RELATIONSHIPS BETWEEN COAL QUALITY PARAMETERS IN BRITISH COLUMBIA COALS

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KEYWORDS: Coal quality, British Columbia, vitrinite reflectance, volatile matter, hydrogen/carbon ratio, rheology, calorific value, ash content.

INTRODUCTION

One of the main objectives of the Coal Quality Project in the British Columbia Geological Survey Branch is to demonstrate how British Columbia coals fit into accepted coal classification systems, and to derive the implied technical utilization potential of our coals. The quality of a given coal can, for many purposes, be considered to be made up of three components, its grade, rank and type (Snyman, 1989), and most classification systems utilize one or more of these components. One proposed system, the so-called "Alpern" classification (Alpern *et al.*, 1989), uses indicators of all three components.

Grade refers to the amount, type and association of mineral matter in coal. Ash content and washability characteristics are two familiar coal properties which are largely dependent on grade. Washability of British Columbia coals is discussed by Holuszko (1992, this volume). Rank refers to the position of a given coal within the metamorphic gradation from peat to meta-anthracite. Many coal properties vary with rank (vitrinite reflectance, ultimate carbon and volatile matter are three examples), but vitrinite reflectance is considered to be useable over a wider range of ranks than any of the others (Bustin *et al.*, 1985). Vitrinite reflectance increases with increasing rank. Type refers to the organic constituent make-up of a coal, and a maceral analysis is the best and most direct way of determining coal type.

As a preliminary step in this endeavour, a series of x-y graphs (scatterplots) demonstrating correlations between

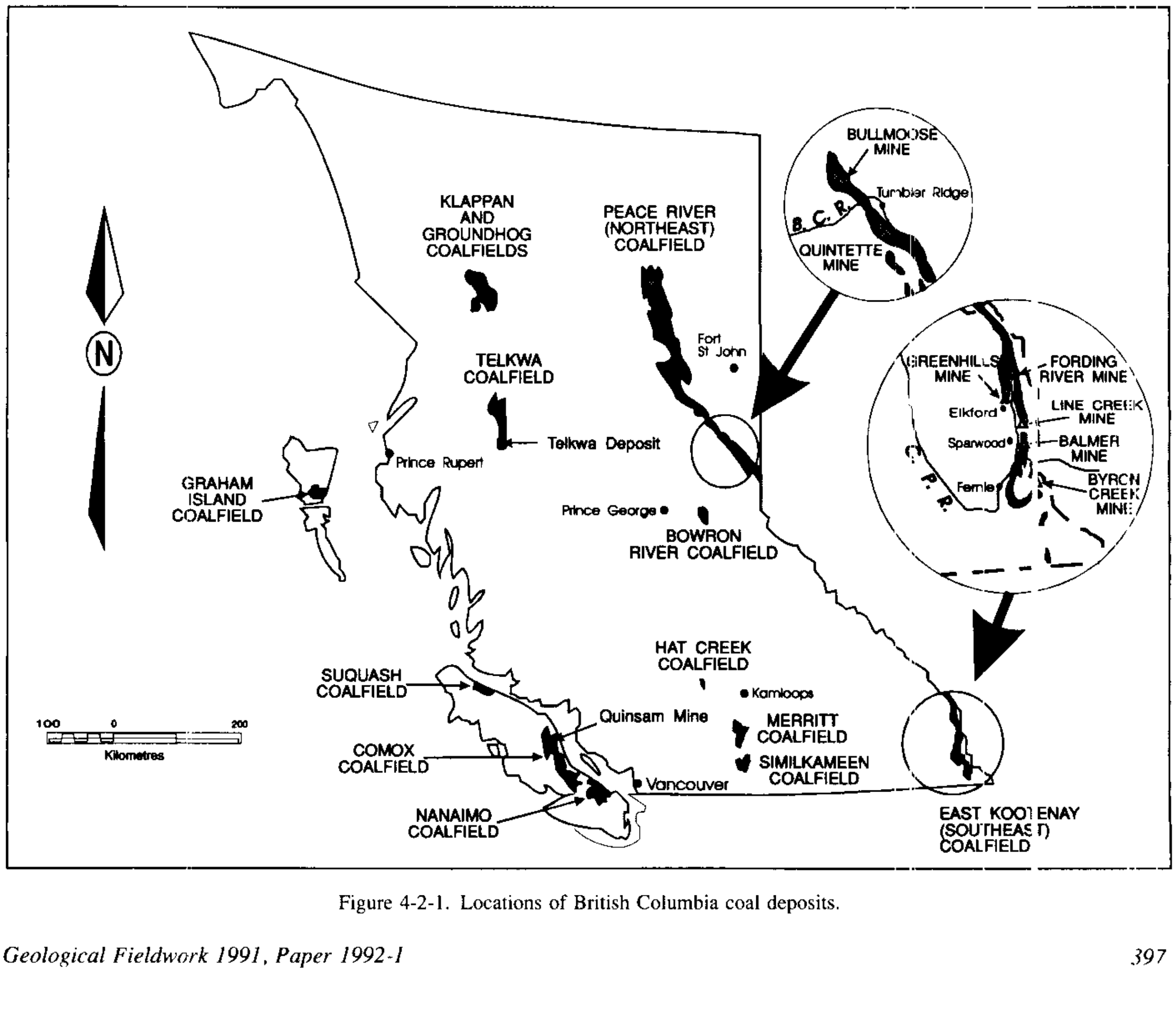

Figure 4-2-1. Locations of British Columbia coal deposits.

coal quality parameters has been generated, together with corresponding regression lines and correlation coefficients. The emphasis is on vitrinite reflectance. Establishment of these relationships will ultimately lead to identification of the coal quality parameters and classification systems which are most appropriate to our coals.

There are three sources of the data presented here: exploration assessment reports, the British Columbia Coal Quality Catalog (2nd edition; Grieve, in press) and analyses of raw run-of-mine coal samples collected at all operating coal mines in the province in 1990. The sources of individual data points are not identified, ensuring confidentiality.

GEOLOGICAL SETTING

British Columbia coal deposits range from Late Jurassic to Tertiary in age, and occur in three of the six major tectonic belts. Coalfields and deposits considered in this article include the Peace River or northeast coalfield, the East Kootenay or southeast coalfields, the Telkwa deposit, the Klappan coalfield, the Hat Creek coalfield and the Comox coalfield (Figure 4-2-1). They represent the whole range of ages and tectonic settings of British Columbia coals.

Coal in the East Kootenay coalfields belongs to the Mist Mountain Formation of the Jurassic-Cretaceous Kootenay Group, and occurs in the Front Ranges of the Rocky Mountains. Gates and Gething Formation coals from the Peace River coalfield are Early Cretaceous in age, and occur in the Foothills of the Rocky Mountains. The Intermontane tectonic belt contains the Klappan coalfield and Telkwa deposit of northwestern British Columbia, and the Hat Creek coalfield of south-central British Columbia. The Klappan coalfield is hosted by the Jurassic-Cretaceous Bowser Lake Group, and the Telkwa deposit by the Early Cretaceous Skeena Group. Hat Creek coal is Eocene in age, and contained in the Kamloops Group. Lastly, the Insular tectonic belt contains the Quinsam mine in the Comox coalfield, where coals are Late Cretaceous in age and belong to the Nanaimo Group.

SAMPLING AND ANALYSIS

A total of 36 raw run-of-mine coal samples was collected at all eight of the province's coal mines in the summer of 1990 (*see* Table 4-2-1 for a list of samples, and Figure 4-2-1 for mine locations). The samples, which were approximately 30 kilograms in weight, were collected from piles of excavated coal in the pits, and each sample represents one seam. In the case of the underground coal sample from Quinsam mine, the pile of coal on the surface at the end of the conveyor was sampled.

Samples were processed and analyzed for chemical and rheological properties according to ASTM standard conditions and procedures. Representative splits of −20-mesh coal were supplied to the author for petrographic analysis, using vitrinite reflectance techniques developed by Kilby (1988).

TABLE 4-2-1
LIST OF RAW RUN-OF-MINE COAL SAMPLES COLLECTED AT ACTIVE MINES IN 1990

Sample	Property	Pit	Seam
90-01	Balmer	Camp 8 Ext.	8UX
90-02	Balmer	A	A
90-03	Balmer	Baldy 8UA	7RC
90-04	Balmer	Adit 29E	10 (Balmer)
90-05	Balmer	Adit 29E	8UC
90-06	Line Creek	Main	10A
90-07	Line Creek	Main	10B
90-08	Line Creek	Main	9
90-09	Line Creek	North Line	7
90-10	Line Creek	North Line	8
90-11	Greenhills	Cougar 2	20
90-12	Greenhills	Cougar 2	16 (upper 1/2)
90-13	Greenhills	Cougar 2	16 (lower 1/2)
90-14	Greenhills	Cougar 3	17
90-15	Greenhills	Bighorn	10
90-16	Greenhills	Falcon	1
90-17	Byron Creek	14	1 (Mammoth)
90-18	Byron Creek	12	1 (Mammoth)
90-19	Byron Creek	14	1 (Mammoth)
90-20	Fording	Taylor	4
90-21	Fording	Taylor	5
90-22	Fording	Taylor	11 upper
90-23	Fording	Eagle	15
90-24	Fording	Eagle South	14-2
90-25	Fording	Eagle South	13
90-26	Fording	Brownie	9
90-27	Bullmoose		A1
90-28	Bullmoose		B
90-29	Bullmoose		C
90-30	Bullmoose		D
90-31	Bullmoose		E
90-32	Quintette	Deputy	J
90-33	Quintette	Mesa	E
90-34	Quintette	Wolverine	F
90-35	Quinsam	Underground	1
90-36	Quinsam	Surface	1

MAXIMUM VERSUS RANDOM REFLECTANCE

The set of 36 samples was subjected to determination of petrographic rank (vitrinite reflectance). As both mean maximum ($\bar{R}_{max}$) and mean random ($\bar{R}_m$) reflectance are routinely determined in our lab, it is possible to compare these parameters over the range of ranks of productive coal seams in the province. Figure 4-2-2 shows their relationship, and indicates that there is almost perfect correlation between them ($r=0.997$). The regression equation is:

$$\bar{R}_{max} = -0.0632 + 1.107\ \bar{R}_m.$$

There is some suggestion that the slope of the regression line is diminishing at the high rank end.

Given the high coefficient, this equation can serve as a reliable conversion formula for British Columbia high-volatile A and medium-volatile bituminous coals. Its application to petrographic rank boundaries is provided under "Discussion and Summary."

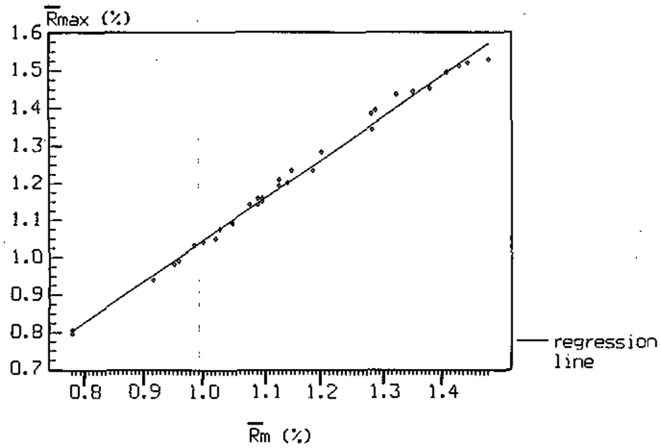

Figure 4-2-2. $\bar{R}_{max}$ versus $\bar{R}_m$ for raw run-of-mine samples collected at active coal mines in 1990. The regression equation and correlation coefficient are given in the text.

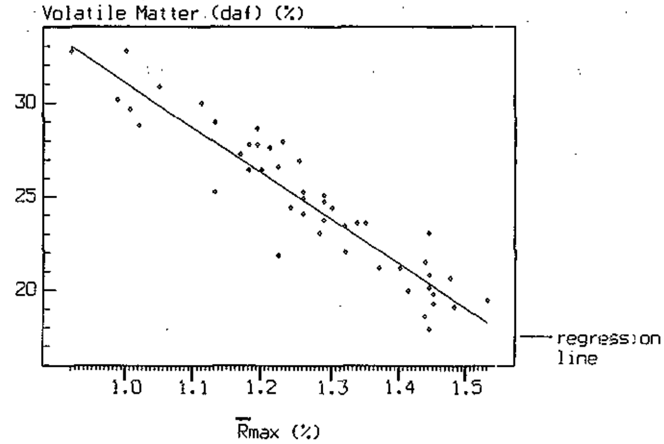

Figure 4-2-5. $\bar{R}_{max}$ versus volatile matter for clean Mist Mountain Formation coals in the East Kootenay coalfields. All data are from assessment reports. *See* Table 4-2-2 for correlation coefficient.

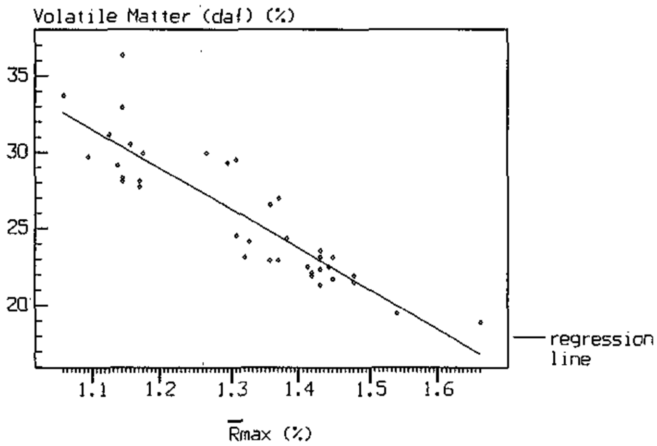

Figure 4-2-3. $\bar{R}_{max}$ versus volatile matter (daf) for clean Gething Formation coals in the Peace River coalfield. All data are from assessment reports. *See* Table 4-2-2 for correlation coefficient.

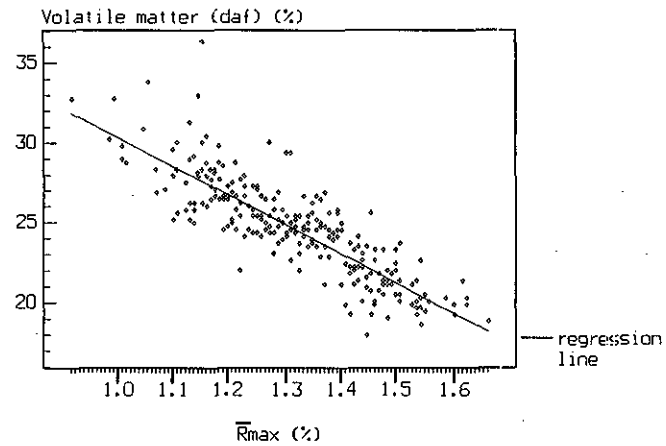

Figure 4-2-6. Combination of all data in Figures 4-2-3 to 5, representing clean coal in the Peace River and East Kootenay coalfields. *See* Table 4-2-2 for correlation coefficient.

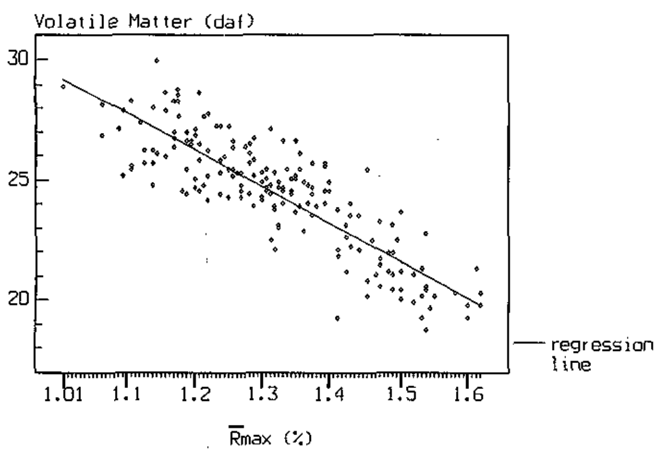

Figure 4-2-4. $\bar{R}_{max}$ versus volatile matter (daf) for clean Gates Formation coals in the Peace River coalfield. All data are from assessment reports. *See* Table 4-2-2 for correlation coefficient.

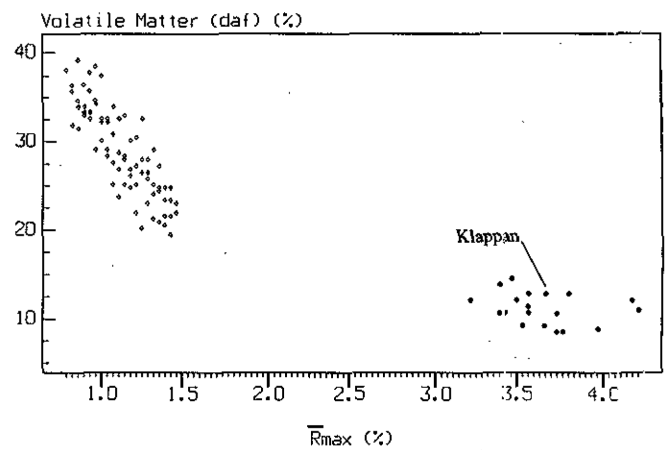

Figure 4-2-7. $\bar{R}_{max}$ versus volatile matter (daf) for raw coals from the Peace River, East Kootenay and Klappan coalfields. All data are from assessment reports.

VITRINITE REFLECTANCE VERSUS VOLATILE MATTER

Volatile matter on a dry, mineral matter free (dmmf) basis is the parameter used in the ASTM classification of coal by rank for coals of high-volatile A bituminous rank and higher (ASTM D388:1984). During coalification, as rank increases, volatile matter decreases, and thus there is an inverse relationship between vitrinite reflectance and volatile matter. A series of five graphs has been generated to explore this relationship in British Columbia coals (Figures 4-2-3 to 7). Correlation results for the Gething, Gates and Mist Mountain formations, assuming the relationships are linear over the observed rank range, are summarized in Table 4-2-2. Volatile matter has been converted to a dry, ash-free (daf) basis rather than the dmmf basis specified by the ASTM rank classification. This is because reliable formulae for converting ash to mineral matter contents have not been developed for British Columbia coals. All the data in Figures 4-2-3 to 7 have been taken from assessment reports. Most represent analyses of drill-core samples; no rotary-drill samples are included. With very few exceptions the drill-core recovery for all samples included is greater than 65 per cent. Both raw and clean coal data were collected, but as much as possible, clean coal data are presented here, as the correlation coefficients are consistently higher in clean coal.

Figure 4-2-3 shows the $\bar{R}_{max}$ versus volatile matter (daf) relationship for clean Gething Formation coals (Peace River coalfield). The correlation coefficient (r) is -0.89, and the degree of scatter is attributable to a number of factors. To begin with, volatile matter is controlled not only by rank, but also by type of coal. That is, at a given rank level, two coals of differing maceral compositions will have different volatile contents, with the more reactive-rich coal having the higher volatiles. Another factor is the varying amount and nature of mineral matter, as a portion of the volatile matter in any coal is derived from the inorganic fraction. Thirdly, these reflectance readings were generated by three or more different labs, which introduces potential systematic analytical errors of up to ± 0.1 per cent $\bar{R}_{max}$ (Bustin *et al.*, 1985).

Figure 4-2-4 shows the $\bar{R}_{max}$ versus volatile matter (daf) relationship for clean Gates Formation coals (Peace River). The correlation coefficient is -0.85 and the comments concerning the origin of data scatter noted for Figure 4-2-3 apply here also.

TABLE 4-2-2
CORRELATION COEFFICIENTS (r)
VITRINITE REFLECTANCE VS. VOLATILE MATTER (DAF) IN CLEAN COALS OF THE PEACE RIVER AND EAST KOOTENAY COALFIELDS*

Coalfield	r	Critical r (99%)
Peace River (Gething)	−0.89	0.41
Peace River (Gates)	−0.85	0.19
East Kootenay	−0.93	0.36
Combined data	−0.84	0.16

* All data are from assessment reports

Figure 4-2-5 shows the $\bar{R}_{max}$ versus volatile matter (daf) relationship for clean East Kootenay coals. The correlation coefficient is -0.93 and the origins of scatter are also the same as for the data in Figure 4-2-3. If the clean coal data from the Peace River and East Kootenay coalfields are combined (Figure 4-2-6), the correlation coefficient is -0.84.

Figure 4-2-7 shows the $\bar{R}_{max}$ versus volatile matter (daf) relationship for raw coals from the Klappan coalfield, together with raw coals from the Peace River and East Kootenay coalfields for comparison. The Klappan coals are characterized by reflectance values above 3.0 per cent and volatile matter contents under 14 per cent. At this high rank level (anthracitic) reflectance is clearly not a good predictor of volatile matter.

VITRINITE REFLECTANCE VERSUS CARBON AND HYDROGEN

Correlations between $\bar{R}_{max}$ and chemical analytical results obtained on the 36 samples (Table 4-2-1) are shown in Table 4-2-3. Carbon and hydrogen contents in coal are determined, together with oxygen, nitrogen and sulphur, during an ultimate analysis. Carbon content, when expressed on a daf or dmmf basis, increases with rank, while hydrogen content decreases. Both can be used as rank indicators, and they are the two basic components of the well-known Seyler coal classification system (Carpenter,

TABLE 4-2-3
CORRELATION COEFFICIENTS (r)*
VITRINITE REFLECTANCE VS. CHEMICAL PARAMETERS IN RAW RUN-OF-MINE SAMPLES COLLECTED FROM ACTIVE COAL MINES IN 1990

Volatile Matter (daf)	−0.84
C (daf)	0.59
H (daf)	−0.68
H/C	−0.75
O (daf)	−0.56
O/C	−0.56

* Critical value of r is 0.41 at the 99 per cent confidence level.

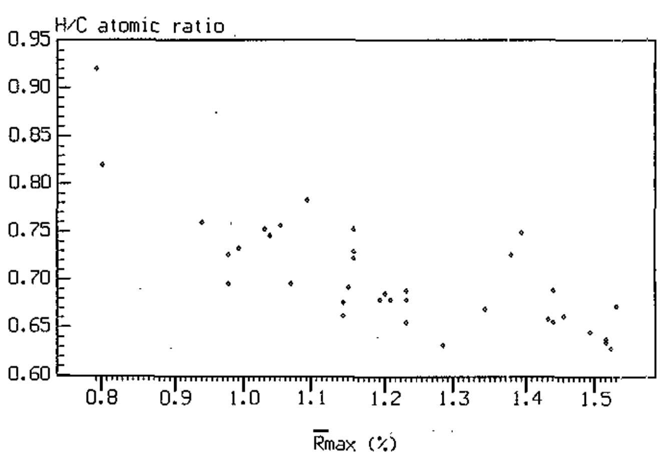

Figure 4-2-8. $\bar{R}_{max}$ versus the ratio H/C for raw run-of-mine samples collected at active coal mines in 1990. *See* Table 4-2-3 for correlation coefficient.

1988). Table 4-2-3 shows a significant positive correlation between carbon (daf) and $\bar{R}_{max}$ (r=0.59), and a significant negative correlation between hydrogen (daf) and $\bar{R}_{max}$ (r=−0.68). When expressed as the ratio hydrogen/carbon the negative correlation with $\bar{R}_{max}$ becomes stronger (r=−0.75). This relationship is shown in Figure 4-2-8. This suggests that the hydrogen/carbon ratio is probably a better rank indicator than either element by itself for coals currently being produced in British Columbia, although it is still not as good an indicator as volatile matter (daf; r=−0.84 in Table 4-2-3). The last relationship was considered in some depth in the previous section, based on larger data populations.

VITRINITE REFLECTANCE VERSUS RHEOLOGICAL PROPERTIES

The set of 36 samples was tested for fluidity and dilatation properties. Correlation coefficients between $\bar{R}_{max}$ and Geiseler fluidity parameters are shown in Table 4-2-4 and between $\bar{R}_{max}$ and dilatation parameters are shown in Table 4-2-5. In the former case one sample did not soften, and so the matrix is based on 35 samples. In the latter case, all 36 samples contracted, but only 12 had a positive net dilatation. Therefore, the correlations involving maximum dilatation and temperature of maximum dilatation are based on only 12 sets of results.

The temperatures recorded during the fluidity test, namely the temperatures of initial softening, maximum fluidity and resolidification, are positively correlated to a significant degree with $\bar{R}_{max}$ (Table 4-2-4). Figures 4-2-9 and 4-2-10 show the relationship between $\bar{R}_{max}$ and temperatures of initial softening (r=0.64) and maximum fluidity (r=0.77), respectively. In other words, critical temperatures of fluidity increase with rank of coal, through the rank range represented. The fluid temperature range of these samples is not correlated to $\bar{R}_{max}$, and the actual value of the fluidity, in dial divisions per minute, is only marginally correlated, in a negative manner, with $\bar{R}_{max}$.

None of the parameters derived from the dilatation analysis show significant correlation with $\bar{R}_{max}$ (Table 4-2-5).

TABLE 4-2-4

CORRELATION COEFFICIENTS (r)*
VITRINITE REFLECTANCE VS. GEISELER FLUIDITY IN RAW RUN-OF-MINE SAMPLES COLLECTED FROM ACTIVE COAL MINES IN 1990

Initial softening temp.	0.64
Temp. of maximum fluidity	0.77
Temp. of resolidification	0.58
Fluid range	−0.35
Maximum fluidity	−0.46

* Critical value of r is 0.42 at the 99 per cent confidence level.

TABLE 4-2-5

CORRELATION COEFFICIENTS (r)*
VITRINITE REFLECTANCE VS. DILATATION IN RAW RUN-OF-MINE SAMPLES COLLECTED FROM ACTIVE COAL MINES IN 1990

Softening temp.	0.31
Maximum contraction	0.06
Temp. of maximum dilatation	−0.02
Maximum dilatation	0.15

* Critical values of r at the 99 per cent confidence level — softening temperature and maximum contraction: 0.41; maximum dilatation and temperature of maximum dilatation: 0.661.

CALORIFIC VALUE VERSUS ASH CONTENT

Calorific value on a moist, mineral matter free (mmmf) basis is the rank parameter used in the ASTM classification for low-rank coals (up to high-volatile A bituminous). It increases with increasing rank over the low-rank range. When not expressed on an ash-free or mineral matter free basis, however, calorific value can be a very good indicator of the grade of a coal deposit (Cameron, 1989). As the amount of inorganic material, expressed as ash or mineral matter, increases, the calorific value of a coal decreases. A

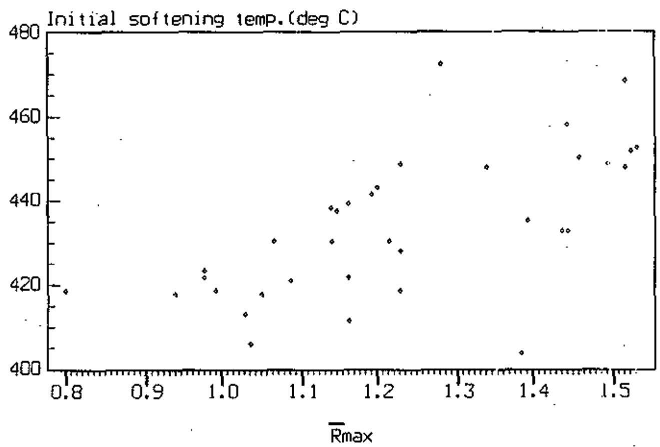

Figure 4-2-9. $\bar{R}_{max}$ versus initial softening temperature for raw run-of-mine samples collected at active coal mines in 1990. *See* Table 4-2-4 for correlation coefficient.

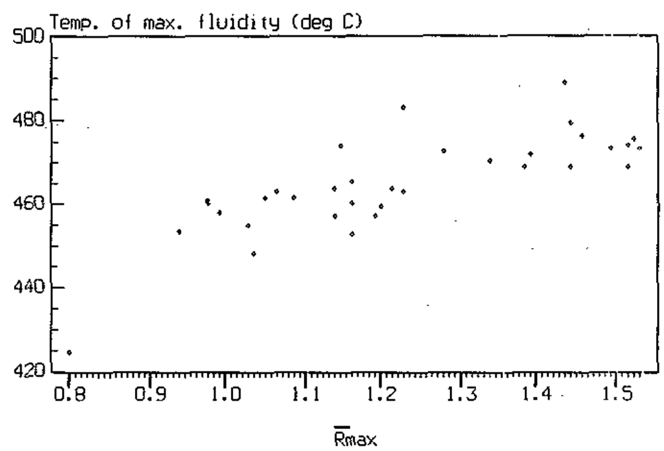

Figure 4-2-10. $\bar{R}_{max}$ versus temperature of maximum fluidity for raw run-of-mine samples collected at active coal mines in 1990. *See* Table 4-2-4 for correlation coefficient.

series of six graphs showing the relationship between calorific value and ash content has been generated for raw coals in five British Columbia coalfields (Figures 4-2-11 to 16). Results are summarized in Table 4-2-6. All the data are originally from assessment reports, but are not intended to be a comprehensive collection of the data available for each deposit. They mainly represent drill-core samples, with the exception of the East Kootenay data (Figure 4-2-13), which represent bulk and channel samples. The East Kootenay and Hat Creek data (Figure 4-2-14) are expressed on a dry basis, while the data for the other coalfields are expressed on an air-dried (ad) basis.

The results show very strong inverse relationships between ash content and calorific value for raw coals from all coalfields. Correlation coefficents are all between −0.9 and −1.0, with some being extremely close to the latter value (Table 4-2-6). The poorest correlation, which is for data from the Telkwa deposit (Figure 4-2-15), represents the smallest range in ash values. It is a safe and obvious assumption that coal grade is a major factor influencing calorific value of raw coals in British Columbia.

In order to compare the various coalfields, calorific values at an arbitrary 15 per cent raw-ash content have been predicted, based on the calorific value versus ash relationships shown in Figures 4-2-11 to 16. The predictions are presented for discussion purposes only and are not intended to be rigorous or realistic, because they do not include the statistical uncertainty of the predictions, and because product coals are obviously much higher in moisture than air-dried or dry coals. In the case of Hat Creek, moreover, the 15 per cent ash level is lower than in any potential unbeneficiated product.

The predicted values are as follows: Gething Formation, Peace River, 29.01 megajoules per kilogram (ad); Gates Formation, Peace River, 30.09 (ad); East Kootenay, 29.23 (dry); Hat Creek, 25.33 (dry); Telkwa, 28.59 (ad); Klappan, 29.09 (ad). Note that the East Kootenay value would be reduced by only 1 to 2 per cent if recalculated on an air-dried basis. These results indicate that the predicted cal-

TABLE 4-2-6
CORRELATION AND REGRESSION COEFFICIENTS CALORIFIC VALUE VS. ASH CONTENT, RAW BRITISH COLUMBIA COALS*
(MEGAJOULES/KILOGRAM)

Coalfield	r	Critical r (99%)	Intercept	Slope
Peace River (Gething) *ad basis*	−0.94	0.42	34.41	−0.36
Peace River (Gates) *ad basis*	−0.99	0.83	35.80	−0.38
East Kootenay *dry basis*	−0.99	0.68	34.58	−0.36
Hat Creek *dry basis*	− 0.999	0.80	30.97	−0.38
Telkwa *ad basis*	−0.92	0.71	34.18	−0.37
Klappan *ad basis*	−0.99	0.42	34.95	−0.39

* All data are from Grieve (in press)

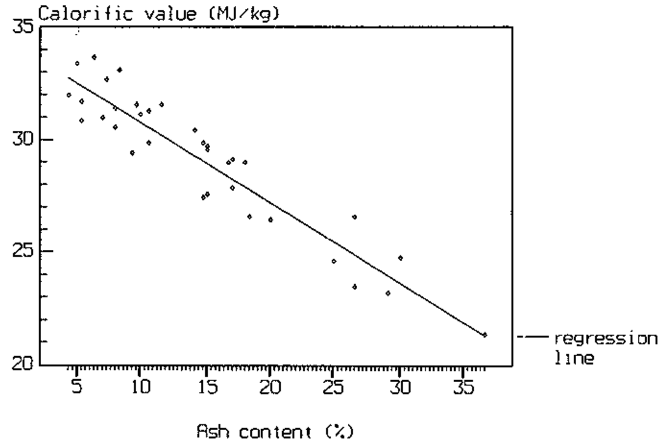

Figure 4-2-11. Calorific value (air-dried) versus ash content for raw coals from the Gething Formation in the Peace River coalfield. Data are taken from Grieve (in press). *See* Table 4-2-6 for results of linear regression analysis.

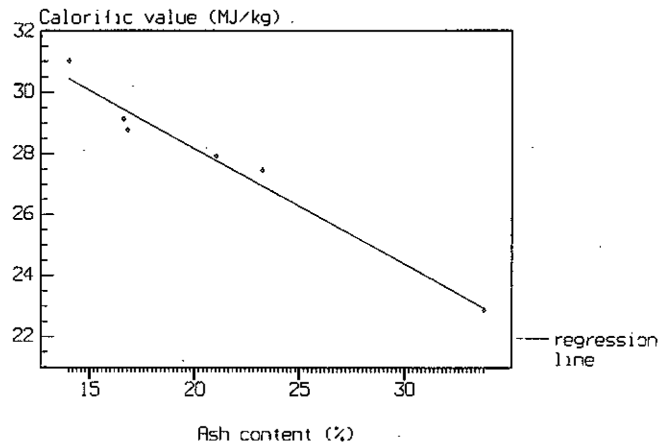

Figure 4-2-12. Calorific value (air-dried) versus ash content for raw coals from the Gates Formation in the Peace River coalfield. Data are taken from Grieve (in press). *See* Table 4-2-6 for results of linear regression analysis.

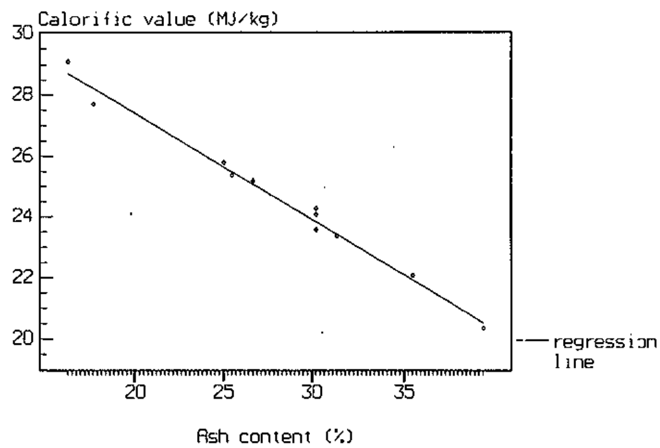

Figure 4-2-13. Calorific value (dry) versus ash content for raw coals from the Mist Mountain Formation in the East Kootenay coalfields. Data are taken from Grieve (in press). *See* Table 4-2-6 for results of linear regression analysis.

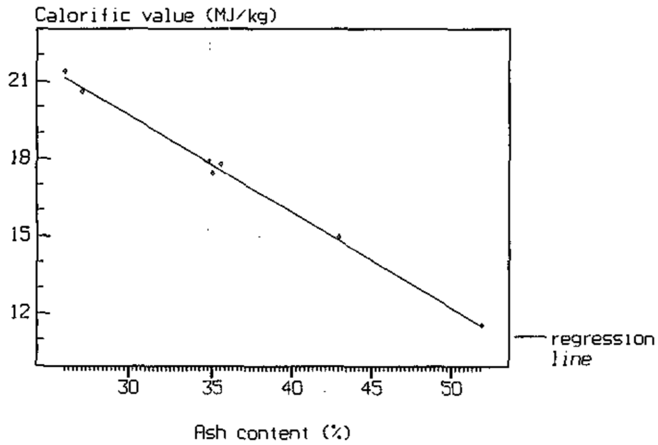

Figure 4-2-14. Calorific value (dry) versus ash content for raw coals from the Hat Creek coalfield. Data are taken from Grieve (in press). *See* Table 4-2-6 for results of linear *regression analysis.*

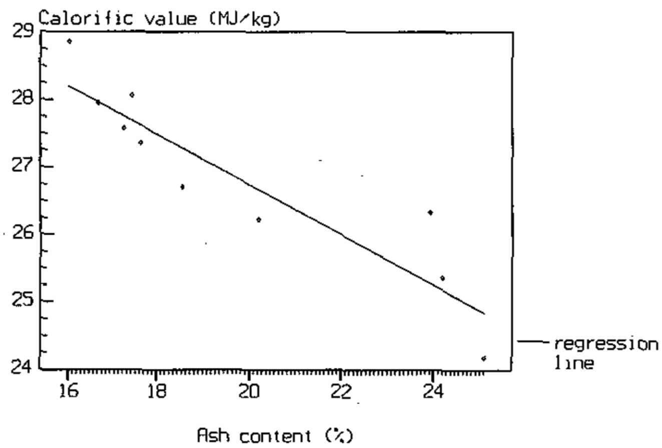

Figure 4-2-15. Calorific value (air-dried) versus ash content for raw coals from the Telkwa deposit. Data are taken from Grieve (in press). *See* Table 4-2-6 for results of linear *regression analysis.*

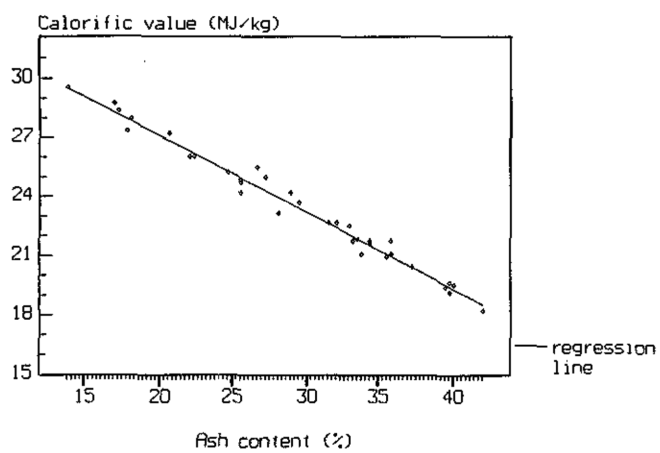

Figure 4-2-16. Calorific value (air-dried) versus ash content for raw coals from the Klappan coalfield. Data are taken *from Grieve (in press). See* Table 4-2-6 *for results of linear* regression analysis.

orific values of raw, air-dried coals from the Peace River, East Kootenay, Telkwa and Klappan coalfields, at the given ash level of 15 per cent, are all on the order of 29 to 30 megajoules per kilogram. The deposit with the lowest average rank of this group, Telkwa, has the lowest predicted calorific value, while the Gates Formation has the highest. This general similarity in predicted values does not imply that coals from these four regions will behave similarly in actual usage. *There are significant differences between* them in volatile matter, mineral matter composition and coal type; all these factors have a potentially large influence on coal behaviour during combustion.

DISCUSSION AND SUMMARY

Given that vitrinite reflectance is a widely used and applicable coal rank parameter, correlation results obtained in this study (Table 4-2-3) suggest that volatile matter content (daf), the hydrogen/carbon ratio, hydrogen content (daf) *and carbon content (daf), in order of decreasing effective*ness, are to some extent also rank indicators in the high-volatile A through medium-volatile bituminous range in British Columbia coals.

The correlations between $\bar{R}_{max}$ and volatile matter content (daf) in the Rocky Mountain coalfields are strongly negative (−0.84 to −0.93; Tables 4-2-2 and 3). Despite these high correlations the reflectance versus volatile matter (daf) relationships illustrated by Figures 4-2-3 to 5 display a considerable amount of scatter and can not be used to *predict the volatile matter content of specific reflectance* levels, except in a very approximate way. The sources of these uncertainties were summarized earlier. As an example of their influence, based on inspection of the actual data points shown in Figure 4-2-4, a clean Gates Formation coal with a reflectance of 1.3 per cent might have between 22 and 27 per cent volatile matter content (daf).

It is also inappropriate to use the graphs in Figures 4-2-3 to 6 to determine reflectance values corresponding to rank category boundaries. These should only be determined on *vitrinite concentrates or coals with uniformly high vitrinite* contents. A good evaluation of variations in fixed carbon (dmmf) with reflectance in Western Canadian coals was published recently by Cameron (1989). He recommends using 0.95 per cent $\bar{R}_m$ as the boundary between ASTM high-volatile A and medium-volatile bituminous coals, and 1.45 per cent for the ASTM medium-volatile/low-volatile bituminous boundary. Using the relationship between $\bar{R}_{max}$ and $\bar{R}_m$ established earlier in this paper, these values can be converted to 0.99 and 1.54 per cent $\bar{R}_{max}$. This is a slightly wider range for medium-volatile coals than I have used previously (1.1 to 1.5 per cent), but I consider Cameron's new boundaries to be valid and applicable.

Fluidity and dilatation tests have been shown to be inappropriate measures of the coking potential of Western Canadian coals (Price and Gransden, 1987). Nevertheless, the actual temperatures of fluid behaviour of an individual coal are very important parameters in coke production from coal blends. This is because there must be overlap between the fluid temperature ranges among the various coals in the blend. These *preliminary results show that critical fluidity* temperatures are partly dependent on rank of coal.

Strong inverse relationships, with correlation coefficients ranging from −0.92 to −0.999, between ash content and calorific value for raw British Columbia coals (Table 4-2-6) substantiate the well-known dilutant effect of ash on calorific value. Crude predictions based on these relationships suggest that at 15 per cent ash, raw coals of high-volatile A bituminous through anthracitic rank have calorific values (ad basis) that are on the order of 29 to 30 megajoules per kilogram.

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