



Mineral content of some Gething Formation coals

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Ministry of
Energy, Mines and
Low Carbon Innovation

GeoFile 2021-12

**Ministry of Energy, Mines and Low Carbon Innovation
Mines, Competitiveness, and Authorizations Division
British Columbia Geological Survey**

Recommendation citation: Riddell, J., Soriano, J., and Lane, G., 2021. Mineral content of some Gething Formation coals. British Columbia Ministry of Energy, Mines and Low Carbon Innovation, GeoFile 2021-12, 10p.

Front cover: Coals of the Gaylard member of the Gething Formation, Pit 7S (2020), Willow Creek mine. **Photo by David Thompson, courtesy of Conuma Resources Limited.**

Back cover: Coal core from the Gething Formation, Carbon Creek, northern British Columbia. **Photo by Paul Jago.**



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Abstract

With few exceptions, non-carbonaceous mineral matter poses problems for the coal industry. Mineral matter displaces the marketable combustible organic material, its residue after combustion can interfere with coal use, and some coals contain hazardous heavy metals such as arsenic, selenium, and cadmium. Thus, it is important to establish the identity and amount of the mineral phases in a coal deposit. Ten Gething Formation coal samples from the Willow Creek mine in the Peace River coalfield of northeastern British Columbia were analyzed with TESCAN Integrated Mineral Analyzer system to identify and quantify the mineralogy of the non-carbonaceous material. Quartz, kaolinite, feldspars and siderite are most abundant; micas, other carbonate minerals, crandallite group minerals, apatite, illite and smectite, and sulphide minerals were found in trace to small amounts in most samples. Iron is most commonly hosted in carbonate minerals. Calcium occurs mainly in feldspars, phosphate minerals, and micas. Magnesium is held mainly in siderite. The ash chemistry of Willow Creek mine samples is generally similar to that of Gething Formation samples regionally, except that on average the Willow Creek mine samples contain about 50% less iron, and about 80% more phosphate.

Keywords: Mineral matter in coal, Gething Formation, Bullhead Group, Peace River coalfield, TESCAN mineral analyzer, mineral deportment, coal ash chemistry

1. Introduction

All coals contain mineral matter. Mineral matter in coal can be phytogenic, detrital, or authigenic. Phytogenic minerals are components of plants such as silica from horsetails and grasses, detrital minerals are transported by water or wind, and authigenic minerals are diagenetic, forming during coalification by migrating subsurface fluids (Mackowsky, 1975; Diessel, 1992). With few exceptions, this mineral matter poses problems for the coal industry. It displaces the marketable combustible organic material and its residue after combustion can interfere with coal use. Furthermore, because some coals contain hazardous heavy metals such as arsenic, selenium, and cadmium, special care may be required for disposal. Although coal mine wash plants attempt to remove mineral matter, some always remains. Establishing the identity and amount of the mineral phases in a coal deposit is important for designing the best removal strategies, predicting their effects during coal use, and planning for environmental management (see Ward, 2016).

Upper Jurassic to Eocene coal coalfields in British Columbia align along the southeast-to-northwest tectonic and physiographic grain of the province (Fig. 1). Currently, all coal mining is in the Rocky Mountain belt of eastern British Columbia; in northeastern British Columbia the deposits constitute the Peace River coalfields. For most of these deposits, mineral data are sparse; herein we present analyses of ten coal

samples from the Gething Formation (Cretaceous) provided by Conuma Resources Limited from the Willow Creek mine in the Peace River coalfields (Fig. 2). Collecting and analyzing a larger suite of Gething Formation samples from other localities in the coalfields was prevented by the Covid-19 pandemic.

2. Geologic setting of the Gething Formation samples

The Gething Formation is one of three Cretaceous rock units that host economically important deposits of metallurgical coal in British Columbia (Fig. 3). These units record three major transgressive-regressive cycles (Stott, 1984) and include marine, prodeltaic, deltaic, nearshore, and alluvial deposits. The Mist Mountain Formation is part of the lowest sequence; it hosts metallurgical coal in the East Kootenay coalfields (Fig. 1). The Gething and Gates formations are parts of the second cycle which, in the Peace River coalfield, includes Lower Cretaceous marine and non-marine siliciclastic rocks of the Bullhead and Fort St. John groups (Figs. 2, 3). Part of the Bullhead Group, the Gething Formation lies above the Cadomin Formation, an important regional conglomeratic marker. The Gething Formation is Hauterivian to late lower Albian and includes conglomerate, coarse- to fine-grained sandstone, siltstone, mudstone, claystone and coal.

Of the several schemes developed to subdivide the Gething Formation (summarized by Legun, 1990), herein we use the



Fig. 1. Coalfields of British Columbia.

nomenclature defined by Gibson (1992), which is used at the currently operating mines (Fig. 4). The oldest unit is the Gaylard member, which is mainly non-marine and hosts coal. The Gaylard member is overlain by the Bullmoose member, which consists of marine shales. The Chamberlain member overlies the Bullmoose member. Like the Gaylard member, it is mainly non-marine and hosts coal. The ten samples analyzed in this study come from the Gaylard member, the only coal unit exposed at the Willow Creek mine (Cathyl-Huhn, 2019).

3. Methods

Ten washed coal samples (1.5 specific gravity float fraction) from the Gaylard member were selected and split. All samples had been washed to very low ash contents (3% and less). Half of each sample was sent to PMC Laboratory Ltd. in Maple Ridge, British Columbia for mineral analyses using the Tescan Integrated Mineral Analyzer method (TIMA) equipped on the Tescan Vega 3 Scanning Electron Microscope (SEM), using

the Line Scan mode to determine bulk modal mineralogy and speciation of the samples. In addition, the sections were submitted for Optical Imaging Analysis (OIA) to examine the carbonaceous materials that are not observable with backscattered electron microscopy in the SEM. ‘Crandallite group’ minerals identified by TIMA were further analysed using the Hitachi FlexSEM system equipped with the Aztec semi-quantitative energy dispersive X-ray spectra (SQEDX) to determine the elemental composition of this group. Optical examinations of the polished sections using a petrographic microscope were also conducted to verify observed mineral assemblages. The other half of the sample split was sent to Birtley Laboratories in Calgary, Alberta for ash chemistry analysis using the ASTM D3682 standard (ASTM International, 2021).

3.1. Integrated TIMA-OIA

Approximately 50g of each sample was homogenized

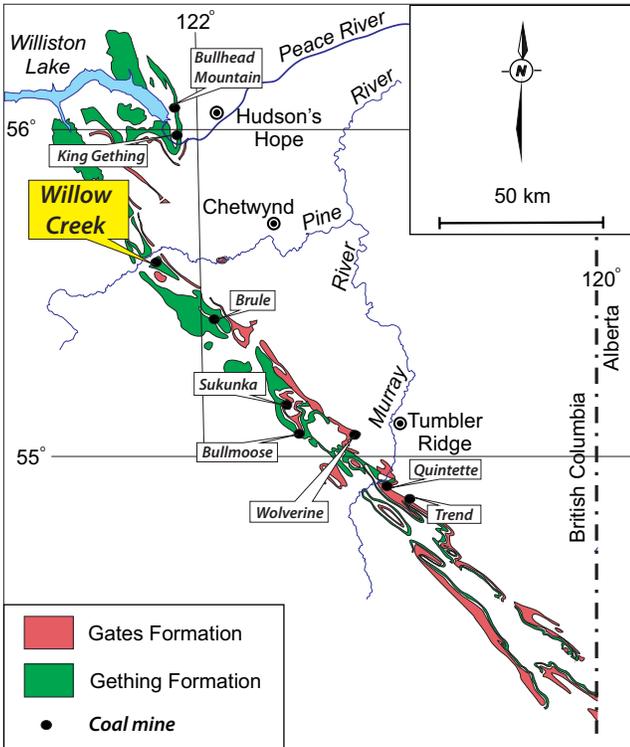


Fig. 2. Peace River coalfield map. Samples for this study are from the Willow Creek mine.

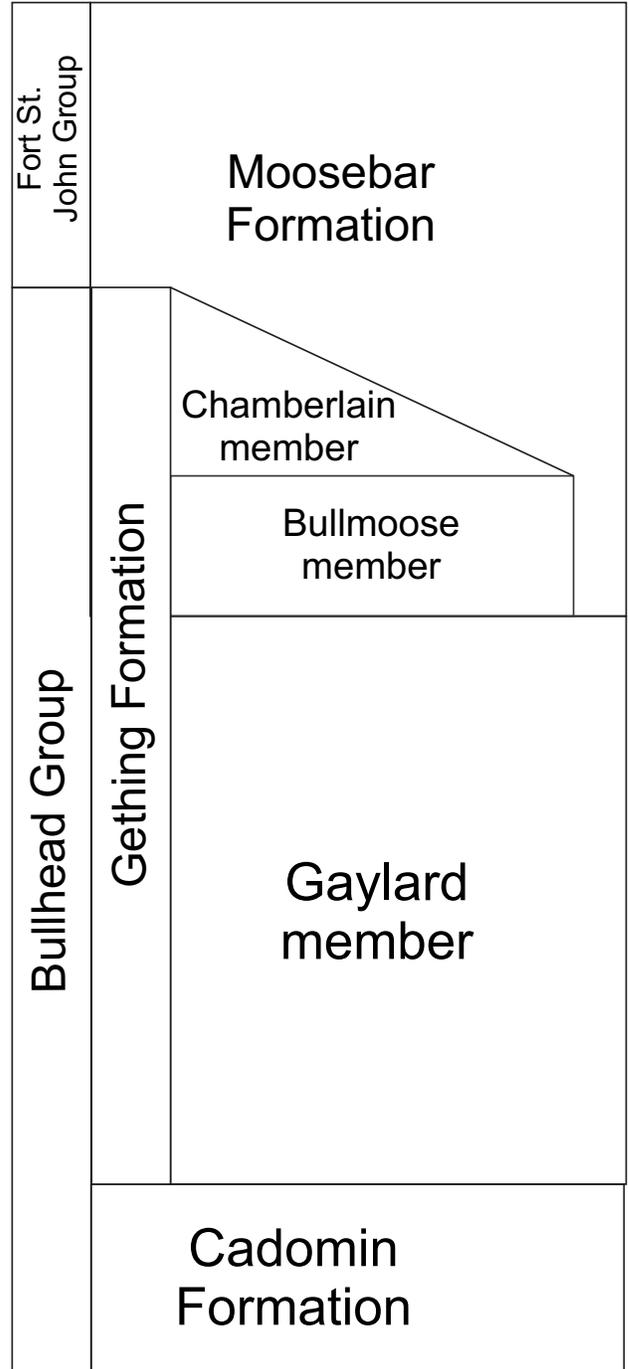


Fig 4. Internal stratigraphy of the Gething Formation, from Gibson (1992).

Era	Period & Epoch	BC Rocky Mountains					
		Peace River Coalfields	Elk River & Crowsnest Coalfields				
Cenozoic	Cretaceous	Upper	Fort St. John Group	Dunvegan			
				Boulder Creek			
				Gates			
				Gething			
				Cadomin			
				Lower	Blairmore Group	Alberta Group	
						Mill Creek	
						Beaver Mines	
						Gladstone	
				Mesozoic	Jurassic	Upper	Kootenay Group
Mist Mountain							
Morrissey							
Middle	Ferne Group	Ferne Group	Ferne Group				
					Lower	Ferne Group	Ferne Group

Fig. 3. Stratigraphic setting of economic metallurgical coal-bearing units in the Rocky Mountains of British Columbia. The Jurassic to Cretaceous (145 Ma) and Lower Cretaceous to Upper Cretaceous time boundaries are from Cohen et al. (2013).

and representative portions were riffled to prepare 40mm diameter polished block sections. The sections were scanned in the TESCAN Integrated Mineral Analyzer (TIMA) system, using the line scan mode at 20 kV to determine bulk modal mineralogy and speciation. TIMA collects backscattered electron (BSE) images and subsequently acquires energy dispersive X-ray spectra (EDX), to identify the mineral based on the EDX spectrum.

Due to the low BSE intensity of the carbonaceous grains

and their similarity with the low BSE intensity of the epoxy used in polished section preparation, the detection of carbonaceous material is unreliable for SEM-based data acquisition. Thus, Optical Imaging Analysis (OIA) was then used to improve recognition of these coal particles. The OIA, applied with reflected light microscopy, was used to resolve coal particle boundaries and to show mineral associations with carbonaceous material. The OIA system acquires reflected light images, determines broad mineral categories, and analyzes the images to determine quantity, size, and association data for observed phases. The data are then normalized against the TIMA data to produce a combined dataset of assemblage data for carbonaceous material and mineral matter.

4. Results

4.1. Modal abundance of mineral species

The main minerals in the sample set include quartz, kaolinite and other clays, carbonates, feldspars and phosphates (Table 1, Fig. 5). Quartz and kaolinite are the two most abundant minerals in five samples. All samples contain potassium feldspar in amounts between 3 and 40%. Also in all samples,

Table 1. Modal abundance of mineral species, by sample and coal zone.

Coal zone	100 (Top)	110	201	202	300	300	401	400	440 480 (Bottom)	
Mineral Phase	WC20144	WC20156	WC20147	WC20160	WC20161	WC20149	WC20151	WC20167	WC20153	WC20171
Quartz	11.93	20.20	34.54	21.79	37.16	20.00	27.52	34.32	18.26	20.76
Kaolinite	15.19	14.95	29.90	41.80	24.90	13.33	40.94	37.28	18.85	10.36
Illite, smectite, chlorite, other clays	5.57	5.64	2.06	5.82	3.07	6.67	3.36	2.96	5.46	14.29
Siderite	18.67	28.75	1.55	0.16	11.49	0.00	3.36	2.37	24.62	8.65
Ca-rich Siderite	8.16	6.78	0.52	0.00	1.53	0.00	1.34	1.18	3.73	4.97
Ankerite	1.29	2.45	2.58	0.60	1.92	0.56	3.36	2.37	1.96	0.80
Ca Dominant Carbonate	1.88	4.47	2.06	0.22	1.92	0.56	2.68	2.37	3.82	0.87
Fe Dominant Carbonate	1.62	2.89	0.00	0.02	0.38	0.00	0.67	0.00	1.33	0.20
Calcite	0.14	0.22	1.03	0.25	0.77	1.11	0.00	0.00	0.11	0.29
Plagioclase	5.78	3.41	6.70	8.36	3.83	10.00	3.36	3.55	6.12	9.48
K-Feldspar	22.86	5.50	12.37	17.91	7.28	39.44	3.36	5.33	12.87	23.53
Apatite	0.22	0.35	1.03	0.05	0.38	0.56	2.01	1.78	0.38	0.76
Crandallite Group	2.42	2.71	3.09	0.50	2.30	1.67	5.37	4.14	0.85	1.11
Mica group	1.86	0.63	0.52	1.11	0.77	3.33	0.00	0.59	0.43	0.93
Pyrite	0.89	0.23	0.52	0.07	0.38	0.56	0.67	0.00	0.07	0.41
Chalcopyrite	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Sphalerite	0.08	0.03	0.00	0.08	0.38	0.00	0.67	0.59	0.25	0.30
Other Silicates	0.78	0.47	1.03	1.10	0.77	1.67	0.67	0.59	0.56	2.07
Other	0.64	0.28	0.52	0.17	0.77	0.56	0.67	0.59	0.34	0.21

Table 2. Table 2. Carbonate species in this study. As measured by Semi-Quantitative Energy Dispersive X-ray Spectrometry, siderite in the present study is estimated to contain up to 1.3% Mg and is thus 'magnesio-siderite'.

Mineral phase	Chemical Formula
Calcite	CaCO_3
Siderite	FeCO_3
Ca-rich Siderite	$\text{Ca}_{<0.1}\text{Fe}_{>0.9}\text{CO}_3$
Ankerite	$\text{Ca}(\text{MgFe})(\text{CO}_3)_2$
Fe-rich Calcite	$\text{Fe}_{0.03-0.1}\text{Ca}_{0.9}\text{CO}_3$
Dolomite	CaMgCO_3
Magnesite	MgCO_3
Ca Dominant Carbonate	$\text{Ca}_{>1.0}(\text{Fe},\text{Mg})_{<1.0}(\text{CO}_3)_2$
Fe Dominant Carbonate	$\text{Fe}_{>1.0}(\text{Ca},\text{Mg})_{<1.0}(\text{CO}_3)_2$

plagioclase is less abundant (3-10%).

The approximate Ca-Fe-Mg chemical content of the carbonate phases as defined for this study are in Table 2. Carbonate content varies through the section, with more significant amounts in near the top and base of the mine section (Fig. 5). The most abundant (up to 29%) carbonate mineral is siderite; ankerite and calcite and other iron and calcium rich carbonate species generally account for <5%. The most abundant phosphate phase is crandallite (which includes all members of the crandallite group) which varies between 1 and 6 %. Apatite is present in all samples in amounts less than 2%. Most samples contain sulphides (< 1%) such as pyrite, chalcopyrite and sphalerite.

4.2. Elemental department

It is useful to know which mineral species hold various elements, in order to identify the best method for removing these elements from the coal product. We determined the elemental department of iron, calcium and magnesium.

By far, most iron resides in carbonate minerals, most commonly in siderite (Table 3, Fig. 6). In two exceptions (samples from coal zones 200 and 300), the iron resides mainly in undifferentiated clay minerals (not including kaolinite)

which include illite and smectite. The amount of iron in pyrite is generally <4% but ranges up to 10.2%. Chalcopyrite, sphalerite, and micas host minor amounts of the iron.

Calcium in the ten samples is held mainly in plagioclase feldspar, phosphate minerals and carbonate minerals (Table 4, Fig. 7.) Minor amounts (<1%) are held in illite or smectite. The phosphate minerals that carry calcium are apatite and minerals of the crandallite group, including gorceixite and goyazite.

Most of the magnesium in the sample set is hosted by carbonate minerals, mainly siderite and ankerite (Table 5, Fig. 8). Minor amounts (<1% in most samples, but as high as 13.2 % in one sample in coal zone 202) are held in mica minerals. In a few samples, small amounts of magnesium are held in illite and smectite.

4.3. Ash chemistry

Ash chemistry is an inexpensive analysis that provides

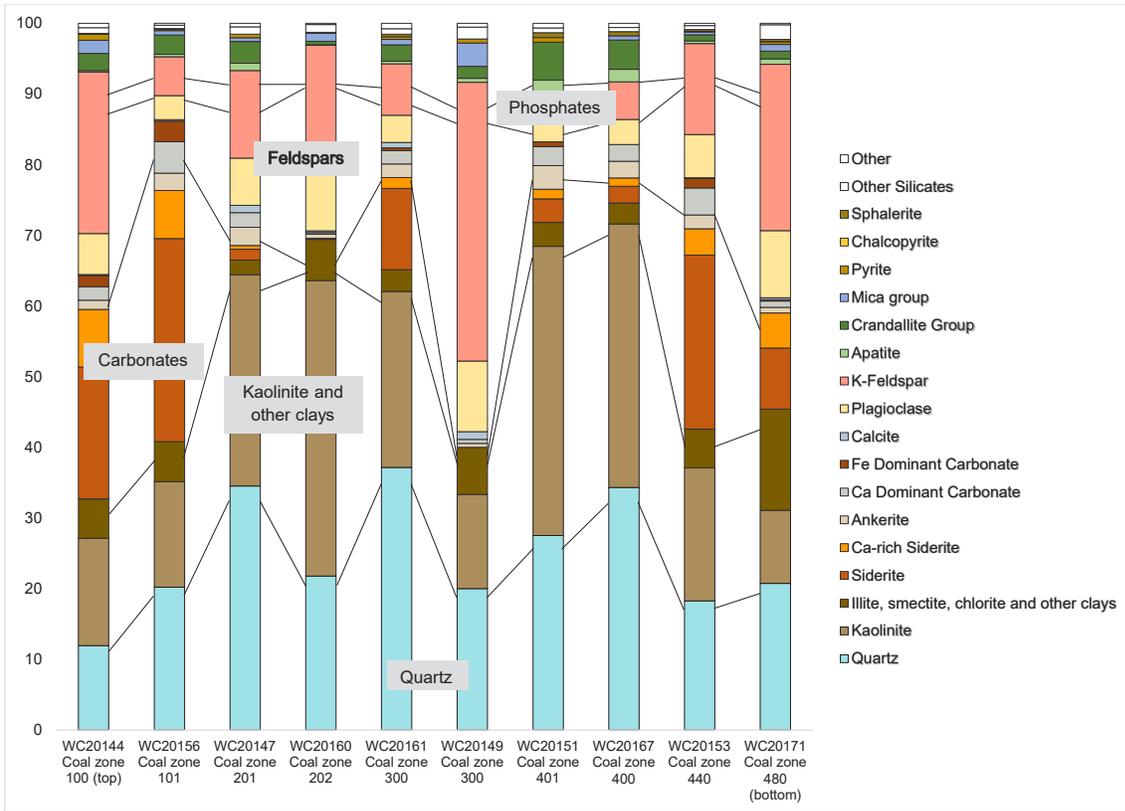


Fig. 5. Modal abundance of mineral species. Coal zones ('480' at base to '100' at top) are from Cathyl-Huhn et al. (2013).

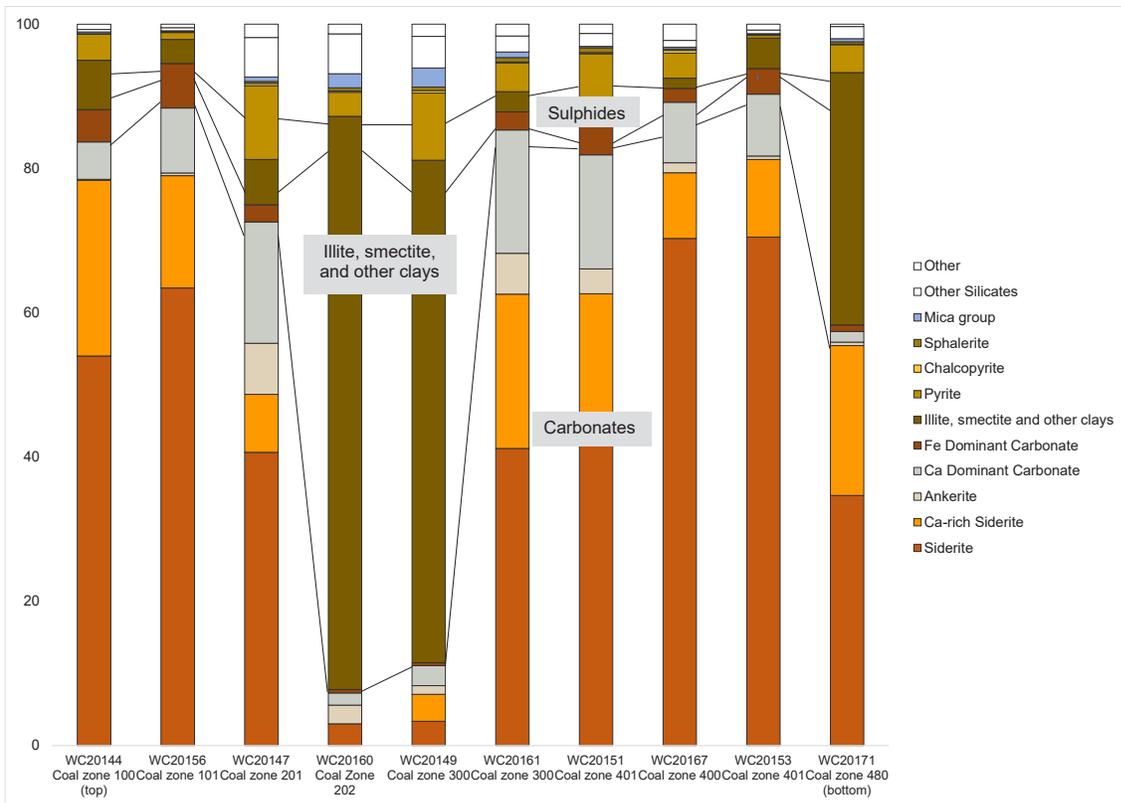


Fig. 6. Iron department by sample and coal zone.

Table 3. Iron department by sample and coal zone.

Coal zone	100 (top)	101	101	202	300	300	401	400	440	480 (bottom)
Mineral phase	WC20144	WC20156	WC20147	WC20160	WC20161	WC20149	WC20151	WC20167	WC20153	WC20171
Siderite	54.01	63.42	40.65	3.02	3.35	41.18	42.19	70.29	70.48	34.67
Ca-rich Siderite	24.34	15.59	8.03	0.00	3.75	21.38	20.44	9.10	10.76	20.77
Ankerite	0.15	0.36	7.09	2.58	1.20	5.67	3.44	1.39	0.48	0.47
Ca Dominant Carbonate	5.18	8.99	16.83	1.68	2.78	17.11	15.81	8.39	8.58	1.49
Fe Dominant Carbonate	4.49	6.18	2.37	0.50	0.41	2.50	5.74	1.93	3.54	0.90
Illite, smectite and other clays	6.84	3.34	6.26	79.44	69.65	2.81	0.73	1.42	4.22	34.99
Pyrite	3.61	0.95	10.23	3.34	9.32	3.97	7.55	3.47	0.39	3.86
Chalcopyrite	0.02	0.08	0.34	0.18	0.32	0.13	0.16	0.36	0.04	0.09
Sphalerite	0.04	0.06	0.27	0.45	0.51	0.61	0.66	0.22	0.12	0.31
Mica group	0.23	0.10	0.60	1.93	2.64	0.78	0.21	0.24	0.08	0.43
Other Silicates	0.36	0.44	5.47	5.54	4.38	2.22	1.79	0.95	0.50	1.68
Other	0.72	0.49	1.86	1.34	1.69	1.64	1.28	2.24	0.81	0.34

Table 4. Calcium department by sample and coal zone.

Coal zone	100 (top)	101	201	202	300	300	401	400	440	480 (bottom)
Mineral Phase	WC20144	WC20156	WC20147	WC20160	WC20149	WC20161	WC20151	WC20167	WC20153	WC20171
Plagioclase	22.50	13.31	4.37	62.69	38.32	2.89	3.94	4.06	21.98	43.18
Crandallite Group	13.58	12.60	14.17	4.61	16.20	18.33	19.71	13.72	4.56	6.05
Apatite	5.61	8.02	16.50	4.11	2.50	28.84	30.00	14.02	8.98	17.85
Ankerite	16.95	21.82	23.67	13.94	0.36	22.04	22.34	19.34	23.47	10.40
Siderite	12.73	15.02	1.39	0.17	18.21	1.15	1.74	8.88	12.75	4.14
Ca-rich Siderite	14.00	8.34	0.52	0.00	0.12	1.53	1.89	2.47	5.60	5.27
Calcite	2.92	3.48	16.33	7.40	9.73	4.08	4.07	18.22	2.17	3.86
Dolomite	0.00	0.00	0.00	0.00	8.54	0.00	0.00	0.00	0.00	0.00
Ca-dominant Carbonate	5.18	10.70	16.90	3.40	4.23	19.72	13.26	11.89	15.59	5.63
Fe-dominant Carbonate	3.89	4.98	0.23	0.08	0.06	0.27	0.80	0.79	2.78	0.35
Illite, smectite, other clays	0.72	0.67	0.25	0.69	0.55	0.38	0.66	0.52	0.58	1.27
Micas	0.00	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.00
Other Silicates	1.56	1.03	2.89	2.61	0.02	0.68	1.19	1.60	1.35	1.58
Other	0.36	0.03	2.78	0.30	1.14	0.09	0.38	4.49	0.19	0.42

insight into the character of the mineralogy of the inorganic material in a coal sample and it's potential for causing problems during use. The analysis reports the relative amounts of major element oxides that remain as ash residue when a coal sample is combusted. In general, the lower the amounts of reactive oxides (those of iron, calcium, magnesium, sodium, and potassium) that remain relative to the amounts of non-reactive oxides (those of silicon, aluminum, and titanium), the better the coal will perform. This is commonly quantified with the Base-

$$\text{BAR} = \frac{\text{Fe}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O} + \text{MgO}}{\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2}$$

Acid Ratio (BAR).

Coals with base ash ratios of <0.2 are considered preferable; they have a higher melting point and cause less slagging and fouling in a furnace. For coking coals, a lower BAR can indicate a better potential for a stronger resultant coke (Price et al., 1992). This has proven to be a reliable predictor of coke strength for British Columbia's Rocky Mountain coking coals (Ryan et al., 1999; Riddell, 2020).

All samples in the present study have favourable base-acid (BAR) ratios (<0.2; Table 6). The highest BAR values correspond with the samples in which carbonate minerals are >30% of the modal abundance (Fig. 5). All other samples have BARs of < 0.1.

4.4. Mineral correlation coefficients

Correlation coefficients between minerals in the study are presented in Table 7. Strong positive correlations exist

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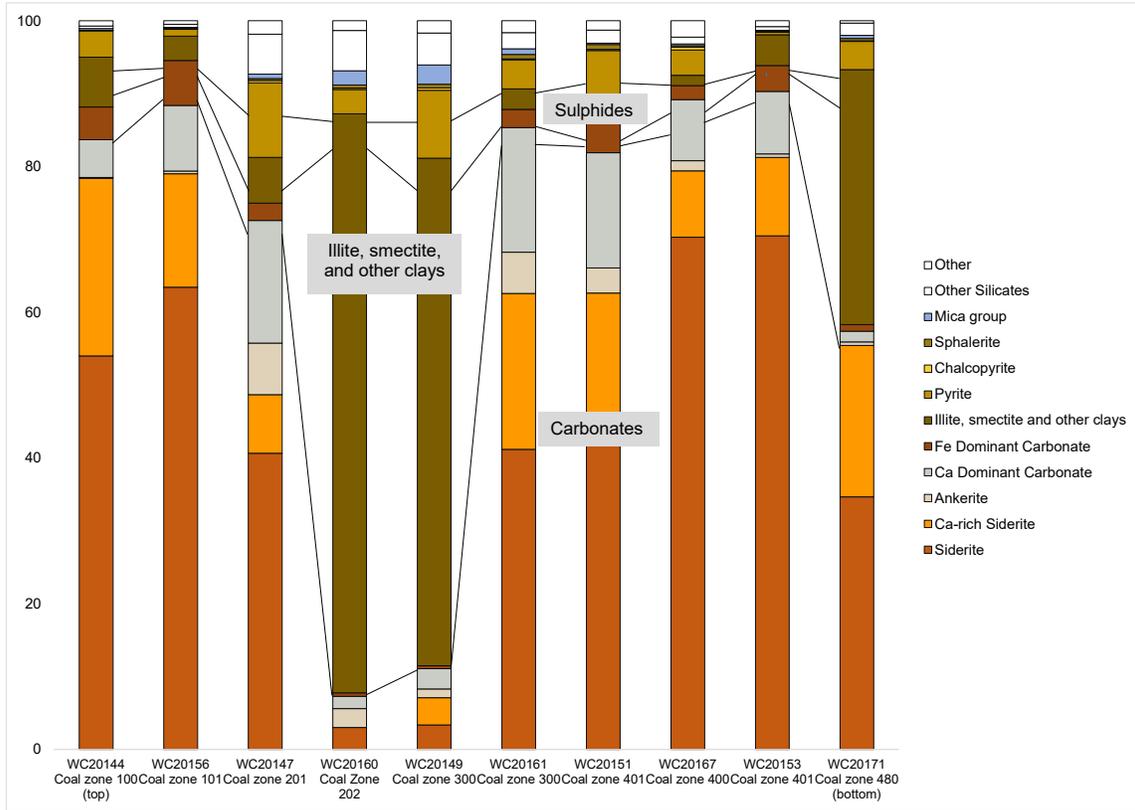


Fig. 7. Calcium department by sample and coal zone.

Table 5. Magnesium department by sample and coal zone.

Coal zone	100 (top)	101	101	202	300	300	401	400	440	480 (bottom)
Mineral phase	WC20144	WC20156	WC20147	WC20160	WC20161	WC20149	WC20151	WC20167	WC20153	WC20171
Siderite	49.32	49.96	9.17	1.86	7.55	49.32	11.79	44.78	44.28	32.10
Ankerite	22.98	30.12	53.74	53.56	53.64	22.98	60.44	34.39	32.15	29.90
Ca-rich Siderite	5.37	2.75	0.34	0.00	1.08	5.37	1.33	1.28	1.93	4.05
Fe-dominant Carbonate	5.79	6.38	0.59	0.32	0.73	5.79	2.18	1.57	3.71	1.03
Ca-dominant Carbonate	2.66	5.25	22.10	7.16	27.66	2.66	17.97	11.13	9.16	8.57
Dolomite	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Illite, smectite, other clays	0.15	0.09	0.03	1.36	0.11	0.15	0.05	0.07	0.20	0.78
Mica group	3.72	1.10	2.76	13.20	1.85	3.72	0.92	1.54	1.15	4.08
Other silicates	5.44	3.69	10.33	15.18	6.76	5.44	5.25	4.48	6.22	14.81
Other	4.57	0.66	0.88	7.36	0.62	4.57	0.07	0.76	1.20	4.68

Table 6. Ash oxides analyses and corresponding base-acid ratios.

ab #	Sample ID	SiO ₂	Al ₂ O ₃	TiO ₂	CaO	BaO	SrO	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	P ₂ O ₅	SO ₃	Undet.	BAR
202348	WC20144	54.78	23.26	1.57	2.18	1.34	0.39	6.86	0.80	0.96	1.18	3.02	1.57	2.09	0.15
202351	WC20147	60.00	25.38	1.99	1.92	1.83	0.39	1.88	0.68	1.06	1.07	2.15	1.42	0.23	0.08
202353	WC20149	62.22	22.45	1.69	2.14	0.85	0.23	2.06	0.61	0.81	1.55	2.16	1.40	1.83	0.08
202355	WC20151	57.96	26.49	1.45	2.00	0.96	0.34	3.00	0.68	1.35	0.78	2.82	1.37	0.80	0.09
202357	WC20153	58.74	23.83	1.76	2.17	0.82	0.19	4.19	0.76	1.66	0.94	2.10	1.77	1.07	0.12
202360	WC20156	52.39	24.40	1.34	2.78	1.47	0.37	9.39	0.81	1.22	0.71	2.83	2.15	0.14	0.19
202364	WC20160	60.62	27.63	1.86	1.72	0.80	0.18	0.97	0.46	1.17	1.10	1.61	1.12	0.76	0.06
202365	WC20161	62.10	24.66	1.84	1.39	0.82	0.22	2.95	0.56	0.53	1.17	1.60	1.07	1.09	0.07
202371	WC20167	57.20	28.16	2.26	2.06	0.59	0.19	1.49	0.68	0.65	0.86	1.70	1.72	2.44	0.07
202375	WC20171	58.12	23.09	1.43	1.97	2.11	0.48	2.56	0.60	0.62	1.20	4.13	1.30	2.39	0.08

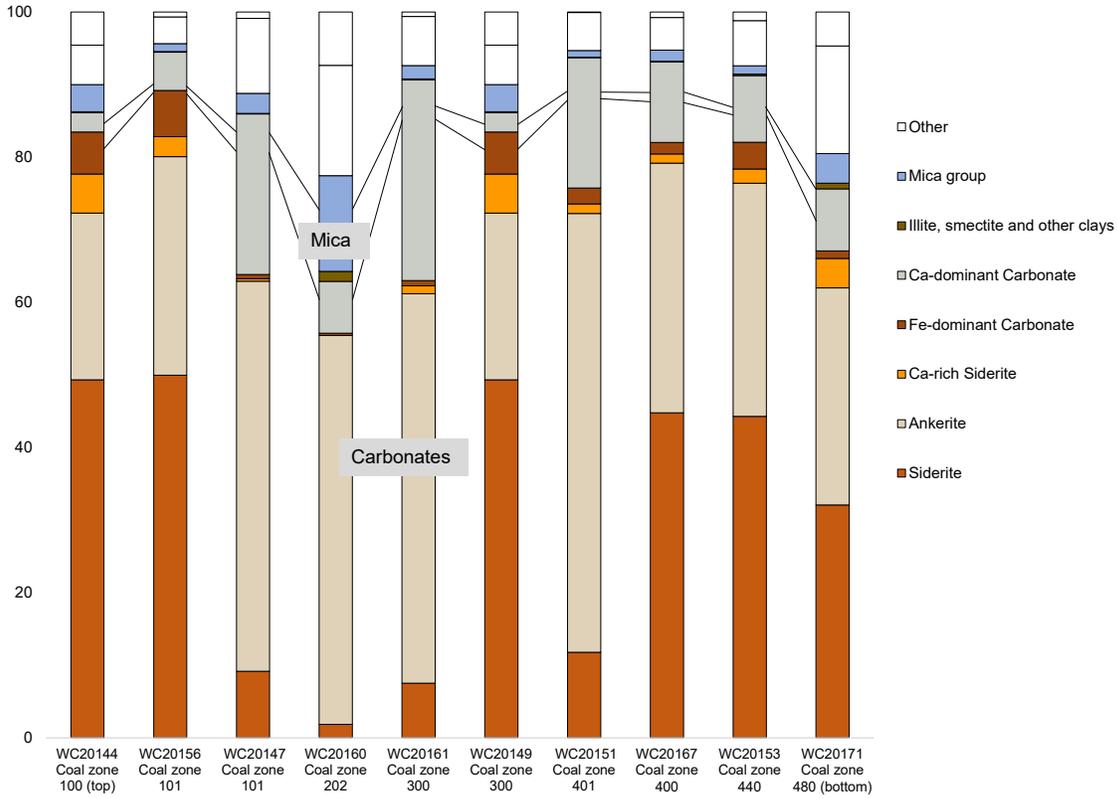


Fig. 8. Magnesium department by sample and coal zone.

between mica and potassium feldspar, between plagioclase and potassium feldspar, and between ankerite and siderite. Significant negative correlations are seen between plagioclase and crandallite, between quartz and illite-smectite, and between quartz and plagioclase.

5. Discussion

5.1. Comparison of Gething coal mineralogy with that of the Mist Mountain and Gates formations

Grieve et al. (1996) identified minerals in coals from the Mist Mountain and Gates formations using X-ray diffraction on

material left after organics were removed by low temperature ashing (LTA). They reported semi-quantitative data (i.e., significant vs trace amounts) on the mineralogy of samples from the Mist Mountain Formation (61) and Gates Formation (8), finding that, with the exception of two samples, quartz and kaolinite are the two most abundant minerals in both units. In contrast, quartz and kaolinite are predominant in only 50% of the Gething Formation samples from the Willow Creek mine in the present study. In the Gates Formation, quartz and kaolinite are followed in abundance by illite, siderite, calcite and dolomite; ankerite and anatase are present but sparse. In the

Table 7. Correlation matrix for minerals in the sample set. Correlation coefficients of 0.70 and greater are highlighted in yellow; those greater than 0.80 are highlighted in green.

	qtz	kaol	-ank	plag	ksp	sider	pyrite	calc	ill-smec	crand	apat	mica
qtz	—											
kaol	0.67	—										
ank	-0.23	-0.37	—									
plag	-0.70	-0.40	-0.43	—								
ksp	-0.63	-0.60	-0.51	0.83	—							
siderite	-0.51	-0.42	0.81	-0.02	-0.19	—						
pyrite	-0.24	-0.40	0.29	-0.16	0.21	0.22	—					
calc	0.59	0.13	0.35	-0.20	0.03	-0.53	0.05	—				
ill-smec	-0.73	-0.64	-0.04	0.74	0.63	0.08	0.06	-0.45	—			
crand	0.53	0.21	0.31	-0.81	-0.51	-0.05	0.33	0.21	-0.66	—		
apat	0.68	0.45	-0.22	-0.51	-0.41	-0.39	-0.15	0.04	-0.41	0.56	—	
mica	-0.62	-0.53	-0.34	0.64	0.91	-0.16	0.31	0.01	0.52	-0.03	-0.38	—

Mist Mountain Formation, quartz and kaolinite are followed in abundance by siderite, illite, apatite, calcite, muscovite, and dolomite; gorceixite and ankerite are rare.

The crandallite group of minerals, which includes the barium-rich member gorceixite, and strontium-rich member goyazite, are the most abundant phosphate minerals in the Willow Creek samples. Crandallite group minerals range in abundance from 0.50 to 5.37% (average 2.42%). Apatite minerals are present in much lower amounts, ranging from 0.05 to 2.01% (average 0.75%). Grieve et al. (1996) found apatite in more than trace amounts in 14 out of 61 Mist Mountain Formation samples, but only in trace amounts in one Gates Formation sample; they also reported trace gorceixite, in one Mist Mountain sample. The correlation coefficient between crandallite minerals and apatite is positive, and not especially strong, so it does not appear that crandallite formed through the breakdown of apatite in the Willow Creek samples.

5.2. Comparison of ash chemistry between regional Gething Formation coals and samples from the Willow Creek mine

With two main exceptions, the ash chemistry of our limited sample set (ten samples, Table 8) is similar to a larger dataset (175 samples) of Gething Formation coals reported by Riddell and Han (2017). First, the mean value of iron oxides in Willow Creek mine samples is less than half that of samples from the regional study, and the mean value of phosphorous oxide is about 78% higher in the Willow Creek mine samples. Second, the BAR is more than 50% less in the Willow Creek samples, probably reflecting lower amounts of iron oxide. However, it remains unclear if this difference may merely be because Riddell and Han (2017) included results from both raw and washed coals.

6. Summary

Ten Gething Formation coal samples from the Willow Creek mine were analysed with TESCAN Integrated Mineral Analyzer (TIMA) system to identify and quantify the mineralogy of the non-carbonaceous material. All samples contain abundant quartz, kaolinite, potassium feldspar and siderite and lesser micas, crandallite group minerals, apatite, carbonate minerals (excluding siderite), and undifferentiated clays (excluding kaolinite) like illite and smectite. Sulphide minerals pyrite, chalcopryrite and sphalerite occur in most samples, but in amounts <1%. Iron is mainly in carbonate minerals, but in two samples (from coal zones 202 and 300) most of the iron resides in undifferentiated clays, like illite and smectite (excluding kaolinite). In two samples, more than 5% of the iron is in pyrite. Calcium is mainly in plagioclase, potassium feldspar, phosphate minerals, and carbonate minerals. Magnesium is mainly in siderite and other carbonate minerals, and micas. The ash chemistry of Willow Creek mine samples is generally similar to that of Gething Formation samples regionally, except that on average the Willow Creek mine samples contain about 50% less iron, and about 80% more phosphate. All the samples in the study are washed coals, so this may be more indicative of the relative difficulty or ease of removing the iron and phosphate minerals than a true local difference.

Acknowledgements

We are grateful to Christy Burres and David Thompson of Conuma Coal for providing the samples for this study. The senior author thanks Gwyneth Cathyl-Huhn for her insights on the Gething Formation at Willow Creek.

Table 8. Ash chemistry of Willow Creek Gething coals compared to regional Gething ash chemistry.

	Major oxides										Minor oxides			
	SiO ₂	Al ₂ O ₃	TiO ₂	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	P ₂ O ₅	SO ₃	BaO	SrO	BAR	
Riddell and Tian 2017	57.08	21.41	0.88	7.78	2.90	1.28	0.90	1.44	1.35	2.20	1.57	0.31	.206	mean
	175	175	175	175	175	175	175	174	170	174	3	5	175	# samples
	Major oxides										Minor oxides			
	SiO ₂	Al ₂ O ₃	TiO ₂	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	P ₂ O ₅	SO ₃	BaO	SrO	BAR	
This study	58.41	24.91	1.72	3.54	2.03	0.66	1.00	1.06	2.41	1.49	1.16	0.30	.099	mean
	10	10	10	10	10	10	10	10	10	10	10	10	10	# samples

References cited

- ASTM International, 2021. Standard test method for major and minor elements in combustion residues from coal utilization processes. <<https://www.astm.org/Standards/D3682.htm>> last accessed June 27, 2021.
- Cathyl-Huhn, C.G., 2019. Coal assessment report for the Willow Creek coal lease. British Columbia Ministry of Energy, Mines and Petroleum Resources Coal Assessment Report 1048.
- Cathyl-Huhn, C.G., LeMay, L.R., and Singh, P., 2013. Coal assessment report for the Willow Creek coal lease. British Columbia Ministry of Energy, Mines and Petroleum Resources Coal Assessment Report 988.
- Cohen, K.M., Finney, S.C., Gibbard, P.L., and Fan, J.-X., 2013. The ICS International Chronostratigraphic Chart. Episodes 36, 199-204. <<https://stratigraphy.org/ICSchart/ChronostratChart2020-03.pdf>> last accessed June 27, 2021.
- Diessel, C.F.K., 1992. Coal-bearing depositional systems; Springer-Verlag, 721p.
- Gibson, D.W., 1992. Stratigraphy, sedimentology, coal geology and depositional environments of the Lower Cretaceous Gething Formation, northeastern British Columbia and west-central Alberta. Geological Survey of Canada Bulletin 431, 127p.
- Grieve, D.A., Holuszko, M.E., and Goodarzi, F., 1996. British Columbia coal quality survey. British Columbia Ministry of Employment and Investment, British Columbia Geological Survey Bulletin 96, 114 p.
- Legun, A., 1990. Stratigraphic trends in the Gething Formation. British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Open File 1990-33, 18p.
- Mackowsky, M., 1975. Minerals and trace elements occurring in coal. In: Stach's Textbook of Coal Petrology, Second Edition, Gebruder Borntraeger, Berlin, pp. 121-131.
- Price, J.T., Gransden, J.F., Khan, M.A., and Ryan, B.D., 1992. Effect of selected minerals on high temperature properties of coke, Proceedings of the 2nd International Coke Making Congress, 1, pp. 286-292.
- Riddell, J., 2020. Evaluation of coal ash chemistry indices for predicting CSR (coke strength after reaction with CO₂) for coking coals of the Rocky Mountains, British Columbia. British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey GeoFile 2020-06, 18p.
- Riddell, J., and Han, T., 2017. Ash chemistry database for British Columbia Rocky Mountain bituminous coals. Ministry of Energy and Mines, British Columbia Geological Survey GeoFile 2017-10, 15p.
- Ryan, B., Leeder, R., Price, J.T., and Gransden, J.F., 1999. The effect of coal preparation on the quality of clean coal and coke. In: Geological Fieldwork 1998, Ministry of Energy and Mines, British Columbia Geological Survey Paper 1991-1, pp. 247-245.
- Stott, D.F., 1984. Cretaceous sequences of the foothills of the Canadian Rocky Mountains. In: Stott, D.F., and Glass, D.J., (Eds.), The Mesozoic of middle North America. Canadian Society of Petroleum Geologists, Memoir 9, pp. 85-107.
- Ward, C.R., 2016. Analysis, origin and significance of mineral matter in coal: An updated review. International Journal of Coal Geology, 165, 1-27.



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