A Critical Review of Published Coal Quality Data From the Southwestern Part of the Powder River Basin, Wyoming

Open-File Report 2011–1148

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U.S. Geological Survey, Reston, Virginia: 2011

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Abstract

A review of publicly available coal quality data during the coal resource assessment of the southwestern part of the Powder River Basin, Wyoming (SWPRB), revealed significant problems and limitations with those data. Subsequent citations of data from original sources often omitted important information, such as moisture integrity and information needed to evaluate the issue of representativeness. Occasionally, only selected data were quoted, and some data were misquoted. Therefore, it was important to try to resolve issues concerning both the accuracy and representativeness of each available dataset. The review processes demonstrated why it is always preferable to research and evaluate the circumstances regarding the sampling and analytical methodology from the original data sources when evaluating coal quality information, particularly if only limited data are available.

Use of the available published data at face value would have significantly overestimated the coal quality for all the coal fields from both the Fort Union and Wasatch Formations in the SWPRB assessment area. However, by using the sampling and analytical information from the original reports, it was possible to make reasonable adjustments to reported data to derive more realistic estimates of coal quality.

Introduction

A review of publicly available coal quality data during the 2010 coal resource assessment of the southwestern part of the Powder River Basin, Wyo. (SWPRB; fig. 1), revealed problems and limitations with those data. Because a detailed discusion of the coal quality data issues exceeded the scope of the assessment, a more thorough discussion of the coal quality data review is presented separately in this report.

Coal quality is one of the major factors in the marketability of coal and is an important parameter in economic evaluations. Coal quality directly impacts the cost of generating electric power. Quality parameters such as increased ash content, which lowers the gross calorific value (British thermal units per pound [Btu/lb]), increase the operating and maintenance costs at coal-fired powerplants. Coals with lower ash content, and therefore higher gross calorific values, command a premium selling price.

Furthermore, the Clean Air Act Amendments (CAAA) have enforced emission limits to reduce certain air pollutants such as sulfur dioxide. The sulfur dioxide emissions limits for all new powerplants built after 1976 were capped at 1.2 pounds of sulfur dioxide per million Btu (U.S. Environmental Protection Agency, 1980). Any coal that could be burned and meet the sulfur dioxide emission standards for air quality (emitting less than 0.6 pound of sulfur per million Btu or 1.2 pounds of sulfur dioxide per million Btu) without the need for flue-gas desulfurization was designated "compliance coal," also known as low-sulfur coal (U.S. Energy Information Administration, 2010). Subsequent phases of the CAAA have further restricted sulfur dioxide emissions. Currently, New Source Performance Standards (NSPS) establish uniform national U.S. Environmental Protection Agency air emission standards that limit the amount of pollution allowed from new sources or from modified existing sources. Under NSPS, Best Available Control Technology (BACT) emission limitations are based on the maximum degree of reduction of each pollutant subject to regulation under the Clean Air Act (U.S. Environmental Protection Agency, 2006). The minimum BACT standard for sulfur dioxide emissions is 90 percent regardless of the sulfur content. The abundance of low-ash and low-sulfur coal in the Powder River Basin (PRB) has been a significant factor in the steadily growing demand for coal from this region.

In-Place Coal Quality

There are currently no active mines in the SWPRB assessment area, but historically, very limited production from coal beds in both the Fort Union and Wasatch Formations has occurred. Lacking the relatively thick, shallow coal beds found in the Gillette coal field (fig. 1) on the eastern flank of the PRB, mining has not been widespread. As a result, publicly available coal quality information from coal exploration cores and mines is sparse, with the notable exception of the now abandoned Dave Johnston Mine near Glenrock, Wyo. (figs. 1 and 2). Limited coal quality data from deeper coal beds have been generated from a few wells during recent coal bed methane development (Stricker and others, 2007).

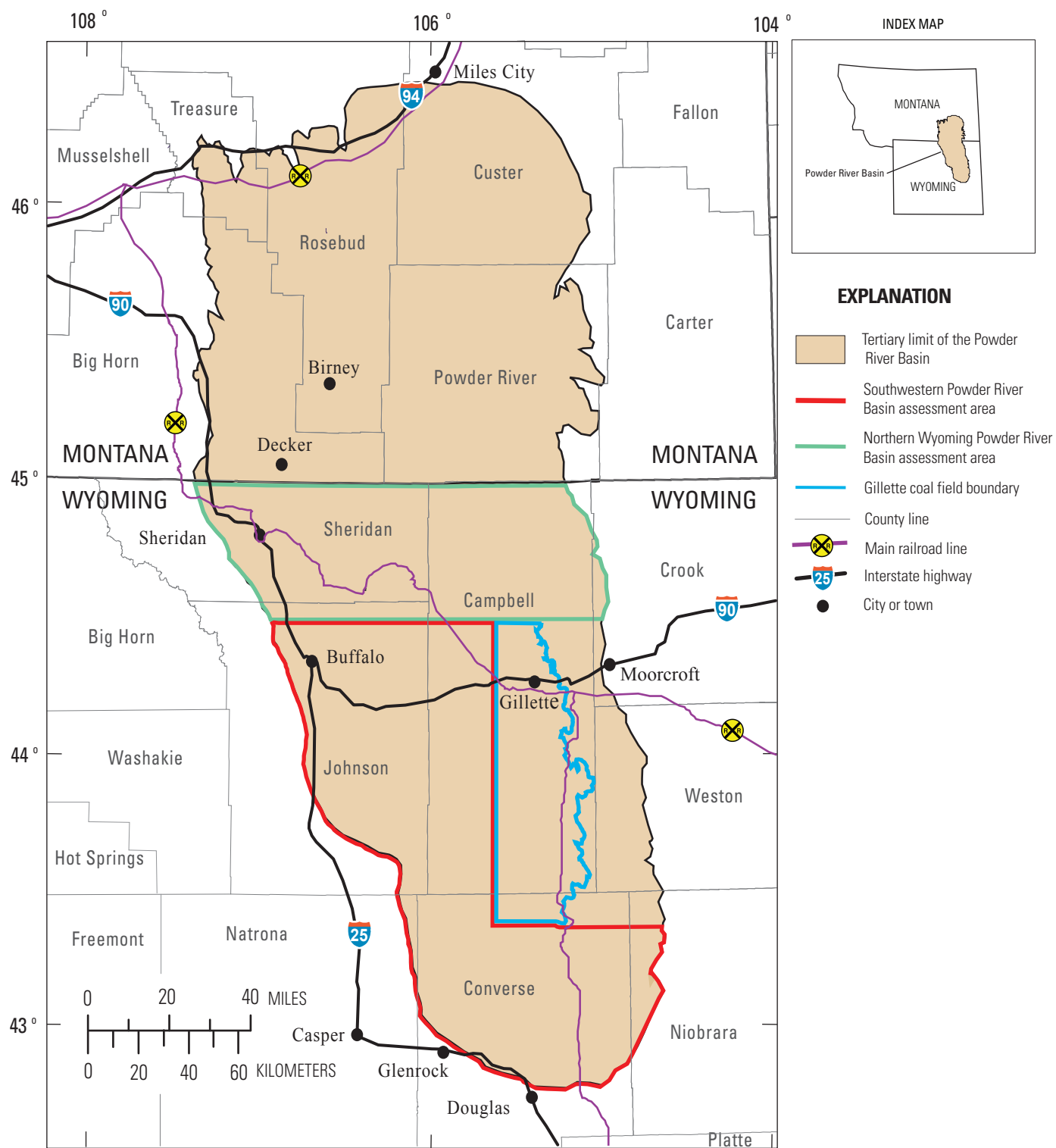**Figure 1.**   Location of Southwestern Wyoming Powder River Basin, Northern Wyoming Powder River Basin, and Gillette coal field, Wyoming.
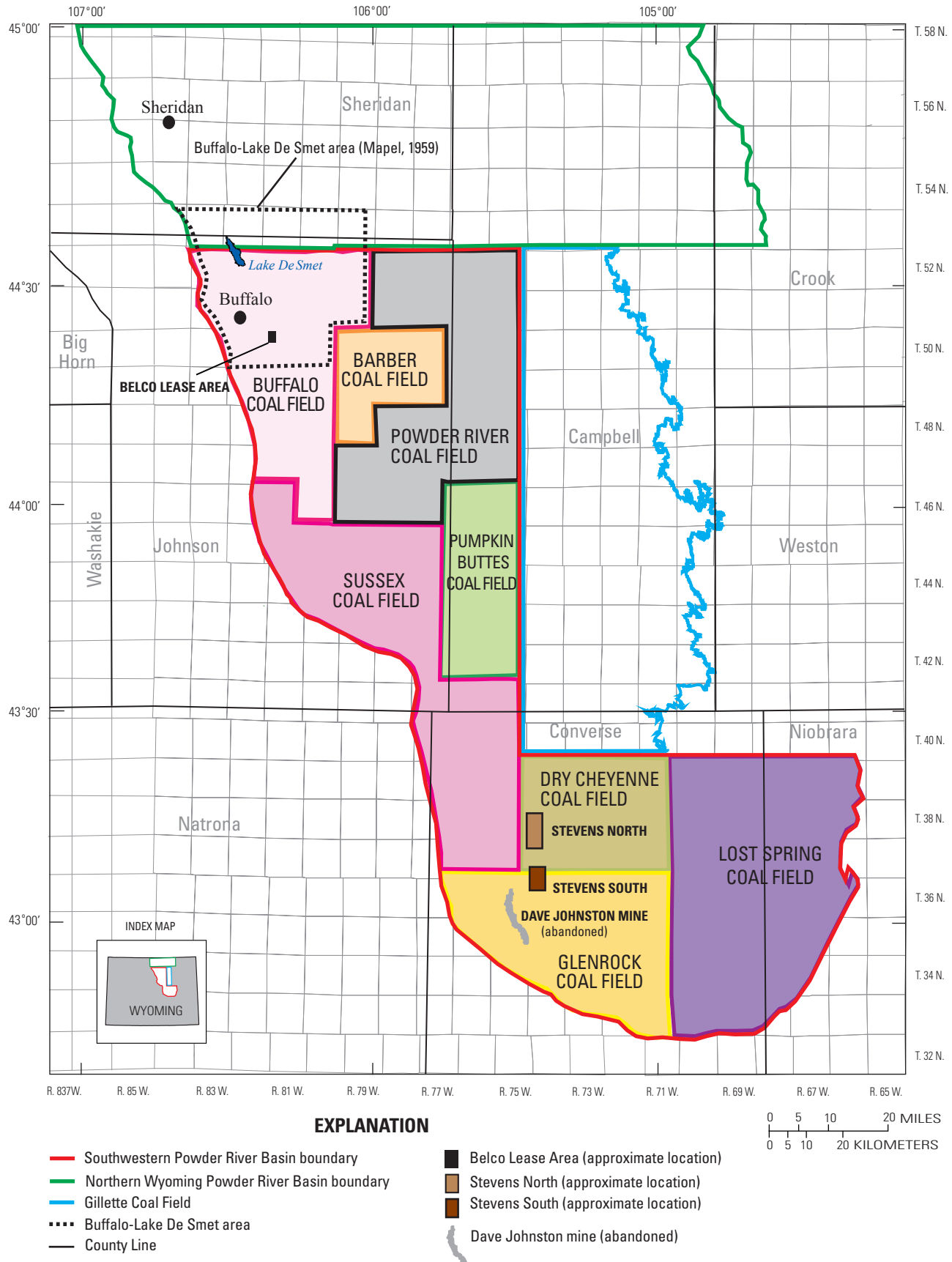
Figure 2. Location of coal fields in the Southwestern Powder River Basin (modified from Glass, 1976).

Assessing the coal quality variations is usually straight-forward for regions like the Gillette coal field, where mining has been extensive and coal analytical data are abundant. However, when dealing with relatively few coal analyses, as is the case of the SWPRB, it is especially important to try to assess both the accuracy and the representativeness of each available dataset. During the review of published coal quality data for the SWPRB, two recurring problems were apparent. These problems were either anomalously low moisture values, representativeness issues, or both. The anomalous moisture problems are due to unexplained moisture loss during sampling, shipment, or processing the samples or from the sampling of partially dried coal beds. The issue of representativeness is related to partial coal bed samples, whole bed core samples with significant core loss, or deliberate exclusion of high-ash partings. Because coal quality differs between the Fort Union and Wasatch Formations, they are discussed separately.

Fort Union Formation Coal Quality

The available in-place coal quality data for the Fort Union Formation coal beds in the SWPRB assessment area are summarized in table 1. Essentially all of the shallow coal bed data in the SWPRB are from the Dry Cheyenne and Glenrock coal fields in the south and the Sussex coal field in the west (fig. 2). An initial review of the data from table 1 reveals a relatively wide range in coal quality, especially for moisture contents (18.8 to 28.8 percent). The higher gross calorific values (7,581 to 9,160 Btu/lb) are directly dependent on what appears to be an unusually wide range in as-received moisture values for a single coal field. Typically, variations in the degree of coalification within individual coal fields or adjacent fields are not significant. Luppens (1988) demonstrated that a linear, inverse relationship exists between moisture and ash values in low-rank coals (lignite and subbituminous C ranks) for a single coal field. Any moisture values with similar ash contents that fell more than 1.5 to 2 percent from a best-fit trendline through an ash versus moisture data crossplot were reanalyzed. A similar linear, inverse relationship exists between gross calorific and ash values in low-rank coals for a single coal field (Hoeft and others, 1983). Because of these linear relationships, coal analyses with similar ash values will also have similar moisture and gross calorific values.

As moisture or ash contents, or both, decrease, gross calorific values increase and vice versa. As a general rule of thumb for low-rank coals, a 1-percent change in ash or moisture value is equivalent to a change in the gross calorific value of approximately 100 to 120 Btu/lb (J.A. Luppens, unpub. data, 2011). For example, a 5-percent decrease in moisture would result in an increase in the gross calorific value of about 500 Btu/lb. A 5-percent decrease in moisture (+500 Btu/lb) coupled with an increased ash content of 2 percent (−200 Btu/lb) would result in a net increase in the gross calorific value of about 300 Btu/lb. Knowledge of these coal quality data relationships is particularly useful in identifying potentially anomalous data (Hoeft and others, 1983).

Three sets of published coal quality data from the Dry Cheyenne and Glenrock coal fields (fig. 2) were found. The analyses from the Stevens North and South areas (table 1) were performed on coal cores (Western Fuels Association, Inc., 1983). The sample types from the Roland and Smith coal beds from the Dave Johnston Mine (table 1) were either face channel or coal core samples (Glass, 1975).

The analytical data from the Dry Cheyenne and Glenrock coal fields should be very similar because of the relative proximity of the samples (fig. 2). Therefore, samples with similar ash contents should also have similar moisture and gross calorific values. The published average moisture content of 26.6 percent for the produced coal from the Dave Johnston mine (Keystone Coal Industry Manual, 1997), owned by Pacific Power and Light Company (PPL), is the most reliable estimate of the moisture content (at 12.1 percent ash) in the Glenrock and Dry Cheyenne coal fields (table 1). However, 5 of the 10 moisture values from those coal fields, which range from 19.5 to 23.5 percent (table 1), appear to be anomalously low.

In 1974, an extensive face channeling program was initiated by the Geological Survey of Wyoming to collect coal samples to characterize the coal quality in 4 of the 10 major coal-bearing regions in the state (Glass, 1975). The extensive suite of coal analyses performed on these samples included proximate and ultimate analyses, plus tests for gross calorific values, sulfur forms, major and minor oxides, ash fusion temperatures, Hardgrove grindability, and trace elements. As part of that sampling program, Glass (1975) collected two face channel samples (74-36 and 74-37, table 1) totaling 37 and 38 feet in thickness, respectively, from the Smith coal bed (originally correlated as the School coal bed) at the Dave Johnston mine. The "typical" core analyses for the Smith bed supplied by PPL also were presented by Glass (1975) to compare the results of the face channeling results to the expected quality at the mine.

Sampling the vertical highwalls of thick beds in the PRB posed significant logistical and safety challenges from trying to cut a uniform channel through the thick coal beds and collecting the coal by use of multiple 30-foot-long extension ladders. Typically, highwall faces in PRB mines will be exposed for weeks to a month or more before the coal is actually recovered. As soon as the face is exposed, weathering effects begin, initially as moisture loss. This moisture loss results in blocky fracturing due to coal shrinkage, which can extend into the exposed coal faces for up to several feet. Prolonged exposure can result in a decrease in the gross calorific values due to oxidation. Normally, the width and depth of the face channels were gauged to yield a minimum of 6 pounds of coal per vertical foot of channel (Glass, 1975). A 3.5-inch by 3.5-inch channel will yield just over 6 pounds per channel foot. Therefore, the relatively shallow depth of the face channels would most certainly mean that sampling was limited to the zone subjected to partial drying.

Table 1. Available as-received coal quality data from the Fort Union formation in the SWPRB assessment area. Average values are shown in bold type.

Area and coal bed name	No. of analyses	Moisture (percent)	Sulfur (percent)	Ash (percent)	Gross calorific value (Btu/lb)	Pounds of SO$_2$ per million Btu	Gross calorific value[9] (Btu/lb$_{m,mmf}$)	Apparent rank[10]
Dry Cheyenne coal field–Stevens North area[3]								
Roland (Baker) coal bed	5	28.7	0.51	7.7	7,831	1.30	8,540	subC
Smith coal bed	2	26.1	0.47	7.5	8,247	1.14	8,974	subC
Glenrock coal field–Stevens South area[3]								
Roland (Baker) coal bed	1	22.2	0.42	14.7	7,860	1.07	9,344	subC
Smith coal bed	1	23.5	0.38	4.4	9,010	0.84	9,460	subC
Glenrock coal field–Dave Johnston Mine								
Roland (Baker) coal bed[4]	5	27.4	0.45	7.9	7,950	1.13	8,690	subC
Smith coal bed face channel sample 74-36[4]	1	20.7	0.5	15.7	7,850			
Smith coal bed face channel sample 74-37[4]	1	19.5	0.7	8.8	8,870			
"Typical" Smith coal bed core sample analyses from Dave Johnston Mine[4]	1	26.4	0.5	9.7	7,830			
Smith coal bed[5,7] (average of 3 analyses above from Glass, 1975)	3	**22.2**	**0.6**	**11.4**	**8,180**	**1.47**	**9,329**	**subC**
Dave Johnston Mine (produced averages)[7]	–	**26.6**	**0.45**	**12.1**	**7,581**	**1.19**	**8,720**	**subC**
Sussex coal field[4,5]								
Reported value[1,4]	1	23.5	0.49	5.2	9,160	1.07	9,707	subB
Basin 2[1,6]	1	28.8	0.56	6.7	7,930	1.41	8,547	subC
Basin 3[1,6]	1	23.6	0.68	7.8	8,450	1.61	9,228	subC
Basin 4[1,6]	1	18.8	0.57	7.8	9,160	1.24	10,006	subB
Basin 5[1,6]	1	23.5	0.49	5.2	9,050	1.08	9,590	subB
Basin 6[1,6]	1	28.1	0.45	4.6	8,350	1.08	8,786	subC
Average of 5 basin analyses		**24.6**	**0.55**	**6.4**	**8,588**	**1.28**	**9,228**	**subC**
Estimated average of 5 basin analyses (adjusted to 30 percent moisture)[1]		**30.0**	**0.51**	**6.0**	**7,969**	**1.28**	**8,515**	**subC**
Deep basin coal bed								
Smith (Big George) coal bed[2,8]	–	22.6	0.25	3.5	9,750	0.51	10,135	subB

[1]Partial bed sample.

[2]Unweighted average of 30 incremental samples from a 200-foot-thick cored portion of the bed below 1,000 feet.

[3]Western Fuels Association, Inc. (1983).

[4]Glass (1975).

[5]Glass and Jones (1992).

[6]Wegemann (1912).

[7]Keystone Coal Industry Manual (1997).

[8]Keystone Coal Industry Manual (2010).

[9]Moist, mineral-matter-free (m,mmf) basis.

[10]Subbituminous C (subC), subbituminous B (subB).

The coal from both face channel samples was described as having "blocky" or "cubical fractures," which is consistent with the blocky fractures caused by shrinkage due to moisture loss. Additionally, the condition of sample 74-36 was listed as "weathered" (Glass, 1975), which corroborates the assumption that the as-received moisture content of sample 74-36 was not representative of the true in-place moisture. Although the condition of sample 74-37 was listed as "fresh," its moisture content was over 1 percent lower than that for sample 74-36, which confirms that moisture integrity of both channel samples was compromised by significant moisture loss. In fact, Glass (1975, p. 164) states that "the routine analysis of Sample No. 74-37 compares favorably with the company [PPL] analyses except in as-received moisture and heat values [gross calorific values]. Like Sample No. 74-36, the moisture is lower than the company analyses [19.5 versus 26.4 percent] while the heat content is over 1,000 Btu/lb higher [8,870 versus 7,830 Btu/lb]" (table 1).

Using the simple rule of thumb of 100 to 120 Btu/lb change per for each 1-percent change in moisture or ash contents, the approximately 7-percent difference in moisture would equate to a difference in the gross calorific values of about 700 to 840 Btu/lb. There was also about a 1-percent difference in ash (table 1), which would account for an additional 100 to 120 Btu/lb. The combined estimated difference in moisture and ash contents in terms of impacts to the gross calorific value is 800 to 960 Btu/lb, which closely approximates the "over 1,000 Btu/lb difference" noted by Glass (1975).

Glass and Jones (1992) characterized the coal quality of the Smith bed in the Glenrock coal field using only the two face channel analyses, 74-36 and 74-37, and the core hole analyses provided by PPL (table 1; Glass, 1975), even though it was acknowledged that the face channel samples were described as weathered and had anomalously low moisture contents. Additionally, the coal quality summary was simply an average of those three samples, with data ranges, without any critical information concerning the sample type, condition of the samples, limitations of the data, or source of the data. Only the author's personal knowledge of the 1974 channel sampling program allowed tracing of the average values in Glass and Jones (1992) back to Glass (1975). The use of data that are not representative of the coal to characterize coal quality of a given area is disappointing from a professional standpoint because of the ripple effect. The three-sample summary, with little documentation from Glass and Jones (1992), was cited in subsequent publications (Keystone Coal Industry Manual, 1997, 2005), thus perpetuating the impression that the coal quality in the Glenrock coal field is better than it actually is. The inclusion of samples with anomalously low moisture increased the average gross calorific value.

The moisture values for the two cores from the Stevens South area of the Glenrock coal field (table 1) also look anomalously low. Because this area lies between the Stevens North area and the Dave Johnston Mine, the moisture contents should be similar. It is assumed that unaccounted-for moisture loss during the coring or core handling occurred, but no

documentation was available. Additionally, the ash content of 4.4 percent for the Smith bed analysis (table 1) in the Stevens South area also appears to be especially low, especially when compared to other Wyoming PRB coal quality. The Gillette coal field, which produces coal with some of the lowest ash content in the Nation, has as-received ash contents from the south to the north areas that range from 5.2 to 6.4 percent, respectively. Ranges for other as-received coal quality parameters from the south to the north areas in the Gillette coal field were moisture, 26.7 to 30.0 percent; and gross calorific values, 8,200 to 8,810 Btu/lb.

Given the documented problems with the use of samples with anomalously low moisture contents from Glass (1975) and Glass and Jones (1992), more realistic ranges in coal quality from these two coal fields are estimated to be moisture, 26 to 29 percent; ash, 7.5 to 12 percent; sulfur, 0.4 to 0.6 percent; and gross calorific values, 7,500 to 8,000 Btu/lb. The range in moisture is more consistent with that for the Gillette coal field. The gross calorific values are also consistent with those for the Gillette area, given that the average ash content in the Glenrock and Dry Cheyenne coal fields is significantly higher than in the Gillette coal field. It is interesting to note that one of the reasons for closing the Dave Johnston Mine in 2000 was deteriorating coal quality due to higher ash (PacifiCorp, 2008).

The author encountered a similar situation while evaluating purchase of a coal property in the Gillette coal field near Gillette, Wyo. (J.A. Luppens, unpub data, 1998). The seller provided coal quality data from cores drilled in the 1960s, with moisture values ranging from 18 to 34 percent and averaging about 28 percent. However, moisture values from adjacent mines ranged from 30 to 32 percent. A coring program was initiated to resample over 20 original core sites with suspect analyses. The result of the recoring program was a revised average moisture content of about 31.5 percent, consistent with that from the neighboring mines. Subsequent interviews with laboratory personnel who conducted the original analyses confirmed suspicions regarding the conditions of the core samples as received at the laboratory. Many samples had been stored for weeks before shipment to the laboratory in unlined cardboard boxes without plastic bags or other means of preventing moisture loss. Problems caused by unaccountable moisture loss are more common than often realized, especially with coal samples collected years ago when neither materials to prevent moisture loss nor expedited shipping options were available.

The problems with the published coal quality data from the Sussex coal field (fig. 2) stem not only from moisture issues similar to those for the Dry Cheyenne and Glenrock coal fields but also from representativeness issues. Additionally, only select data were reported in more recent publications, and citation errors were introduced.

Table 2 illustrates the progression of reported coal quality data over the past nearly 100 years since the original data were reported. The original assessment of the Sussex coal field reported a total of six coal sample analyses (Wegemann,

1912). Smith and others (1972) reported three of the original six analyses. More recently, only a single coal analysis for the Sussex coal field was reported by Glass and Jones (1992; tables 1 and 2), and it does not exactly match any of the analyses from the original data (table 2). Evidently, the moisture, ash, volatile, fixed carbon, and sulfur contents from sample 10827 were combined with the gross calorific value from sample 10804. It is unknown whether this reporting was due to intentional compositing or was a result of a typographical error. Nevertheless, it demonstrates the value in reviewing the original reports rather than relying on subsequent interpretations. The quotation of the single erroneous analysis from Glass and Jones (1992) by the Keystone Coal Industry Manual (2005) demonstrates how misleading and incorrect citations can easily be perpetuated.

Based on this single reported proximate analysis (Glass and Jones, 1992), the coal quality of the Sussex field appears to be relatively high for the PRB. However, after one reviews the original report on the Sussex coal field (Wegemann, 1912), a different perspective is gained. A total of five analyses from various "basins" within the Sussex coal field with at least as-received moisture, ash, sulfur, and gross calorific values was given in the original report (table 1). The analytical results show a fairly wide range in moisture (and consequently gross calorific values), whereas ash contents are all fairly low. The lower moisture analyses (less than 28 percent moisture) likely reflect unaccountable moisture loss. This conclusion is supported by the nature of the samples. All of the analyses were performed on samples collected at small, shallow, wagon mines along the coal bed outcrops. The author even cautioned "this form [as-received] is not well suited for comparison, because the amount of moisture as it comes from the mine is largely a matter of accident, and consequently analyses of the same coal in this form may vary widely" (Wegemann, 1912, p. 468).

The averages of the five individual basin analyses from the Sussex coal field are also presented in table 1. Although the average gross calorific value of 8,588 Btu/lb is significantly lower than the 9,160 Btu/lb reported by Glass and Jones (1992), the average moisture values still appear to be anomalously low. Assuming that all samples encountered at least some unaccounted-for moisture loss is reasonable, given the nature of the samples as well as the logistics and time required to ship the samples from the field to the laboratory in 1910; an average moisture content of 30 percent would be more realistic. The 30 percent moisture estimate is only about 1 percent higher than the moisture content for the Basin 2 sample. With an as-received moisture level of 30 percent, the 9,160 Btu/lb reported by Glass and Jones (1992) would be reduced to 8,380 Btu/lb. More realistic estimated average values of the basin samples for all parameters adjusted to an as-received moisture level of 30 percent (ASTM International, 2008c) are also shown in table 1.

The issue of anomalously low moisture data was not the major problem encountered in assessing the coal quality of the Sussex coal field. It is important to recognize that the analytical data for the Sussex coal field presented in table 1 should not be considered representative of average values for the whole field. All of the samples are partial coal bed samples. For example, the Basin 6 sample (Laboratory No. 11048) came from a 5-foot-thick bench of lower-ash coal in the middle of an approximately 13-foot-thick coal bed which has several high-ash layers (up to 1 foot thick) in the upper and lower benches of the coal bed. Similarly, the other four samples are from lower-ash coal bed benches, the higher-ash benches being avoided at each sampling location. In fact, the presence of higher-ash coal layers and mineral partings within the coal measures described by Wegemann (1912) are the rule rather than the exception. Statements such as "too broken by shale partings to be minable" are common. The presence of partings and higher-ash layers is consistent with the coal bed geology in the southwestern part of the PRB. On the western flank, the thick coal beds in the eastern and deep central parts of the basin thin, split, and pinch out (Flores and others, 1999). Unlike problems associated with anomalously low moisture contents, which can be straightforwardly adjusted to more realistic levels, the analytical results on coal samples that are not representative of the entire coal bed are especially difficult to assess.

The high frequency and discontinuous nature of these high-ash layers mean that the typical quality of coals in the Sussex coal field is expected to be even lower than the average values adjusted to 30 percent moisture shown in table 1 (higher ash contents and lower gross calorific values). It is impossible to reasonably predict the impacts of inclusion of higher-ash benches on the average coal quality. The same is true for sulfur content predictions. However, it is not unreasonable to expect that the average ash content of 6.0 percent (at the estimated 30 percent moisture basis) would increase to at least 10 percent given the abundance of high-ash layers in the Sussex coal field. At 10 percent ash, the calorific value would decrease to about 7,550 Btu/lb. This calorific value adjustment assumes a decrease of about 100 Btu/lb per 1-percent ash increase. An estimated coal quality of 30 percent moisture, 10 percent ash, and a calorific value of 7,550 Btu/lb is markedly dissimilar from the reported analysis by Glass and Jones (1992; tables 1 and 2).

Excluding the samples with anomalously low moisture contents (table 1), the near-surface Fort Union Formation coal beds have an apparent rank of subbituminous C (subC; ASTM International, 2008a). However, the apparent rank increases with depth as evidenced by the deep Smith (Big George) bed analysis in table 1. The apparent rank reaches subbituminous A (subA) in the deepest part of the basin (fig. 3; Stricker and others, 2007).

Table 2.   A comparison of reported coal quality data in the Sussex coal field, Wyoming, from successive publications. Analyses not reported are indicated by NR.

Basin – coal bed	Laboratory number	Analysis	Wegemann (1912)	Smith and others (1972)	Glass and Jones (1992)	Keystone Coal Industry Manual (2005)
Basin 2 – ?	10683	Moisture (%)	28.8			
		Ash (%)	6.7			
		Volatile matter (%)	NR			
		Fixed carbon (%)	NR			
		Sulfur (%)	0.56			
		Calorific value (Btu/lb)	7,930			
Basin 3 – ?	10728	Moisture (%)	23.6			
		Ash (%)	7.8			
		Volatile matter (%)	NR			
		Fixed carbon (%)	NR			
		Sulfur (%)	0.68			
		Calorific value (Btu/lb)	8,450			
Basin 3 – ?	10694	Moisture (%)	NR			
		Ash (%)	14.6			
		Volatile matter (%)	NR			
		Fixed carbon (%)	NR			
		Sulfur (%)	0.56			
		Calorific value (Btu/lb)	7,980			
Basin 4 – Upper bed	10804	Moisture (%)	18.8	18.8		
		Ash (%)	7.6	7.6		
		Volatile matter (%)	35.7	35.7		
		Fixed carbon (%)	37.9	37.9		
		Sulfur (%)	0.57	0.57		
		Calorific value (Btu/lb)	9,160	9,160		
Basin 4 – Lower bed	10827	Moisture (%)	23.5	23.5	23.5	23.5
		Ash (%)	5.17	5.17	5.17	5.2
		Volatile matter (%)	35.6	35.6	35.6	35.6
		Fixed carbon (%)	35.7	35.7	35.7	35.7
		Sulfur (%)	0.49	0.49	0.49	0.49
		Calorific value (Btu/lb)	9,050	9,050	9,160	9,160
Basin 6 – Upper bed	11048	Moisture (%)	28.1	28.1		
		Ash (%)	4.62	4.62		
		Volatile matter (%)	31.6	31.6		
		Fixed carbon (%)	35.7	35.7		
		Sulfur (%)	0.45	0.45		
		Calorific value (Btu/lb)	8,350	8,350		
Additional information	Assessment of moisture validity		YES	NO	NO	NO
	Data to assess representativeness		YES	NO	NO	NO

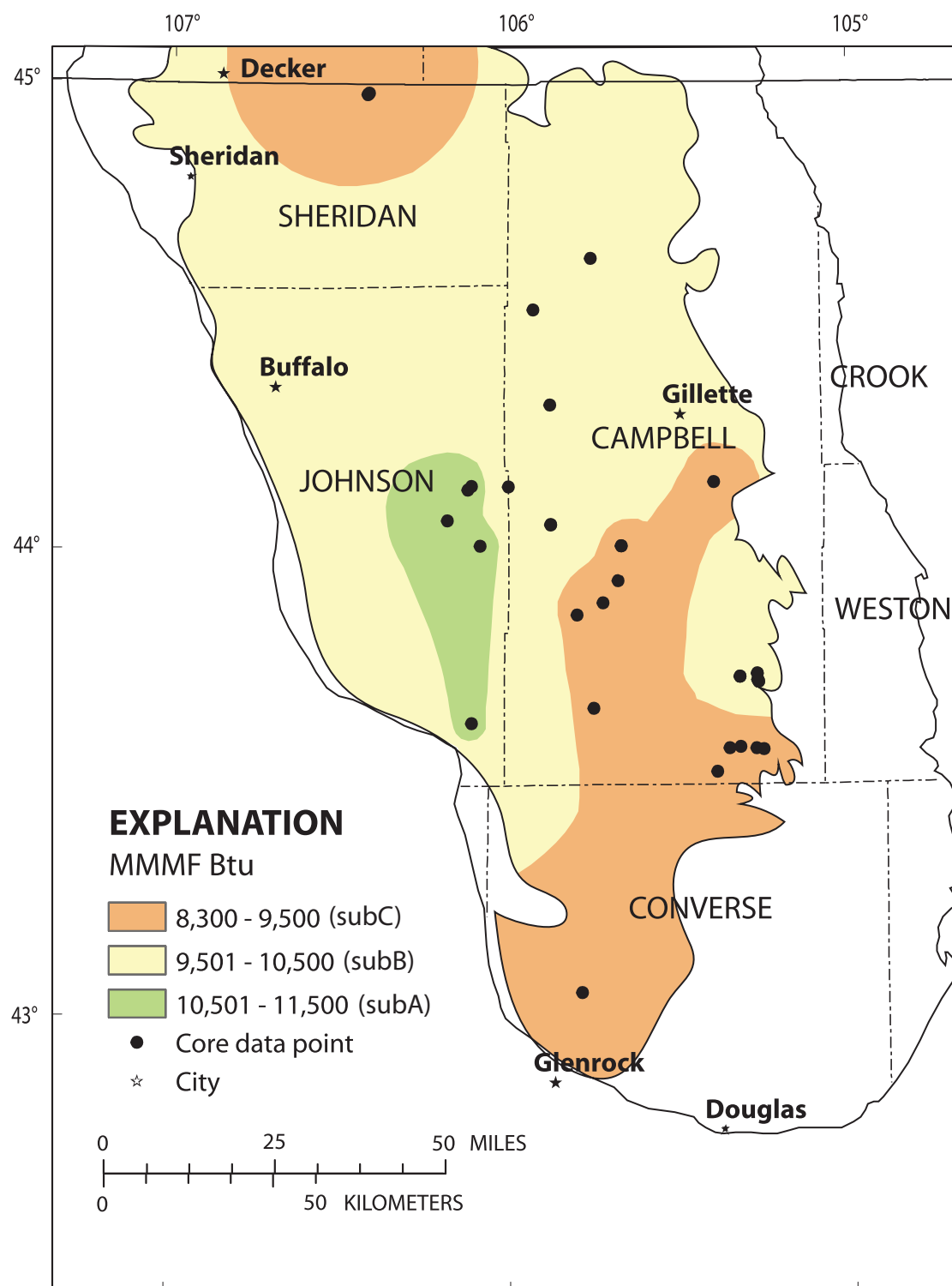**Figure 3.**   Variation in moist, mineral-matter-free (m, mmf) British thermal units (Btu) in the Wyodak-Anderson coal zone in the Powder River Basin, Wyoming (Stricker and others, 2007), showing a trend towards increasing apparent rank of the coal (ASTM International, 2008a) from subbituminous C (subC) at shallow depths to subbituminous B (subB), and finally subbituminous A (subA) in the deepest part of the basin.

Estimation of the Quality of Deep Fort Union Formation Resources

The SWPRB contains significant volumes of thick Fort Union Formation coal beds that are too deep to mine by means of conventional surface mining technology. As an integral part of the assessment of these deep coal resources, an estimation of the coal quality by depth is an important parameter in assessing the viability of resources potentially recoverable by underground mining methods. Coal quality data for the deeper coal resources are especially limited to a relatively few coal cores sampled for coal-bed natural gas assessment work. Furthermore, the results from the analyses of core samples following gas desorption testing require critical evaluation from the standpoint of both representativeness and sample degradation during the desorption process.

The coal quality dataset from Stricker and others (2007) is a compilation of analyses from 963 core samples from 37 core holes that were placed in sealed canisters for gas desorption measurements. Each sample was 2 feet long and 4.0 inches in diameter. The coal, after gas desorption in the canisters, was split into subsamples for an extensive analytical suite including proximate analyses, ultimate analyses, and gross calorific value determinations. The analytical results from the 37 core holes representing 52 beds were summarized by Stricker and others (2007, table 2, p. 11–14). Those data were then imported into a spreadsheet (table 3) to determine whether a relationship between sample depth and gross calorific values could be established by creating crossplots of depth versus gross calorific values.

The process of analyzing coal quality data from desorbed canister samples can be challenging. The desorption process can take several months or longer. During that time, coal may be partially oxidized, resulting in lower gross calorific values. Furthermore, samples tend to dry out during gas desorption (Mavor and Pratt, 1996). Moisture losses result in anomalously higher as-received gross calorific values. Perhaps one of the greatest challenges is deciding whether or not the canister samples are representative of the entire coal bed. For example, for Bore Hole No. 26 (table 3), a total of fifty-one 2-foot-long canister samples from the Smith (Big George) bed were desorbed, but proximate and gross calorific value analyses were performed on only three of those canister samples.

Representativeness refers not only to parameters like ash but also to the maceral assemblages of each canister sample. Although North American coals tend to be rich in vitrinite (Mathews and others, 2007), there are typically petrographic facies or layers within a coal bed where exinite or inertinite may be enriched relative to vitrinite (Flores and others, 1989). Exinite has a markedly higher calorific value and volatile matter content than vitrinite due to its high hydrogen content. Conversely, the relatively low calorific value of inertinite is due to its lower hydrogen content (Stach and others, 1982). Thus, a canister from a facies enriched in exinite might have an anomalously higher calorific value compared to a whole bed sample from the same sampling location, and the opposite would be true for a facies enriched in inertinite.

Given all the challenges and limitations of interpreting coal quality data from canister samples, it is not surprising that the first attempt to establish a trend of depth versus as-received gross calorific values from table 3 was unsatisfactory (fig. 4). The plot exhibits fairly poor agreement between the two parameters. The least squares trendline had an R^2 of only 0.255. Furthermore, the trendline projection of about 7,000 Btu/lb at shallow depths does not reflect typical values for the PRB at similar depths (table 1).

A review of the data from table 3 suggests that the previously discussed problems of moisture loss, sample oxidation, anomalously high and low calorific values, and representativeness were all encountered to at least some degree. Equilibrium moisture values will typically be lower than the respective inherent (bed) moisture values for a sample that has been collected at its inherent moisture level (Luppens, 1982; Luppens and Hoeft, 1991). In fact, ASTM D1412 ("Standard Test Method for Equilibrium Moisture of Coal at 96 to 97 Percent Relative Humidity and 30°C") states that "based on experience with low rank coals, equilibrium moisture values that exceed inherent moisture values are due to one or both of two situations, either the sample was not collected with its full complement of inherent moisture (partially dried) or an analytical problem occurred, or both" (ASTM International, 2008b, p. 290). For Wyoming subbituminous coals, equilibrium moisture values ranged from 0.5 to 1.3 percent lower than inherent moisture levels (Luppens and Hoeft, 1991). Therefore, equilibrium moisture values that are higher than total moisture values in table 3 indicate moisture was lost during gas desorption for some samples. Additionally, the 2,557-Btu/lb range between the maximum and minimum moisture- and ash-free (DAF) calorific values for coal beds within the same area is quite large. This is probably due in large part to the impact of atypical maceral assemblages on the relatively few canister intervals with calorific analyses and perhaps the effects of sample oxidation, which lowers DAF calorific values.

An additional tool for verifying coal quality is data interrelationships. The verification process is based on the fact that data interrelationships are almost axiomatic in coal analyses. As the analytical result for one parameter changes, the esults for some other parameter usually changes too. The pair of test results may vary inversely or in direct proportion to each other. Correlations based on these data interrelationships can be used to identify possible outliers or estimate missing data (Hoeft and others, 1983). For example, moisture and ash have an inverse linear relationship (Luppens, 1982). As the ash content increases, moisture content decreases. Thus, for two analyses with similar ash contents from the same coal bed and depth, the moisture contents should be similar as well.

Table 3. Properties and composition of coal beds cored in the Powder River Basin, Wyoming (modified from Stricker and others, 2007, table 2). Figure 4 shows the plot of the depth versus as-received calorific values for these data.

Core hole	Mean depth, in feet	Coal zone	Coal bed name as used by gas operators	Number of samples	Moisture Total (%)	Moisture Equilibrium (%)	Ash yield (%)	As-received calorific value (Btu/lb)	Dry ash yield (Btu/lb)	Dry colorific value	Dry, ash free (DAF) calorific value (Btu/lb)
9	143.4	Wyodak-Anderson	Upper Wyodak	5	19.27	22.18	12.22	9,280	15.14	11,495	13,095
10	167.0	Wyodak-Anderson	Upper Wyodak	2	26.46	27.45	9.31	8,910	12.66	12,116	13,360
9	181.5	Wyodak-Anderson	Middle/Lower Wyodak	26	22.69	25.57	4.52	8,790	5.85	11,370	11,908
10	209.2	Wyodak-Anderson	Middle/Lower Wyodak	27	27.53	26.78	4.59	8,750	6.33	12,074	12,655
13	212.0	Wyodak-Anderson	Upper Wyodak	8	27.25	----	8.88	8,790	12.21	1,2082	13,260
20	248.9	Wyodak-Anderson	Middle/Lower Wyodak	34	27.81	24.77	4.50	8,990	6.23	12,453	13,040
13	252.4	Wyodak-Anderson	Middle/Lower Wyodak	27	28.86	----	4.56	8,750	6.41	12,300	12,887
14	289.0	Wyodak-Anderson	Middle/Lower Wyodak	30	28.88	25.18	3.46	8,890	4.87	12,500	12,948
15	293.1	Wyodak-Anderson	Middle/Lower Wyodak	32	27.93	25.61	3.69	8,740	5.12	12,127	12,592
17	293.1	Wyodak-Anderson	Middle/Lower Wyodak	39	26.54	25.49	3.82	8,770	5.20	11,938	12,413
16	319.4	Wyodak-Anderson	Middle/Lower Wyodak	28	27.13	26.13	4.22	8,600	5.79	11,802	12,322
28	329.3	Wyodak-Anderson	Anderson	8	27.46	27.23	4.22	8,820	5.82	12,159	12,695
34	345.0	Wyodak-Anderson	Anderson	17	24.98	25.35	4.68	9,010	6.24	12,010	12,600
23	346.0	Wyodak-Anderson	School	9	25.49	26.25	12.20	8,020	16.37	10,764	12,259
18	360.2	Wyodak-Anderson	Middle/Lower Wyodak	40	25.56	----	3.75	9,090	5.04	12,211	12,687
8	385.0	Wyodak-Anderson	Smith	15	26.13	----	5.87	9,080	7.95	12,292	13,058
34	519.5	Wyodak-Anderson	Canyon	13	26.31	24.26	3.71	9,090	5.03	12,335	12,811
30	640.0	Wyodak-Anderson	Canyon	7	25.31	25.53	3.74	9,120	5.01	12,210	12,685
6	648.7	Wyodak-Anderson	Canyon	7	32.01	----	5.20	7,630	7.65	11,222	11,838
6	952.0	----	Cook	8	27.77	----	4.54	8,670	6.29	12,003	12,574
33	960.2	Wyodak-Anderson	Big George	10	24.77	23.83	4.22	9,180	5.61	12,203	12,740
8	990.0	Wyodak-Anderson	Canyon	4	25.82	----	4.19	9,340	5.65	12,591	13,142
6	1,074.0	----	Wall	4	27.40	----	5.67	8,760	7.81	12,066	12,791
5	1,076.0	Wyodak-Anderson	Big George	13	26.42	----	3.95	8,920	5.37	12,123	12,621
2	1,138.9	Wyodak-Anderson	Big George	50	19.78	----	3.38	10,300	4.21	12,840	13,289
4	1,142.0	----	Wall	16	25.55	----	5.78	9,440	7.76	12,680	13,457
37	1,166.1	----	Pawnee	7	21.60	20.91	5.58	9,740	7.12	12,423	13,158
3	1,192.0	Wyodak-Anderson	Anderson	2	27.76	26.40	6.30	7,790	8.72	10,783	11,509
35	1,230.9	Wyodak-Anderson	Big George	20	25.55	24.77	3.65	9,150	4.90	12,290	12,756
25	1,243.0	----	Pawnee	5	25.19	24.34	8.14	8,120	10.88	10,854	11,816

Table 3. Properties and composition of coal beds cored in the Powder River Basin, Wyoming (modified from Stricker and others, 2007, table 2). Figure 4 shows the plot of the depth versus as-received calorific values for these data.—Continued

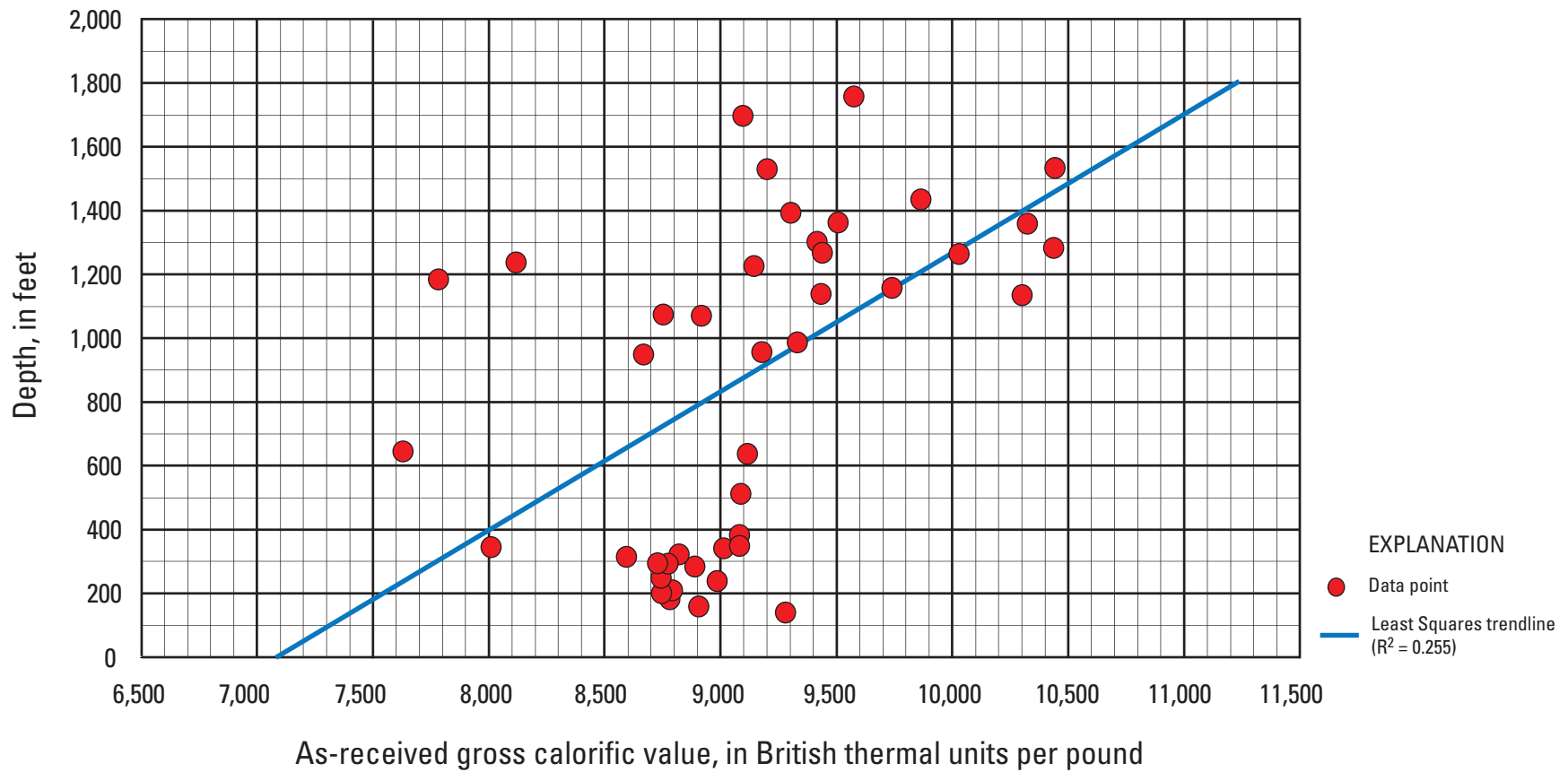| Core hole	Mean depth, in feet	Coal zone	Coal bed name as used by gas operators	Number of samples	Moisture		Ash yield (%)	As-received calorific value (Btu/lb)	Dry ash yield (Btu/lb)	Dry colorific value	Dry, ash free (DAF) calorific value (Btu/lb)
					Total (%)	Equilibrium (%)					
36	1,266.4	----	Pawnee	4	22.01	34.07	6.09	10,030	7.81	12,861	13,695
5	1,276.5	Wyodak-Anderson	Wyodak	24	24.61	----	4.50	9,440	5.97	12,522	13,112
1	1,287.2	Wyodak-Anderson	Big George	60	19.22	18.50	3.67	10,440	4.54	12,924	13,416
19	1,308.0	Wyodak-Anderson	Big George	6	23.49	23.69	3.36	9,420	4.39	12,312	12,740
26	1,365.2	Wyodak-Anderson	Big George	51	19.23	17.67	3.86	10,330	4.78	12,789	13,303
11	1,366.4	Wyodak-Anderson	Big George	12	24.33	23.48	4.51	9,510	5.96	12,568	13,161
12	1,401.0	Wyodak-Anderson	Big George	32	21.90	19.89	4.58	9,300	5.86	11,908	12,479
31	1,440.3	Wyodak-Anderson	Big George	32	17.94	18.15	5.97	9,870	7.28	12,028	12,791
27	1,537.6	----	Pawnee	11	23.43	20.41	4.55	9,200	5.94	12,015	12,588
32	1,541.8	Wyodak-Anderson	Big George	17	17.95	16.51	3.41	10,440	4.16	12,724	13,173
27	1,709.8	----	Cache	16	23.10	22.24	4.77	9,100	6.20	11,834	12,426
11	1,769.0	Wyodak-Anderson	Werner	13	24.60	22.81	2.69	9,570	3.57	12,692	13,043
29	2,197.5	----	Roberts	7	22.64	16.85	9.75	9,820	12.60	12,694	14,065
Average					24.78	23.62	5.22	9,140	**6.94**	**12,144**	**12,813**
Maximum value (MAX)					32.01	34.07	12.22	10,440	**16.37**	**12,924**	**14,065**
Minimum value (MIN)					17.94	16.51	2.69	7,630	**3.57**	**10,764**	**11,509**
MAX-MIN range					14.07	17.56	9.53	2,810	**12.81**	**2,160**	**2,557**

Figure 4. Estimated variability of as-received gross calorific values versus depth from table 3 data for the Wyodak coal beds in the Powder River Basin, Wyoming.

For Core Holes 30 and 6 (table 3), the ash contents and depths are very similar, but the moisture contents are significantly different (25.31 versus 32.01, respectively). Furthermore, the relatively high moisture content for Core Hole 6 resulted in anomalously lower dry and DAF calorific values. Therefore, Core Hole 6 was considered suspect. Core hole samples with equilibrium moisture values that were more than 1 percent higher than the total moisture values also were discarded. The remaining data in table 3 were similarly edited, and coal bed analyses that appeared to be anomalous (mostly because of suspect moisture and calorific values) also were discarded. Also, to reduce variations due to differences in bed characteristics, only coal beds in the Wyodak-Anderson coal zone (Smith through the Werner beds) were used (fig. 5).

Of the 43 coal bed analyses in table 3, only 25 were retained as a result of the editing process (table 4). All the ranges in the maximum and minimum values in table 4 are much more realistic. For example, the range in DAF calorific values was reduced from 2,557 Btu/lb (table 3) to 938 Btu/lb (table 4). More importantly, the plot of depth versus calorific values from the edited data (fig. 6) visually demonstrates a more reliable relationship than the plot made from the unedited data (fig. 4). Additionally, the R^2 of 0.744 from figure 6 represents a significant improvement over that in figure 4. A trendline based on the moist, mineral-matter-free calorific values from table 4 was also plotted on figure 6 to illustrate the relationship between apparent coal rank and depth. It must be stressed that, given the limitations of the desorbed-gas-canister analyses combined with the discarding of analyses through an editing process based solely on author experience with coal quality relationships in the PRB, the results should be refined as more data become available.

Two sources of independent data verification shown on figure 6 corroborate the relationship between calorific values and depth. Testa and Pratt (2003) also examined the relationship between calorific values and depth. The trendline of their depth versus moist, mineral-matter-free calorific values was added to figure 6. The two trendlines exhibit marked concurrence. The slopes are nearly parallel, and calorific values generally agree within 100 Btu/lb. The second source of verification is the published deep basin analyses of the Smith bed (Big George) from table 1. The calorific value of 9,750 Btu/lb represents the "unweighted average of 30 incremental samples from a 200-ft thick cored portion of the bed below 1000 feet" (Keystone Coal Industry Manual, 2010, p. 617). Further investigation revealed that the exact depth interval for this Smith bed was 1,580 to 1,780 feet (N.R. Jones, unpub. data, 2010). This 200-foot sample interval with an average calorific value is plotted on figure 6 as a box, which the trendline for the calorific values versus depth trendline nearly bisects. Although the depth versus calorific values plot in figure 6 is based on relatively few selected data points, the multiple sources of independent data verification support the use of that trendline as a reasonable technique for estimating the expected coal quality of the thick coals to a depth of 2,000 feet.

Wasatch Formation Coal Quality

As with the Fort Union Formation, only limited coal quality data for the Wasatch Formation are available. No significant, large-scale mining has occurred in the Wasatch coal beds in the PRB despite the fact that the Healy bed in the Lake De Smet coal field (fig. 2) is the thickest known coal bed in the contiguous United States (Keystone Coal Industry Manual, 2010). A summary of coal quality data for the Wasatch Formation is presented in table 5.

In general, Wasatch coal beds have higher ash and sulfur contents and lower calorific values than the Fort Union Formation coals currently being produced in the PRB (Luppens and others, 2008). Partings are common and fairly persistent in many Wasatch coal beds (Mapel and others, 1953; Mapel, 1959; Keystone Coal Industry Manual, 2010), which probably accounts, in part, for the lower quality. The apparent rank of Wasatch coal beds based on published data ranges from lignite A to subbituminous C (table 5). As with the Fort Union Formation coal quality for the SWPRB, limitations with existing published Wasatch coal quality information stem from both the accuracy and the representativeness of the data.

The issue of accuracy is, again, basically one of the reliability of the moisture results. The total moisture contents for the Lake De Smet coal cores in table 5 ranges from 23.6 to 30.5 percent. This range in moisture values for cores with similar ash contents from the same area seems large, especially because the face channel samples from the mine in the Lake De Smet area indicate moisture contents exceeding 30 percent (table 5). The USGS-2A core had a moisture content of 30.5 percent, which is comparable to the two mine face channel samples. It was recognized that moisture in the Bureau of Reclamation (BOR) core (table 5) was at least 5 percent below that of the other cores, which was attributed to moisture loss during handling and shipping (Mapel and others, 1953). Yet, despite this core having an acknowledged anomalously low moisture content, it was used as reported in the calculation of the average coal quality parameters, biasing the average calculated coal quality.

The fluids used in the coring process can add excess surface moisture to the cores (Luppens and others, 1992). Therefore, it would be expected that the average total moisture of the cores should be at or at least slightly higher than—rather than significantly less than—the total moisture values of the mine face channel samples. It is suspected that moisture was lost during shipping and that subsequent partial drying occurred through handling and processing of the core. All the cores were either coated with paraffin wax or wrapped in wax paper to preserve the moisture in the core samples; however, both practices are imperfect barriers to moisture loss. Any additional core breakage during shipping could have compromised the wax coating. Furthermore, the cores were sliced in half by means of a saw with a dry blade (Mapel and others, 1953) prior to core logging and analysis, which also could have contributed to additional, unaccounted-for moisture loss.

Formation name	Kent and others (1980)	Pierce and others (1990)	USGS Fort Union Coal Assessment Team (1999) and Glass (1997)	Ellis and others (2002)	Gillette coal field (Luppens and others, 2008)	Northern Wyoming Powder River Basin (Scott and others, 2010)	Current SWPRB assessment area
	Bed names						
Wasatch		Felix			Upper Felix / Felix	Upper Healy / Healy / Ucross / Felix / Lower Felix	Upper Healy, Healy / Murray / Ucross / Felix / Lower Felix
Fort Union (Tongue River Member)	Smith	Roland/ Badger	Roland	Wyodak / Rider	Roland	Roland (Upper Rider) / Roland of Baker, 1929 / Roland of Taff, 1929	Roland (Upper Rider) / Roland (Lower Rider) / Roland of Baker, 1929
	Upper Wyodak	Wyodak or Upper Wyodak (Anderson/ Canyon)	Wyodak-Anderson coal zone=Smith (Swartz), Badger, School, Sussex, Big George, Wyodak, Anderson, Dietz, Canyon (Monarch), Werner	Upper Wyodak	Smith	Smith	Smith
					Anderson Rider, Anderson	Anderson	Anderson
						Lower Anderson Dietz 1, Dietz 2, Dietz 3, Dietz 4	Dietz 3
					Dietz		Upper Canyon
	Canyon			Canyon	Canyon	Canyon	Canyon
						Lower Canyon	Lower Canyon
				Lower Wyodak		Ferry	
	Werner	Lower Wyodak			Werner	Werner	Werner
						Otter	Otter
	Gates/ Kennedy	Upper Kennedy		Gates/ Kennedy	Gates	Gates	Gates
					Pawnee	Pawnee	Pawnee
						Odell	
							Deep 1
							Deep 2
							Deep 3
						Roberts	Roberts

Wyodak-Anderson coal zone

Figure 5. Coal bed and coal zone names used in different publications in the Powder River Basin, including current SWPRB coal assessment area (L. Osmonson, U.S. Geological Survey, unpub. data, 2010).

Table 4. Edited version of table 3 in which core holes with anomalous data were deleted. Of the total of the 43 coal bed analyses in table 3, only 25 were retained as a result of the editing process. Figure 6 shows the plot of the depth versus as-received calorific values for these data. A trendline for the calculated moist, mineral-matter-free calorific value is also shown on figure 6 to illustrate the relationship with apparent rank versus depth.

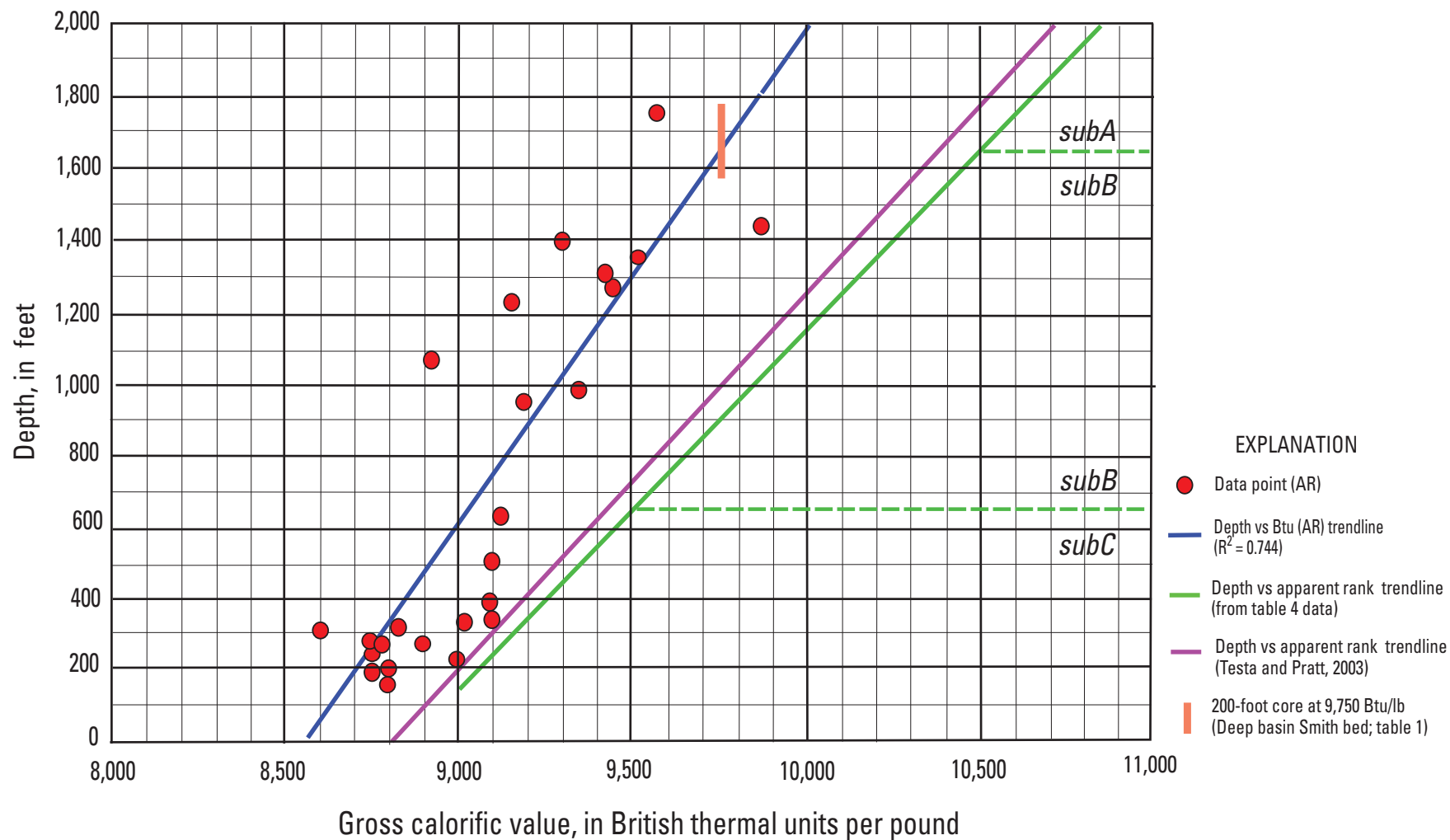| Core hole	Mean depth, in feet	Coal zone	Coal bed name as used by gas operators	Number of samples	Moisture Total (%)	Moisture Equilibrium (%)	Ash yield (%)	As-received calorific value (Btu/lb)	Dry ash yield (Btu/lb)	Dry colorific value	Dry, ash free (DAF) calorific value (Btu/lb)
10	167.0	Wyodak-Anderson	Upper Wyodak	2	26.46	27.45	9.18	8,790	12.49	11,953	13,162
10	209.2	Wyodak-Anderson	Middle/Lower Wyodak	27	27.53	26.78	4.59	8,750	6.33	12,074	12,655
13	212.0	Wyodak-Anderson	Upper Wyodak	8	27.25	----	8.88	8,790	12.21	12,082	13,260
20	248.9	Wyodak-Anderson	Middle/Lower Wyodak	34	27.81	24.77	4.50	8,990	6.23	12,453	13,040
13	252.4	Wyodak-Anderson	Middle/Lower Wyodak	27	28.86	----	4.56	8,750	6.41	12,300	12,887
14	289.0	Wyodak-Anderson	Middle/Lower Wyodak	30	28.88	25.18	3.46	8,890	4.87	12,500	12,948
15	293.1	Wyodak-Anderson	Middle/Lower Wyodak	32	27.93	25.61	3.69	8,740	5.12	12,127	12,592
17	293.1	Wyodak-Anderson	Middle/Lower Wyodak	39	26.54	25.49	3.82	8,770	5.20	11,938	12,413
16	319.4	Wyodak-Anderson	Middle/Lower Wyodak	28	27.13	26.13	4.22	8,600	5.79	11,802	12,322
28	329.3	Wyodak-Anderson	Anderson	8	27.46	27.23	4.22	8,820	5.82	12,159	12,695
34	345.0	Wyodak-Anderson	Anderson	17	24.98	25.35	4.68	9,010	6.24	12,010	12,600
18	360.2	Wyodak-Anderson	Middle/Lower Wyodak	40	25.56	----	3.75	9,090	5.04	12,211	12,687
8	385.0	Wyodak-Anderson	Smith	15	26.13	----	5.87	9,080	7.95	12,292	13,058
34	519.5	Wyodak-Anderson	Canyon	13	26.31	24.26	3.71	9,090	5.03	12,335	12,811
30	640.0	Wyodak-Anderson	Canyon	7	25.31	25.53	3.74	9,120	5.01	12,210	12,685
33	960.2	Wyodak-Anderson	Big George	10	24.77	23.83	4.22	9,180	5.61	12,203	12,740
8	990.0	Wyodak-Anderson	Canyon	4	25.82	----	4.19	9,340	5.65	12,591	13,142
5	1,076.0	Wyodak-Anderson	Big George	13	26.42	----	3.95	8,920	5.37	12,123	12,621
35	1,230.9	Wyodak-Anderson	Big George	20	25.55	24.77	3.65	9,150	4.90	12,290	12,756
5	1,276.5	Wyodak-Anderson	Wyodak	24	24.61	----	4.50	9,440	5.97	12,522	13,112
19	1,308.0	Wyodak-Anderson	Big George	6	23.49	23.69	3.36	9,420	4.39	12,312	12,740
11	1,366.4	Wyodak-Anderson	Big George	12	24.33	23.48	4.51	9,510	5.96	12,568	13,161
12	1,401.0	Wyodak-Anderson	Big George	32	21.90	19.89	4.58	9,300	5.86	11,908	12,479
31	1,440.3	Wyodak-Anderson	Big George	32	17.94	18.15	5.97	9,870	7.28	12,028	12,791
11	1,769.0	Wyodak-Anderson	Werner	13	24.60	22.81	2.69	9,570	3.57	12,692	13,043
Average					**25.74**	24.47	**4.58**	**9,079**	**6.17**	**12,227**	**12,816**
Maximum value (MAX)					**28.88**	27.45	**9.18**	**9,870**	**12.49**	**12,692**	**13,260**
Minimum value (MIN)					**17.94**	18.15	**2.69**	**8,600**	**3.57**	**11,802**	**12,322**
MAX-MIN range					**10.94**	9.30	**6.49**	**1,270**	**8.92**	**890**	**938**

Figure 6. Estimated variability of as-received (AR) and moist, mineral-matter-free (m,mmf) gross calorific values versus depth from table 4 for the Wyodak coal beds in the Powder River Basin, Wyoming. The m,mmf gross calorific values calculated from the table 4 data are used to determine apparent rank, and the ranges are subbituminous C (subC), less than 9,500 Btu/lb$_{m,mmf}$; subbituminous B (subB), 9,500–10,500 Btu/lb$_{m,mmf}$; and subbituminous A (subA), greater than 10,500 Btu/lb$_{m,mmf}$.

Table 5.   Available as-received coal quality data from the Wasatch Formation in the Lake De Smet area and other Watsatch coal beds. Average values are shown in bold type.

Area and coal bed name	No. of analyses	Coal bed interval		Total coal bed interval cored	Total feet shale, pyrite excluded	Net total coal feet analyzed[6]	Percent of excluded shale to total recovered core	Percent of core interval analyzed	Moisture (%)	Sulfur (%)	Ash (%)	Calorific value (Btu/lb)	Pounds of SO₂ per million Btu	Calorific value (Btu/lb$_{m.mmf}$)[4]	Apparent rank[5]
		From	To												
						Lake De Smet area									
Healy coal bed[1,2]	15								28.5	0.60	7.6	7,880	1.52	8,583	subC
USGS-1 core[1,3]	1	59.0	141.7	82.7	7.1	47.1	13.1	57.0	29.1	0.60	5.1	7,970	1.51	8,432	subC
USGS-2A core[1,3]		66.0	119.0	53.0	1.8	40.8	4.2	77.0	30.5	0.50	6.1	7,845	1.27	8,396	subC
USGS-3 core[1,3]		101.0	159.7	58.7	1.1	37.2	2.9	63.4	28.3	0.60	7.7	7,890	1.52	8,604	subC
USGS-6 core[1,3]		172.0	292.0	120.0	33.8	68.1	33.2	56.8	29.3	0.60	9.2	7,515	1.60	8,341	subC
Bureau of Reclamation core[1,3]		95.0	224.9	129.9	20.2	101.6	16.6	78.2	23.6	1.00	9.7	8,270	2.42	9,239	subC
Average of all 5 core holes[3]	5				**12.8**		**14.0**	**66.5**	**27.0**	**0.70**	**8.1**	**7,940**	**1.76**	**8,700**	subC
Estimated average of 5 core holes (at 30.5% moisture)	5								**30.5**	**0.67**	**7.7**	**7,559**	**1.76**	**8,243**	ligA
Healy bed (face channel mine sample)	1								30.7	0.40	5.1	7,900	1.01	8,359	subC
Bed 120 feet below Healy bed (face channel mine sample)	1								31.1	1.40	8.8	7,350	3.81	8,114	ligA
						Other Wasatch coal beds									
Felix coal bed[2]	42								28.0	0.89	7.8	8,050	2.21	8,789	subC
Murray/Ucross beds[2]	15								30.2	1.50	4.3	8,000	3.75	8,383	subC

[1]Partial bed sample.

[2]Keystone Coal Manual (2010).

[3]Mapel and others (1953). (Individual cores from Healy beds.)

[4]Moist, mineral-matter-free (m,mmf) basis.

[5]Subbituminous C (subC), subbituminous B (subB), lignite A (ligA).

[6]Total coal recovered minus shale partings deliberately excluded from analytical samples.

To derive a more realistic estimate of the coal quality for the Lake De Smet coal field, the weighted average of the five cores in table 5 was normalized to 30.5 percent moisture. The 30.5-percent moisture estimate was based largely on the moisture levels of the mine face channel samples and USGS-2A core (table 5). The moisture adjustment resulted in a decrease of more than 300 Btu/lb in the average calorific value to 7,559 Btu/lb and lowered the estimated apparent rank to the lignite A/subbituminous C boundary (table 5). Because the Wasatch Formation is younger than the underlying Fort Union Formation, the slightly lower apparent rank of the Wasatch coal beds relative to the Fort Union coal beds in the nearby Sussex coal field (fig. 1, table 1) is consistent with their relative burial depths.

Unlike the moisture issue, the representativeness of the data is much more difficult to evaluate because of a combination of incomplete core recovery for all core holes and the intentional exclusion of all high-ash intervals. The percentage of the coal bed recovered ranged from about 57 to 78 percent (table 5). This range of core loss is significant (Luppens and others, 1992) and certainly raises questions about the representativeness of the core samples. Frequently, higher-ash zones with interbedded coal and non-coal lamina sustain lower recovery rates during the coring process. The dissimilar lamina create more bedding-plane weaknesses, leading to more fractured core and greater potential for core loss. If this situation contributed to increased core loss, the recovered samples would be biased towards lower-ash contents. However, without corroborating data such as geophysical logs, it is impossible to evaluate the recovered cores from a representativeness perspective.

The most serious problem from a representativeness standpoint was the systematic removal of all high-ash zones and partings greater than 3/8 inch in thickness from all core samples (Mapel and others, 1953). U.S. Geological Survey guidelines in place at the time of sampling mandated that their samplers strictly follow the exclusionary procedure for partings and pyrite of certain thicknesses (Golightly and Simon, 1989). The elimination of the high-ash layers follows the practices in the ASTM D388 standard on the classification of coals by rank (ASTM International, 2008b). This standard specifies excluding mineral partings more than 1 centimeter (3/8 inch) for samples used for the determination of coal rank. The excluded intervals were not analyzed separately. By analyzing both the retained and the excluded materials as well as the coal quality for each, whole bed core could have been mathematically composited. Whole bed core analyses are a fundamental component for all coal resource assessments. Despite the exclusionary practice, the detailed documentation of the core sampling process (Mapel and others, 1953) makes it possible to at least estimate the magnitude of the effect on the reported average coal quality (table 5) if the excluded high ash and pyrite partings were reconstituted with the analyzed core samples. The total thickness of the excluded shale partings for the five cores ranged from 1.1 to 33.8 feet and averaged 12.8 feet (table 5).

Because the total percentage of excluded shale to total coal core analyzed for drill core USGS-1 was very close to the average of the five cores (table 5), USGS-1 was studied more closely to better understand impacts of this exclusionary sampling methodology. To begin, the laboratory descriptions of drill core USGS-1 were reviewed. The USGS-1 core hole spanned a total of 18 black shale partings totaling 7.1 feet, which were removed and discarded prior to analyzing the core samples. The thickness of individual partings ranged from 1/2 inch to 16 3/4 inches. Figure 7 illustrates the distribution and magnitude of the excluded partings, as well as the intervals of lost core. As indicated by this figure, it seems unlikely that selective mining to exclude these parting would be practical given the range in parting thicknesses and their interbedded relationship with the coal layers throughout the entire bed; therefore, from the standpoint of a coal resource assessment, a predicted quality for the whole coal bed is needed.

The first step in arriving at the composited quality is estimating ash and calorific values for the excluded shale fraction. Based on the analyses of numerous coal bed roof and floor samples from Texas, Louisiana, Mississippi, and Wyoming (J.A. Luppens, unpub. data, 2010), the as-received ash and calorific values chosen were 65 percent and 1,500 Btu/lb, respectively. When compositing analyses, it is also important to consider the method by which the proportional amounts of each sample are calculated. Often, one can make the mistake of simply using a volumetric approach (dividing the length of each sample by the total length of the interval to be composited). If the densities of each interval are similar, the volumetric method is appropriate; however, in cases where there are significant density differences (such as partings composed of mineral matter versus coal), the volumetric method is flawed (Luppens and others, 1992). The density of mineral matter should be determined for each lithology and then used to calculate composite values. To evaluate compositing on a mass basis, the average densities of the coal and shale are estimated to be 1.3 grams per cubic centimeter (g/cm^3) and 1.9 g/cm^3.

Table 6 illustrates the differences between results from volume (thickness) weighting versus density weighting to calculate coal quality averages for the USGS-1 core hole interval samples. The volumetric method overestimates the calorific value of the recovered core by nearly 300 Btu/lb and underestimates the ash by 2.7 percent. Most important are the significant differences between the estimated quality from the composited results (table 6) and the original reported values in table 5 for the USGS-1 core hole from Mapel and others (1953). The combined effects of adjusting the moisture level to a more realistic value of 30.5 percent and estimating the impact of including the discarded shale partings was an increase in ash from 5.1 to over 15 percent and a decrease in the calorific value from 7,970 to about 6,700 Btu/lb.

With a significant volume of unrecovered core (fig. 7) for USGS-1 (28.5 feet, or 34.4 percent of the total interval cored), the issue of representativeness cannot be fully resolved (table 6). A compositing case that assumed that the entire unrecovered core was coal is presented in table 6 as a
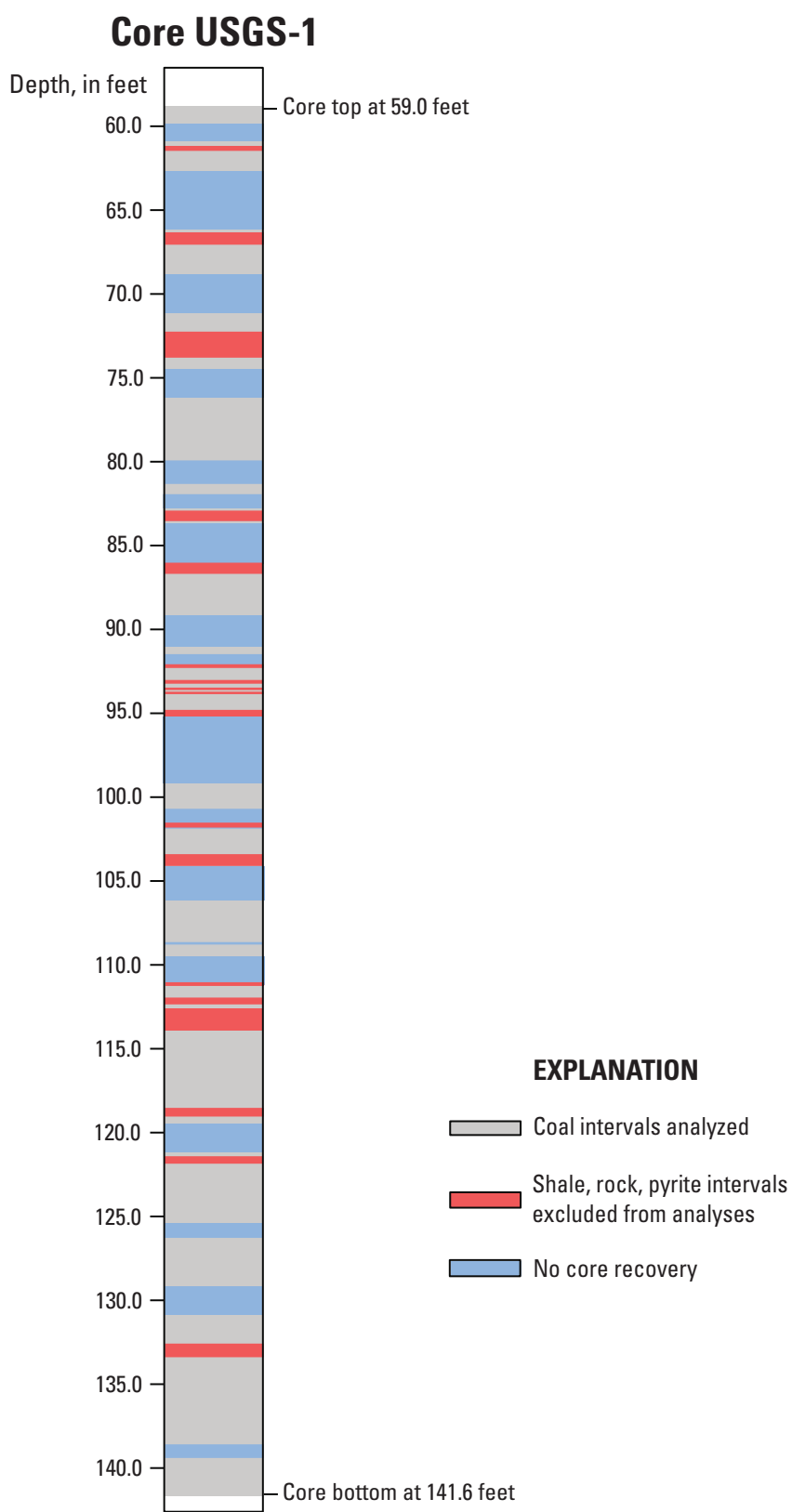
Figure 7.   Core log for core hole USGS-1 in the Lake De Smet coal field, Wyoming, illustrating core intervals analyzed, shale intervals excluded from the analyses, and lost-recovery intervals (from Mapel and others, 1953).

Table 6.   Estimated impacts of compositing the originally excluded shale, pyrite, and other high-ash parting material with the coal analyses for the USGS-1 core hole (Mapel and others, 1953) from the Lake De Smet coal field, Wyoming. Because these coal quality parameters are reported on a weight basis, mass weighting is the more appropriate method of mathematically compositing samples (Luppens and others, 1992).

Lithologies	Total core thickness (ft)	Analytical parameters		Volumetric weighting			Mass weighting				
		Ash (%)[a]	Calorific value[a] (Btu/lb)	Volume	Ash % × vol %	Calorific value × vol % (Btu/lb)	Density (g/cm³)[b]	Thickness × density	Mass	Ash % × mass %	Calorific value × mass % (Btu/lb)
Shale excluded	7.1	65.0	1,500	13.1%	8.5	196	1.9	13.5	17.7%	11.5	266
Total coal analyzed	47.1	5.0	7,813	86.9%	4.3	6,790	1.3	62.6	82.3%	4.1	6,429
Total	54.2			100.0%	**12.9**	**6,986**		76.1	100.0%	**15.6**	**6,694**

[a]Ash and calorific values are the averages for USGS-1 core adjusted to 30.5 percent moisture and estimated values for the excluded shale.

[b]Density values are estimated.

best-case scenario in terms of deriving a whole coal bed esti-mate. However, this best-case estimate still more than doubles the average ash content from the original reported value. More than likely, the actual quality of the whole coal bed interval is somewhere between the volumetric and mass-weighted esti-mates in table 6. Additionally, the effects on the average sulfur content of the composited estimates were impossible to assess because of a lack of data; but intuitively, the sulfur content for the whole bed should be higher than reported given the delib-erate exclusion of the black shale and pyrite-rich partings.

The thorough review of the original report for the Lake De Smet coal field resulted in a projected average coal quality that was significantly lower than the published data. With estimated values of 12 to nearly 16 percent ash, calorific values of about 6,700 to 7,000 Btu/lb, and sulfur contents perhaps as high as 1.0 percent or higher, the coal quality of this coal field is not competitive with any other coal currently being produced in the PRB. Despite the thickness of the coal bed, no significant, large-scale mining has occurred to date. It is suspected that the relatively inferior coal quality might be a contributing factor to the lack of development in the area.

Conclusions

From the previous discussion, it is demonstrated why it is always preferable to research and evaluate the circumstances regarding the sampling and analytical results from the origi-nal data sources when evaluating coal quality information, especially if only limited data are available. Cited data often omit important information, such as moisture integrity and the information needed to evaluate the issue of representativeness. Furthermore, only selected data may be quoted or data may be misquoted, as in the case of Glass and Jones (1992).

Using the available published data at face value would have significantly overestimated the coal quality for all the coal fields from both the Fort Union and the Wasatch

Formations in the SWPRB assessment area. However, if suf-ficient sampling information is provided, it may be possible to make adjustments to reported data to derive more reasonable estimates of coal quality.

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