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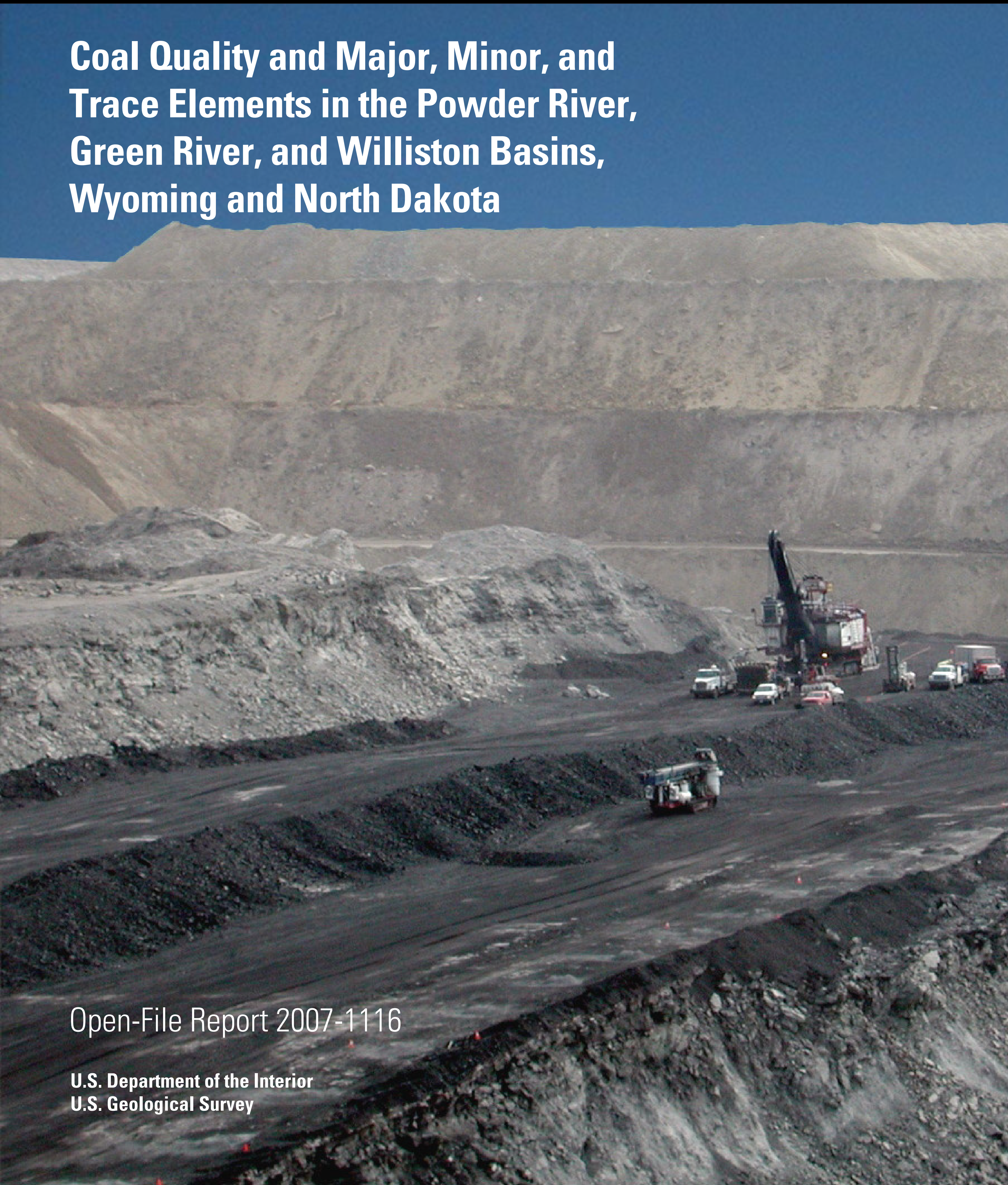
Coal Quality and Major, Minor, and Trace Elements in the Powder River, Green River, and Williston Basins, Wyoming and North Dakota



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U.S. Department of the Interior
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Coal Quality and Major, Minor, and Trace Elements in the Powder River, Green River, and Williston Basins, Wyoming and North Dakota

By Gary D. Stricker[1], Romeo M. Flores[1], Michael H. Trippi[2], Margaret S. Ellis[1], Carol M. Olson[1], Jonah E. Sullivan[1], and Kenneth I. Takahashi[1]

Introduction

The U.S. Geological Survey (USGS), in cooperation with the Wyoming Reservoir Management Group (RMG) of the Bureau of Land Management (BLM) and nineteen independent coalbed methane (CBM) gas operators in the Powder River and Green River Basins in Wyoming and the Williston Basin in North Dakota, collected 963 coal samples from 37 core holes (fig. 1; table 1) between 1999 and 2005. The drilling and coring program was in response to the rapid development of CBM, particularly in the Powder River Basin (PRB), and the needs of the RMG BLM for new and more reliable data for CBM resource estimates and reservoir characterization. The USGS and BLM entered into agreements with the gas operators to drill and core Fort Union coal beds, thus supplying core samples for the USGS to analyze and provide the RMG with rapid, real-time results of total gas desorbed, coal quality, and high pressure methane adsorption isotherm data (Stricker and others, 2006).

The USGS determined the ultimate composition of all coal core samples; for selected samples analyses also included proximate analysis, calorific value, equilibrium moisture, apparent specific gravity, and forms of sulfur. Analytical procedures followed those of the American Society of Testing Materials (ASTM; 1998). In addition, samples from three wells (129 samples) were analyzed for major, minor, and trace element contents. Ultimate and proximate compositions, calorific value, and forms of sulfur are fundamental parameters in evaluating the economic value of a coal. Determining trace element concentrations, along with total sulfur and ash yield, is also essential to assess the environmental effects of coal use, as is the suitability of the coal for cleaning, gasification, liquefaction, and other treatments. Determination of coal quality in the deeper part (depths greater than 1,000 to 1,200 ft) of the PRB (Rohrbacher and others, 2006; Luppens and others, 2006) is especially important, because these coals are targeted for future mining and development.

[1]U.S. Geological Survey, Denver, Colorado 80225

[2]U.S. Geological Survey, Reston, Virginia 20192

This report contains summary tables, histograms, and isopleth maps of coal analyses. Details of the compositional internal variability of the coal beds are based on the continuous vertical sampling of coal sequences, including beds in the deeper part of the PRB. Such sampling allows for close comparisons of the compositions of different parts of coal beds as well as within the same coal beds at different core hole locations within short distances of each other.

General Geology

Powder River Basin

Coal samples collected in the PRB targeted thick coal beds and coal zones that are producing CBM or have potential for CBM production. The sampled coal beds and coal zones are in the Tongue River Member of the Paleocene Fort Union Formation; they include, in ascending order, the Roberts, Cache, Pawnee, Wall, and Cook coal beds and beds in the Wyodak–Anderson coal zone. The later is comprised of the Werner, Canyon–Wyodak, Anderson–Big George, School, Badger, and Smith coal beds (fig. 2), with individual beds ranging in thickness from 20 to 205 ft. The zone extends laterally about 190 mi north-south and 63 mi east-west (Flores and others, 1999c). Within it, beds split and merge, and several are the most widespread in the PRB.

Names of the sampled coal beds used in this study are those given by gas operations, and do not necessarily follow USGS names and correlations as established in earlier studies by Mapel (1973), Kent (1986), Culbertson and others (1979), and Flores and others (1999c). Figure 3 shows some of the inconsistencies that have arisen in the naming and correlation of the Cook, Canyon, and Anderson coal beds by gas operators in two different but adjacent lease areas of the PRB (Flores and others, 2005). Because of these inconsistencies, discussions and comparisons of coal quality and major, minor, and trace element data are limited to coal beds of the Wyodak–Anderson coal zone (Anderson–Big George and Canyon–Wyodak) for which stratigraphic positions and correlations are considered to be less problematic (see Flores and others, 1999c; McGarry and Flores, 2004).

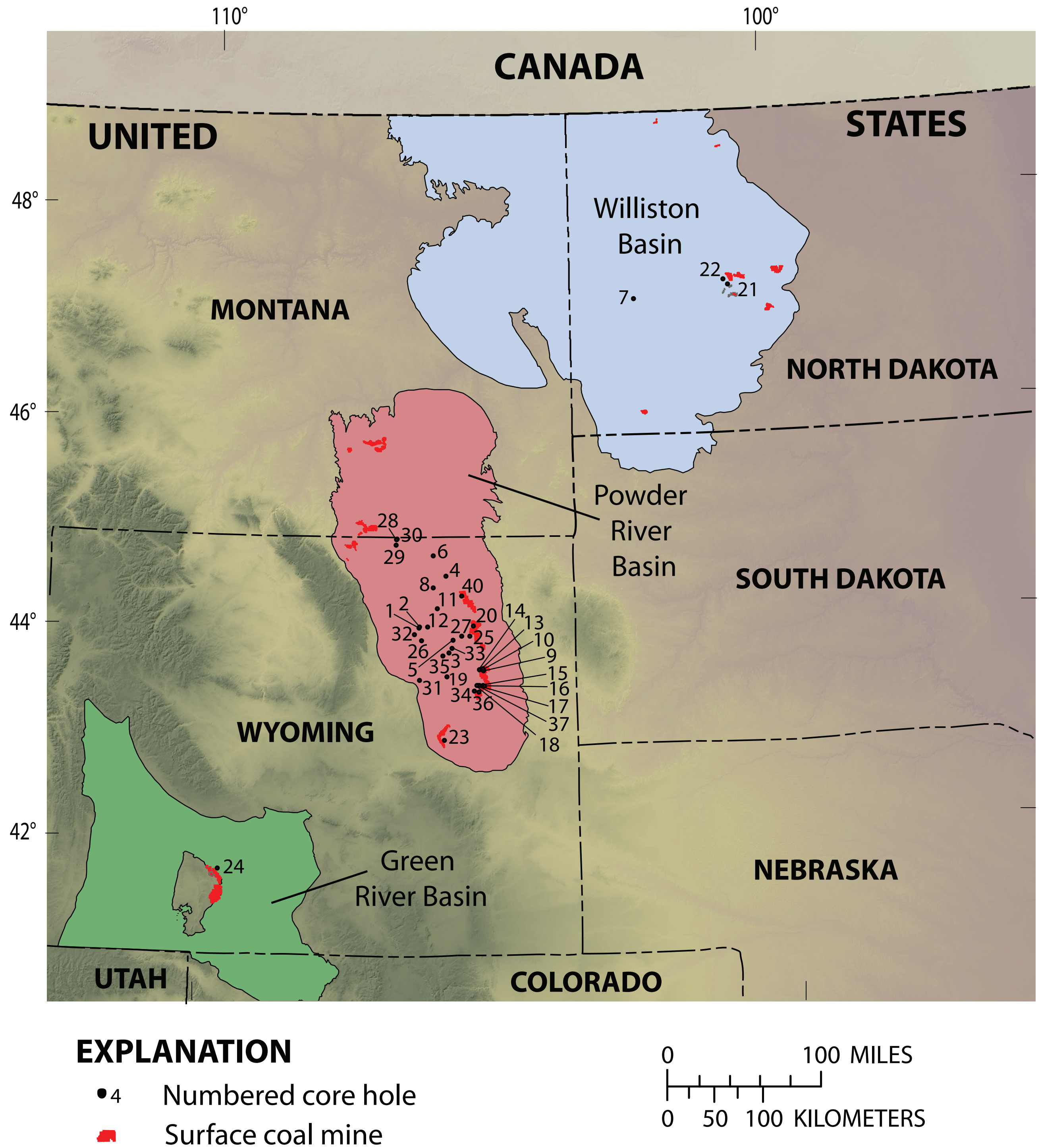

Figure 1. Location of core holes in the Powder River and Green River Basins, Wyoming and Williston Basin, North Dakota.

Table 1. List of core holes used in coal studies, Powder River, Green River, and Williston Basins, Wyoming and North Dakota.

[WY, Wyoming; ND, North Dakota; PRB, Powder River Basin; WB, Williston Basin; GRB, Green River Basin; NA, no API number]

Core hole number	Gas operator	Core hole name	American Petroleum Institute (API) well number	State	Basin
1	MichiWest Energy Inc.	Pilot State16-14	049-019-21068	WY	PRB
2	MichiWest Energy Inc.	Pilot State 16-32	049-019-21071	WY	PRB
3	Ocean Energy Inc.	Schlautmann 9-10-45-74WY (Ocean 43-10C)	049-005-34173	WY	PRB
4	Pennaco Energy Inc.	Sorenson 2-33-54-74W	049-005-35137	WY	PRB
5	Barrett Resources Corporation	Haas 32-31	049-005-35287	WY	PRB
6	CMS Oil and Gas Company	West 6-19W	049-005-35339	WY	PRB
7	Gregory Water and Energy Inc.	Leroy Gregory 1	NA	ND	WB
8	CMS Oil and Gas Company	Laramore 11-6C	049-005-37516	WY	PRB
9	Kennecott Energy	Kennecott CBM-1	NA	WY	PRB
10	Kennecott Energy	Kennecott CBM-2	NA	WY	PRB
11	Barrett Resources Corporation	CARU State 22-16-5075W	049-005-38103	WY	PRB
12	Barrett Resources Corporation	Schoonover Road Unit (SRU) State 12-16-4876	049-005-36110	WY	PRB
13	Rim Operating Inc.	CBM H 11-04	049-005-37359	WY	PRB
14	Rim Operating Inc.	CBM C 33-1R	049-005-37386	WY	PRB
15	Peabody Natural Gas, LLC.	PNG 34-1	NA	WY	PRB
16	Peabody Natural Gas, LLC.	PNG 33-1	NA	WY	PRB
17	Peabody Natural Gas, LLC.	PNG 31-1	NA	WY	PRB
18	Peabody Natural Gas, LLC.	PNG 35-1	NA	WY	PRB
19	Barrett Resources Corporation	All Night Creek (ANCU) Iberlin 21-33-4374	049-005-37965	WY	PRB
20	Peabody Natural Gas, LLC.	PNG 16-2	NA	WY	PRB
21	The Coteau Properties Co.	Coteau MC00250C	NA	ND	WB
22	The Coteau Properties Co.	Coteau MC00251	NA	ND	WB
23	Ammonite Energy Texas, Inc.	Thomas Jefferson State 36-3	049-009-22996	WY	PRB
24	Bridger Coal Co.	BCX-9	NA	WY	GRB
25	Peabody Natural Gas, LLC.	PNG Duvall 13J-D	049-005-44594	WY	PRB
26	Barrett Resources Corporation	KU Harriett 41-34-4777	049-019-21774	WY	PRB
27	Peabody Natural Gas, LLC.	PNG Carter-Federal 18F-D	049-005-37063	WY	PRB
28	Nance Petroleum Corporation	Remington 587930 07A	049-033-23127	WY	PRB
29	Nance Petroleum Corporation	Remington 57-79-18-03R	049-033-23136	WY	PRB
30	Nance Petroleum Corporation	Remington 587930 01C	049-033-23131	WY	PRB
31	Williams Production RMT Company	Bullwacker Creek Unit (BCU) 32-9-4277	049-019-21969	WY	PRB
32	Lance Oil and Gas Company Inc.	Whiskey Draw Unit 12-12-4778	049-019-22873	WY	PRB
33	Lance Oil and Gas Company Inc.	McBeth 12-30-4673-BG	049-005-50378	WY	PRB
34	Williams Production RMT Company	State 23-16-4171	049-005-50711	WY	PRB
35	Williams Production RMT Company	Groves 12-19-4574	049-005-51276	WY	PRB
36	Peabody Natural Gas, LLC.	PNG 24-1	NA	WY	PRB
37	Peabody Natural Gas, LLC.	PNG 26-1	NA	WY	PRB

Table 1. List of core holes used in coal studies—Continued

Core hole number	Decimal latitude	Decimal longitude	Section, Township, and Range	Date cored
1	44.12838N	106.12824W	SW/4 SW/4 Sec 16 T48N R77W	January 27, 1999
2	44.13568N	106.11822W	SW/4 NE/4 Sec 16 T48N R77W	April 7, 1999
3	43.88730N	105.73104W	NE/4 SE/4 Sec 10 T45N R74W	June 25, 1999
4	44.62333N	105.76500W	NW/4 NE/4 Sec 33 T54N R74W	August 13, 1999
5	44.00851N	105.67651W	SW/4 NE/4 Sec 31 T47N R73W	September 24, 1999
6	44.81796N	105.93621W	SE/4 NW/4 Sec 19 T56N R75W	September 27, 1999
7	47.23228N	103.14541W	SE/4 SE/4 Sec 6 T143N R98W	October 13, 1999
8	44.51333N	105.93560W	NE/4 SW/4 Sec 6 T52N R75W	December 10, 1999
9	43.71728N	105.27447W	SW/4 NW/4 Sec 9 T43N R70W	January 5, 2000
10	43.72136N	105.27680W	SW/4 NW/4 Sec 9 T43N R70W	January 6, 2000
11	44.31003N	105.88602W	SE/4 NW/4 Sec 16 T50N 75W	February 20, 2000
12	44.13523N	106.00883W	SW/4 NW/4 Sec 16 T48N R76W	February 29, 2000
13	43.73564N	105.27828W	NW/4 NW4 Sec 4 T43N R70W	March 22, 2000
14	43.72872N	105.32945W	NW/4 SE/4 Sec 1 T43N R71W	April 27, 2000
15	43.57330N	105.26031W	NE/4 NW/4 Sec 34 T42N R70W	June 2, 2000
16	43.57583N	105.28145W	NE/4 NW/4 Sec 33 T42N R70W	June 2, 2000
17	43.57895N	105.32843W	NE/4 NW/4 Sec 31 T42N R70W	June 3, 2000
18	43.57624N	105.35947W	SW/4 NE/4 Sec 35 T42N R71W	July 12, 2000
19	43.66122N	105.75760W	NE/4 NW/4 Sec 33 T43N R74W	July 14, 2000
20	44.14510N	105.40291W	NW/4 NW/4 Sec 9 T48N R71W	July 31, 2000
21	47.33781N	101.82531W	C SE/4 NE/4 36 T145N R88W	August 22, 2000
22	47.38478N	101.88874W	C NE/4 NE/4 16 T145N R88W	August 24, 2000
23	43.05322N	105.79355W	NE/4 NE/4 Sec 36 T36N R75W	September 7, 2000
24	41.80364N	108.70250W	SW/4 NW/4 Sec 11 T21N R100W	October 24, 2000
25	44.04874N	105.45364W	NW/4 SE/4 Sec 13 T47N R72W	June 10, 2001
26	44.00798N	106.09271W	NE/4 NE/4 Sec 34 T47N R77W	June 13, 2001
27	44.05166N	105.56000W	SE/4 NW/4 Sec 18 T47N R72W	July 21, 2001
28	44.97265N	106.42874W	SW/4 NE/4 Sec 30 T58N R79W	December 5, 2001
29	44.91805N	106.43215W	NE/4 NW/4 Sec 18 T57N R79W	December 8, 2001
30	44.97623N	106.42377W	NE/4 NE/4 Sec 30 T58N R79W	December 8, 2001
31	43.62830N	106.11680W	SW/4 NE/4 Sec 9 T42N R77W	January 18, 2002
32	44.06227N	106.18863W	SW/4 NW/4 Sec 12 T47N R77W	January 8, 2003
33	43.93458N	105.68611W	SW/4 NW/4 Sec 30 T46N R73W	April 22, 2003
34	43.52525N	105.39694W	NE/4 SW/4 Sec 16 T41N R71W	July 9, 2003
35	43.86103N	105.80693W	SW/4 NW/4 Sec 19 T45N R74W	October 22, 2003
36	43.51627N	105.33530W	SE/4 SW/4 Sec 24 T41N R71W	October 25, 2003
37	43.57958N	105.34513W	SE/4 SE/4 Sec 26 T42N R71W	October 28, 2003

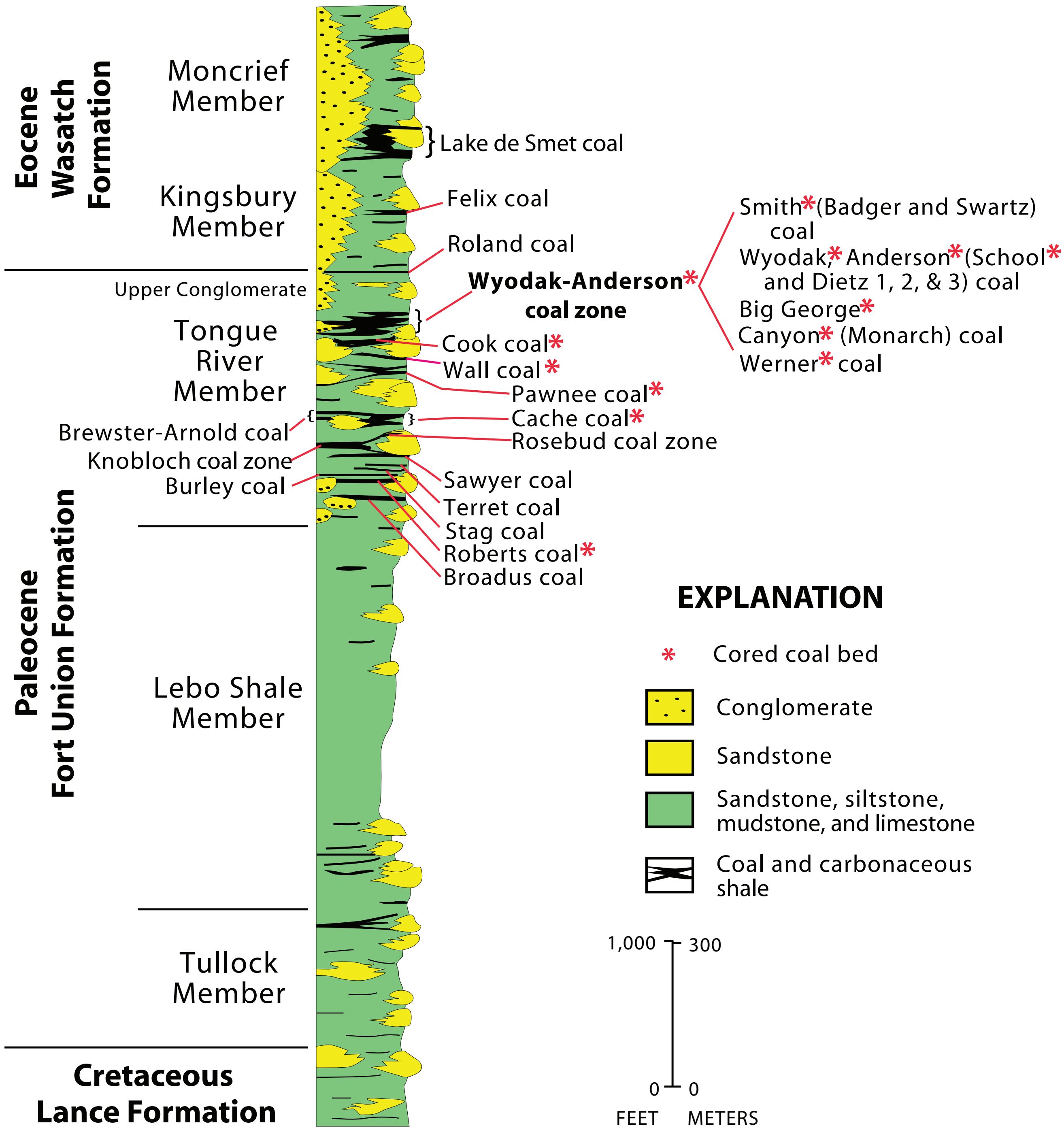

Figure 2. Stratigraphic column for the Fort Union Formation in the Powder River Basin, Wyoming and Montana.

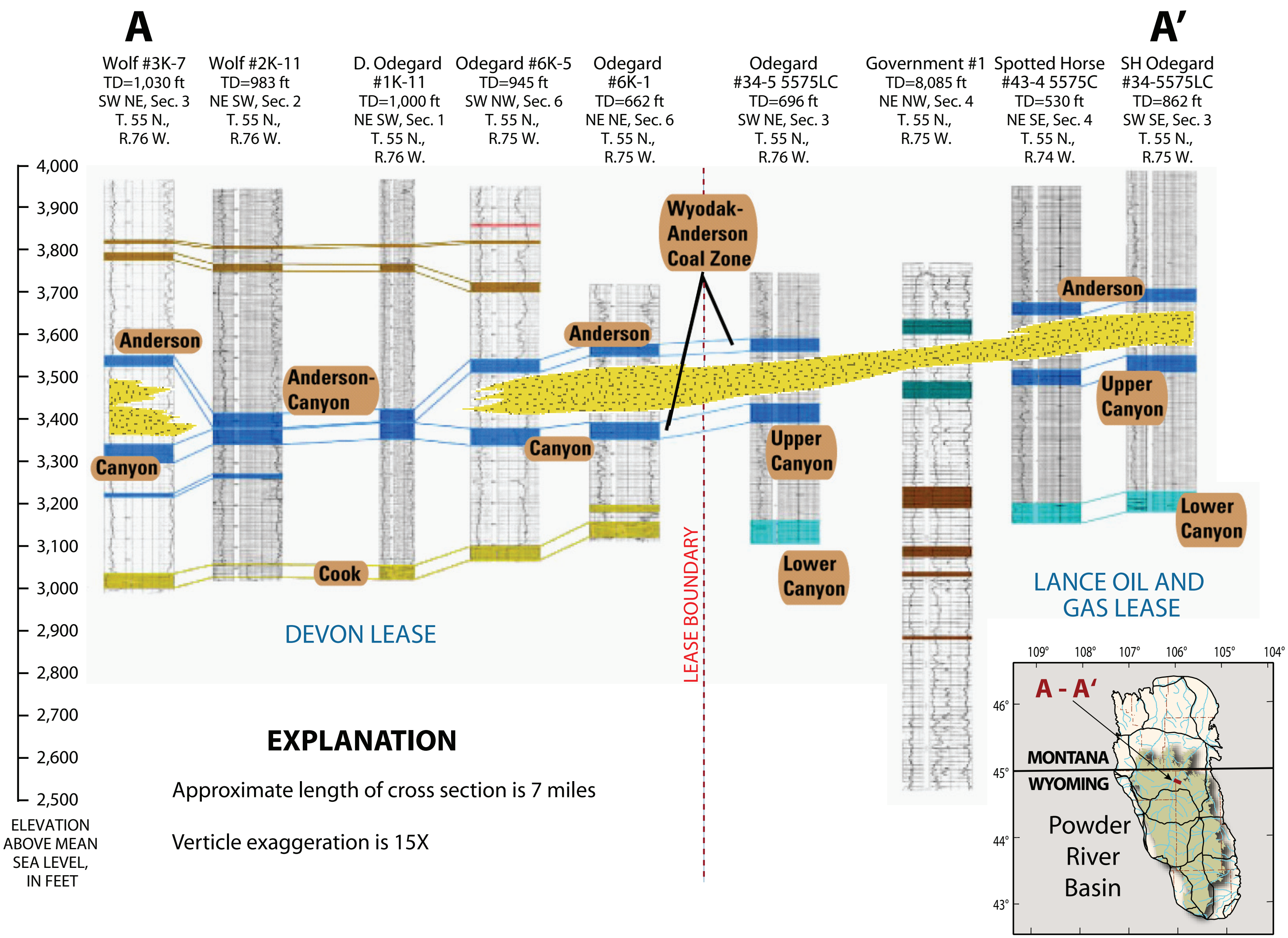

Figure 3. Cross section of coal correlations and coal bed names used by both gas operators and the U.S. Geological Survey for beds in the Wyodak–Anderson coal zone in the Powder River Basin, Wyoming (coal bed names from Fort Union Assessment Team, 1999; figure modified from Flores and others, 2005).

Green River Basin

The Fort Union Formation in the Green River Basin contains two coal zones; Deadman, in the lower part of the Fort Union Formation, and Cherokee, in the upper part. These zones, containing more than 8 individual coal beds (fig. 4), are separated by an interval dominated by fluvial channel sandstones (Hettinger and Kirschbaum, 1991). The sampled coal bed was the Deadman 4 coal (Flores and others, 1999b) in the Bridger Coal Mine (core hole 24, table 1) where it is as much as 20 ft thick.

Williston Basin

The Fort Union Formation in the Williston Basin contains 3 coal-bearing intervals: Harmon–Hansen coal zone in the lower part, Hagel coal zone in the middle part, and Beulah–Zap coal zone in the upper part (Flores and others, 1999a); (fig. 5). One coal bed (unnamed 1) sampled in the Leroy 1 well (core hole 7, table 1) is as much as 14 ft thick, and is probably in the Harmon–Hansen zone. Four other coal beds sampled were in the Beulah–Zap coal zone, where they are as much as 50 ft thick. The samples were obtained from the Coteau Coal Mine MC00250C (Beulah and unnamed 2) and MC00251 (unnamed 3 and 4) wells (core holes 21 and 22, respectively; table 1).

Methods

Coal sampling followed the methods suggested by Stanton (1989), analyses followed the methods of the American Society of Testing Materials (1998), and major-, minor-, and trace-element analyses followed the methods of the USGS (Bullock and others, 2002). The 963 samples that were collected were placed in sealed canisters 2-ft long and 4.0 in. in diameter; and mean sample weight was 3,532 g. The coal, after gas desorption in the canisters (see Stricker and others, 2006), was split into subsamples for (1) ultimate and proximate analysis; (2) determining calorific value, equilibrium moisture value, apparent specific gravity, and forms of sulfur (about 300 g for (1) and (2)); (3) major-, minor-, and trace-element analysis (about 200 g); and (4) archival purposes (about 3,000 g). The samples were put in plastic bags and sealed to minimize moisture loss and possible contamination.

Samples for analyses listed as (1) and (2) above were sent to an outside laboratory (Geochemical Testing) who were also responsible for coal grinding and sample splitting. General procedures are described in the Staff, Office of the Director Coal Research (1967), and specific analyses are described in ASTM (1998). Ultimate analysis included (in percent) ash yield, carbon, hydrogen, oxygen, sulfur, and nitrogen. All of the above analyses are reported and discussed on an as-received basis.

In the USGS laboratory, a sample reserved for major-, minor-, and trace-element analysis was split into two subsamples, one for analysis of whole coal and the other for ashed coal. Elements analyzed on a whole coal basis include chlorine, mercury, total sulfur, and selenium; all other elements were determined on coal ash. Included in the total suite of elements were those of environmental concern (also referred to as hazardous air pollutants or HAPs), which include antimony, arsenic, beryllium, cadmium, chromium, cobalt, lead, manganese, mercury, nickel, selenium, and uranium. For our study, all major-, minor-, and trace-element data analyzed in the USGS laboratory are reported on a whole coal dry basis, as given in Appendix III and shown with bar graphs in Appendix IV.

Results of the ultimate, proximate, calorific value, and forms of sulfur analyses are given in Appendix I, and bar graphs of these data are shown in Appendix II. A statistical summary of data in Appendix I is presented in tables 2 and 3. All analytical data and bar graphs in Appendices I through IV are arranged in ascending order by core hole number. The data will be discussed for selected coal beds according to vertical stratigraphic distribution (in descending order) of the coal beds in each basin.

Powder River Basin Coal Beds

Twelve different Fort Union Formation coal beds, designated by the names applied by gas operators, were cored and sampled in the PRB (fig. 1). The Wyodak–Anderson coal zone and its contained coal beds Smith, School, Werner, Canyon, Wyodak, Big George, and Anderson and their merged beds (for example, the merged Big George consisting of the combined Anderson and Canyon beds in the west-central part of the PRB, and the merged Wyodak consisting of the combined Anderson and Canyon beds near surface mines in the eastern part of the PRB) contributed the most coal samples (712). This was followed by the Pawnee coal bed (26 samples), Cook coal bed (25 samples), Wall coal bed (20 samples), Cache coal bed (17 samples), Smith coal bed (15 samples), and Roberts coal bed (7 samples). The greatest number of samples were collected from the Wyodak–Anderson coal beds because they are the most productive of CBM in the basin.

Wyodak–Anderson Coal Zone

Core holes that penetrated the coal beds in the Wyodak–Anderson coal zone are as follows: Smith, core hole 8; School, core hole 23; Anderson or Big George, core holes 3, 5, 8, 19, 28, 33, 34, and 35; Canyon or Wyodak, core holes 5, 6, 8, 30, and 34; Wyodak (merged Anderson–Canyon or upper, middle, and lower Wyodak), core holes 9, 10, 13-18, and 20; Big George (merged Anderson–Canyon), core holes 1, 2, 11, 12, 26, 31, and 32; and Werner, core hole 11 (see table 2).

Smith Coal Bed

The Smith coal bed is stratigraphically the highest (youngest) bed cored in the PRB. In core hole 8 (table 1) it consists of the lower and upper Smith beds, which are split by a mudstone in the depth interval 375-363 ft (see core hole 8a,

Appendix I-13 in Stricker and others, 2006). Listed below are coal properties and composition:

- Apparent rank: subbituminous B
- Calorific value (mean): 9,080 Btu
- Moist-mineral-matter-free Btu (mean): 9,550
- Proximate analysis (mean percent): ash yield, 5.87; volatile matter, 33.08; fixed carbon, 36.46; total moisture, 26.13
- Ultimate analysis (mean percent): hydrogen, 6.22; carbon, 51.27; nitrogen, 0.85; total sulfur, 0.35; oxygen, 35.45
- Forms of sulfur (mean percent): sulfate, 0.03; pyritic, 0.04; organic, 0.28

Vertical variations in the proximate and ultimate analyses, calorific value, and forms of sulfur in the lower and upper Smith coal beds are shown in bar graphs for core hole 8 (Appendix II). Moisture in the lower Smith coal bed (375-386 ft) does not vary as much as in the upper Smith coal bed (344-363 ft). Ash yield is higher in the lower Smith coal than in the upper Smith coal. For the combined Smith coal beds, the volatile matter decreases upward and fixed carbon increases upward. Hydrogen, carbon, nitrogen, and oxygen do not show significant variations between the lower and upper Smith coal beds. However, sulfur content shows an increasing upward trend in the lower Smith coal bed and a decreasing upward trend throughout the upper Smith coal bed.

Calorific value is slightly higher in the lower Smith coal bed. Sulfate sulfur is higher in the lower Smith coal bed, whereas pyritic sulfur is highest in the top and bottom of the upper Smith coal bed and in the middle part of the lower Smith coal bed. Organic sulfur increases upward in the lower Smith coal bed but decreases upward in the upper Smith coal bed.

The most distinctive vertical changes in coal quality for the Smith coal bed are ash yield, total sulfur content, and forms of sulfur (Appendix I). The general upward increase in ash yield may be related to the depositional environment, as both the lower and upper Smith coal beds are overlain and separated by floodplain mudstone, which reflects incursions of floodwaters into a low-lying swamp (Pocknall and Flores, 1987; Flores, 1983; 1986) that gradually choked the peat-forming environment and caused the upward increase in ash yield now observed in the beds. The relatively high total sulfur content (0.35 percent), of the lower Smith coal bed when compared to other coal beds in the Wyodak–Anderson coal zone (Wyodak is 0.18 percent), may be related to the high sulfate and organic sulfur contents.

School Coal Bed

The School coal bed is in the southwestern part of the PRB. In core hole 23 (table 1), it is subbituminous C in apparent rank with the following properties and composition:

- Calorific value (mean): 8,020 Btu
- Moist-mineral-matter-free Btu (mean): 8,860
- Proximate analysis (mean percent): ash yield, 12.20; volatile matter, 34.11; fixed carbon, 30.81; total moisture, 25.49
- Ultimate analysis (mean percent): hydrogen, 6.22; carbon, 44.86; nitrogen, 0.65; total sulfur, 0.56; oxygen, 35.50
- Forms of sulfur (mean percent): sulfate, 0.03; pyritic, 0.11; organic, 0.42

Vertical variations exhibited by proximate and ultimate analyses, calorific values, and forms of sulfur in the School coal bed are shown for core hole 23 in Appendices I and II. The ash yield generally decreases upward with a spike (36 percent) in the depth interval 342-343 ft. Total sulfur content increases upward with a spike (1.7 percent) in the depth interval 344-346 ft. The high ash interval corresponds to a parting (see Stricker and others, 2006; core hole 23, Appendix I-33) in the coal directly overlying the high sulfur interval. Pyritic and organic sulfur contents are also correspondingly high in this interval.

The upward decease in ash yield in the School coal bed indicates either a waning flow of floodwaters into the swamp or a gradual raising of the ground level into a raised bog (Flores, 1986). The high ash yield and total sulfur content of this bed were correlated to highly degraded maceral types in it, particularly at the point of splitting, which is an interpretation similar to that given by Moore (1985) for an area of splitting of the Anderson and Dietz coal beds in the Decker area in Montana.

Anderson–Big George and Canyon–Wyodak Coal Beds

In general, the Anderson–Big George and Canyon–Wyodak coals range from subbituminous C to A in apparent rank (see tables 2 and 3). The low rank coal (subbituminous C) is located primarily in the shallower part of the basin (surface to 1,000 ft), the high rank coal (subbituminous A) is in the deeper part (greater than 1,400 ft), whereas the middle coal rank (subbituminous B) is at an intermediate depth (1,000 to 1,400 ft). Listed below are coal properties and composition:

- Calorific values (range of means): 7,630 to 10,440 Btu
- Moist-mineral-matter-free Btu (range of means): 8,240 to 10,990
- Proximate analysis (range of means in percent): ash yield, 2.92 to 12.22; volatile matter, 27.11 to 38.51; fixed carbon, 33.18 to 43.79; total moisture, 17.95 to 32.01
- Ultimate analysis (range of means in percent): hydrogen, 5.99 to 6.69; carbon, 47.41 to 61.46; nitrogen, 0.51 to 1.29; total sulfur, 0.10 to 1.13; oxygen, 27.60 to 39.66
- Forms of sulfur (range of means in percent): sulfate, 0.01 to 0.04; pyritic, 0.00 to 0.15; organic, 0.11 to 0.56

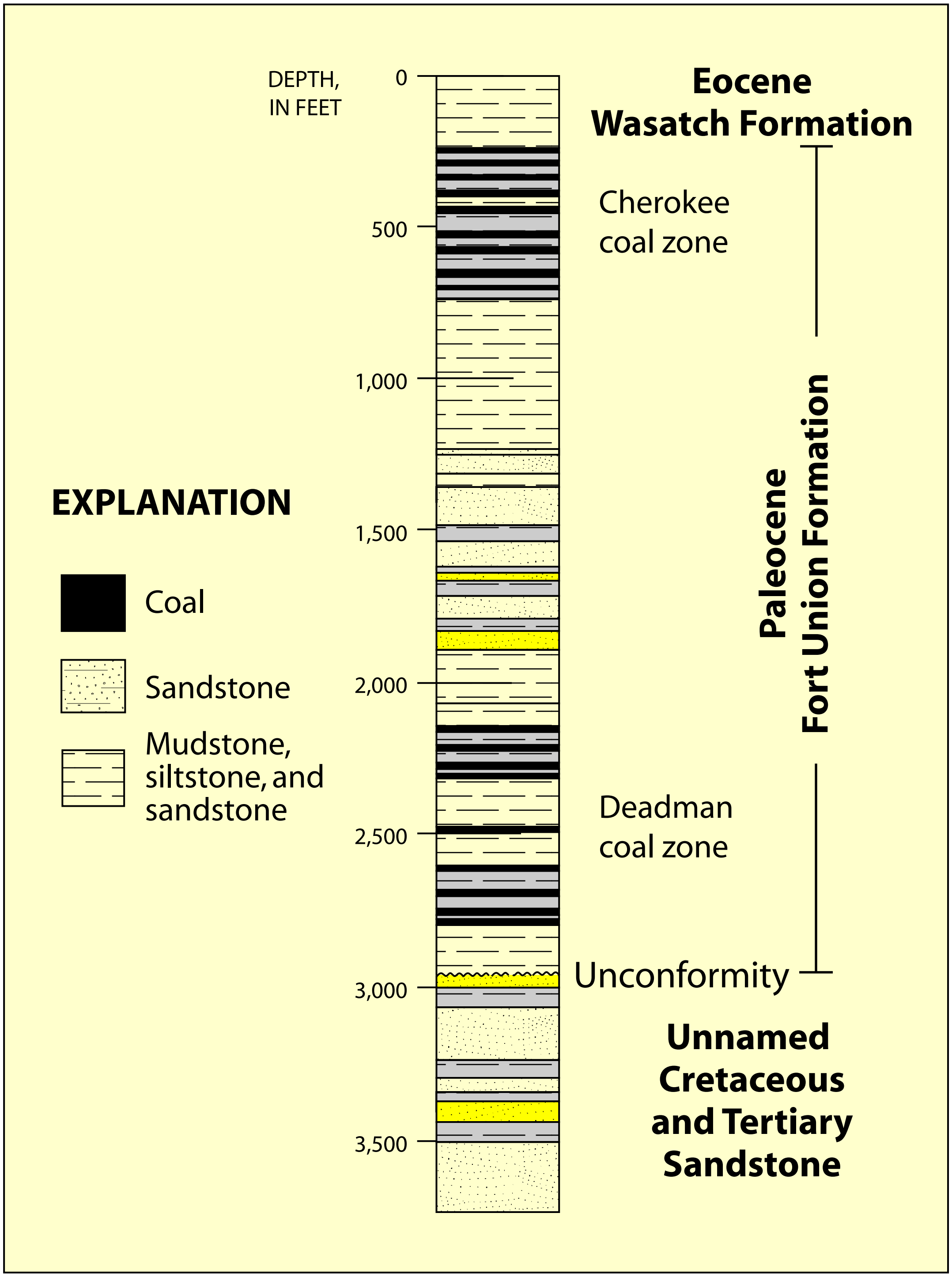

Figure 4. Stratigraphic column for the Fort Union Formation in the Green River Basin, Wyoming.

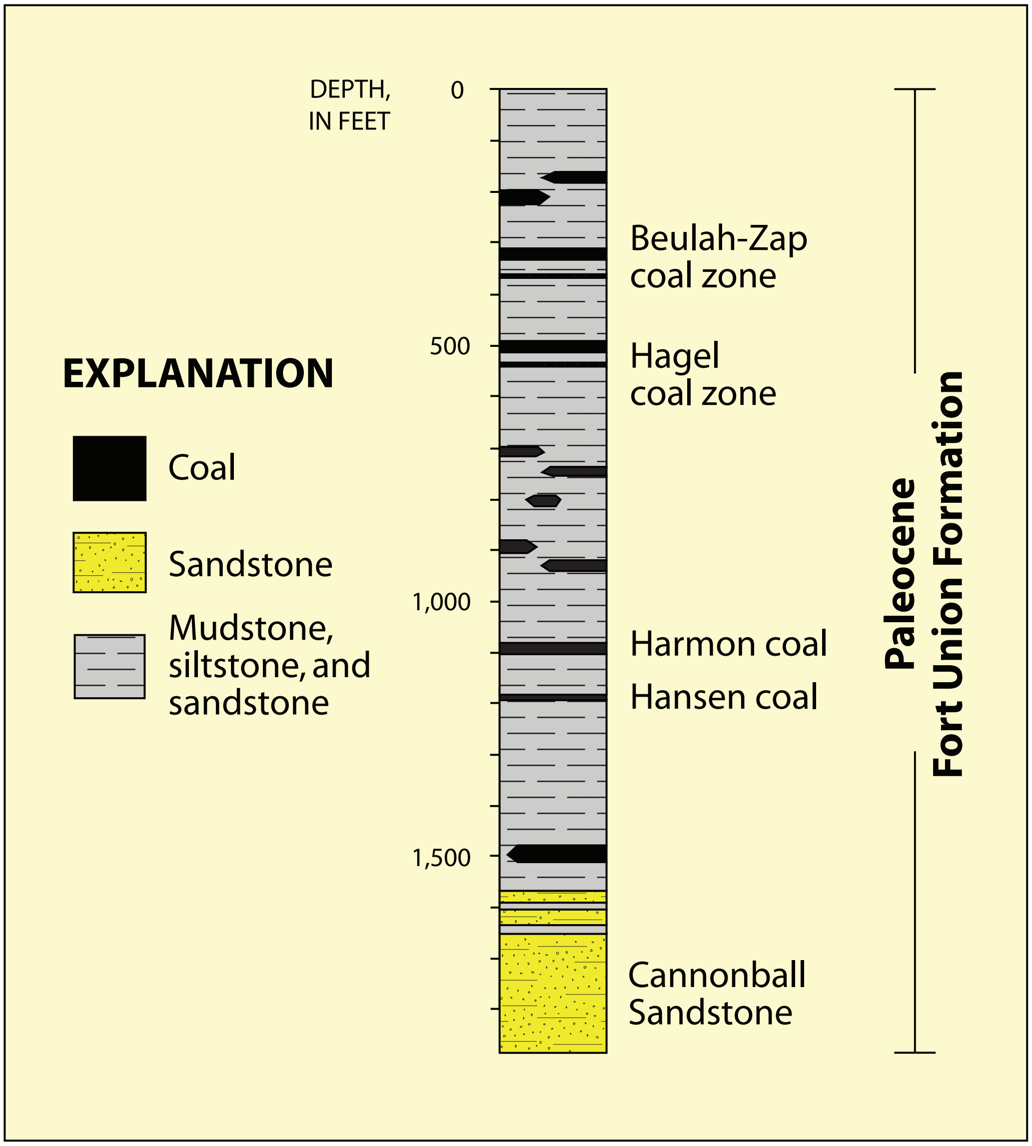

Figure 5. Stratigraphic column for the Fort Union Formation in the Williston Basin, North Dakota.

Table 2. Properties and composition of coal beds cored in the Powder River, Green River, and Williston Basins, Wyoming and North Dakota.

[----, not analyzed or not applicable; Btu, British thermal units per pound; g/cc, grams per cubic centimeter; LigA, lignite A coal; SubC, subbituminous C coal; SubB, subbituminous B coal; SubA, subbituminous A coal. Values reported on an as-received basis]

Core hole	Core hole name	Mean depth, in feet	Coal zone	Coal bed name as used by gas operators	Number of samples	Moisture, in percent				Apparent specific gravity, in g/cc
						Residual	Air dry loss	Total	Equilibrium	
1	Pilot State 16-14	1,287.2	Wyodak-Anderson	Big George	60	9.59	10.61	19.22	18.50	1.28
2	Pilot State 26-32	1,138.9	Wyodak-Anderson	Big George	50	7.50	13.27	19.78	----	----
3	Ocean 43-10C	1,192.0	Wyodak-Anderson	Anderson	2	10.32	19.09	27.76	26.40	----
4	Sorenson 2-33-54-74	825.3	----	Cook	10	7.53	21.42	27.30	----	----
4	Sorenson 2-33-54-74	1,142.0	----	Wall	16	9.61	17.61	25.55	----	----
5	Haas 32-31 2	1,076.0	Wyodak-Anderson	Big George	13	10.79	17.49	26.42	----	----
5	Haas 32-31 2	1,276.5	Wyodak-Anderson	Wyodak	24	9.58	16.60	24.61	----	----
6	West 6-19	648.7	Wyodak-Anderson	Canyon	7	9.95	24.50	32.01	----	----
6	West 6-19	952.0	----	Cook	8	10.87	18.80	27.77	----	----
6	West 6-19	1,074.0	----	Wall	4	11.92	17.58	27.40	----	----
7	Leroy 1	944.7	----	unnamed 1	7	13.59	20.83	31.61	----	----
8	Laramore 11-6	385.0	Wyodak-Anderson	Smith	15	14.50	13.58	26.13	----	----
8	Laramore 11-6	785.2	Wyodak-Anderson	Anderson	6	7.59	19.65	25.76	----	----
8	Laramore 11-6	990.0	Wyodak-Anderson	Canyon	4	7.33	16.30	25.82	----	----
8	Laramore 11-6	1,345.0	----	Cook	5	5.73	12.66	17.64	----	----
9	Kennecot CBM1	143.4	Wyodak-Anderson	Upper Wyodak	5	4.95	15.08	19.27	22.18	----
9	Kennecot CBM1	181.5	Wyodak-Anderson	Middle/Lower Wyodak	26	7.27	16.62	22.69	25.57	----
10	Kennecott CBM2	167.0	Wyodak-Anderson	Upper Wyodak	2	6.96	20.93	26.46	27.45	1.26
10	Kennecott CBM2	209.2	Wyodak-Anderson	Middle/Lower Wyodak	27	9.43	19.92	27.53	26.78	1.28
11	Caru State 22-16-5079W	1,366.4	Wyodak-Anderson	Big George	12	8.56	17.21	24.33	23.48	1.25
11	Caru State 22-16-5079W	1,769.0	Wyodak-Anderson	Werner	13	9.18	16.95	24.60	22.81	1.27
12	SRU State	1,401.0	Wyodak-Anderson	Big George	32	8.95	14.20	21.90	19.89	1.38
13	Rim CBM H11-04	212.0	Wyodak-Anderson	Upper Wyodak	8	10.10	19.09	27.25	----	----
13	Rim CBM H11-04	252.4	Wyodak-Anderson	Middle/Lower Wyodak	27	11.76	19.35	28.86	----	----
14	Rim 33-1R	289.0	Wyodak-Anderson	Middle/Lower Wyodak	30	8.09	22.60	28.88	25.18	1.37
15	PNG 34-1	293.1	Wyodak-Anderson	Middle/Lower Wyodak	32	9.28	20.47	27.93	25.61	1.28
16	PNG 33-1	319.4	Wyodak-Anderson	Middle/Lower Wyodak	28	10.53	18.50	27.13	26.13	1.30
17	PNG 31-1	293.1	Wyodak-Anderson	Middle/Lower Wyodak	39	11.14	17.30	26.54	25.49	1.33
18	PNG 35-1	360.2	Wyodak-Anderson	Middle/Lower Wyodak	40	12.03	15.34	25.56	----	----
19	Ancu Iberlin 21-33-4374	1,308.0	Wyodak-Anderson	Big George	6	14.00	11.00	23.49	23.69	1.28
20	PNG 16-2	248.9	Wyodak-Anderson	Middle/Lower Wyodak	34	10.49	19.33	27.81	24.77	----

Table 2. Properties and composition of coal beds cored—continued

Core hole	Core hole name	Average depth, in feet	Coal zone	Coal bed name as used by gas operators	Number of samples	Moisture, in percent				Apparent specific gravity, in g/cc
						Residual	Air dry loss	Total	Equilibrium	
21	Coteau MC00250C	172.5	----	Beulah	2	16.51	21.41	34.41	----	----
21	Coteau MC00250C	442.6	----	unnamed 2	4	17.05	20.34	33.93	----	----
21	Coteau MC00250C	572.2	----	unnamed 3	1	16.93	18.27	32.11	----	----
22	Coteau MC00251	793.0	----	unnamed 4	3	13.00	21.30	31.59	29.81	1.39
23	AET T.J. State 36-3	346.0	Wyodak-Anderson	School	9	14.07	13.29	25.49	26.25	1.35
24	BCX-9 (Bridger Coal Co.)	949.0	----	Deadman 4	6	6.75	10.81	16.85	17.38	1.32
25	PNG Duvall 13J-D	1,243.0	----	Pawnee	5	7.49	19.12	25.19	24.34	1.37
26	KU Harriet 41-34-47777	1,365.2	Wyodak-Anderson	Big George	51	5.29	14.60	19.23	17.67	1.31
27	PNG Federal Carter 18F	1,537.6	----	Pawnee	11	10.04	14.87	23.43	20.41	1.30
27	PNG Federal Carter 18F	1,709.8	----	Cache	16	9.60	14.86	23.10	22.24	1.30
28	Nance Petroleum Remington 587930 07A	329.3	Wyodak-Anderson	Anderson	8	13.70	15.93	27.46	27.23	1.31
29	Nance Petroleum Remington 577918 03R	2,197.5	----	Roberts	7	5.44	18.20	22.64	16.85	1.34
30	Nance Petroleum Remington 587930 01C	640.0	Wyodak-Anderson	Canyon	7	11.05	15.98	25.31	25.53	1.31
31	BCU Federal 32-9-4277	1,440.3	Wyodak-Anderson	Big George	32	6.60	12.15	17.94	18.15	1.31
32	WDU 12-12-4778	1,541.8	Wyodak-Anderson	Big George	17	7.03	11.73	17.95	16.51	1.33
33	McBeth-12-30-4673-BG	960.2	Wyodak-Anderson	Big George	10	12.96	13.56	24.77	23.83	1.29
34	State 23-16-4171	345.0	Wyodak-Anderson	Anderson	17	8.43	18.04	24.98	25.35	----
34	State 23-16-4171	519.5	Wyodak-Anderson	Canyon	13	5.91	21.65	26.31	24.26	----
35	Groves 12-19-4574	1,230.9	Wyodak-Anderson	Big George	20	7.56	19.42	25.55	24.77	1.29
36	PNG CBM 24-1	1,266.4	----	Pawnee	4	5.26	17.69	22.01	34.07	1.34
37	PNG CBM 26-1	1,166.1	----	Pawnee	7	5.90	16.33	21.60	20.91	1.34

Table 2. Properties and composition of coal beds cored—continued

Core hole	Proximate analysis, in percent			Ultimate analysis, in percent					Calorific value, in Btu	Moist, mineral-matter-free Btu	Apparent rank	Forms of sulfur, in percent		
	Ash yield	Volatile matter	Fixed carbon	Hydrogen	Carbon	Nitrogen	Sulfur	Oxygen				Sulfate	Pyritic	Organic
1	3.67	35.26	42.47	6.07	59.47	0.69	0.34	29.77	10,440	10,810	SubA	0.01	0.02	0.22
2	3.38	34.44	43.25	6.05	59.50	0.74	0.33	30.00	10,300	10,610	SubA	0.03	0.07	0.24
3	6.30	28.44	33.56	6.43	48.78	0.54	0.22	37.75	7,790	8,690	SubC	----	----	----
4	10.67	----	----	6.14	47.55	0.78	0.22	34.66	----	----	----	0.01	0.04	0.16
4	5.78	33.36	38.00	6.28	53.14	0.87	0.34	33.59	9,440	9,910	SubB	0.01	0.10	0.23
5	3.95	33.03	36.65	6.54	52.33	0.59	0.22	36.36	8,920	9,300	SubC	0.02	0.01	0.19
5	4.50	34.37	38.07	6.27	54.47	0.59	0.18	33.99	9,440	9,830	SubB	0.02	0.02	0.12
6	5.20	27.11	33.18	6.63	47.41	0.77	0.33	39.66	7,630	8,240	LigA	0.02	0.10	0.22
6	4.54	30.53	37.48	6.38	51.39	0.85	0.14	36.70	8,670	9,190	SubC	0.01	0.01	0.12
6	5.67	29.74	39.08	6.32	50.46	0.89	0.15	36.52	8,760	9,050	SubC	0.02	0.01	0.12
7	14.49	28.85	27.58	6.19	39.49	0.67	0.93	38.23	7,160	8,200	LigA	0.12	0.26	0.55
8	5.87	33.08	36.46	6.22	51.27	0.85	0.35	35.45	9,080	9,550	SubB	0.03	0.04	0.28
8	2.92	----	----	6.22	54.45	0.72	0.10	35.58	----	----	----	0.04	0.01	0.06
8	4.19	32.38	38.59	6.25	53.21	0.82	0.27	35.26	9,340	9,750	SubB	0.03	0.04	0.20
8	24.74	----	----	5.05	42.55	0.67	0.72	26.27	----	----	----	0.05	0.27	0.40
9	12.22	38.51	33.60	5.99	49.18	0.75	1.05	30.82	9,280	10,160	SubB	0.01	0.06	0.56
9	4.52	33.22	36.82	6.13	53.32	0.76	0.27	34.98	8,790	9,430	SubC	0.02	0.02	0.16
10	9.31	32.84	34.60	6.46	48.40	0.76	0.53	34.55	8,910	9,430	SubC	0.02	0.05	0.47
10	4.59	32.15	34.84	6.59	51.56	0.76	0.29	36.21	8,750	9,840	SubB	0.02	0.07	0.22
11	4.51	35.46	36.32	6.61	53.95	0.77	0.36	33.79	9,510	9,940	SubB	0.01	0.05	0.37
11	2.69	30.30	41.87	6.53	56.29	0.86	0.07	33.56	9,570	9,870	SubB	0.01	0.01	0.06
12	4.58	33.11	38.19	6.30	55.99	0.70	0.34	32.09	9,300	10,100	SubB	0.02	0.19	0.45
13	8.88	31.98	35.04	6.48	47.41	0.75	1.13	35.36	8,790	9,180	SubC	0.01	0.15	0.49
13	4.56	32.11	35.18	6.67	50.17	0.77	0.32	37.52	8,750	9,210	SubC	0.01	0.01	0.20
14	3.46	30.92	37.37	6.69	50.62	0.63	0.23	38.36	8,890	9,210	SubC	0.00	0.02	0.19
15	3.69	31.53	36.69	6.51	51.15	0.70	0.19	37.77	8,740	9,200	SubC	0.01	0.02	0.18
16	4.22	31.19	36.22	6.55	51.24	0.72	0.19	37.08	8,600	9,160	SubC	0.01	0.07	0.21
17	3.82	31.24	37.78	6.58	52.30	0.70	0.20	36.40	8,770	9,120	SubC	0.01	0.01	0.17
18	3.75	32.16	38.32	6.57	53.24	0.70	0.22	35.52	9,090	9,440	SubC	0.01	0.02	0.16
19	3.36	34.78	38.72	6.44	54.74	0.64	0.16	34.67	9,420	9,780	SubB	----	----	----
20	4.50	34.27	34.93	6.60	50.38	0.68	0.35	37.46	8,990	9,510	SubB	0.02	0.04	0.29

Table 2. Properties and composition of coal beds cored—continued

Core hole	Proximate analysis, in percent			Ultimate analysis, in percent					Calorific value, in Btu	Moist, mineral-matter-free Btu	Apparent rank	Forms of sulfur, in percent		
	Ash yield	Volatile matter	Fixed carbon	Hydrogen	Carbon	Nitrogen	Sulfur	Oxygen				Sulfate	Pyritic	Organic
21	6.02	----	----	6.77	43.14	0.63	0.88	42.57	----	----	----	0.07	0.26	0.55
21	6.91	30.73	30.53	6.70	42.56	0.70	0.51	42.62	7,590	8,030	LigA	0.05	0.03	0.42
21	8.08	----	----	6.62	43.00	0.76	0.67	40.87	----	----	----	0.02	0.05	0.60
22	12.78	26.66	25.24	6.34	40.20	0.67	0.85	39.16	6,460	8,180	LigA	0.06	0.18	0.61
23	12.20	34.11	30.81	6.22	44.86	0.65	0.56	35.50	8,020	8,860	SubC	0.03	0.11	0.42
24	8.74	31.99	45.06	5.70	58.60	1.07	0.65	25.25	10,640	11,130	SubA	0.02	0.29	0.34
25	8.14	26.64	35.05	6.30	51.18	0.76	0.38	33.23	8,120	9,580	SubB	0.02	0.19	0.17
26	3.86	34.65	42.97	6.22	58.92	0.82	0.30	29.87	10,330	10,810	SubA	0.02	0.01	0.11
27	4.55	30.99	37.76	6.28	55.53	0.88	0.11	32.63	9,200	10,190	SubB	0.02	0.00	0.09
27	4.77	29.31	38.89	6.32	56.24	0.91	0.23	31.53	9,100	10,090	SubB	0.02	0.02	0.18
28	4.22	30.88	37.34	6.64	51.46	1.19	0.39	36.10	8,820	9,240	SubC	0.01	0.02	0.30
29	9.75	32.28	39.62	6.29	52.35	1.09	0.30	30.22	9,820	10,360	SubB	0.01	0.06	0.23
30	3.74	30.01	40.14	6.41	53.82	1.29	0.26	34.48	9,120	9,640	SubB	0.02	0.03	0.21
31	5.97	36.59	38.79	6.38	57.66	0.51	0.39	29.10	9,870	10,540	SubA	0.02	0.07	0.31
32	3.41	34.02	43.79	6.26	61.46	1.06	0.20	27.60	10,440	10,990	SubA	----	----	----
33	4.22	34.25	36.97	6.69	53.10	0.68	0.21	35.11	9,180	9,640	SubB	----	----	----
34	4.68	32.20	37.94	6.42	52.09	0.69	0.21	35.91	9,010	9,400	SubC	0.01	0.01	0.17
34	3.71	30.97	39.08	6.45	52.82	0.76	0.13	36.13	9,090	9,560	SubB	0.02	0.00	0.16
35	3.65	33.53	37.94	6.48	52.71	0.55	0.20	36.41	9,150	9,700	SubB	----	----	----
36	6.09	34.22	38.76	6.07	55.50	0.99	0.43	30.92	10,030	10,970	SubA	0.01	0.66	0.11
37	5.58	31.74	41.82	5.98	56.00	0.97	0.19	31.31	9,740	10,320	SubB	0.02	0.01	0.08

Table 3. Coal quality data for coal beds in the Fort Union Formation in the Powder River Basin, Wyoming.

[*n* , number of samples; PRB, Powder River Basin; Btu, British thermal units per pound; MMMF, moist, mineral-matter-free; SubC, subbituminous C; SubB, subbituminous B; SubA, subbituminous A; ----, not determined. Values reported on an as-recieved basis]

Variable	All PRB samples					Anderson					Big George				
	n	Range		Mean	Standard deviation	*n*	Range		Mean	Standard deviation	*n*	Range		Mean	Standard deviation
		Minimum	Maximum				Minimum	Maximum				Minimum	Maximum		
Depth, in feet……………	819	138.0	2,202.5	853.3	535.7	33	318.0	1,190.0	471.2	254.1	303	950.0	1,560.0	1,296.8	138.4
Coal weight, in grams…..	819	962.7	5,970.8	3,540.7	696.0	33	2,504.9	4,809.3	4,061.0	611.0	303	1,171.4	5,180.4	3,775.4	687.2
Moisture, in percent															
Residual………	819	0.31	17.26	9.19	2.97	33	4.27	16.15	9.67	3.46	303	0.31	17.26	8.07	2.67
Air dry loss……	819	6.42	27.68	16.36	3.90	33	13.26	24.91	17.88	2.44	303	6.42	24.01	13.57	3.07
Total……………	819	13.54	33.93	24.08	3.95	33	22.93	29.34	25.89	1.59	303	13.73	28.34	20.59	2.99
Equilibrium……	92	13.33	34.07	23.20	3.86	7	23.86	27.35	26.31	1.23	32	13.33	26.39	19.92	3.23
Apparent specific gravity, in grams per cubic centimeter……………….	82	1.23	1.56	1.31	0.05	4	1.27	1.34	1.31	0.03	32	1.23	1.56	1.31	0.06
Proximate analysis, in percent															
Ash yield..……..	819	1.52	67.54	4.66	4.70	33	2.44	15.87	4.34	2.48	303	1.52	38.86	4.03	3.94
Volatile mattter………..	128	23.39	40.54	32.58	2.69	7	28.44	34.70	31.10	1.98	44	30.04	40.54	34.48	2.26
Fixed carbon….	128	28.35	48.05	38.32	3.70	7	33.56	38.57	37.06	1.80	44	29.29	48.05	40.68	3.75
Ultimate analysis, in percent															
Hydrogen...……	819	2.70	7.07	6.37	0.36	33	2.54	6.85	6.44	0.24	303	4.29	6.79	6.26	0.32
Carbon…………	819	4.90	63.17	54.03	4.81	33	44.96	55.52	52.17	2.19	303	32.80	63.17	57.66	4.04
Nitrogen………	819	0.21	1.34	0.74	0.16	33	0.52	1.26	0.81	0.23	303	0.29	1.29	0.71	0.17
Sulfur…………	819	0.02	6.15	0.29	0.35	33	0.08	0.64	0.24	0.14	303	0.03	6.15	0.31	0.47
Oxygen…………	819	19.20	41.58	33.91	3.60	33	32.15	38.12	36.01	1.34	303	21.05	39.32	31.03	2.95
Calorific value, in Btu…..	127	6,780	10,940	9,250	750	7	7,780	9,360	8,750	470	44	7,540	10,950	9,900	660
MMMF Btu………………	127	8,180	11,710	9,770	690	7	8,690	9,720	9,230	310	44	9,130	11,550	10,360	570
Apparent rank…………..	127	SubC	SubB	SubB	----	7	SubC	SubB	SubC	----	44	SubC	SubA	SubB	----
Forms of sulfur, in percent															
Sulfate…………	374	0.00	0.27	0.02	0.02	12	0.01	0.07	0.02	0.02	84	0.00	0.27	0.02	0.03
Pyritic…………	374	0.00	1.69	0.05	0.14	12	0.01	0.03	0.01	0.01	84	0.00	1.69	0.07	0.23
Organic………..	374	0.01	2.85	0.22	0.15	12	0.01	0.54	0.15	0.14	84	0.08	1.01	0.27	0.17

Table 3. Coal quality data—Continued

Variable		Cache *n*	Cache Range Minimum	Cache Range Maximum	Cache Mean	Cache Standard deviation	Canyon *n*	Canyon Range Minimum	Canyon Range Maximum	Canyon Mean	Canyon Standard deviation	Cook *n*	Cook Range Minimum	Cook Range Maximum	Cook Mean	Cook Standard deviation
Depth, in feet……………		16	1,702.0	1,731.0	1,718.8	9.3	31	505.5	992.0	635.6	150.6	23	813.0	1,348.0	981.3	203.6
Coal weight, in grams…..		16	1,320.6	2,458.7	2,037.6	300.3	31	2,261.0	4,707.2	3,785.9	752.3	23	2,679.8	5,244.2	3,396.8	578.9
Moisture, in percent	**Residual………**	16	4.32	14.77	9.71	2.90	31	3.72	13.54	8.16	2.82	23	1.81	12.27	8.30	2.83
	Air dry loss……	16	9.34	20.12	14.88	2.92	31	13.77	27.68	20.63	3.67	23	11.18	25.71	18.60	4.18
	Total……………	16	21.21	24.40	23.22	0.95	31	23.98	33.93	27.16	2.97	23	13.54	31.02	25.36	5.27
	Equilibrium……	2	22.37	23.40	22.89	0.73	5	24.04	26.17	25.02	0.83	0	----	----	----	----
Apparent specific gravity, in grams per cubic centimeter……………….		2	1.26	1.28	1.27	0.01	3	1.27	1.36	1.31	0.05	0	----	----	----	----
Proximate analysis, in percent	**Ash yield...……..**	16	3.33	6.19	4.03	0.71	31	2.37	10.51	3.92	1.82	23	2.86	67.54	11.59	16.68
	Volatile mattter………..	2	28.93	29.60	29.27	0.47	9	27.03	31.92	29.73	1.80	2	29.30	31.75	30.53	1.73
	Fixed carbon….	2	40.74	43.22	41.98	1.75	9	29.99	42.68	38.73	3.74	2	36.22	38.73	37.48	1.77
Ultimate analysis, in percent	**Hydrogen...……**	16	6.15	6.63	6.35	0.11	31	6.08	6.76	6.46	0.16	23	2.75	6.69	5.98	1.02
	Carbon…………	16	54.38	58.34	56.78	0.89	31	42.86	56.75	52.24	3.14	23	10.15	57.14	47.80	10.48
	Nitrogen………	16	0.86	1.02	0.92	0.04	31	0.70	1.34	0.90	0.22	23	0.21	0.95	0.78	0.16
	Sulfur…………	16	0.07	1.09	0.23	0.26	31	0.08	0.78	0.22	0.15	23	0.05	1.09	0.30	0.28
	Oxygen…………	16	29.81	32.66	31.70	0.85	31	33.25	41.49	36.27	2.34	23	19.20	38.41	33.54	5.70
Calorific value, in Btu…..		2	9,430	9,580	9,510	110	9	7,250	9,750	8,890	790	2	8,600	8,740	8,670	100
MMMF Btu………………		2	10,040	10,110	10,080	50	9	8,180	10,040	9,370	660	2	8,950	9,430	9,190	340
Apparent rank…………..		2	SubB	SubB	SubB	----	9	LigA	SubB	SubC	----	2	SubC	SubC	SubC	----
Forms of sulfur, in percent	**Sulfate…………**	16	0.00	0.05	0.02	0.02	20	0.01	0.06	0.02	0.01	23	0.00	0.12	0.02	0.03
	Pyritic…………	16	0.01	0.13	0.02	0.03	20	0.00	0.21	0.05	0.06	23	0.01	0.66	0.08	0.16
	Organic………..	16	0.04	0.43	0.13	0.09	20	0.06	0.52	0.19	0.12	23	0.08	0.45	0.20	0.13

Table 3. Coal quality data—Continued

	Variable	Middle / Lower Wyodak					Pawnee					Roberts				
		n	Range		Mean	Standard deviation	*n*	Range		Mean	Standard deviation	*n*	Range		Mean	Standard deviation
			Minimum	Maximum				Minimum	Maximum				Minimum	Maximum		
	Depth, in feet……………	283	152.0	403.0	277.0	56.6	27	1,154.0	1,547.0	1,346.0	165.7	7	2,188.5	2,200.5	2,196.5	4.3
	Coal weight, in grams…..	283	2,365.9	5,970.8	3,339.3	374.5	27	962.7	4,089.9	2,331.2	710.1	7	4,084.5	5,104.5	4,759.5	333.2
Moisture, in percent	**Residual………**	283	4.77	16.90	10.26	2.66	27	4.18	13.49	7.70	2.49	7	3.46	6.40	5.44	1.02
	Air dry loss……	283	9.89	27.04	18.59	3.29	27	12.24	21.36	16.44	2.31	7	15.05	21.20	18.20	2.09
	Total……………	283	17.06	33.14	26.99	2.47	27	19.09	26.85	22.99	1.84	7	17.99	25.19	22.64	2.35
	Equilibrium……	30	22.74	28.74	25.88	1.47	6	20.41	34.07	24.17	5.16	3	14.71	18.11	16.85	1.84
	Apparent specific gravity, in grams per cubic centimeter………………	26	1.24	1.46	1.30	0.05	6	1.25	1.48	1.34	0.08	3	1.28	1.38	1.34	0.05
Proximate analysis, in percent	**Ash yield..……..**	283	1.92	14.58	4.11	1.67	27	2.67	24.28	6.16	4.62	7	3.87	38.58	9.75	12.73
	Volatile mattter………..	38	28.98	37.31	31.96	1.87	6	23.39	34.22	29.94	3.63	3	30.32	33.40	32.28	1.70
	Fixed carbon….	38	30.41	38.61	36.25	2.03	6	28.35	41.82	36.86	5.34	3	39.19	39.87	39.62	0.38
Ultimate analysis, in percent	**Hydrogen...……**	283	5.41	7.07	6.55	0.23	27	5.54	6.63	6.16	0.29	7	4.65	6.69	6.29	0.73
	Carbon…………	283	45.07	58.21	51.58	1.87	27	38.71	57.74	54.55	3.73	7	31.64	57.84	52.35	9.27
	Nitrogen………	283	0.56	0.88	0.71	0.07	27	0.56	1.02	0.89	0.10	7	0.71	1.23	1.09	0.17
	Sulfur…………	283	0.03	1.43	0.25	0.17	27	0.03	0.78	0.24	0.19	7	0.11	0.78	0.30	0.25
	Oxygen…………	283	30.59	41.58	36.80	1.79	27	27.42	35.21	32.01	1.83	7	23.64	32.95	30.22	3.08
	Calorific value, in Btu…..	38	8,130	9,360	8,800	260	6	6,780	10,030	8,920	1,210	3	9,510	10,070	9,820	290
	MMMF Btu………………	38	8,860	10,040	9,260	250	6	9,180	11,710	10,320	850	3	10,110	10,620	10,360	260
	Apparent rank…………..	38	SubC	SubB	SubC	----	6	SubC	SubA	SubB	----	3	SubB	SubA	SubB	----
Forms of sulfur, in percent	**Sulfate…………**	131	0.00	0.13	0.01	0.02	18	0.00	0.04	0.02	0.01	7	0.00	0.02	0.01	0.01
	Pyritic…………	131	0.00	0.27	0.03	0.05	18	0.00	0.66	0.10	0.18	7	0.03	0.23	0.07	0.07
	Organic………..	131	0.06	1.06	0.22	0.15	18	0.05	0.36	0.14	0.08	7	0.07	0.60	0.25	0.21

Table 3. Coal quality data—Continued

Variable		School					Smith					Upper Wyodak				
		n	Range		Mean	Standard deviation	*n*	Range		Mean	Standard deviation	*n*	Range		Mean	Standard deviation
			Minimum	Maximum				Minimum	Maximum				Minimum	Maximum		
Depth, in feet…………….		9	335.0	351.0	345.0	5.5	15	341.0	382.0	362.2	15.0	15	136.0	216.0	182.0	33.2
Coal weight, in grams…..		9	2,934.7	4,174.3	3,476.4	329.4	15	2,715.5	3,625.9	3,351.4	271.7	15	2,225.5	4,474.9	3,475.0	577.0
Moisture, in percent	Residual……….	9	10.32	15.45	14.07	1.56	15	10.92	17.25	14.50	1.77	15	3.35	12.70	7.96	3.07
	Air dry loss……	9	9.78	15.75	13.29	1.73	15	11.34	16.78	13.58	1.63	15	11.61	22.30	18.00	3.20
	Total……………	9	21.11	28.41	25.49	2.21	15	22.68	28.53	26.13	1.37	15	14.57	31.38	24.48	4.82
	Equilibrium……	2	25.01	27.48	26.25	1.75	----	----	----	----	----	2	22.18	27.45	24.82	3.73
Apparent specific gravity, in grams per cubic centimeter……………….		2	1.34	1.36	1.35	0.01	----	----	----	----	----	1	1.26	1.26	1.26	----
Proximate analysis, in percent	Ash yield...……	9	5.28	36.14	12.20	9.34	15	2.72	16.54	5.87	3.89	15	3.73	23.91	10.05	6.63
	Volatile matter………..	2	33.44	34.78	34.11	0.95	3	31.10	35.53	33.08	2.25	3	31.98	38.51	34.44	3.55
	Fixed carbon….	2	28.39	33.23	30.81	3.42	3	34.48	38.69	36.46	2.12	3	33.60	35.04	34.41	0.74
Ultimate analysis, in percent	Hydrogen...……	9	4.82	6.64	6.22	0.55	15	5.44	6.46	6.22	0.24	15	5.02	6.89	6.31	0.51
	Carbon………..	9	29.58	50.01	44.86	6.05	15	45.57	53.70	51.27	2.32	15	40.07	53.59	48.13	3.94
	Nitrogen……….	9	0.50	0.75	0.65	0.07	15	0.78	0.93	0.85	0.04	15	0.67	0.85	0.75	0.04
	Sulfur…………	9	0.26	1.65	0.56	0.42	15	0.05	0.98	0.35	0.26	15	0.53	2.53	1.02	0.56
	Oxygen………..	9	28.70	39.10	35.50	3.10	15	31.35	38.59	35.45	1.90	15	26.68	39.30	33.74	3.56
Calorific value, in Btu…..		2	7,920	8,130	8,020	150	3	8,960	9,220	9,080	130	3	8,790	9,180	8,990	250
MMMF Btu………………		2	8,650	9,070	8,860	300	3	9,440	9,760	9,550	180	3	9,180	10,160	9,590	510
Apparent rank…………..		2	SubC	SubC	SubC	----	3	SubC	SubB	SubB	----	3	SubC	SubB	SubB	----
Forms of sulfur, in percent	Sulfate…………	9	0.00	0.16	0.03	0.05	15	0.00	0.06	0.02	0.02	3	0.01	0.02	0.01	0.00
	Pyritic…………	9	0.01	0.77	0.10	0.25	15	0.01	0.20	0.04	0.07	3	0.05	0.14	0.08	0.05
	Organic……….	9	0.21	0.57	0.39	0.12	15	0.06	0.76	0.24	0.19	3	0.49	0.56	0.51	0.04

Table 3. Coal quality data—Continued

Variable		Wall					Werner					Wyodak				
		n	Range		Mean	Standard deviation	*n*	Range		Mean	Standard deviation	*n*	Range		Mean	Standard deviation
			Minimum	Maximum				Minimum	Maximum				Minimum	Maximum		
Depth, in feet……………		20	1,068.0	1,182.3	1,142.8	38.2	13	1,749.0	1,779.0	1,768.0	9.5	24	1,364.0	1,414.0	1,390.6	15.8
Coal weight, in grams…..		20	2,703.7	3,878.4	3,276.7	307.4	13	1,920.3	4,655.9	3,986.3	749.3	24	3,119.2	5,022.8	4,228.1	512.7
Moisture, in percent	**Residual……….**	20	7.01	12.92	10.18	2.14	13	6.48	12.42	9.18	2.00	24	7.01	13.41	9.58	1.44
	Air dry loss……	20	14.98	20.45	17.41	1.67	13	14.76	19.82	16.95	1.66	24	11.42	20.31	16.60	2.12
	Total……………	20	22.62	28.70	25.83	1.65	13	22.85	26.64	24.60	1.14	24	20.23	27.66	24.61	1.68
	Equilibrium……	----	----	----	----	----	3	22.05	24.31	22.81	1.30	----	----	----	----	----
Apparent specific gravity, in grams per cubic centimeter………………		----	----	----	----	----	3	1.25	1.30	1.27	0.03	----	----	----	----	----
Proximate analysis, in percent	**Ash yield..……..**	20	2.56	14.17	5.51	3.17	13	1.88	3.90	2.69	0.62	24	1.79	20.15	4.50	3.88
	Volatile mattter………..	3	29.72	33.36	30.95	2.09	3	28.52	31.34	30.30	1.55	3	31.93	36.84	34.37	2.46
	Fixed carbon….	3	38.00	39.22	38.72	0.64	3	41.77	42.00	41.87	0.12	3	36.61	40.44	38.07	2.07
Ultimate analysis, in percent	**Hydrogen...……**	20	5.81	6.55	6.30	0.22	13	6.34	6.80	6.53	0.13	24	5.52	6.44	6.27	0.18
	Carbon………..	20	45.90	56.28	52.88	2.27	13	54.83	57.04	56.29	0.71	24	43.34	56.84	54.47	2.56
	Nitrogen……….	20	0.80	0.96	0.88	0.04	13	0.80	0.91	0.86	0.04	24	0.48	0.67	0.59	0.06
	Sulfur…………	20	0.11	0.86	0.31	0.22	13	0.02	0.13	0.07	0.05	24	0.02	0.64	0.18	0.12
	Oxygen………..	20	30.26	38.02	34.13	2.04	13	31.91	35.25	33.56	0.90	24	28.91	37.06	33.99	1.99
Calorific value, in Btu…..		3	8,760	9,430	8,990	390	2	9,380	9,770	9,570	280	3	9,180	9,780	9,440	310
MMMF Btu………………		3	9,010	9,910	9,340	500	2	9,690	10,050	9,870	250	3	9,430	10,240	9,790	420
Apparent rank…………..		3	SubC	SubB	SubC	----	2	SubB	SubB	SubB	----	3	SubC	SubB	SubB	----
Forms of sulfur, in percent	**Sulfate…………**	20	0.00	0.07	0.01	0.02	13	0.00	0.01	0.01	0.00	3	0.02	0.03	0.02	0.00
	Pyritic…………	20	0.01	0.46	0.09	0.13	13	0.01	0.02	0.01	0.00	3	0.01	0.03	0.01	0.01
	Organic……….	20	0.08	0.46	0.21	0.10	13	0.06	0.12	0.08	0.02	3	0.10	0.18	0.14	0.04

A comparison of the proximate and ultimate analyses (values in mean percent) shows (1) ash yield of the Anderson–Big George coal bed ranges from 2.92 to 6.30 percent and that of the Canyon–Wyodak coal bed ranges from 3.46 to 12.22 percent; and (2) total sulfur content for the Anderson–Big George coal bed ranges from 0.10 to 0.39 percent and that for Canyon–Wyodak from 0.13 to 1.13 percent.

Ash yield and total sulfur content within the Anderson–Big George coal bed show a generally increasing upward trend interrupted by higher values in the middle part of the bed (for example, see core hole 21; Appendix II), whereas these constituents in the Canyon–Wyodak coal bed show both increasing upward and downward trends locally interrupted by higher values in the middle (for example, see core hole 5; Appendix II). Spikes of higher organic and pyritic forms of sulfur in these beds correspond to local spikes of higher ash yield.

The merged Wyodak coal bed shows generally increasing upward trends for ash yield and total sulfur content (for example, see core hole 14; Appendix II). The merged Big George coal bed shows spikes of moderate to higher ash yield and total sulfur content throughout the coal bed (for example, see core hole 2; Appendix II). Higher organic and sulfate forms of sulfur appear to be directly related to the moderate to higher ash yields.

Variations of MMMF Btu, moisture content, ash yield and total sulfur content were investigated for the Wyodak–Anderson coal zone in the Wyoming part of the PRB. Figure 6 shows low Btu values (8,300-9,500) in the southern and northwestern parts of the basin, high values (10,500-11,500) in the west-central part of the basin, and intermediate values (9,500-11,500) elsewhere. Moisture content (fig. 7) shows low values (12-23 percent) in the west-central part of the basin, locally high values (27-35 percent) in the eastern and northeastern parts, and intermediate values (24-26 percent) in other parts. Basinwide variations of ash yield (fig. 8) show high values (10-17 percent) locally in the southern and northern parts of the basin and low values (3.7 percent) in the central part. Total sulfur variations basinwide (fig. 9) show high values (0.5-0.8 percent) in the southern and eastern part of the basin and low values (0.1-0.4 percent) in the central part.

The average ash yields in the Anderson–Big George and Canyon–Wyodak coal beds indicate no significant changes within and between beds, except for local spikes of high ash yield (> 20 percent); these higher values may be caused by clay partings introduced by sediment-laden floodwaters or volcanic ash falls. Average sulfur content both within and between these beds also shows no significant difference. Local spikes of moderate to high sulfur are related to thin ash units, especially in the merged Wyodak and Big George coal beds, as exemplified by the presence of as many as 3 ash partings in the merged Wyodak coal bed that can be correlated over a distance of 4 mi (fig. 10). These coal beds, which formed in raised, ombrotrophic mires, were more prone to being inundated by volcanic detritus rather than by floodwaters (Flores, 1986). High ash yield and total sulfur content are commonly correlated to highly degraded maceral types, but, in the merged Wyodak and merged Big George coal beds as indicated above, the partings are mainly formed by volcanic ashfalls. These were nutrient-rich sediments that affected pH conditions and may have increased plant growth in the mires.

The basinwide variations in MMMF Btu, moisture content, ash yield, and total sulfur content of the Wyodak–Anderson coal zone are controlled by tectonism, burial history, and depositional environments. The increase in MMMF Btu toward the west-central part of the PRB in Wyoming was caused by tectonic subsidence in which the basin center was downwarped, exposing the strata to higher temperature and pressure. However, the low MMMF Btu of the Wyodak–Anderson coal zone in the southern part differs from previous reports (Stricker and Ellis, 1999) that calorific values increase toward the southern part of the Gillette coalfield. Thus, the decreasing MMMF Btu toward the southern part of the basin and in the Gillette coalfield indicates a shallower burial history than was originally thought.

Werner Coal Bed

The Werner coal bed was identified by Kent and others (1980) in the Recluse 1° x 30' quadrangle, Wyoming as lying below the Canyon coal bed, where it laterally merges with the Wyodak coal bed toward the south margin of the quadrangle. In the present report, the Werner coal bed was sampled in core hole 11 (see Appendix I, Appendix II). The Werner coal bed is subbituminous B in apparent rank with the following properties and composition:

- Calorific value (mean): 9,570 Btu
- Moist-mineral-matter-free Btu (mean): 9,870
- Proximate analysis (mean percent): ash yield, 2.69; volatile matter, 30.30; fixed carbon, 41.87; total moisture, 24.60
- Ultimate analysis (mean percent): hydrogen, 6.53; carbon, 56.29; nitrogen, 0.86; total sulfur, 0.07; oxygen, 33.56
- Forms of sulfur (mean percent): sulfate, 0.004; pyritic, 0.006; organic, 0.058

The vertical variations in ash yield, total sulfur content, and forms of sulfur are displayed in core hole 11 (Appendix II). Ash yield generally decreases upward except for local spikes. Total sulfur content generally increases upward, with random sharp spikes coincident with the higher ash yields. The upward increase of total sulfur is correlated to upward increases of pyritic and organic sulfur.

The upward increasing ash yield and sulfur content of the Werner coal bed may be related to increasing influx of floodwater detritus deposited as partings in the coal in a low-lying swamp. Local spikes of higher ash yield indicate recurring discharges of suspended mud into a swamp, probably during overbank flooding.

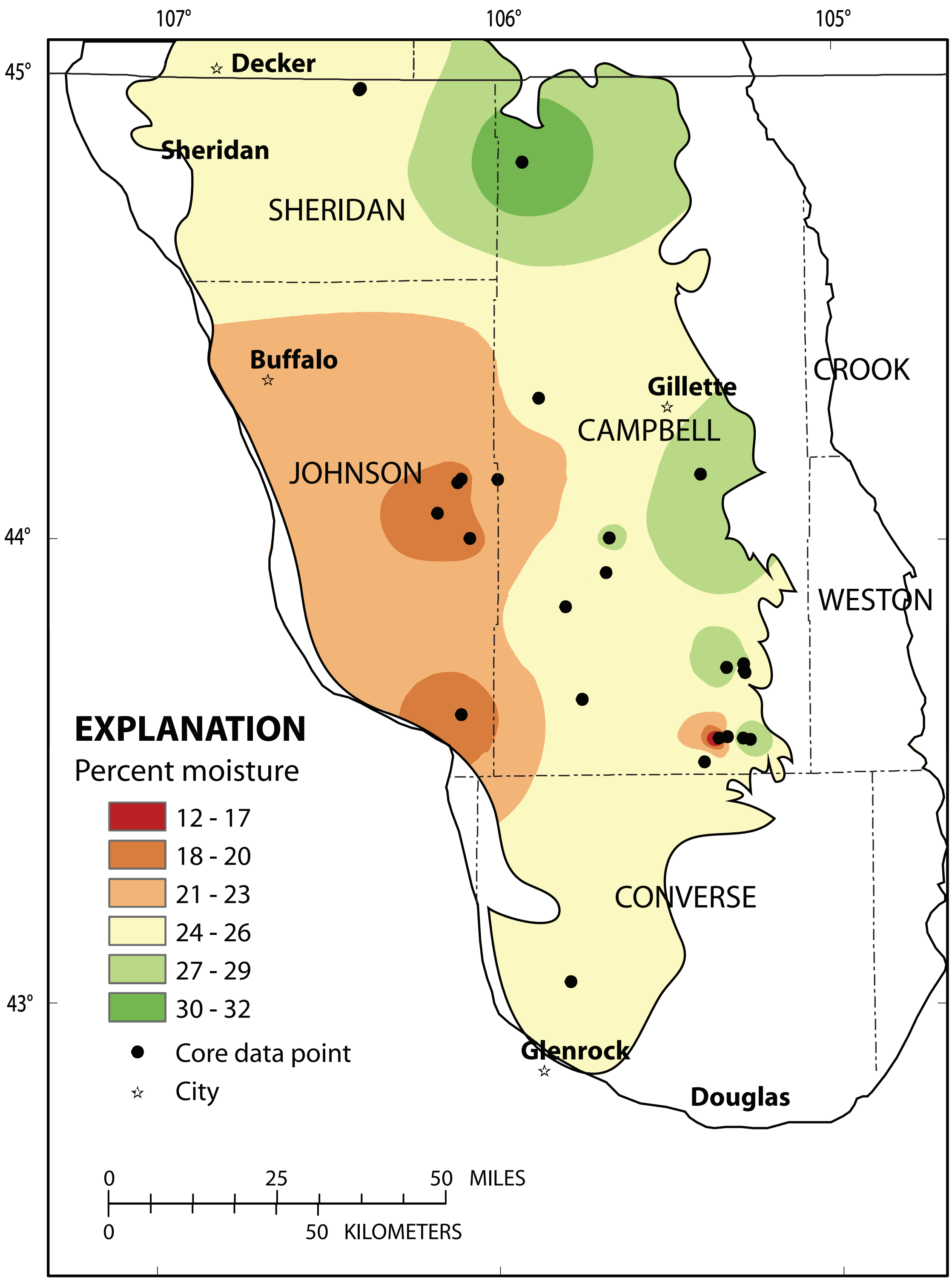

Figure 6. Variation of moist, mineral-matter-free (MMMF) British thermal units (Btu) in the Wyodak-Anderson coal zone in the Powder River Basin, Wyoming.

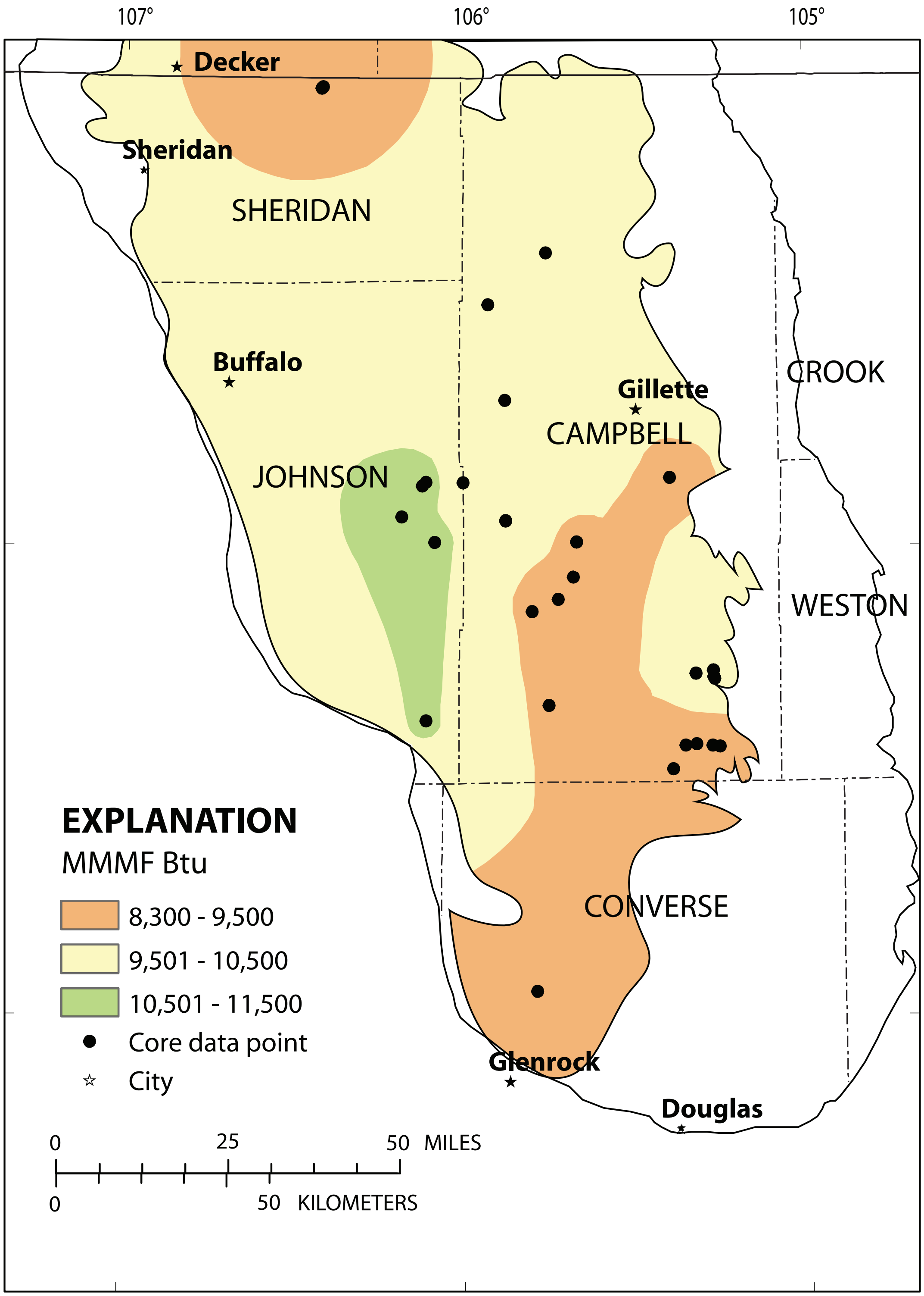

Figure 7. Variation of moisture content in the Wyodak-Anderson coal zone in the Powder River Basin, Wyoming.

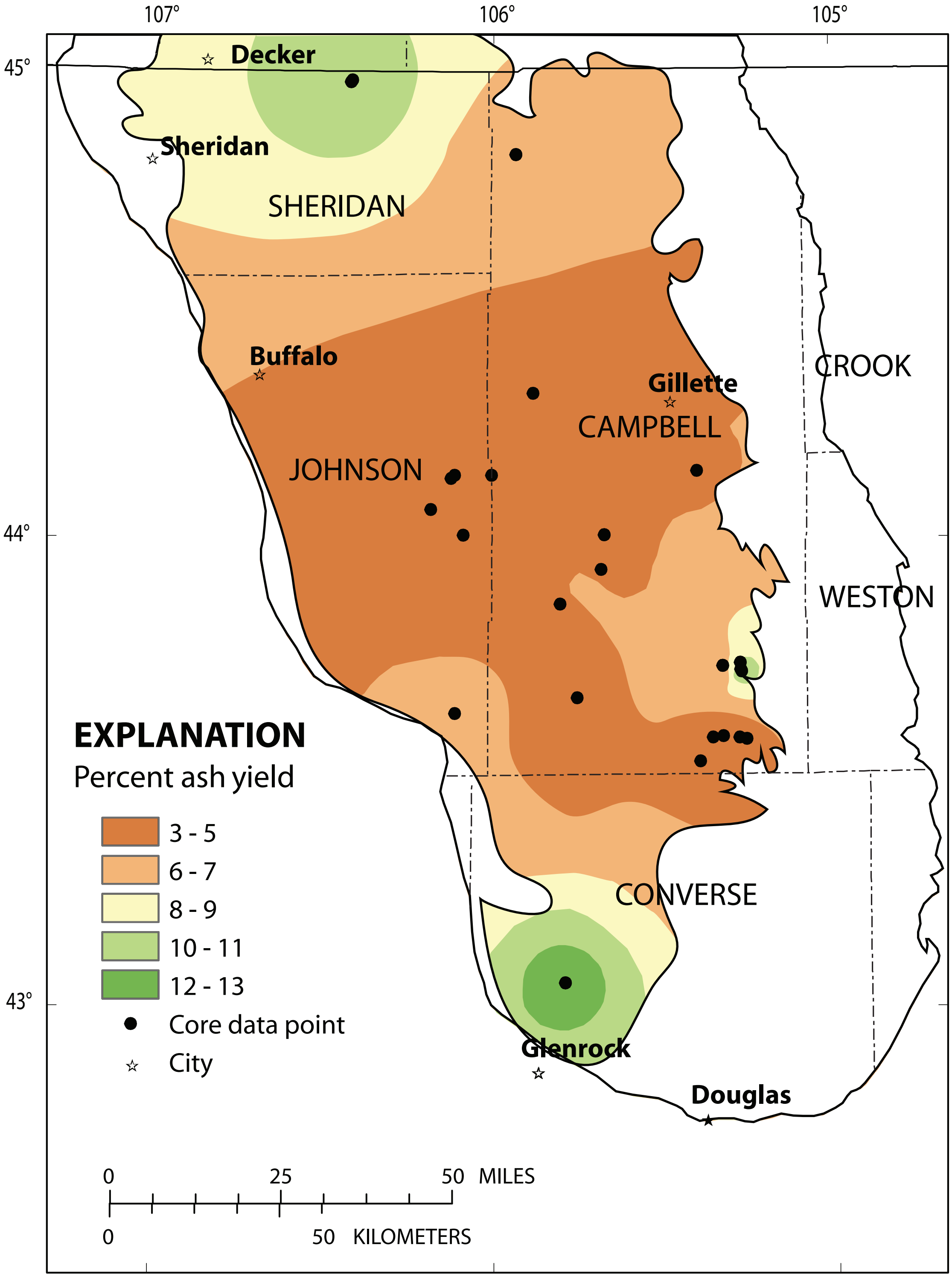

Figure 8. Variation of ash yield in the Wyodak-Anderson coal zone in the Powder River Basin, Wyoming.

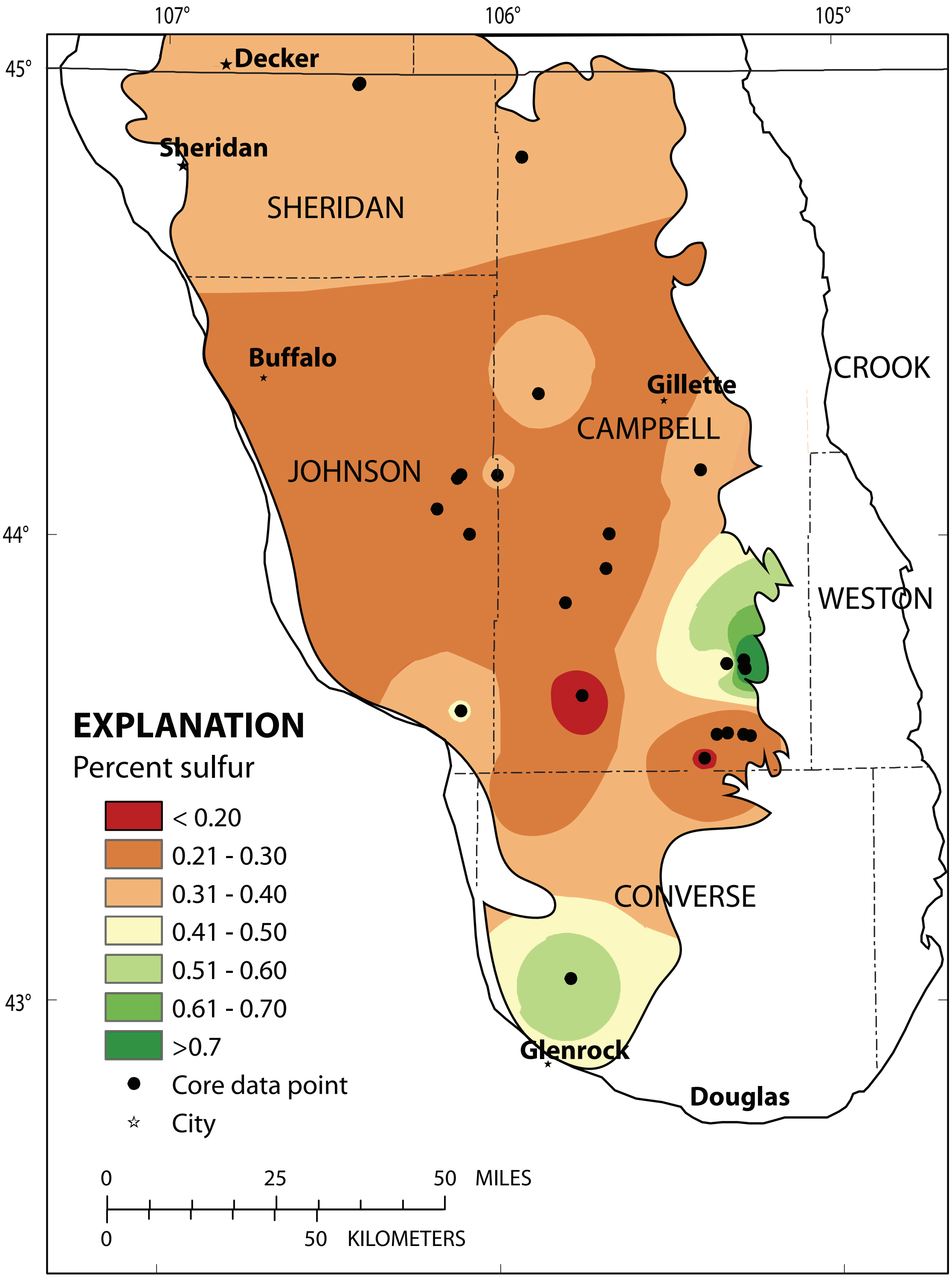

Figure 9. Variation of sulfur content in the Wyodak-Anderson coal zone in the Powder River Basin, Wyoming.

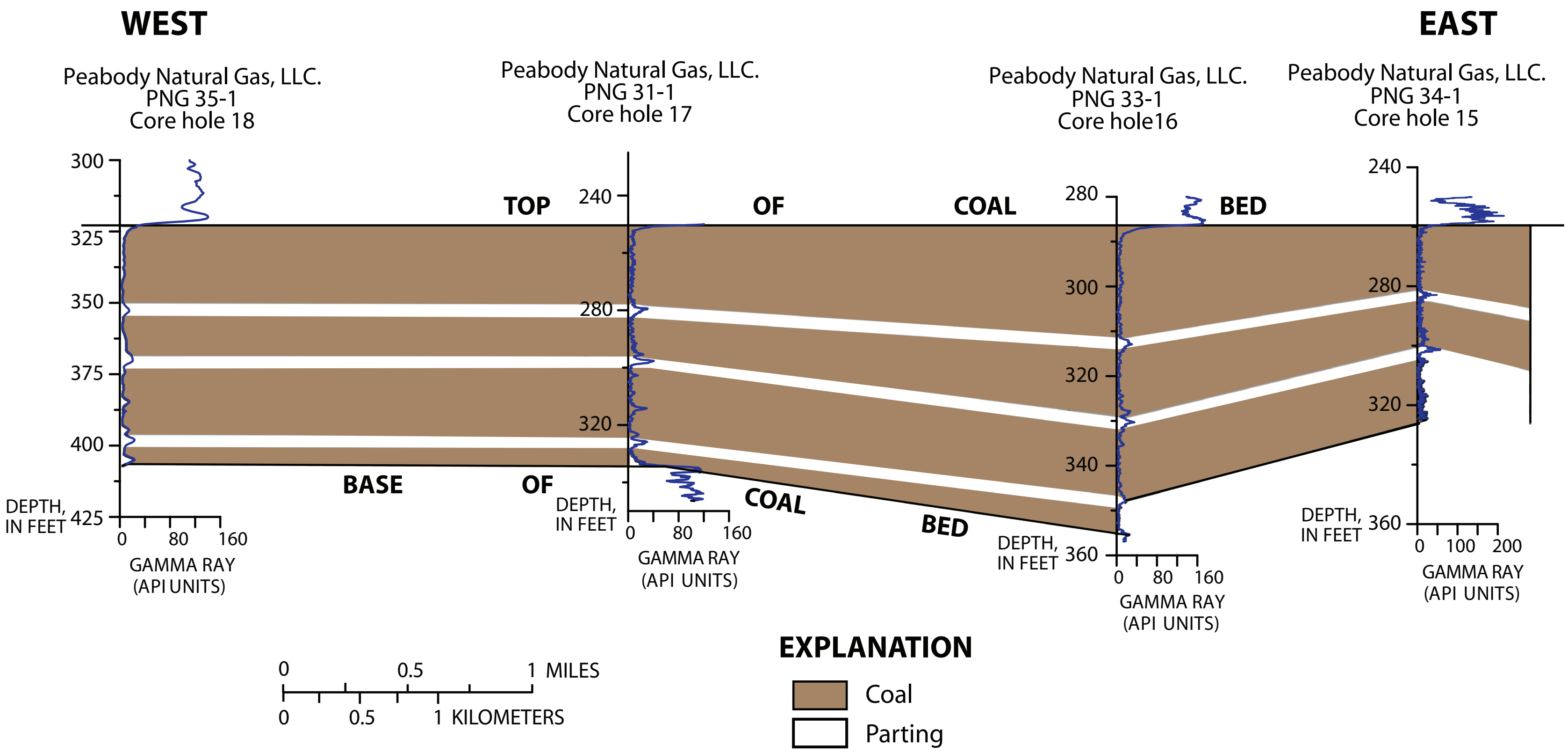

Figure 10. Ash partings in the merged Wyodak coal bed correlated for core holes 15-18 (fig. 1) in the eastern part of the Powder River Basin, Wyoming.

Cook Coal Bed

The Cook coal bed was sampled in core holes 4, 6, and 8 (Appendix I, Appendix II). It is subbituminous C in apparent rank with the following properties and composition:

- Calorific value (mean): 8,670 Btu
- Moist-mineral-matter-free Btu (mean): 9,200
- Proximate analysis (mean percent): ash yield, 11.59; volatile matter, 30.53; fixed carbon, 37.48; total moisture, 25.36
- Ultimate analysis (mean percent): hydrogen, 5.98; carbon, 47.80; nitrogen, 0.78; total sulfur, 0.30; oxygen, 33.54
- Forms of sulfur (mean percent): sulfate, 0.02; pyritic, 0.08; organic, 0.20

Vertical variations in the proximate and ultimate analyses are best displayed by ash yield and total sulfur content as related to the sulfate, pyritic, and organic forms of sulfur shown in core holes 4, 6, and 8 (Appendix II). There is a general upward increase in ash yield in core holes 6 and 8, with spikes near the middle of the cores, whereas there is an upward decrease in core hole. The total sulfur content in generally decreases upward in core holes 4 and 8 and increases upward in core hole 6. The upward decrease of total sulfur in core hole 4 may be related to the upward decrease of pyritic and organic sulfur. However, the upward increase of pyritic and organic sulfur in core hole 6 is directly related to upward increases in pyritic and organic sulfur.

The high ash yield (as high as 24.74 percent) of the Cook coal bed may be related to its depositional setting, which was probably a low-lying swamp inundated by sediment-laden floodwaters. That the swamp was low lying is indicated by spikes of high ash in the middle part of the coal bed as shown in core holes 6 and 8 (Appendix I, Appendix II). The higher total sulfur content (as much as 0.72 percent) may also be related to flooding events.

Wall Coal Bed

The Wall coal bed was sampled in core hole 4 (Appendix I, Appendix II). The coal is subbituminous B in apparent rank with the following properties and composition:

- Calorific value (mean): 9,440 Btu
- Moist-mineral-matter-free Btu (mean): 9,910
- Proximate analysis (mean percent): ash yield, 5.67; volatile matter, 29.74; fixed carbon, 39.08; total moisture, 27.40
- Ultimate analysis (mean percent): hydrogen, 6.32; carbon, 50.46; nitrogen, 0.89; total sulfur, 0.15; oxygen, 36.52
- Forms of sulfur (mean percent): sulfate, 0.017; pyritic, 0.011; organic, 0.117

The vertical variations of the ash yield, total sulfur content, and forms of sulfur in the Wall coal bed are displayed in core hole 4 (Appendix II). The ash yield generally decreases upward, except for a local spike near the base of the coal. The total sulfur content generally increases upward, with random spikes coincident with the spikes of higher ash. The upward increase of total sulfur is correlated to upward increases in pyritic and organic sulfur contents.

The moderate and variable ash yields and upward increasing sulfur content of the Wall coal bed may be related to a more or less constant influx of floodwater detritus into a low-lying swamp. Local spikes of higher ash yield and total sulfur indicate recurring discharges of suspended mud, probably during overbank flooding.

Pawnee Coal Bed

The Pawnee coal bed was sampled in core holes 25, 27, 36, and 37 (Appendix I, Appendix II). This coal ranges in apparent rank from subbituminous C to A with the following properties and composition:

- Calorific value (range of means): 8,120-10,030 Btu
- Moist-mineral-matter-free Btu (range of means): 9,590-10,970
- Proximate analysis (range of means in percent): ash yield, 5.58-8.14; volatile matter, 26.64-34.22; fixed carbon, 35.05-41.82; total moisture, 21.60-25.19
- Ultimate analysis (range of means in percent): hydrogen, 5.98-6.30; carbon, 51.18-56.00; nitrogen, 0.76-0.99; total sulfur, 0.19-0.43; oxygen is 29.87-31.31
- Forms of sulfur (range of means in percent): sulfate, 0.01-0.02; pyritic, 0.01-0.66; organic, 0.08-0.17

Variable increasing to decreasing upward trends in the ash yield, total sulfur content, and forms of sulfur in the Pawnee coal bed are exhibited in core holes 25, 27, 36, and 37 (Appendix II), which may, in part, be due to the small number of analyzed core samples. In core hole 27 (Appendix II), both ash yield and total sulfur (dominantly organic sulfur) are highest at the top and bottom of the bed.

This trend (in core hole 27) may not be related to flooding events, but rather reflects the normal beginning and ending of the swamp.

Cache Coal Bed

The Cache coal bed is represented in core hole 27 (Appendix I, Appendix II). Apparent rank is subbituminous B with the following properties and composition:

- Calorific value (mean): 9,100 Btu
- Moist-mineral-matter-free Btu (mean): 10,090
- Proximate analysis (mean percent): ash yield, 4.77; volatile matter, 29.31; fixed carbon, 38.89; total moisture, 23.10

- Ultimate analysis (mean percent): hydrogen, 6.32; carbon, 56.24; nitrogen, 0.91; total sulfur, 0.23; oxygen, 31.53
- Forms of sulfur (mean percent): sulfate, 0.02; pyritic, 0.02; organic, 0.18

The vertical variations of the ash yield, total sulfur content, and forms of sulfur are shown in core hole 27 (Appendix II). Both the ash yield and sulfur content generally decrease upward, with a spike of high sulfur in the uppermost part. The vertical trend for sulfur content follows a general decreasing trend for the pyritic and organic sulfur components.

The mean yield for the Cache coal bed is generally higher than that for the Wyodak–Anderson coal zone (3 percent to more than 6 percent), indicating that the original depositional swamp was frequently inundated by floodwaters. Although floodwaters abated through time, spikes of high ash probably reflect intermittent overbank sedimentation into a low-lying swamp. The decreasing upward trend of total sulfur content indicates that there is no relation between sulfur content and overbank flooding. The spike of high sulfur at a depth of 1,710 ft does not appear to be related to any increase in ash yield. However, at the depth of 1,710 ft, an increase in ash or possibly a “mud” parting is indicated on the gamma ray log (Stricker and others, 2006; Appendix I-38).

Roberts Coal Bed

The Roberts coal bed, the lowermost bed sampled in this study of the Fort Union Formation in the PRB, is represented in core hole 29 (Appendix I, Appendix II). The coal is subbituminous B in apparent rank with the following properties and composition:

- Calorific value (mean): 9,820 Btu
- Moist-mineral-matter-free Btu (mean): 10,360
- Proximate analysis (mean percent): ash yield, 9.75; volatile matter, 32.28; fixed carbon, 39.62; total moisture, 22.64
- Ultimate analysis (mean percent): hydrogen, 6.29; carbon, 52.35; nitrogen, 1.09; total sulfur, 0.30; oxygen, 30.22
- Forms of sulfur (mean percent): sulfate, 0.01; pyritic, 0.06; and organic, 0.23

The vertical variations in ash yield, total sulfur content, and forms of sulfur are shown in core hole 29 (Appendix II). The ash yield generally increases upward with a spike (38 percent) at the top of the bed. The total sulfur content gradually increases upward, attaining highest content at the top of the coal bed; organic sulfur content also follows this trend.

The Roberts coal bed, which contains uniform ash yield near 5 percent, except for a spike of 38 percent at the top of the bed, and a total sulfur content that increases upward, is interpreted to have been deposited in a low-lying swamp. The swamp was frequently inundated by sediment-laden floodwaters, then experienced a peak flooding event that terminated the swamp-like conditions.

Green River Basin

Six samples were collected from the Deadman 4 coal bed in the Fort Union Formation of the Green River Basin (core hole 24; Appendix I, Appendix II). The coal is subbituminous A in apparent rank with the following properties and composition:

- Calorific value (mean): 10,640 Btu
- Moist-mineral-matter-free Btu (mean): 11,130
- Proximate analysis (mean percent): ash yield, 8.74; volatile matter, 31.99; fixed carbon, 45.06; total moisture, 16.85
- Ultimate analysis (mean percent): hydrogen, 5.70; carbon, 58.60; nitrogen, 1.07; total sulfur, 0.65; oxygen, 25.25
- Forms of sulfur (mean percent): sulfate, 0.02; pyritic, 0.29; organic, 0.34

Vertical variations in ash yield, total sulfur content, and forms of sulfur are shown in Appendix II. Ash yield is higher in the middle part of the coal bed than in the lower and upper parts; yields of 12 and 18 percent reflect two ash partings. Total sulfur content generally decreases upward, but attains its highest concentration of more than 0.8 percent where the ash yield is also highest. Pyritic sulfur mimics the total sulfur content, with sulfate and organic forms of sulfur locally high, also corresponding with ash partings.

The Deadman 4 coal bed, which contains high ash yield in the middle part of the bed, is interpreted to have been formed in a low-lying swamp. The sediment-laden floodwaters may have interrupted and drowned peat accumulation twice during the life of the swamp.

Williston Basin

Seventeen samples were collected from the Beulah coal and 4 unnamed coal beds in the Fort Union Formation in the Williston Basin; these were from core holes 7, 21, and 22 (Appendix I, Appendix II). The coals are lignite A in apparent rank with the following properties and composition:

- Calorific value (range of means): 6,460-7,590 Btu
- Moist-mineral-matter-free Btu (range of means): 8,030-8,200
- Proximate analysis (range of means in percent): ash yield, 6.02-14.49; volatile matter, 26.66-30.73; fixed carbon, 25.24-30.53; total moisture, 31.59-34.41
- Ultimate analysis (range of means in percent): hydrogen, 6.19-6.70; carbon, 39.49-43.00; nitrogen, 0.67-0.76; total sulfur, 0.51-0.93; oxygen, 38.23-42.62

- Forms of sulfur (range of means in percent): sulfate, 0.02-0.12; pyritic, 0.03-0.26; organic, 0.42-0.61

Vertical variations in ash yield, total sulfur content, and forms of sulfur are shown in Appendix II. Ash yield decreases upward in the Beulah coal bed, but increases in the lowermost and uppermost parts of the unnamed coal beds. Sulfur content decreases upward in the Beulah coal bed and also in the unnamed 1 coal bed, but increases upward in the unnamed 2 and the 4 coal beds.

The upward decrease in ash yield in the Beulah coal bed reflects deposition in a swamp that was unaffected by sediment-laden floodwaters. However, for the unnamed coal beds, in which ash yield is, in general, high, flooding events occurred during peat accumulation that was probably a topographically low-lying swamp.

Trace Elements

Our study of trace elements focused on the merged Big George and merged Wyodak coal beds in the Fort Union Formation of the PRB. Two cores of the Wyodak were obtained, one from core hole 17 (depth 290 ft) and the other from core hole 18 (depth 370 ft), and one core of the Big George was collected from core hole 2 (depth 1,100 ft). Although 45 trace elements were analyzed on a whole coal-dry basis (table 4, Appendix III, Appendix IV), primary emphasis was given to 12 trace elements of environmental concern (TEEC) and to comparison of their concentrations both between beds and vertically within beds.

Core holes 17 and 18, from which the two merged Wyodak cores were collected, are located about 1.5 mi apart in the shallow eastern part of the PRB (fig. 1). Except for cadmium, beryllium, and uranium, the majority of the TEEC do not vary significantly between the two core holes in the Wyodak coal bed (see table 4). Mean values for core holes 17 and 18, respectively, for the three elements mentioned are: cadmium, 0.073 and 0.041 ppm; beryllium, 0.082 and 0.200 ppm; and uranium, 0.58 and 0.46 ppm.

Core hole 2 is located in the deep central part of the PRB, 90 mi northwest of core holes 17 and 18 (fig. 1). Comparing the merged Big George coal bed in core hole 2 with the merged Wyodak coal bed in core holes 17 and 18, several of the TEEC vary significantly, as shown by the following (values in mean ppm; Wyodak first, Big George second): arsenic, 1.0 vs. 2.6; beryllium, 0.14 vs. 0.31; cadmium, 0.057 vs. 0.049; manganese, 8.7 vs. 14; nickel, 1.3 vs. 2.4; selenium, 0.44 vs. 0.97; and uranium, 0.52 vs. 0.27.

Discussion of the vertical variations of TEEC within the merged Wyodak and Big George coal beds includes all of those listed above, except for cadmium. In clay partings (ash content greater than 50 percent) and high ash coal (ash content greater than 15 percent) within these beds, arsenic content is higher than in the beds with lower ash content (less than 15 percent). The Big George, for example, has an arsenic concentration as high as 66 ppm where it contains the highest ash content (13.95 percent, in the depth interval 1,193.5-1,197.5 ft), and the Wyodak has arsenic concentrations of 9.2 and 6.0 ppm at its base where the ash content is highest. Beryllium and cadmium increase toward the base and top of the Wyodak coal bed and it decreases upward in the Big George coal bed. Manganese generally increases directly above or below clay partings in the Wyodak coal bed and generally increases upward in the Big George coal bed. Nickel increases toward the base and top of the Wyodak and decreases upward in the Big George. Selenium is invariably high just above or below higher ash yield portions of both coal beds. Uranium is high above and below clay partings and at the base of the Wyodak coal bed and generally increases upward, but is locally variable, above and below clay partings in the Big George coal bed.

In general, the TEEC content of the Wyodak and Big George coal beds, particularly arsenic, beryllium, cadmium, manganese, nickel, selenium, and uranium, is directly related to clay partings or high ash content zones. This indicates that these trace elements are associated either with volcanic ash falls or sediment-laden flood water. The high concentrations at the base and top of the coal beds are due to detrital sedimentation during the early and latter parts of the peat accumulation period. Assuming that these thick coals were deposited in raised bogs (Flores, 1986), detrital sedimentation probably occurred during early development of a low-lying swamp. However, after the swamp evolved into a raised bog, it was seldom drowned by sediment-laden floodwaters. The volcanic ashfalls that created the higher ash zones in these raised bogs are a well-known source of trace elements (Stricker and Flores, 2003).

High contents for TEEC such as arsenic, manganese, nickel, and selenium in the Big George coal bed reflects the proximity of the original depositional swamp to detrital sediments along the western part of the PRB. In addition, proximity to the Elkhorn volcanic arc in southwest Idaho, where the volcanic ash was erupted, accounts for the high TEEC content (Flores and others, 2006). High values for such TEEC as cadmium and uranium in the Wyodak coal bed reflects proximity to provenance to the east and south of the basin (Flores and others, 1994).

Summary

Fort Union Formation coal beds range from lignite A to subbituminous A in apparent rank. In the Powder River Basin, the apparent rank increases from subbituminous C in the eastern shallow margins of the basin to subbituminous A in the deeper central part. The minable coal beds (as much as 200 ft thick) in the Wyodak-Anderson coal zone generally have low ash yield and low total sulfur content. The original ash content is either the result of flood events or volcanic ashfalls; the latter is common in coal beds formed on raised ombrotrophic mires. Trace elements of environmental concern are low in the Powder River Basin coals for which major, minor, and trace element contents were determined.

Table 4. Major, minor, and trace elements in Wyodak and Big George coal beds, Powder River Basin, Wyoming.

[ppm, parts per million; L, means contain less than value(s) (see Appendix III) and were calculated by multipling less than values by 0.5. All data are on a whole coal dry basis. Number of samples shown in parentheses. Red and blue values are statistically different at the 95 percent level (T-test). *, elements of environmental concern]

Element	Core hole number			
	Core holes 17 and 18 (79)	Core hole 2 (50)	Core hole 17 (39)	Core hole 18 (40)
	Middle/Lower Wyodak	Big George	Middle/Lower Wyodak	Middle/Lower Wyodak
Aluminum, in percent	0.48	0.40	0.45	0.50
Calcium, in percent	0.84	0.49	0.89	0.79
Chlorine, in percent	0.0079	0.0055L	0.0099L	0.0059L
Iron, in percent	0.24	0.18	0.24	0.24
Magnesium, in percent	0.17	0.12	0.18	0.17
Phosphorous, in percent	0.023	0.0058L	0.023L	0.023L
Potassium, in percent	0.011	0.016	0.0092	0.013
Silicon, in percent	0.63	0.51	0.58	0.67
Sodium, in percent	0.057	0.14	0.052	0.061
Titanium, in percent	0.045	0.040	0.045	0.045
Antimony, in ppm*	0.11	0.088	0.11	0.10
Arsenic, in ppm*	1.0	2.6	1.1	1.0
Barium, in ppm	450	170	620	290
Beryllium, in ppm*	0.14	0.31	0.082L	0.20L
Bismuth, in ppm	0.044	0.031	0.047	0.042
Boron, in ppm	30	34	28	33
Cadmium, in ppm*	0.057	0.049L	0.073	0.041
Cesium, in ppm	0.041	0.037	0.024L	0.059L
Chromium, in ppm*	2.6	2.8	2.3	2.8
Cobalt, in ppm*	2.0	1.8	1.9	2.0
Copper, in ppm	9.5	9.4	9.4	9.6
Gallium, in ppm	1.4	1.5	1.4	1.4
Germanium, in ppm	0.21	0.22	0.18	0.24
Gold, in ppm	0.26	0.22L	0.27L	0.26L
Lead, in ppm*	1.4	0.84	1.2	1.6
Lithium, in ppm	2.7	3.8	2.6	2.9
Manganese, in ppm*	8.7	14	8.1	9.4
Mercury, in ppm*	0.069	0.087L	0.063L	0.074L
Molybdenum, in ppm	0.37	0.35(*50*	0.39	0.34
Neodymium, in ppm	1.2	0.83	1.3	1.0
Nickel, in ppm*	1.3	2.4L	1.6L	1.0L
Rubidium, in ppm	0.53	0.60	0.40	0.67
Scandium, in ppm	1.1	1.4	1.0	1.2L
Selenium, in ppm*	0.44	0.97	0.45L	0.42L
Silver, in ppm	0.52	0.029L	0.053L	0.050L
Strontium, in ppm	160	76	150	160
Tellurium, in ppm	0.12	0.11	0.12	0.11
Thallium, in ppm	0.051	0.11L	0.031L	0.072
Thorium, in ppm	1.3	0.69L	1.4L	1.3L
Tin, in ppm	0.31	0.29	0.31L	0.31L
Uranium, in ppm*	0.52	0.27	0.58	0.46
Vanadium, in ppm	10	10	9.4	11
Yttrium, in ppm	2.2	1.7	1.8L	2.6
Zinc, in ppm	13	4.9	14	13
Zirconium, in ppm	14	12	13	14
Average depth, in feet	329	1,100	290	370

However, arsenic, beryllium, cadmium, manganese, nickel, selenium, and uranium are higher in the beds with high ash content. Fort Union Formation coal beds in the Green River and Williston Basins are not as low in ash yield and total sulfur content as those in the Powder River Basin. These coals, which are generally thin, formed in low-lying swamps prone to flood events, as evidenced by the clay partings, and were probably deposited along actives areas of fluvial deposition where floods were a common occurrence.

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