are county boundaries, geological structures, mines, and cities. Coal-bed methane may be targeted for exploration in the eastern (shallow) and southwestern (deep) parts of the basin (Bureau of Land Management, 1999).

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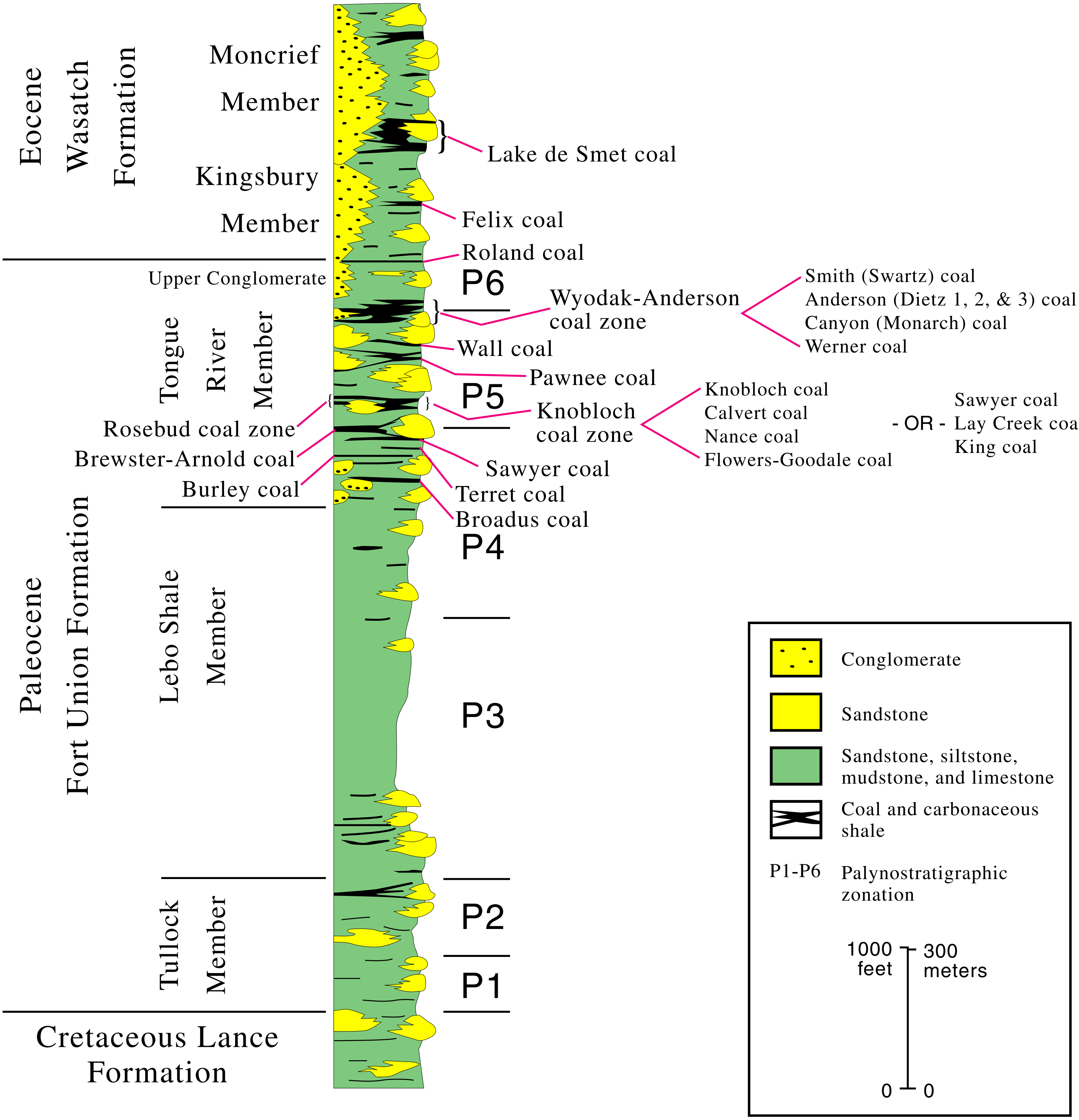

Figure PS-2. Composite stratigraphic column showing subdivisions of Upper Cretaceous rocks, Paleocene Fort Union Formation, and Eocene Wasatch Formation in the Powder River Basin, Wyoming and Montana. Major coal beds and zones are identified in the Fort Union and Wasatch Formations. Biostratigraphic zones(P1–P6) of the Fort Union Formation are also shown. The Wyodak-Anderson coal zone is synonymous to the Big George and Sussex coal in the central part of the Powder River Basin.

Click here or on this symbol
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Figure PS-3. Upper Fort Union conglomerate (more than 1,200 ft thick) exposed in the Castle Rock area north of Buffalo. The conglomerate is lateral facies to the Tongue River Member. Photograph by R.M. Flores.

Click here or on this symbol
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Figure PS-4. The erosional-based Fort Union conglomerate and coarse sandstone are interbedded with variegated siltstone and mudstone, which were formed in alluvial fan and interfan environments. Photograph by R.M. Flores.

Click here or on this symbol
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Figure PS-5. Variegated and mottled siltstone and mudstone (lower part of picture) are capped by partly oxidized, rooted carbonaceous mudstone (central part of picture) representing a paleosol formed in the interfan environment. Photograph by R.M. Flores.

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Figure PS-6. Pebble conglomerate of the Tongue River Member exposed north of Kaycee; represents braided stream deposits. Photograph by R.M. Flores.

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Figure PS-7. Floodplain mudstone, siltstone, and silty sandstone underlain by fluvial channel sandstone beds (lower part of photo). The floodplain deposits have undergone pedogenesis that transformed the deposits into a stack of palesols. Each palesol consists of carbonaceous mudstone deposits with roots in the upper part and ironstone deposits in the lower part. These deposits underlie the “Sussex” coal zone and exposed north of Linch, Wyoming. Photograph by R.M. Flores.

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Figure PS-8. Coarsening-upward mudstone, siltstone, and silty sandstone crevasse splay deposits. These rocks are exposed along the Powder River in northeastern Wyoming. Photograph by R.M. Flores

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Figure PS-9. Vertically stacked fluvial channel sandstone deposits interbedded with floodplain and crevasse splay deposits. These deposits are below the "Sussex" coal zone, which is exposed north of Linch, Wyoming. Photograph by R.M. Flores.

Click here or on this symbol
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PS-10. Fluvial channel deposit consisting of multi-erosional, crossbedded sandstone intercalated with basally erosional mudstone deposits that are abandoned "clay plugs." These deposits are below along the "Sussex" coal zone, which is exposed north of Linch, Wyoming.

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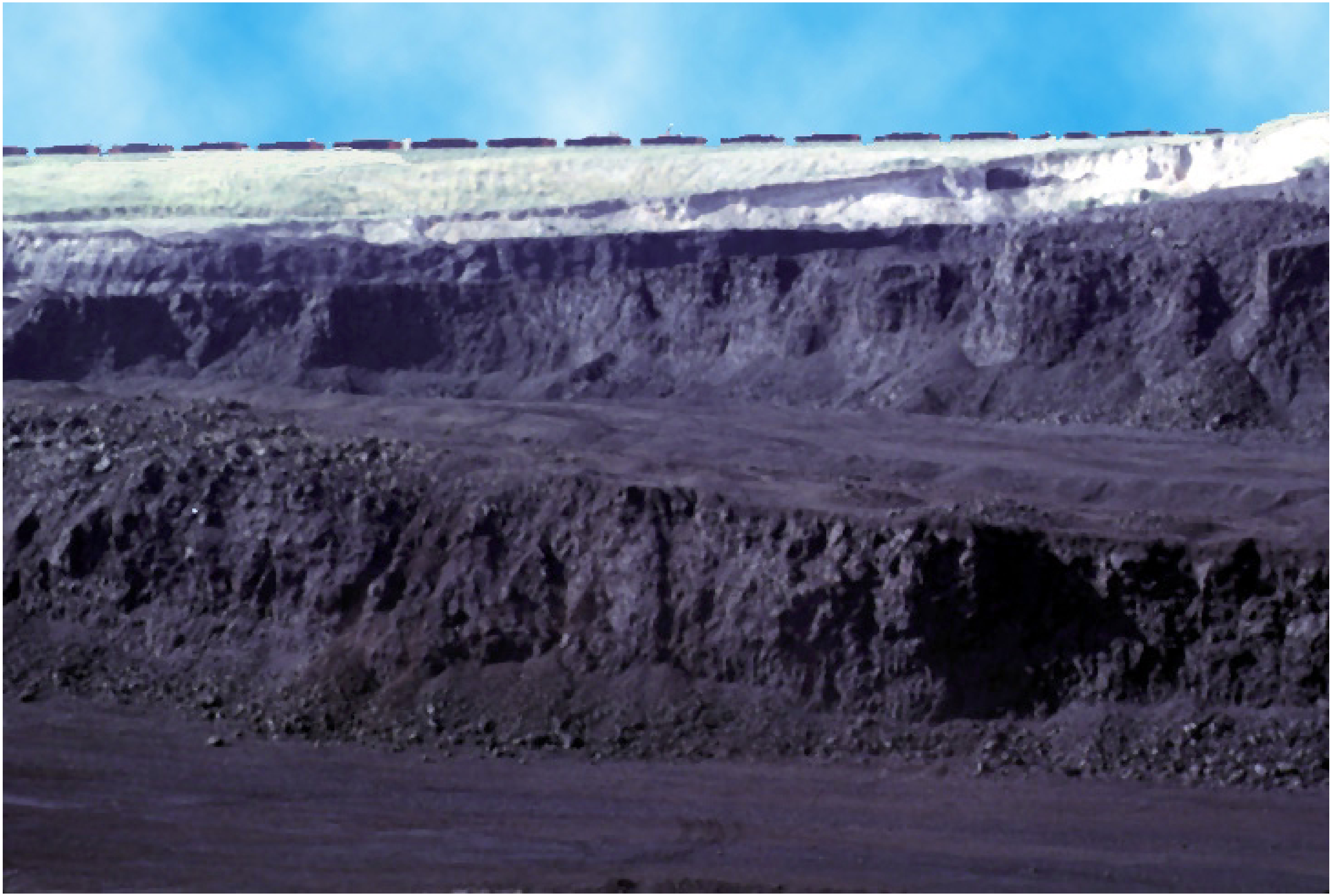

Figure PS-11. Wyodak–Anderson coal, which is more than 100 ft thick, in the Eagle Butte coal mine in the Gillette coalfield in Wyoming. Coal train is on horizon in background. Photograph by R.M. Flores.

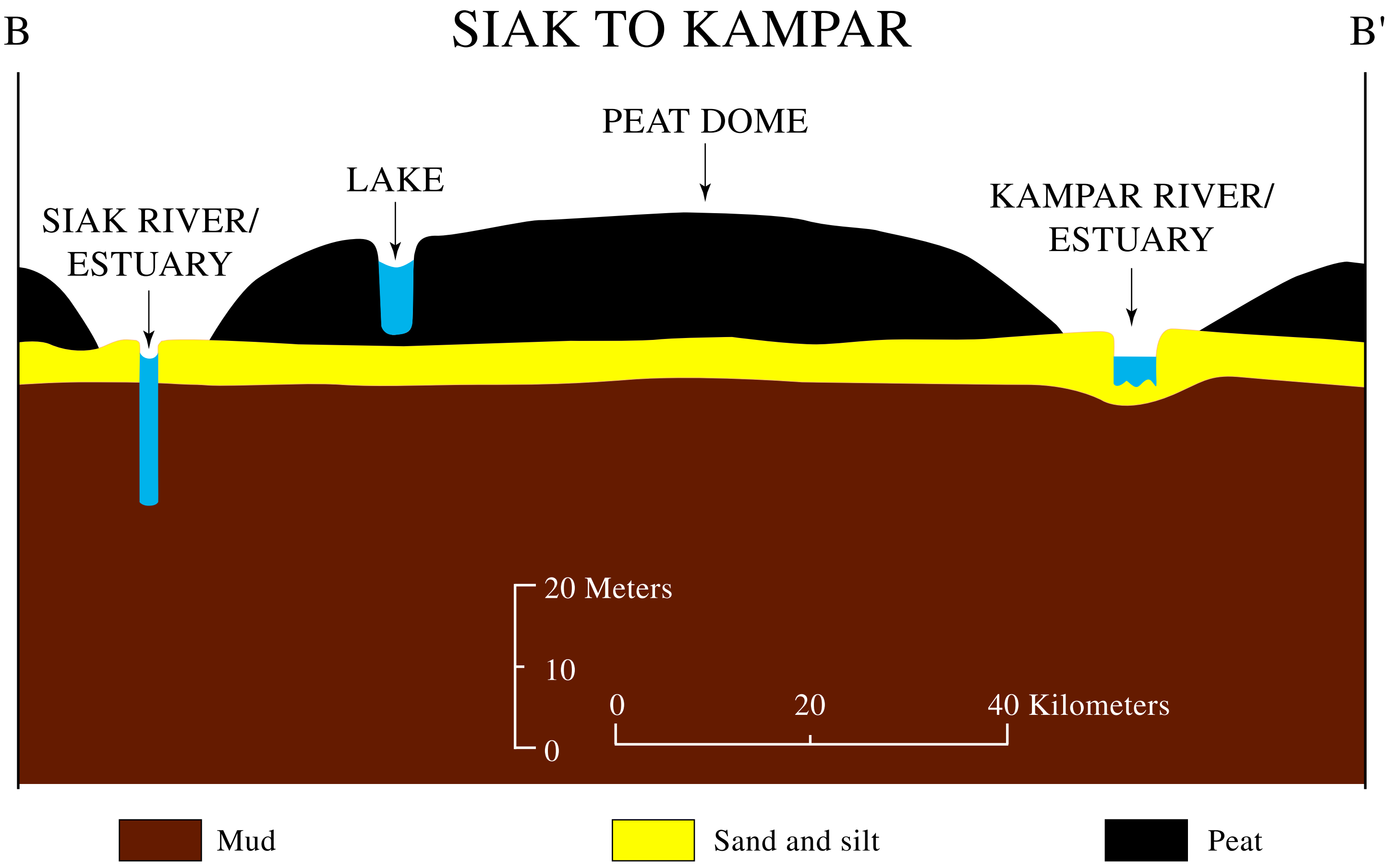

Figure PS-12. Diagrammatic cross section of a raised bog between two river estuaries in Sumatra, Indonesia. The thickest peat measured here is 13 meters (modified from Neuzil and others, 1993).

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Figure PS-13. Peat exposed along a drainage ditch cut near the margin of a raised bog in central Kalimantan, Borneo. Photograph by C. Blaine Cecil.

Click here or on this symbol
in the toolbar to return.

Figure PS-14. Wyodak–Anderson coal (Anderson–Dietz coal), showing a thin carbonaceous shale, coaly mudstone parting in the Spring Creek coal mine in Montana. Photograph by R.M. Flores.

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in the toolbar to return.

Figure PS-15. The split Wyodak–Anderson coal zone (upper bed is Anderson or Dietz 1 coal and the lower bed is Dietz 2 coal) in the Decker coal mine in Montana. The coal beds are split by tabular crevasse splay sandstone interbedded with mudstone and siltstone. Photograph by R.M. Flores.

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Figure PS-16. The merged Wyodak–Anderson coal, which is more than 80 ft thick, in the Spring Creek coal mine in Montana. Photograph by R.M. Flores.

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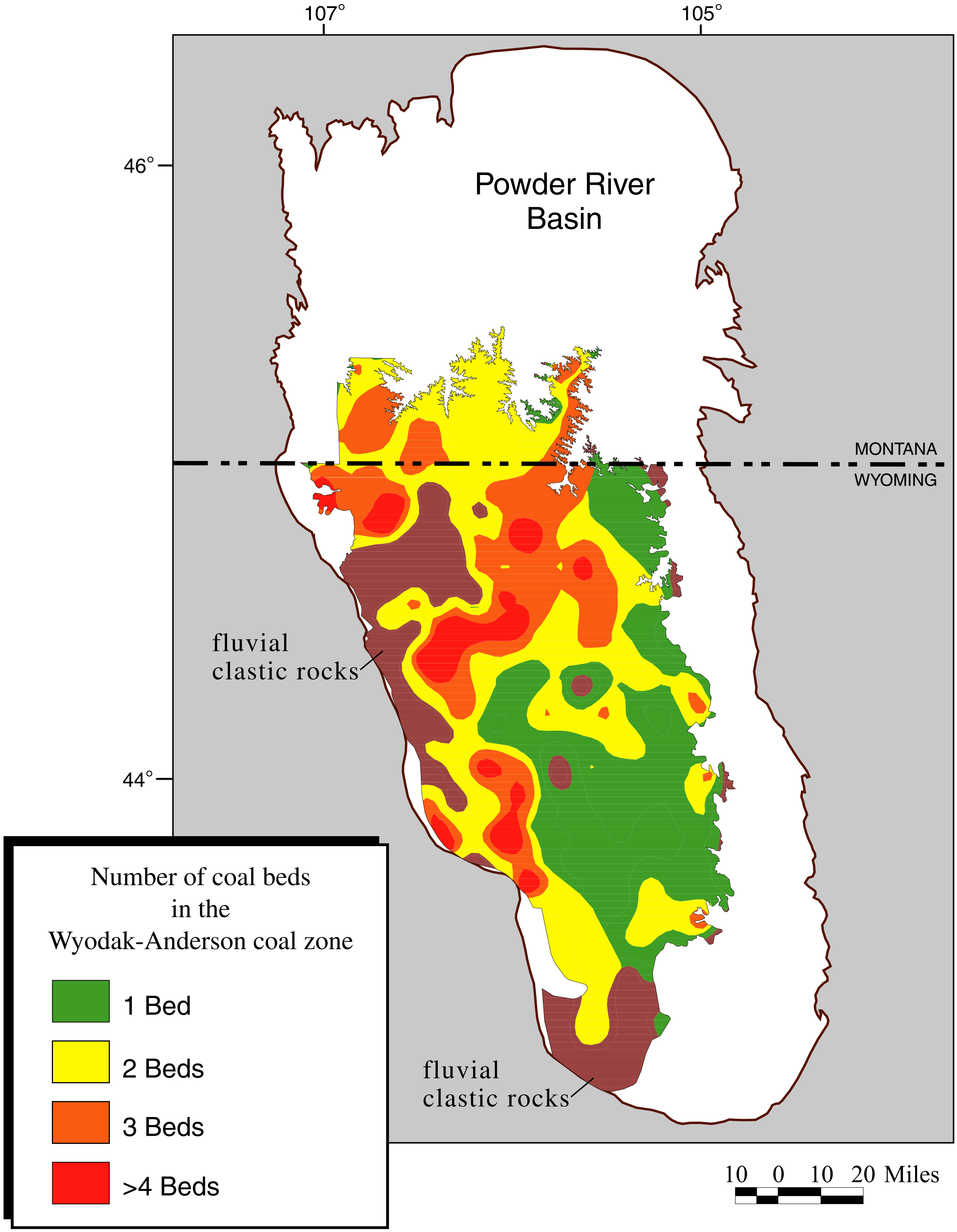

Figure PS-17. Distribution of the number of coal beds in the Wyodak-Anderson coal zone in the Powder River Basin.

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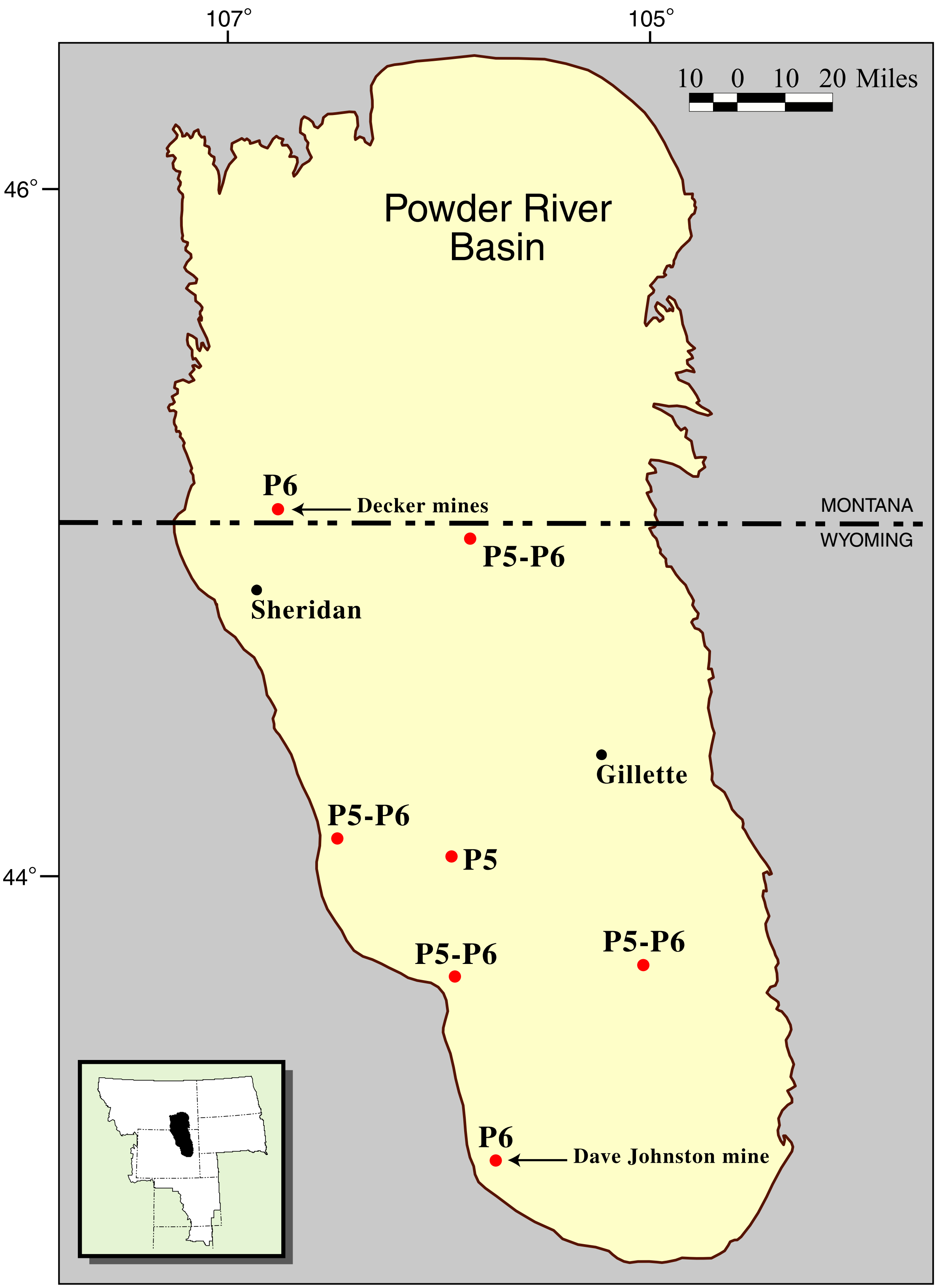

Figure PS-18. Biozones of the Wyodak-Anderson coal zone indicate early late Paleocene (P5) to latest Paleocene (P6) from the center to the margins of the basin. P5–P6 biozone is between these Paleocene ages (see Chapter PB, Biostratigraphy by Nichols, in this CD-ROM).

Click here or on this symbol
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Figure PS-19. Clinker (orange-red) of the Anderson coal bed (upper clinker) and Canyon coal bed (lower clinker) of the Wyodak–Anderson coal zone along the valley wall of the Powder River in Wyoming. Here, the coal beds are susceptible to burning, which progresses downdip (to the left of photo). Photograph by R.M. Flores.

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Figure PS-20. A closer view of the clinker consisting of black, vesicular, cryptocrystalline to glassy fused rock, orange-red baked mudstone, siltstone, and sandstone, and breccia composed of angular unfused to slightly fused rock fragments (Coates, 1980).

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Figure PS-21. Clinker (orange-red at the left of the picture) of the Anderson or Dietz 1 coal bed (at the right of the picture) on the Decker coal mine in Montana. Burning has reduced the reserve of the Anderson coal bed. Photograph by R.M. Flores.

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Figure PS-22. An outcrop (north of Linch, Wyoming) of the “Sussex” coal zone consisting of a more than 20-ft- thick coal bed (upper part of picture) and there underlying thin coal beds that are interbedded with silty sandstone, siltstone, and mudstone representing floodplain deposits. The “Sussex” coal zone is underlain by a fluvial channel sandstone. Photograph by R.M. Flores.