PYRITE OCCURRENCES IN TELKWA AND QUINSAM COAL SEAMS

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INTRODUCTION

Sulphur in coal is a major environmental concern. The use of coal for combustion requires the control of sulphur dioxide emissions. To reduce these emissions, the total sulphur content in coal product must be decreased. This can be accomplished by using low-sulphur coal, cleaning coal prior to combustion. retaining sulphur during combustion, or by treatment of flue gases after combustion. The use of low-sulphur coal is limited to the areas where such coals are available, and retaining the sulphur during combustion is a process in the experimental stage. The remaining alternatives are to clean coal before combustion or reduce sulphur dioxide emissions by flue gas desulphurization. Physical cleaning before combustion, however, is still the most economical option.

Sulphur is found in coal in both inorganic and organic forms. The inorganic sulphur occurs: as iron disulphide, either pyrite (cubic) or marcasite (orthorhombic); as a sulphate, chiefly gypsum and iron sulphate; and as elemental sulphur. Elemental sulphur and sulphate are usually found in very small concentrations, generally less than 0.2 per cent and 0.1 per cent, respectively (Greer, 1979). The organic sulphur is bound to the coal structure. Pyritic and organic sulphur, however, account for most of the sulphur in coal.

Conventional cleaning is not adequate for the removal of organic sulphur, and chemical cleaning would be more appropriate. Pyritic sulphur is the only sulphur form which can be removed by physical methods. Therefore attention is usually focused on the forms of pyrite. For physical sulphur removal to be successful it is necessary to understand the nature and occurrences of pyrite in the coal.

The sulphur contents of most British Columbia coals are considered to be low (<1%). The two major coalfields, the Northeast and Southeast, produce coals with sulphur contents in the range 0.30 to 0.60 per cent. Coals from the Telkwa, Bowron River and Comox coalfields, have, on average, sulphur values greater than 1 per cent, and are exceptions.

British Columbia low-sulphur coal seams contain predominantly organic sulphur. Table 5-3-1(a) shows the distribution of sulphur forms in low-sulphur seams. Total sulphur ranges from 0.23 to 0.69 per cent and the organic sulphur comprises from 55.4 to 96.5 per cent of the total. A decrease in the proportion of organic sulphur is usually accompanied by an increase in pyritic sulphur. Organic sulphur is assumed to be part of the organic coal structure, and it is convenient to express it on a dry ash-free basis, to emphasize this association.

Coals from the Comox, Telkwa and Bowron River coalfields generally average between 0.5 and 1.6 per cent sulphur. Compared with sub-bituminous coals, thermal coals from these areas are relatively high rank (higher kcal/kg), and therefore the elevated sulphur content in these seams will have much less effect on the possible sulphur dioxide emissions.

In coals with higher sulphur content an increase of total sulphur content is mainly due to an increase in pyritic sulphur (see part b of Table 5-3-1). The proportion of organic sulphur decreases drastically and may be as low as 4.5 per cent of the total sulphur in some cases. The organic sulphur content, as calculated on a dry ash-free basis, however, appears to be much higher than the organic sulphur in the low-sulphur coals. For Telkwa seams, organic sulphur is as much as 1.81 per cent of organic matter. For Quinsam No. 2 seam and No. 1-Rider seam it ranges from 0.80 to 0.87 per cent, whereas, for low-sulphur coals, organic sulphur on a dry ash-free basis averages 0.56 per cent.

The objective of this study is to investigate pyrite occurrences in Telkwa and Quinsam coals, as these coalfields produce higher sulphur coal. Pyrite occurrences will be discussed in terms of size and association with macerals (microlithotypes) with a view to assessing their possible influence on the cleaning processes.

BACKGROUND

ORIGIN OF SULPHUR IN COAL

Sulphur in coal may be either syngenetic or epigenetic. Most is syngenetic; the early syngenetic sulphur is introduced during the peat formation process, and late syngenetic sulphur is accumulated during the gelification-humification stage of coalification. Epigenetic sulphur, mostly pyritic, is present in cleats and fracture fillings (Renton and Bird, 1991).

Because organic and pyritic sulphur comprise most of the sulphur in coal, special attention is given to the origin of these two forms. The organic sulphur in low sulphur coals is derived primarily from sulphur contained in plants forming the peat deposit. Only a small part is derived from hydrogen sulphide generated by the microbial reduction of the sulphate of interstitial water. Coals rich in organic sulphur imply a syngenetic contribution from fluids with a high sulphate content (Querol et al., 1991; Price and Casagrande, 1991). According to Casagrande and Nug (1979) organic sulphur originates from complexing of sulphur from sulphate ions and hydrogen sulphide by humic acids during coalification.

Organic sulphur in coal can be classified into four types (Markuszewski et al., 1980):

- Aliphatic or aromatic thiols (mercaptans thiophenols);
- Aliphatic, aromatic or mixed sulphide (thioethers);

TABLE 5-3-1
(A) DISTRIBUTION OF SULPHUR FORMS IN LOW-SULPHUR COAL SEAMS FROM BRITISH COLUMBIA
(B) DISTRIBUTION OF SULPHUR FORMS IN HIGH-SULPHUR COAL SEAMS FROM BRITISH COLUMBIA

(A)

Coalfield	Property	Seam	Moisture %	Ash %	Sulphur % Total	Organic	Sulphate	Puritic	% S_{org}/ S_{tot}	% S_{org} d.a.f.*
Southeast	Byron Ck	Mammoth	0.96	21.70	0.23	0.21		0.02	91.30	0.27
	Line Ck	10A	0.72	12.40	0.52	0.50	0.01	0.01	96.20	0.58
		8	0.67	49.00	0.31	0.28	0.01	0.02	90.30	0.56
	Greenhills	16	0.93	16.80	0.56	0.46	0.02	0.08	82.14	0.56
		22	3.33	6.12	0.58	0.56	0.01	0.01	96.55	0.62
		20	0.80	32.70	0.60	0.46	0.02	0.12	76.67	0.69
		3	0.51	19.30	0.65	0.41	0.04	0.20	63.08	0.51
	Balmer	7RX	0.41	32.10	0.63	0.52	0.02	0.09	82.54	0.77
		7S	0.55	26.00	0.69	0.45	0.12	0.12	65.22	0.61
		4	0.57	24.80	0.62	0.48	0.01	0.13	77.44	0.64
Northeast	Bullmoose	A1	0.76	21.30	0.65	0.36	0.01	0.28	55.40	0.46
		D	1.00	22.10	0.58	0.42	0.03	0.13	72.41	0.55
		E	1.10	21.70	0.55	0.45	0.02	0.08	81.82	0.58
	Quintette	J3	0.86	13.80	0.60	0.38	0.08	0.14	63.33	0.45

* calculated on dry-ash-free basis

(B)

Coalfield	Property	Seam	Moisture %	Ash %	Sulphur % Total	Organic	Sulphate	Pyritic	% S_{org}/ S_{tot}	% S_{org} d.a.f.*
Comox	Quinsam	Quinsam River (bulk)		14.40	1.57	0.07		1.50	4.50	0.08
		Hamilton Lake (bulk)		27.00	2.21	0.82		1.39	37.10	1.12
		2	2.30	30.90	2.63	0.53	0.08	2.02	20.20	0.79
		Rider	2.30	20.50	3.73	0.67	0.16	2.90	18.00	0.87
		1	2.50	9.80	0.58	0.33	0.01	0.24	56.90	0.38
	Telkwa	Lower coal zone	0.49	23.12	3.52	1.38	0.15	1.99	39.20	1.81

* calculated on dry-ash-free basis

- Aliphatic, aromatic or mixed disulphides (bisthioethers);
- Heterocyclic compounds of the thiophene type (dibenzothiophene).

The proportion of different organic sulphur-bearing compounds is a function of rank and type of coal. The aliphatic (organic sulphur bound to the aliphatic hydrocarbon compound) to aromatic sulphur ratio varies significantly with maceral type and coal rank. Vitrinite macerals typically contain more of the aromatic-heterocyclic sulphur than either the inertinite or exinite macerals. An increase in rank increases the ratio of aromatic to aliphatic sulphur (Huggins, 1992). The distribution of organic sulphur in various macerals has been the subject of many studies (Raymond, 1982; Hippo et al., 1987; Stock et al., 1989).
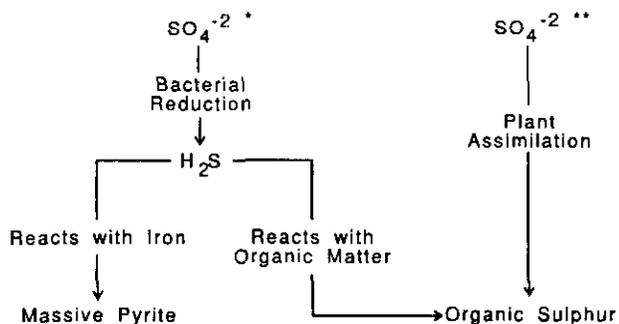
Generally, it was found that macerals from low-sulphur coals contain comparable amounts of organic sulphur. In contrast, the macerals of high-sulphur coals contain significantly different amounts of these substances. Sporinite has the highest content of organic sulphur, while vitrinite has significantly less. Furthermore, organic sulphur in sporinite was found to be more reactive than organic sulphur in vitrinite.

"Pyritic" sulphur includes sulphur contained in either of the two common iron sulphide minerals, pyrite and marcasite. The generation of sulphide in coal depends on the

availability of sulphur and iron, and on the intensity of the sulphate bacterial reduction (Figure 5-3-1). It is generally accepted that coals with the original peat or roof sediments formed in marine-influenced environments have a tendency to have a higher sulphide content than those accumulated in limnic areas (Williams and Keith, 1963). Considering that the sulphate content of seawater is 120 times greater than that of fresh water or ground water this is not surprising (McMillan, 1972).

According to Neavel (in Frankie and Hower, 1985) iron sulphide can only form in peats as a result of bacterial activity, because there is not enough energy for chemical reduction of sulphates to disulphides. The source of sulphur is plant and animal protein, largely bacterial protein, or sulphate ions in streams or sea water. Iron is derived from the weathering of silicate minerals or is carried in with groundwater as Fe-ions. The environmental conditions, especially pH, appear to have dramatic effect on pyrite formation (Casagrande, 1987).

The hydrogen sulphide which is transformed into iron disulphide is produced by sulphate-reducing bacteria, which thrive in high pH environments. The same swamp conditions that produce iron disulphide minerals determine the relative abundances of the various macerals in a particular coal seam. In other words, pH conditions in the swamp control the microbial degradation of plant debris to form the organic part of coal and, at the same time, control the

SO$_4^{-2}$ *

Bacterial
Reduction
↓
┌────── H$_2$S ──────┐
│   │
Reacts with Iron   Reacts with
│   Organic Matter
↓   │
Massive Pyrite   └──────→ Organic Sulphur

SO$_4^{-2}$ **
│
Plant
Assimilation
↓

* Low Sulphur = Brackish to Fresh Water Source
  High Sulphur = Marine Water Source

** Low and High Sulfur from Fresh Water Source

Figure 5-3-1. Sulphide formation in coal
(Price and Shieh, 1979).

reactions that generate pyrite. For example, higher pH leads to increased microbial degradation of the plant and peat components and, as a result decreased content of pre-vitrinitic materials. Increased microbial reduction of sulphate ions subsequently results in the precipitation of iron disulphide minerals, mainly pyrite, in coal. The end result is that coal produced under high pH conditions is more exinite rich and higher in mineral matter, especially in pyritic sulphur. Typically the abundance of exinite and pyritic sulphur exhibit a strong statistical association with each other (Renton and Bird, 1991).

Low pH, by contrast, promotes accumulation of pre-vitrinitic woody tissues and suppresses exinite formation. In addition, metal ions, especially iron, are readily dissolved and removed from the peat, and bacterial reduction of sulphate to iron disulphide is simultaneously suppressed. Coals produced under these conditions are vitrinite rich and pyritic sulphur content is low; most of the sulphur is organic.

Strong relationships between petrographic composition and pyritic sulphur in coal exist due to the same chemical conditions controlling the pyrite formation and abundances of various macerals (Renton and Bird, 1991; Kalkreuth et al., 1991).

PYRITE OCCURRENCES IN COAL

Pyrite may occur in a variety of forms, the most common being as narrow veins up to 150 millimetres thick and several hundred millimetres long, nodules resembling framboids, and discrete crystals. The framboids, which range from a few to several hundred microns in size, are aggregates of octahedral crystals; discrete crystals are usually much smaller (1-2 μm).

There are a number of different classifications of pyrite occurrence in coal. Neavel and Reyes-Navarro (in Frankie and Hower, 1985) classified pyrite as: framboidal, dendritic, euhedral, cleat and massive. Caruccio et al. (1977) consider two main categories, primary and secondary pyrite. Primary pyrite includes sulphur balls, finely disseminated pyrite, and primary emplacement pyrite. They also recognize five types of pyrite according to morphology: primary massive, plant

replacement, primary euhedral, secondary cleat coats and framboidal.

Lowson (1982) suggested that for many purposes it is adequate to consider pyrite as either framboida or euhedral. In another classification, two types of pyrite morphology are defined: type 1 consists of submicron-size grains existing as loose particles or agglomerated in the form of framboids, typically 10 to 20 microns in diameter; type 2 includes larger individual crystals (often >50 μm) with no apparent sub-grain structures (Caley et al., 198?). The latter are described as monolithic. These two types of pyrite morphologies coincide with framboidal and euhedral forms of pyrite discussed by Lowson (1982). It is also believed that these two types may be considered as the end members in a maturity range. The framboidal or sub micron size pyrites are believed to be the least mature, whereas monolithic pyrites are the most mature.

In terms of pyrite reactivity it has also been established that framboidal pyrite is more reactive than other forms and, as result, responsible for forming acid solutions and causing acid mine-drainage problems (Carrucio e. al., 1977; McMillan, 1972). Similarly, the framboidal pyrite displays a higher level of reactivity upon pyrolysis than euhedral pyrite from the same coal (Caley et al., 1989)

SAMPLES AND ANALYTICAL PROCEDURES

Samples were obtained from diamond-drilling projects in the Quinsam and Telkwa coalfields (Matheson, 1989; Matheson and Van Den Bussche, 1989). Locations of Quinsam mine and Telkwa coalfield are shown in Figures 5-3-2 and 5-3-3.

Samples representing Quinsam No. 1, 1-Rider and No. 2 seams were analyzed. These seams have a high pyrite content and are typical of seams which have been influenced by marine transgressions (Kenyon et al., 1991). They are overlain directly by marine strata. A summary of analytical results is presented in Tables 5-3-2 and 5-3-3. Table 5-3-2 presents proximate analysis (Matheson, 1989). Table 5-3-3 shows the distribution of sulphur forms in these seams. Quinsam No. 1 seam, as presented in Table 5-3-3, has been subdivided into three intervals: upper, middle and lower (the first two are 80-centimetre intervals, the third 60 centimetres).

The Telkwa coal measures are part of an interbedded marine and nonmarine sedimentary sequence which is

TABLE 5-3-2
PROXIMATE ANALYSIS IN NO. 1, 1-RIDER AND 2 SEAMS
FROM QUINSAM

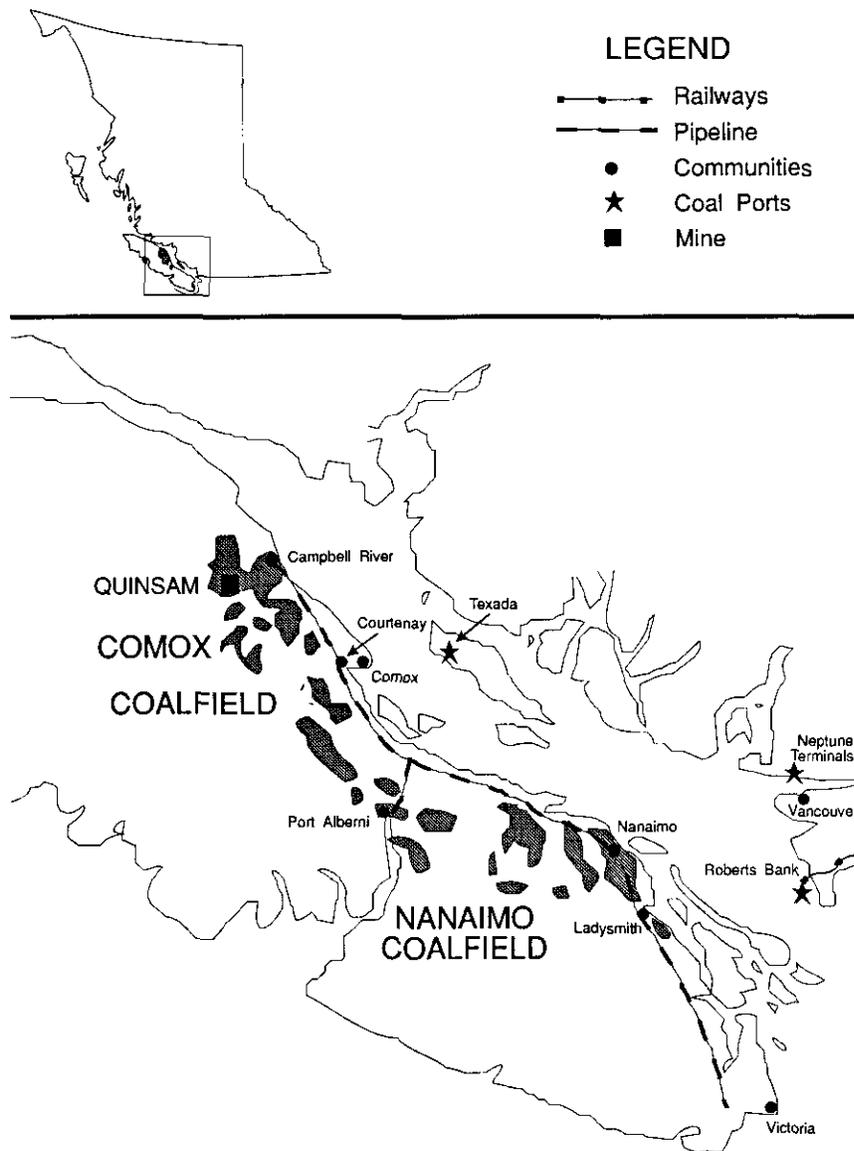| Seam	Moisture %	Ash %	Volatile Matter %	Fixed Carbon %
#2	2.30	30.90	30.00	36.80
#1 Rider	2.30	20.50	35.00	42.20
#1	2.65	9.65	37.00	50.70

Figure 5-3-2. Location of Quinsam mine and Comox coalfield.

divided into three units (Koo, 1984; Matheson and Van Den Bussche, 1989). Only the lower and the upper unit contains coal measures. The coal seam No. 1 and some thin coal seams occur near the top of the lower unit (Matheson and Van Den Bussche, 1989). The upper unit contains ten seams. Palsgrove and Bustin (1991) described coal geology and quality of these seams in greater detail. In general, the uppermost six seams in the upper unit have the highest sulphur content, ranging from 2.00 to 3.80 per cent.

The incremental samples from the Telkwa No. 1 seam in the lower unit were analyzed for pyrite forms. Samples from the upper part of the seam have the highest sulphur contents, especially samples from the top of the seam, where sulphur reaches almost 10 per cent. In general, the sulphur content decreases downward within the seam. The average total sulphur content for this seam is 3.52 per cent; proximate and sulphur forms analyses are presented in Table 5-3-4. Sul-

phur, ash and moisture contents of samples taken in 20-centimetre intervals across the seam are reported in Table 5-3-5.

PETROGRAPHIC ANALYSIS

For detailed petrographic examination, epoxy pellets were prepared from coal samples taken in 10 to 15-centimetre increments from Quinsam No. 1, 1-Rider and No. 2 seams. The Telkwa seam was sampled in 20-centimetre increments. Maceral analyses were performed by counting 500 points on each pellet. Results are summarized in Tables 5-3-6 and 5-3-7. In addition, observations were made with respect to the size, form and association of pyrite with microlithotypes in vertical sequence of these seams. Table 5-3-8 summarizes the maceral composition of the various microlithotypes.

Coal Seam	Moisture %	Ash %	Total	Sulphur % Organic	Sulphate	Pyritic	% S_{org}/S_{tot}	% S_{org} d.a.f.*
#2	2.30	30.90	2.66	0.54	0.08	2.04	20.30	0.80
Rider	2.30	20.50	6.08	0.67	0.27	5.14	11.00	0.87
#1 (first part; 80 cm from the top)	2.60	8.23	1.09	0.46	0.02	0.61	42.20	0.52
#1 (second part; next 80 cm from the top)	2.60	12.92	0.37	0.33	< 0.01	0.03	39.19	0.39
#1 (bottom part; last 60 cm)	2.81	8.84	0.29	0.27	< 0.01	0.01	93.10	0.31

* calculated on dry-ash-free basis

LEGEND

•—•—•—• Railways

• Communities

▲ Coal Deposit
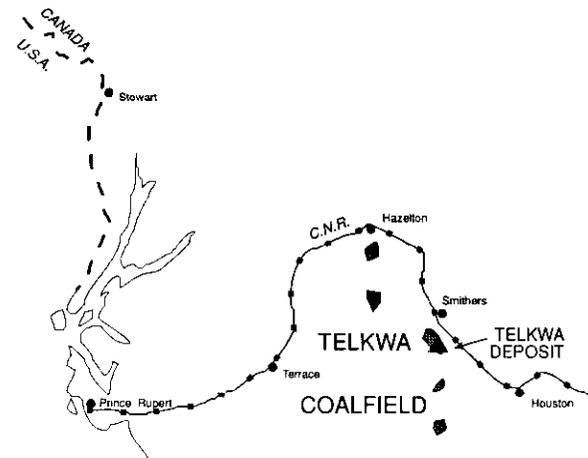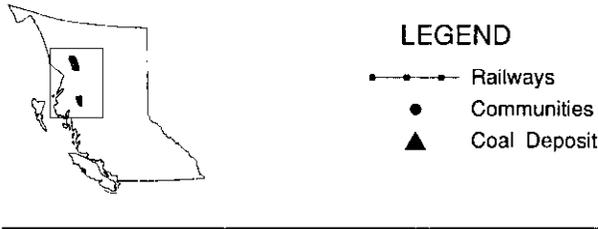
Figure 5-3-3. Location of Telkwa coalfield.

DISTRIBUTION OF SULPHUR AND ASH

Quinsam

The average total sulphur content for Quinsam No. 2 seam is 2.66 per cent. The highest sulphur content, 6.08 per cent, occurs in 1-Rider seam. The sulphur content of the upper part of No. 1 seam is much higher than the remainder of the seam and correlates with an increase in pyrite content (Table 5-3-3). The increasing trend of pyritic sulphur towards the top of the seam is evident and in agreement with other studies (Casagrande, 1987; Querol, 1991 *et al.*).

In the 1-Rider seam, pyritic sulphur comprises 89 per cent of the total sulphur, while in the sample with lowest sulphur content pyrite contributes only a little over 3 per cent of the total sulphur.

No. 2 seam has the highest ash content, followed by 1-Rider seam. The lowest ash content is associated with the uppermost 80-centimetre interval of the No. 1 seam, which is enriched in pyritic sulphur. An increase in ash content in

TABLE 5-3-4
PROXIMATE ANALYSIS AND SULPHUR FORMS
IN TELKWA SEAM

Moisture %	Ash %	Volatile Matter %	Fixed Carbon %
0.49	23.01	28 21	48.29

Total	Organic	Forms of Sulphur Sulphate	Pyritic	% S_{org} S_{tot}	% S_{org} d.a.f.*
3.52	1.38	0.15	1.99	36.9	1.79

TABLE 5-3-5
SULPHUR AND ASH DISTRIBUTION
IN TELKWA SEAM

Sample No.	Moisture	Ash %	Sulphur %
1**	0.96	42.04	9.71
2	0.85	40.99	4.34
3	0.83	12.5	2.38
4	0.98	23.43	2.14
5	0.86	11.61	1.21
6	0.99	10.65	3.12
7	0.88	31.03	3.39
8	1.12	18.93	0.39
9	0.91	17.2	1.19

* analysis are on as received basis
** samples represent 20 cm intervals

the samples from the middle part of No. 1 seam does not have a corresponding increase in the content of pyritic sulphur. There is no apparent correlation between total sulphur content or pyritic sulphur and the ash content.

Telkwa

The average total sulphur content for the Telkwa No 1 seam is 3.52 per cent (Table 5-3-5). Pyritic sulphur comprises 56.5 per cent of the total sulphur content and organic sulphur contributes a further 39.2 per cent. Total sulphur decreases with depth down to the middle section of the seam (Table 5-3-5). This corresponds with a general decrease in

TABLE 5-3-6
MACERAL ANALYSIS OF SAMPLES FROM EXAMINED
QUINSAM SEAMS

Seam	Vitrinite Vol. % *	Exinite Vol. %	Inertinite Vol. %
2 (3)**	87.90	1.40	10.70
Rider (4)	72.90	2.40	24.70
1 (first 80 cm) (8)	80.00	2.50	17.50
1 (next 80 cm) (8)	78.80	2.20	19.00
1 (60 cm) (7)	80.20	2.30	17.50

* volume percent on mineral-matter-free basis
** average based on ( )-number of samples

TABLE 5-3-7
MACERAL ANALYSIS OF SAMPLES FROM EXAMINED
TELKWA SEAM

Sample No.	Vitrinite Vol. % *	Exinite Vol. %	Inertinite Vol. %
1 **	94.60	1.20	4.20
2	81.50	0.60	18.10
3	40.80	1.80	57.40
4	69.60	1.40	29.00
5	60.60	2.20	37.20
6	61.20	1.00	37.80
7	69.60	2.20	28.20
8	59.80	0.60	39.40
9	68.40	0.40	31.20
Average	**67.30**	**1.30**	**31.40**

* Volume percent on mineral-matter-free basis
** Samples represent 20 cm intervals

TABLE 5-3-8
COMPOSITION OF VARIOUS MICROLITHOTYPES (after stach
et al., 1982)

Classification	Microlithotype	Mineral Group Composition
Monomaceral (mineral free)	Vitrite	V > 95%, E+I < 5%
	Liptite	E > 95%, V+I < 5%
	Inertite	I > 95%, V+E < 5%
Bimaceral (mineral free)	Clarite	V+E > 95%, I < 5%
	Vitrinertite	V+I > 95%, E < 5%
	Durite	I+E > 95%, V < 5%
	Trimacerite	V+I+E (each > 5%), > 95%
Maceral Association	Carbominerite	Any above microlithotype with 5-60% by volume mineral matter (5-20% if sulfides)

V - Vitrinite   E - Exinite   I - Intertinite

ash content, with some exceptions. The highest sulphur content (9.71%) is reported in the top sample, the corresponding ash content is 42.04 per cent.

DISTRIBUTION OF PYRITE FORMS

QUINSAM

Examination of samples from Quinsam No. 2 seam, representing the top of the coal sequence, revealed that the coal particles are very much contaminated with pyrite, predominately framboidal, with an average size of approximately 13 microns. There are also massive framboids, 25 to 30 microns in size. Euhedral pyrite is found as very small, liberated particles, usually in cavities and cleats, indicating secondary origin. Some pyrite is intermixed with clays. Almost all particles are contaminated with pyrite, but only a few are heavily contaminated. Other minerals are clays and calcite. The latter is deposited in the cleats of coal particles. Examples of various pyrite forms in Quinsam coal seams are illustrated in Plate 5-3-1.

In 1-Rider seam, the framboidal pyrite appears mainly as large particles, up to 30 microns, while smaller framboids are up to 5 microns. There is also an increased abundance of euhedral pyrite, typically as tiny particles (1 to 2 μm). In general, there is a high content of pyritic sulphur in various forms. Large framboids dominate the coal samples from 1-Rider seam. In the top of the section very tiny euhedral pyrites are found near larger framboids. This suggests that the euhedral pyrite may be the result of disintegration of framboidal pyrite (Figure 5-3-1). Liberation of pyrite in these samples is insignificant, considering the crushing process for pellet preparation (reducing the size down to -20 mesh). Most liberated pyrite particles are euhedral, but some framboidal pyrite is present in the cleats.

The top part of No. 1 seam (uppermost 80 cm) also contains substantial amounts of framboidal and euhedral pyrite. Framboidal pyrite quite often occurs in clusters and some clusters reach 25 microns in size. There are examples of larger euhedral pyrite. The trend in decreasing total sulphur content from the top to the lower part of No. 1 seam is accompanied by a decrease in size of the framboidal pyrite, and a parallel decrease in the ratio of framboidal to euhedral pyrite. In the middle 80-centimetre interval of the seam, there is almost no visible framboidal pyrite; the only pyrite present is very small euhedral grains.

TELKWA

Microscopic analysis of pyrite occurrences in the Telkwa high-sulphur seam shows a variety of its types. A total of nine samples were examined, covering the whole seam. Samples from the upper part of the seam are enriched in massive and very large framboids, some up to 250 microns in diameter. The first two samples appear to have an especially high mineral matter content. The first sample has abundant pyrite, whereas in the second the mineral matter is mostly clays. Plate 5-3-2 shows the pyrite forms found in the Telkwa coal seam.

There is an obvious trend from large framboidal to more irregular pyrite forms with depth. Somewhere in the middle
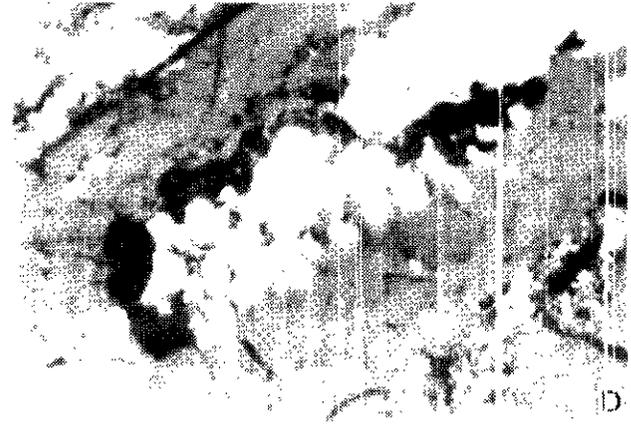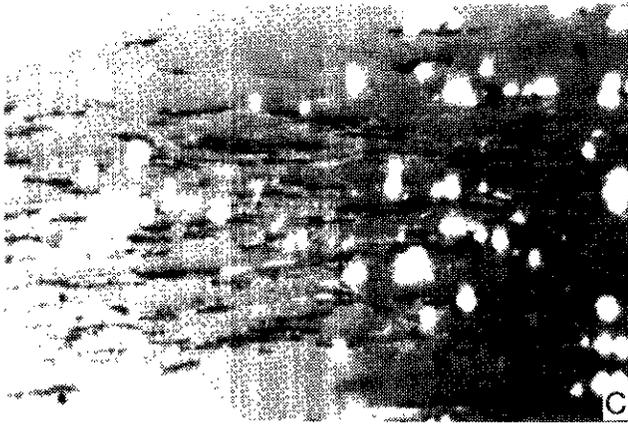
Plate 5-3-1. Pyrite occurences in Quinsam coal seams, (250 m on horizontal). A. Regular framboids; B. Mass ve
framboids; C. Disseminated small framboids; D. Euhedral pyrite.

of the seam, transformation of regular framboidal pyrite into massive "cauliflower-type" occurs. The size of irregular pyrite occurrences is somewhat smaller than the massive framboidal type, reaching on average 50 to 100 microns in diameter. The abundance of euhedral pyrite also increases with depth. This type is usually 4 to 5 microns in size, filling cavities in fusinite or semifusinite. It comprises almost 95 per cent of the total pyrite in the samples from the bottom of the seam.

In general, the liberation of pyrite increases with increase in euhedral grains. Liberated euhedral pyrite usually occurs in small cavities and cleats, but in some cases pyrite appears encapsulated in coal particles. In the part of the seam where the mineral matter is high and framboidal pyrite abundant, liberation of pyrite reaches up to 30 per cent, especially when pyrite particles are contained within the clay bands. Liberation is much less in the parts of the seam where irregular cauliflower pyrite occurs. The irregular form seems to have replaced semifusinite and is usually confined to this maceral.

ASSOCIATION OF PYRITE WITH MACERALS AND MICROLITHOTYPES

QUINSAM

Petrographic analysis (Table 5-3-6) of Quinsam No. 2 seam indicates that this coal is high in vitrinite. The average

exinite content is moderate, with a somewhat higher content of exinite in the top part of the seam. This a so coincides very well with the larger occurrences of framboidal pyrite in this part of the seam. The lower part of the sea n is enriched in smaller framboidal pyrite (5 to 7 μm) and secondary euhedral pyrite is found in cavities in fusinite and semi-fusinite. Framboidal pyrite is mostly associated with vitrinite-rich microlithotypes: vitrite, clarite and trimacerite.

The 1-Rider seam has a lower vitrinite content than No. 2 seam. Its exinite content is higher and this is accompanied by an increase in abundance of inertinite, especially se ni-fusinite. The average vitrinite content is 72.5 per cent by volume (Table 5-3-6), with an increasing trenc from the top to the bottom of the seam. The highest exinite content is at the top of the seam and corresponds to the highest con-centrations of pyrite, as in the No. 2 seam. Massive pyrite and large framboids appear to be always enclosed within the vitrinite particles. It is also evident that framboidal pyrites are usually aligned parallel to the bedding planes. In terms of microlithotype association, framboidal pyrite is usually a part of the vitrite and clarite microlithotype, whereas euhedral pyrite occurs in cavities in fusinite o semifusinite in the inertite lithotype.

Maceral composition throughout No. 1 seam is almost uniform. Vitrinite content is about 80 per cent by volume. exinite and inertinite contents are in the range of 2.2 to 2.5
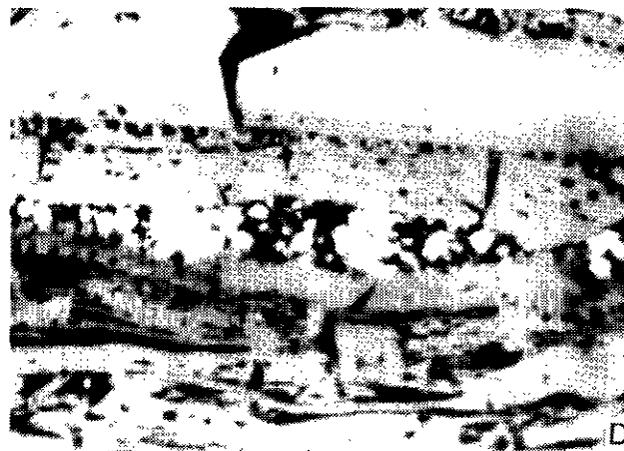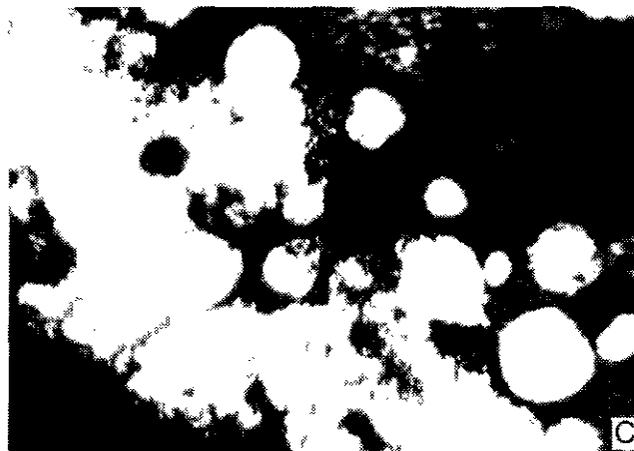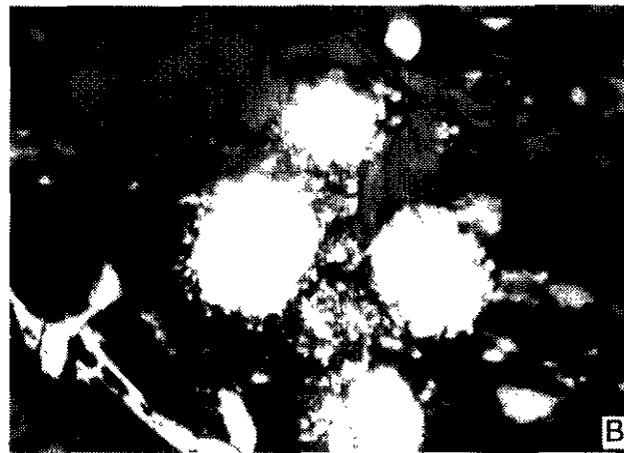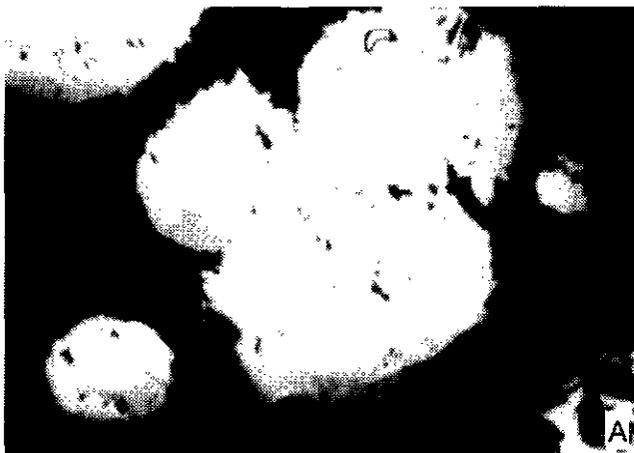
Plate 5-3-2. Pyrite occurences in a Telkwa coal seam. (250 mm on horizontal). A. Large framboids; B. Regular framboids; C. Cauliflower-type; D. Small euhedral pyrite.

and 17.50 to 19.00 per cent, respectively. There is very little variation in association of pyrite with the macerals within the seam. Larger framboidal pyrite is almost always associated with vitrinite, while euhedral pyrite is found in cavities in vitrinite or fusinite. Framboidal pyrite is dominantly associated with vitrite and trimacerites (V+E+I). The higher pyrite content in the top of the seam is not matched by an increased abundance of exinite, as observed in other seams.

TELKWA

In general, maceral composition of the Telkwa seam changes from vitrinite-rich in the top of the seam to inertinite-rich towards the bottom, with some irregularities in between (Table 5-3-7). The highest vitrinite content (94.6% by volume) is at the top of the seam. The variation in exinite content is even less regular. It ranges from 0.60 to 2.2 per cent by volume with no obvious correlation with the stratigraphy of the seam.

Occurrences of mega-framboids (up to 250 μm) of pyrite in the first 20-centimetre interval of the seam are almost exclusively confined to the vitrinite, as this maceral is dominant in this part of the seam. An obvious trend is observed moving downward in the seam; framboids become

more regular in shape and smaller in size (150 μm or less). Regular framboidal pyrite is typically confined to the vitrite and clarite microlithotypes (V+E). In some instances, framboidal pyrite occurs in trimacerites (V+E+I). The cauliflower pyrite is commonly associated with semifusinite in inertite microlithotype.

SUMMARY AND CONCLUSIONS

The high sulphur content in the Quinsam and Telkwa seams reflects marine influence during the deposition. In terms of sulphur distribution within the individual seams, there are no systematic trends. The highest sulphur content, however, is always in the upper portions of these seams. The ash patterns are also variable, with the highest ash content usually accompanying high sulphur content.

High sulphur content is a direct result of increased pyritic sulphur. In the 1-Rider seam at Quinsam, pyritic sulphur comprises almost 90 per cent of total sulphur, while in the upper part of No. 1 seam pyritic sulphur comprises only 57.8 per cent of the total sulphur (Table 5-3-3). In the lower sections of No. 1 seam total sulphur decreases significantly. Here, organic sulphur is dominant and comprises more than 90 per cent of the total sulphur. This is in agreement with trends in other coals (Casagrande et al., 1979; Given and

Miller, 1985); in coals with low total sulphur, the organic sulphur concentration exceeds that of pyritic sulphur, and in coals with higher total sulphur content pyritic sulphur is dominant.

The organic sulphur content of the Telkwa seam, calculated on a dry ash-free basis, is much higher than organic sulphur of Quinsam high-sulphur seams. Organic sulphur, as discussed by many (Renton and Bird, 1991; Price and Casagrande, 1991; Querol et al., 1991), is derived from sulphur in plants or through the direct reaction between hydrogen sulphide derived from microbial reduction, and organic matter. Hydrogen sulphide may react with either organic matter or iron to form pyrite; however, it reacts preferentially with iron (Howarth, 1984; in Palsgrove and Bustin, 1991). Due to the deficiency of iron ions in the low pH peat, sulphur may be tied up in organic matter instead of in sulphides. Bacteria reactions are slower and, as a result, hydrogen sulphide is incorporated into the organic matter.

Lower pH promotes preservation of organic matter and, coupled with the high water table in the peat, leads to vitrinite-rich coal, as evident in the top of the Telkwa seam. Another observation is that a fair amount of pyritic sulphur in this part of the seam, up to 30 per cent, is liberated. This indicates introduction of secondary pyrite into the coal. There is also a possibility that pyrite was introduced during the humification and gelification stage, after formation of vitrinite.

According to the accepted model explaining pyrite formation in relation to the petrographic composition of coal, the chemical conditions favourable for pyrite formation result in exinite-rich and vitrinite-depleted coal. None of the examined seams appear to follow this pattern entirely. In parts of No. 2 and 1-Rider seams at Quinsam, some correlation between exinite and pyritic sulphur content can be observed. It is also noteworthy that these coals are impoverished in exinite, due to the type of vegetation contributing to the peat.

Distribution of various pyrite forms is quite similar for seams from Quinsam and Telkwa. The large framboidal pyrite is almost always dominant in the top of the seams. The size of framboids decreases with depth. The ratio of framboidal to euhedral pyrite also decreases with depth. The size of euhedral pyrite varies from 1 micron (Telkwa) in size to 5 microns (Quinsam). An irregular cauliflower form of pyrite was observed in the middle part of the Telkwa seam. The association of cauliflower pyrite with semifusinite may indicate the secondary replacement of semifusinite by pyrite.

It is evident from microscopic examination of Quinsam and Telkwa high-sulphur coal seams, that pyrite in the Telkwa seam is much coarser grained than the pyrite in the Quinsam seams. The size of pyrite in the Telkwa seam reaches up to 250 microns, whereas in Quinsam seams, the size of the framboidal pyrite averages between 13 and 15 microns, with a maximum size of 25 to 30 microns.

The examination of pyrite size and occurrences in high-sulphur seams from Quinsam and Telkwa suggests that pyrite in the Telkwa seams would be more amenable to removal in commercial cleaning. Large framboids would be much easier to liberate than those found in Quinsam seams.

Distribution of pyrite in the Telkwa seam s also more favourable. The largest framboids are concentrated at the top of the seam, allowing isolation of this section for selective mining, if necessary.

Petrographic analyses of samples from Quinsam and Telkwa seams indicate that in both cases pyrite occurs mostly in vitrite, clarite and trimacerites (V+I+E). Several studies (McCartney et al., 1969; Frankie and Hower, 1935) correlating pyrite size and removal through the various physical cleaning circuits showed that fine pyrite (<20 μm) was always found in the clean coal fractions. It was also shown that clean coal was enriched in euhedral and framboidal pyrite associated with vitrite and clarite. Massive, large framboidal pyrite and pyrite associated with the mineral matter bands were usually concentrated in the refuse. Pyrite particles smaller than 10 microns in size remained in the clean coal.

It is expected that pyrite particles smaller than 20 microns in size and associated with vitrinite-dominated microlithotypes would tend to concentrate in clean coal product when gravity-based cleaning methods are used. Large particles of pyrite from the Telkwa seam would probably be much easier to remove when treated by conventional coal cleaning techniques. Microscopic analysis reveals that the large pyrite occurrences in the Telkwa seam are concentrated in the part of the seam enriched in vitrinite. This would indicate a better chance to release pyrite during the size reduction, as vitrinite is the softest maceral.

Greater reduction in top size would be required to liberate pyrite from Quinsam seams. Due to the fact that pyrite in Quinsam seams is more disseminated than in massive, more middlings will be produced during the preparation, and as a result the use of separators with sharper separation profiles would be necessary.

The coals examined here have weak floatability characteristics, therefore, froth flotation would not be adequate. This would also exclude the option of significant reduction in the top size of coal (e.g., to liberate 25-micron pyrite grains in Quinsam coal), as there are few commercially available processes to treat fines for these coals.

The only viable alternative for treating the pyrite from Quinsam coal, if required, may be the use of the agglomeration process. This would allow further size reduction in order to liberate the pyrite (Pawlak et al., 1987, 1988) Given the fact that larger framboidal pyrite is found mainly associated with the vitrite microlithotype, the probability of liberation and concentration in the fines would be much greater. To obtain maximum effect during agglomeration, the size of coal must be reduced. Size reduction may be impaired, however, by the fact that Quinsam coal has a low grindability index. Furthermore, the cost of adding agglomeration to the cleaning process will have to be balanced against the value of the improved coal quality. The end result may be that coarse coal will have lower sulphur contents, but the fines recovered in form of agglomerates will have to be incorporated into the final coal product

For further reduction in pyritic sulphur in Quinsam coal, the Agglofloat technique would be far superior to agglomeration (Pawlak et al., 1987, 1988). This technique combines both agglomeration and flotation into one pro-

cedure, and is more selective in pyrite removal. It claims to reject up to 70 per cent of pyrite during cleaning, with as high as 96 per cent recovery of combustibles. The main benefit of this technique is that it can treat very fine coal (well below 0.50 μm). The reduction to such fine sizes leads to greater liberation of pyrite particles and therefore greater chances of removal. The Agglofloat product, however, is finer and even more difficult to combine with the rest of the clean coal product.

ACKNOWLEDGMENTS

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