A REVIEW OF SULPHUR IN COAL: WITH SPECIFIC REFERENCE TO THE TELKWA DEPOSIT, NORTH-WESTERN BRITISH COLUMBIA

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INTRODUCTION

The Jura-Cretaceous coal seams of the Currier, Mist Mountain, Gething and Gates formations generally formed in delta or strand plain environments with little marine influence. The sulphur contents of coal from these formations is therefore generally low, nearly always less than 1 % and often less than 0.5 %. Coal-bearing formations of the Cretaceous Nanaimo and Skeena groups were deposited in coastal areas with more marine influence. Consequently sulphur contents are more variable and tend to be higher. It is therefore important to study aspects of sulphur in Cretaceous coal seams such as the seams in the Skeena Group at Telkwa (Figure 1).

This paper studies sulphur in some of the Telkwa coal seams and also provides a short review of some of the voluminous literature on sulphur in coal.

TYPES, SOURCES AND EVOLUTION OF SULPHUR IN COAL

Types of sulphur in coals

Sulphur occurs in coal as sulphides, organic sulphur, elemental sulphur and sulphate. The most important forms are sulphide, mainly as pyrite (FeS_2), and organic sulphur. Sulphate sulphur usually occurs in small amounts, often in sulphate minerals formed during oxidation of coal. Pearson and Kwong (1979) suggest that, in coals with low pyrite concentrations, organic sulphur can oxidize to form gypsum, which can also be introduced by ground-water. Elemental sulphur occurs in trace amounts.

Organic sulphur is bound in a number of forms. Markuszewski *et al.* (1980) classifies organic sulphur into four types.

- Aliphatic or aromatic thiols. Aromaticity refers to the tendency of carbon in coals of higher rank to form hexagonal rings similar to the structure of graphite. Aliphacity refers to the ability of carbon hydrogen complexes to form chains as in most of the oils. This molecular structure tends to disappear at higher ranks. Thiols are hydrogen sulphur pairs, which in this case are incorporated into the above structures.

- Aliphatic, aromatic or mixed sulphide (thioethers). This is a radical+sulphur+radical bond, in which the ring or chain structures form the radials.

- Aliphatic aromatic or mixed disulphides. This a radical+sulphur+sulphur+radical molecule;

- Heterocyclic compounds of thiophene type. This is a ring structured molecule containing carbon and a single sulphur atom. The thiophenic group is thermally the most stable and predominates at higher ranks, whereas the thiols are converted or lost. During carbonization much of the thiol-held sulphur is lost. For medium-volatile coals about 30 % of the organic sulphur is lost during carbonization.

Sulphur in sulphides occurs in coal predominantly as pyrite and sometimes marcasite. Many other sulphides can occur, but usually in trace amounts. Often trace metals in coal are associated with the pyrite fraction.

Sources of sulphur in coal

Primary sulphur (S) in coal can originate from sea water, fresh water, vegetation and extraneous mineral matter. Secondary sulphur can be introduced during (syngenetic) or after (epigenetic) coal formation by ground water, which is probably remobilizing sulphur that originated in sea water or as loosely held organic sulphur in the vegetation.

Fresh water contains 0 to 10 ppm S and therefore, even if there is prolonged circulation of fresh water through the peat, can not donate much sulphur to the coal.
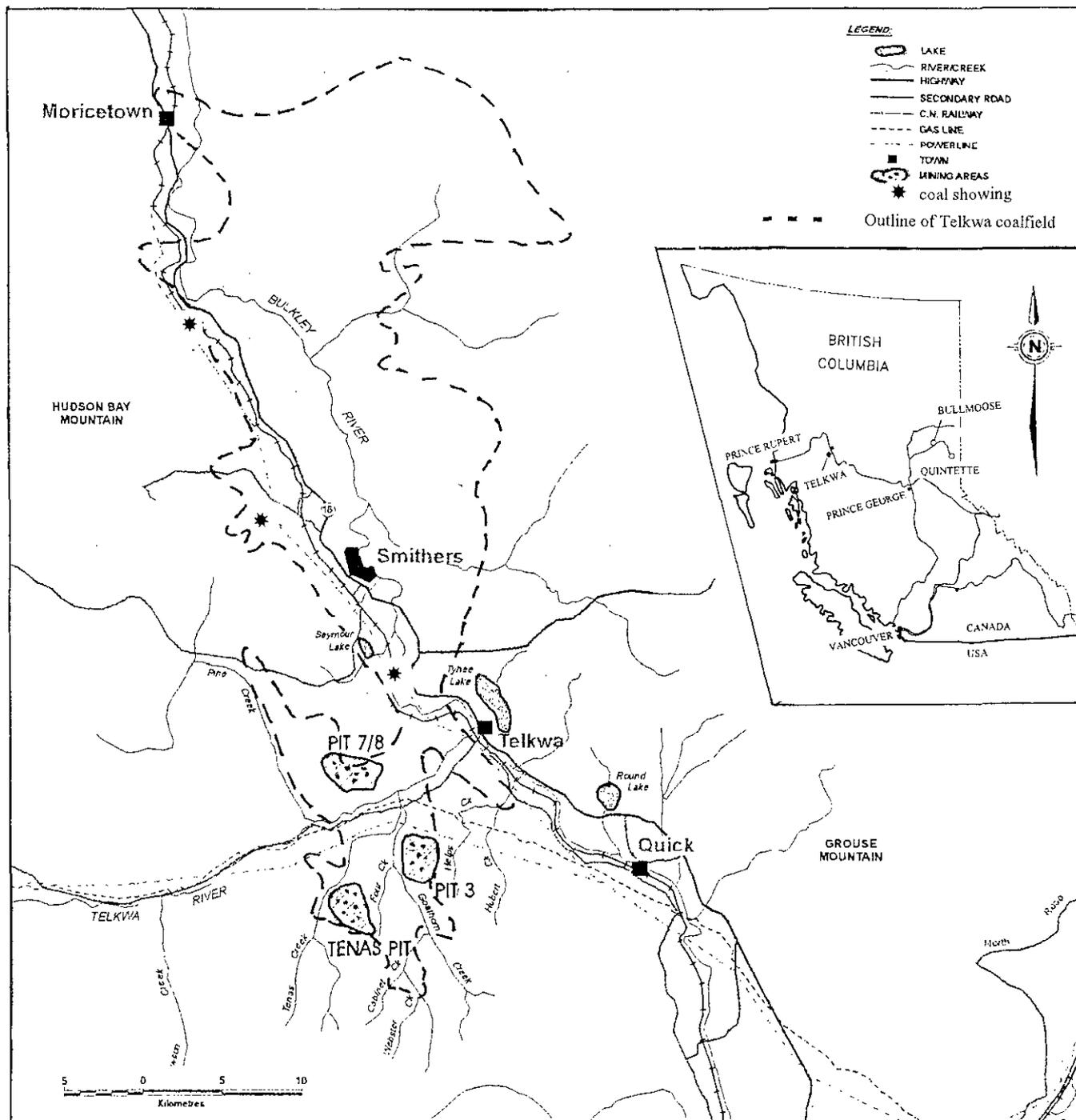
Figure 1: Regional map of the Telkwa coalfield indicating location of the proposed pits.

It is unlikely that much sulphur in coal comes from extraneous mineral matter. If the mineral matter contains sulphides, then they could provide a source of SO_4 and H_2S to the coal, but amounts would usually be small. Even though pyrite is often found in parting material in coal, the sulphur probably originated in the coal. Partings formed by degradation of biomass may contain high concentrations of sulphur liberated from the biomass. Partings composed of extraneous mineral matter will have variable sulphur contents depending on the degree of marine influence and introduction of sulphur.

Vegetation generally has between 0.01 % and 0.5 % S on a dry basis with marine influenced vegetation having higher concentrations. Plants that grow in brackish water have higher organic sulphur contents than fresh water species, probably because they have adapted to a high sulphur environment. A number of authors quote average concentrations of sulphur in vegetation; Salisbury (1969) considers 0.1 % S to be adequate for higher plants; Altschuler et al. (1983) provides sulphur concentrations ranging from 0.01 % to 0.15 % for dry grass with the root material having the highest concentrations; Rankama and Sahama (1950) give an

average of 0.4 % S for angiosperms; Wedepohl (1978) quotes an average for mean concentration plants of 0.5 % S. These concentrations will increase as the vegetation is coalified and volatile matter lost. Even with a 50 % weight loss, which would double these concentrations, there is not enough sulphur in most vegetation to explain sulphur concentrations in coal of over 0.5 % .

If a coal seam contains more than about 0.5 % sulphur, then some of the sulphur was probably derived from sea water, which contains on average 0.265 % SO_4 or 885 ppm S (SO_4 contains 33.4 % S). If a swamp contains 40 % sea water, then this accounts for a total amount of introduced S of: 0.4 x 0.265 x 0.334 = about 0.035 % S.

Water-saturated peat can compact by a factor of 5 or more as it is transformed into bituminous coal. If all the sulphur from the water is taken up by the coal, then 0.035 % S in the peat could increase to a concentration of 0.2 % S or more in bituminous coal. This could account for about 0.37 % pyrite if all the S was used to make pyrite. Many coal seams, with sulphur concentrations in excess of 1 % formed over a protracted time, during which sea water was percolating through the peat and continually providing additional SO_4. Sulphur was extracted from sea water and formed pyrite or increased the organic sulphur content of the coal. This implies repeated influxes of sea water and a hiatus, during which the swamp vegetation did not sink into a hydrological environment isolated from sea water.

Sea water is denser than fresh water and it is interesting to consider various ways that it can be introduced into a paralic environment. One possibility is that occasional high tides cause an influx of sea water over the top of the fresh-water saturated swamp. The sea water sinks and mixes with the underlying fresh water aided by the density difference and various gases, such as methane and carbon dioxide, that are migrating upwards through the swamp. The result is a temporary brackish water environment, that increases the sulphur content of the interstitial water. Over a period of years repeated high tides are able to supply sufficient SO_4 to the swamp to explain sulphur concentrations higher than 1 %. Because the influxes are repeated only once or twice a year they do not inhibit plant growth. Other scenarios exist for the introduction of sea water, such as the percolation of sea water through unconsolidated permeable hangingwall rocks. Models of the hydrology of salt water influxes mixing with fresh water may give some insights as to how sulphur contents vary laterally within seams.

Sea water also introduces large quantities of sodium (10500 ppm), chlorine (1900 ppm), magnesium (1350 ppm) and potassium (380 ppm) along with the 885 ppm sulphur (average concentrations for sea water, Mason, 1966). These extra elements introduced into the swamp generally stay in solution and are eventually dewatered from the peat or expelled as the rank increases. The magnesium, iron and calcium may be trapped in the coal as carbonates, though generally sea water does not introduce much iron (<1 ppm) or calcium (400 ppm).

Secondary sulphur includes sulphur remobilized during coalification to form syngenetic pyrite, which is often found on cleats. This sulphur may originate from less stable, organic sulphur compounds that break down at low rank or from sulphate rich interstitial water that is squeezed out of the coal as it is compacted and rank increases.

Various studies summarized by Chou (1990) indicate that most of the sulphur in coals with less than 1 % sulphur comes from the original vegetation. For coals with more sulphur, an increasing proportion comes from sea water. Price and Shieh (1979) using sulphur isotope data found that 63 % of the sulphur in high sulphur coals (>0.8 % sulphur) is derived from sea water by sulphate reduction and the rest is derived from the original vegetation. For low sulphur coals the proportion of sulphur derived from sea water decreases to 13 %.

Origin of pyrite in coal

It is important when visually estimating the amount of pyrite in a seam to understand the relationship to sulphur contents. Pyrite (FeS_2) has a density of 5.01 g/cc and therefore is about 3.5 times denser than coal. A 1 % visual estimate of the volume of pyrite in a coal seam translates into 3.5 weight % FeS_2, or about 1.9 weight percent sulphur.

Pyrite in coal typically forms from H_2S and Fe in solution. The process involves bacterial reduction of SO_4 to H_2S at pH values of 7 to 4.5 followed by the combining of H_2S, elemental sulphur and ferrous iron oxide (FeO) to form pyrite and water. This is the only way pyrite can form in peats and low rank coals. Consequently the presence of bacteria and the required pH range are very important controls on pyrite formation in coals. The SO_4 may come from sea water or vegetation, but neither of these sources provide iron, which is usually in plentiful supply and comes from other sources. It is probably derived from the breakdown of clay minerals and is possibly carried in solution as stabilized organic colloids (Price and Shieh, 1979).

The availability of iron influences the amount of pyrite and of secondary organic sulphur formed. Sulphur derived from H_2S is much more easily converted into pyrite than into organic sulphur. Therefore if an iron source is not available, then some of the H_2S may stay in solution and escape the swamp. Sources of iron can be limited in a number of ways. The water feeding the swamp may be clean fresh water containing little clay. The water may have a very low pH, which makes it easier for humic acids to flocculate clays before they have a chance to disperse through the swamp. Alternatively the water may be saline and saline water flocculates iron containing colloids (Price and
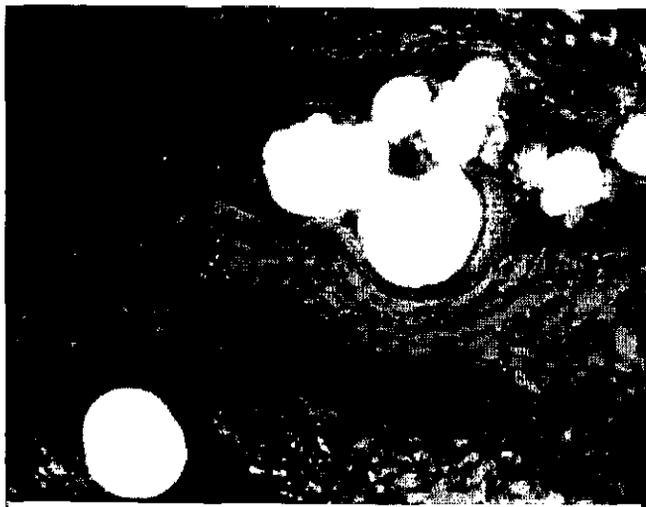
Photo 1: Framboidal pyrite in C seam. All photos taken in oil Immersion 50x10 power with a field of view of about 1.5 millimetres.

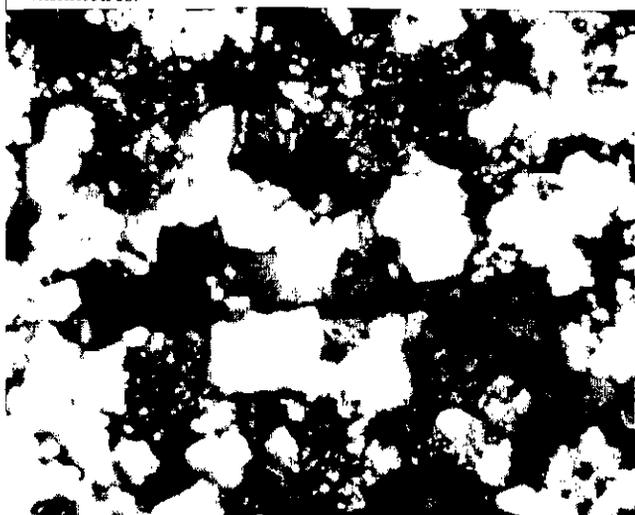Photo 2: Fine euhedral pyrite in 1 seam.

Photo 3: Coarse pyrite in a matrix of detrovitrinite and finely dispersed mineral matter; 1 Upper seam.

Photo 4: Pyrite filling fractured inertinite in 1 seam.

and Shieh, 1979). The last case explains why marine-influenced swamps do not have the highest sulphur contents for coal-forming environments. Despite the availability of a lot of H_2S, there is not a lot of iron available to make pyrite and though some H_2S is converted to organic sulphur some escapes from the swamp.

The Eh and pH environments required by the bacteria to generate H_2S determine the relative amount of pyrite formed in coal. They also influence the preservation of vegetation and the formation of vitrinite and inertinite. At optimum pH conditions (7 to 4.5) bacteria can use SO_4 from sea water or true organic sulphur to generate H_2S, which is then used to make pyrite. Therefore, the organic sulphur content can decrease in some high sulphur coals because it is used to make pyrite (Diessel,

1992). For Australian Permian coals with total sulphur contents above about 1 per cent, organic sulphur contents decreases and pyrite contents increase markedly. This effect, which has implications for acid rock drainage (ARD) because it increases the ratio of pyrite to total sulphur, is not seen in coals from Telkwa.

Within a maceral the concentration of organic sulphur tends to decrease in proximity to pyrite grains; the extent of the affected area increases as the size of the grain becomes larger. This is interpreted to indicate that H_2S is more easily combined with Fe to form pyrite than in being adsorbed into the maceral as organic sulphur (Harvey and Demir, 1992). After the coal was heated the sulphur content around pyrite grains increased because sulphur, released as the pyrite oxidized, was infused into the surrounding coal as elemental sulphur.

Pyrite morphology and genesis

Pyrite can have at least four easily recognized forms as described by Diessel (1992):

- framboidal pyrite composed of fine radiating octahedral crystals, which form spheroids within the macerals;
- euhedral pyrite, which occurs as small (1-10 microns) isolated crystals and cell-filling pyrite within macerals;
- coarse pyrite, which generally surrounds maceral fragments;
- late pyrite in cleats fractures or as nodules.

Other forms include cauliflower pyrite, which appears to develop from framboidal pyrite and dendritic pyrite, which may also be a development from framboidal pyrite. Concretions and cone-in-cone pyrite are late forming and fill cell voids, mainly in semifusinite. The different forms of pyrite crystallize at different times during peat formation and probably under slightly different conditions.

Framboidal pyrite (Photo 1) is composed of spherical clusters of very fine, needle-shaped pyrite crystals (<2 μm). The H_2S used to make framboidal pyrite is usually derived from bacterial reduction of sulphur in vegetation and therefore this form of pyrite forms at the beginning of diagenesis of the peat swamp. Its formation probably does not depend on the availability of SO_4 from sea water. It is usually associated with vitrinite, though its formation predates vitrinite formation as indicated by evidence of compaction and flow of the maceral around the pyrite.

Cohen et al., (1984) suggest a close association of framboid formation and microbial activity. They found that pyrite framboids often formed in rootlet material in mangrove swamps, indicating that the H_2S generating bacteria were part of the root system and were not introduced later during peat accumulation. Love (1957) has noted the common morphology between framboidal pyrite and microbial organisms and it is possible that the pyrite is actually replacing bacterial structures. Caruccio et al., (1977) describe a situation where framboidal pyrite formed in submerged vegetation over a period of 30 years. Obviously, if ideal conditions of low pH, available SO_4 and available ferrous iron exist, then framboidal pyrite can form rapidly.

Altschuler et al. (1983) found that the amount of framboidal pyrite increased downwards through peat at the expense of organic sulphur, indicating that sulphur for making framboidal pyrite was being derived from the vegetation by bacterial activity. This reflects pH conditions, which were more favourable for bacteria deeper in the swamp. They suggested two ways of releasing the sulphur as H_2S from the vegetation: one, indiscriminate release of all organic sulphur in anaerobic conditions followed by reduction of any sulphate

available; or two, degradation of organic sulphur by heterotropic sulphur reducing bacteria. If the swamp is rapidly submerged the increase of framboidal pyrite with depth at the expense of the organic sulphur will be preserved. If, however, there is a hiatus during which saline water is introduced into the top part of the buried peat, then there will be an increase in total sulphur and pyrite in the top part of the seam.

Fine, euhedral pyrite is often found in what appear to be cavities in desmocollinite (Photo 2) or filling cells in semifusinite, which sometimes also contains amorphous pyrite. Euhedral pyrite can also occur associated with disseminated mineral matter. This form of pyrite therefore must crystallize after formation of semifusinite, which may form by charring or burning vegetation during a period of low water table in the swamp (Lamberson et al., 1996). The peat is then submerged, possibly in brackish water, and pyrite crystallizes in the cell porosity.

Inertinite is enriched in the upper part of many seams and consequently euhedral pyrite may predominate in the upper part of seams. Euhedral pyrite found in vitrinite may have the same origin as framboidal pyrite, but the larger crystals and association with cavities imply existence of a stable, probably aqueous environment and a some what later origin.

Euhedral pyrite may form from the direct precipitation of FeS_2, which forms from elemental sulphur and ferrous iron. The elemental sulphur is formed from the oxidation of bacterially-generated H_2S (Altschuler et al., 1983); the ferrous iron is available because higher pH has reduced solubility. These conditions, initially moderate to low pH followed by higher Eh and pH values, are similar to those required for the formation of inertinite and suggest a fluctuating water table.

Coarse pyrite, large clusters of framboids or cauliflower pyrite probably form late in diagenesis when permeable roof rock permits an influx of sulphate-rich sea water. Conditions still permit the bacterial reduction of SO_4 and the formation of pyrite. The peat has undergone some humification, which makes it more susceptible to addition of organic sulphur. The pyrite forms between maceral grains and there is less evidence of compaction around the pyrite. At Tenas Creek this form of pyrite is associated with detrovitrinite clearly indicating a late emplacement (Photo 3).

Coarse pyrite is nearly always found in the seams adjacent to the roof and less commonly the floor. Its concentration will depend in large part on the lithology of the roof rocks. Rocks that indicate a marine incursion, or are more permeable, may signal increased coarse pyrite in the upper part of the underlying seam. This will not necessarily increase the wash sulphur content of the seam, because coarse pyrite is not intergrown with the macerals and is relatively easy to remove in a wash plant.

Epigenetic pyrite forms along fractures and cleats in the coal. It therefore forms after biogenic coalification when the coal is mature enough to fracture or form
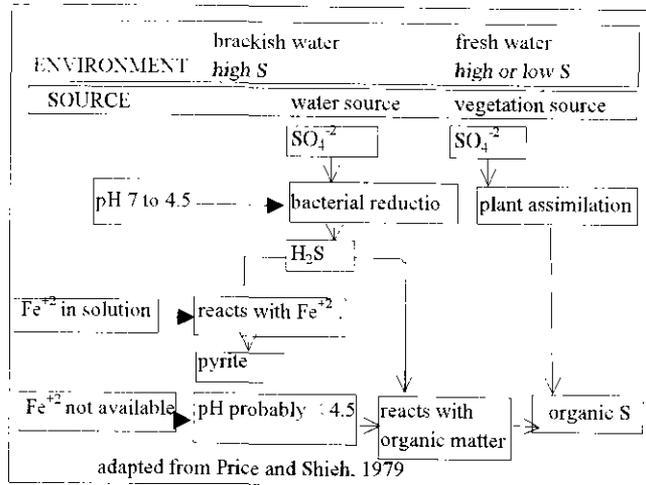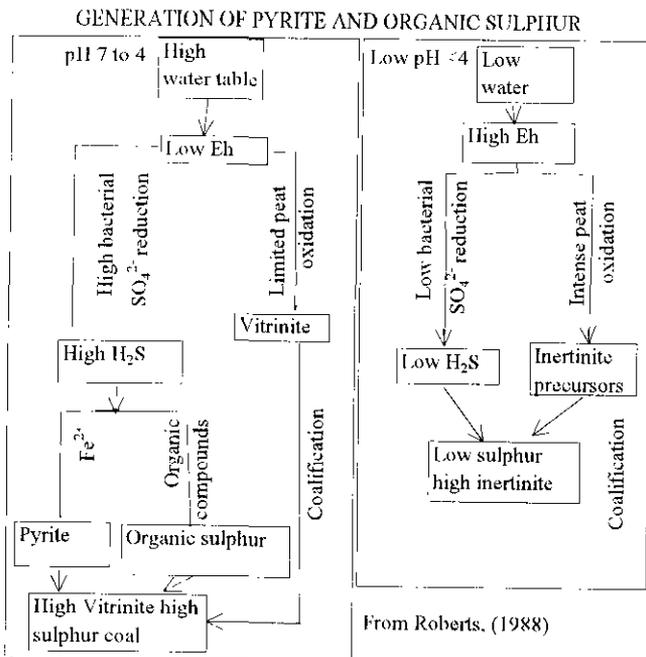
WATER TABLE ——▶ predominently HIGH														predominently LOW ◀—— WATER TABLE														
sea water ————▶ YES				NO										NO				YES◀— sea water									
paralic				limnic										limnic				paralic									
Eh ——▶ low		high		low		high		low		high	low	high ◀— Eh															
pH ——▶ low	mod	high	mod	low	mod	mod	high	low	mod	mod	high	mod	high◀ pH														
Fe+2 Y N	Y N	Y N	Y N	Y N	Y N	Y N	Y N	Y N	Y N	Y N	Y N	Y N	Y N															

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
TS	H	H	H	H	H	H	H	H	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	m	m	m	m
PS	m	l	h	m	m	l	h	l	m	l	m	l	m	l	m	l	m	l	m	l	m	l	m	l	m	l	m	l
OS	m	m	m	h	m	h	l	m	m	l	l	m	l	l	l	l	l	m	m	m	l	m	l	l	l	m	l	l
Ash	L	L	L	L	H	H	M	M	L	L	L	L	L	L	M	M	M	M	L	L	M	M	H	H	m	m	h	h
TI	M	M	L	L	M	M	M	M	M	M	M	M	M	M	H	H	H	H	M	M	M	M	H	H	m	m	h	h
SI	l	l	l	l	h	h	m	m	l	l	l	l	m	m	m	m	m	m	m	m	h	h	h	h	h	h	h	h
USI	h	h	h	h	l	l	m	m	h	h	h	h	m	m	m	m	m	m	m	m	l	l	l	l	l	l	l	l
TV	M	M	H	H	L	L	H	H	M	M	H	H	M	M	L	L	L	L	M	M	M	M	L	L	M	M	L	L
SV	l	l	h	h	m	m	h	h	l	l	h	h	h	h	m	m	l	l	h	h	h	h	m	m	h	h	m	m
USV	h	h	l	l	m	m	l	l	h	h	l	l	l	l	m	m	h	h	l	l	l	l	m	m	l	l	m	m
L	H	H	M	M	H	H	M	M	H	H	M	M	M	M	H	H	H	H	M	M	M	M	H	H	M	M	H	H

Total Sulphur=TS Pyritic Sulphur=PS Organic Sulphur=OS

TI=total Inerts SI=Stuctured inerts (semifusinite+fusinite) USI=Unstructured inerts (macrinite+inertodetrinite)

TR=total vitrinite SV=Structured vitrinite (tellinite+telocollinite) USV=Unstructured vitrinite (desmocollinie+detrovitrinite)

L=liptinite   Y - yes present   N= no not present

H=HIGH   M=AVERAGE   L=LOW   h=higher m=average l=lower

Figure 2: Composite coal formation model indicating possible trends in coal formation based on 5 environmental parameters. The composition of the coal is described in terms of sulphur forms, maceral types and ash. The relative proportions or which are quantified by the letters H, M or L for above average, average or below average. Lower case letters (h, m and l) are used for relative proportions of sub components. The diagram provides a way of illustrating possible relationships between environment and composition of coal. The relationships are probably only rough at best.

cleats. In coal from Tenas Creek pyrite forms on fractures or surrounding fragments of inertinite in seam 1 (Photo 4). Spears and Caswell, (1986) suggest that pyrite forms on cleats at temperatures of less than 35°C and is one of the earliest forming cleat fillings, predating kaolinite and calcite, which deposit at temperatures of over 35°C and 100°C respectively.

Formation of epigenetic pyrite may utilize H_2S formed by bacterial reduction of SO_4 at shallow depths. In this case the sulphate is probably contained in brackish interstitial water (bed moisture) that is 35 weight percent of lignite but is only 10 weight percent in high-volatile coals. Part of this fluid must be expelled along cleats as the coal is compacted and rank increases. The H_2S may also be a component of the interstitial water surviving from an earlier period of bacterial reduction or come from the breakdown of sulphur bearing organic molecules in the coal (Aliphatic or aromatic thiols). The iron probably comes from surrounding mudstones, in which biochemical reduction of Fe oxyhydroxides releases Fe (Spears and Caswell, 1986).

Cleats are preferentially developed in vitrinite but will be developed through the whole seam. Consequently epigenetic pyrite will not be restricted to

the hangingwall or footwall part of the seam. It will be easier to wash out of the coal than euhedral or framboidal pyrite, but may still be deceptively difficult to remove because cleats are often in reality a network of fine interconnecting fractures.

Organic sulphur in coal

The term organic sulphur refers to how the sulphur is bound to the coal molecules; it does not mean that all the sulphur was necessarily derived from the original vegetation. Obviously in many coals the concentration of organic sulphur is increased by the addition of marine-derived sulphate sulphur, which was first reduced to H_2S and then combined with coal molecules.

Sulphur is not evenly distributed through vegetation. Spores, seeds and resin, which later form the liptinite macerals, are enriched in sulphur and resistant to oxidation. Sulphur concentrations in other parts of the vegetation probably vary, but the variation is masked by variable redistribution in the peat swamp and the effects of diagenesis. In general organic sulphur is concentrated in the liptinite and vitrinite macerals with less in the inert macerals.

pH 7 to 4 | High water table

Low pH <4 | Low water

Low Eh

High Eh

High bacterial SO_4^{-2} reduction

Limited peat oxidation

Low bacterial SO_4^{-2} reduction

Intense peat oxidation

Vitrinite

High H₂S

Low H₂S

Inertinite precursors

Fe^{-2}

Organic compounds

Coalification

Low sulphur high inertinite

Coalification

Pyrite | Organic sulphur

High Vitrinite high sulphur coal

From Roberts. (1988)

ENVIRONMENT | brackish water high S | fresh water high or low S

SOURCE | water source | vegetation source

SO_4^{-2} | SO_4^{-2}

pH 7 to 4.5 ----► bacterial reductio | plant assimilation

H₂S

Fe^{+2} in solution ►reacts with Fe^{+2}

pyrite

Fe^{+2} not available ► pH probably <4.5 | reacts with organic matter | organic S

adapted from Price and Shieh. 1979

Figure 3: Pyrite formation models suggested by Roberts (1988). and Price and Shieh (1979)

In limnic coals, which do not contain sulphur introduced by sea water, there should be a positive correlation between the contents of reactive macerals and organic sulphur and an inverse relationship between the contents of organic sulphur and fine framboidal pyrite. The total amount of sulphur in the seam should remain fairly constant, decreasing somewhat as the percentage of semifusinite and fusinite increase, because formation of these macerals is probably accompanied by fire and some volatilization of sulphur. The ratio of pyritic sulphur to total sulphur should tend to increase as the percentage of inert macerals increases.

In paralic coals, the organic sulphur content of coal can be increased by the addition of sulphur derived from sea water. If ferrous iron oxide is not readily available, or is highly soluble because of lower pH conditions, then bacterially generated H₂S can react directly with the vegetation to form organic sulphur compounds (Chou, 1990).

Sulphur is taken up by the pre-liptinite macerals, especially sporinite, which are very efficient at incorporating sulphur. Demir and Harvey (1991) found that the sulphur content in sporinite was higher than in all other macerals and the vegetal precursor. They suggest that macerals rich in hydrogen and aliphatic constituents, which remain fairly stable during the early stages of coalification, are very efficient at taking up any sulphur available as H₂S. The concentration of sulphur in these macerals can range up to 5 % (Demir and Harvey, 1991), but because they make up generally less than 10 % of the coal, they do not effect the average organic sulphur concentration of the coal as much as organic sulphur in vitrinite.

The organic sulphur concentration of vitrinite, which usually makes up more than 50 % of the coal, varies from about 0.4 % to 5 %. Consequently variation in vitrinite contents have a significant effect on the total sulphur content of the coal. Sulphur contents of some vitrinites are higher than in the original vegetation, indicating addition of sulphur from sea water sulphate or redistributed of the original organic sulphur.

The inert macerals generally have less organic sulphur than the reactive macerals and contents range from 0.2 % to 3.5 %. The mean organic sulphur contents decrease in the order semifusinite > fusinite > macrinite (Demir and Harvey, 1991) and are generally less than in the precursor vegetation. Burning of the peat causing sulphur volatilization can explain the low sulphur content in fusinite, but not necessarily in macrinite, from which sulphur may have been removed by bacterial activity prior to charring.

ASSOCIATION OF MACERALS AND SULPHUR

The previous sections partially discuss the relationships between pyrite and organic sulphur and the different macerals. The general environmental processes that influence these relationships are discussed here. The key word is influence; there may not be strong linkages between maceral composition and the environment in which the original vegetation grew, died and matured into coal. The more important processes considered here are changes in water salinity, effects of fire, oxidation, humification, gellification and putrefaction (Diessel, 1992) and sediment influx. On the more specific and local scale they can, in part, be represented by;

• the presence of SO₄ from sea water;

• changes in the level of the water table level, which influences the risk of fires in the swamp;

• changes in the Eh of the water;

• changes in the pH of the water, which together with Eh influence the processes of humification, gellification and putrefaction;

• the amount of clay available, which provides iron for making pyrite.

These five parameters are used to help demonstrate possible relationships between coal compositions and various environments (Figure 2). Figure 2 combines diagrams proposed for maceral formation by Diessel (1992) and diagrams proposed for pyrite formation by Roberts (1988), Price and Shieh, (1979, Figure 3) and Ryan (1997). The five parameters are organized in a hierarchy such that 28 branch-ends are formed. The end of each branch represents a particular coal type, which is described in terms of the relative contents of sulphur, ash, inertinite, vitrinite and liptinite. Figure 2 provides a rough template for working from environment to coal composition or backwards from composition to a number of possible environments.

The level of the water table is one of the most important factors influencing coal formation. Under conditions of high water table, influxes of sea water may be frequent (paralic environment) increasing total sulphur content. The Eh is generally low and fires are rare decreasing the inertinite content and increasing the preservation of vitrinite. If pH conditions are in the range 4.5 to 7, bacterial activity will reduce available SO_4 to H_2S. If the SO_4 originates from sea water, then the coal will have higher sulphur and pyrite concentrations than if the SO_4 originates from vegetation. If the paralic environment does not have periodic influxes of clays to provide iron to make pyrite, then H_2S will either stay in solution and migrate out of the swamp or remain in the coal as additional organic sulphur.

Low water tables, which are associated with a higher potential for fires and an increased inertinite content, are more likely to be found in limnic environments. There will be less chance for introduction of marine SO_4 and sulphur and pyrite contents should be low. Fluctuations in the water table level may result in high Eh and variable pH environments, which will effect vitrinite and organic sulphur contents. A low water table may be associated with a lot of bio-degradation, which will increase the inherent ash of the remaining biomass and contents of inertinite and pre-exinite macerals, which are very resistant to decay and enriched in sulphur. Therefore, higher inherent ash contents may accompany higher sulphur and low vitrinite contents.

In water with intermediate pH values preservation of vitrinite, especially structured vitrinite, is favoured. Under higher pH conditions, which do not favour the solubility of Fe^{+2}, bacterial or fungal attack of vegetation decreases vitrinite content and pyrite is less likely to form. In this case, if the water table is low or fluctuating, then the H_2S may form a gas and escape. The resulting coal will have low organic and pyritic sulphur concentrations and a high content of inertinite. The H_2S can also move downwards in solution through the peat layers into low pH environments where bacteria are not active and in this case the H_2S may combine with the organic material to form organic sulphur. This environment is one of gellification and preservation of unstructured vitrinite. The resulting coal will have a high content of organic sulphur and vitrinite and low pyrite contents.
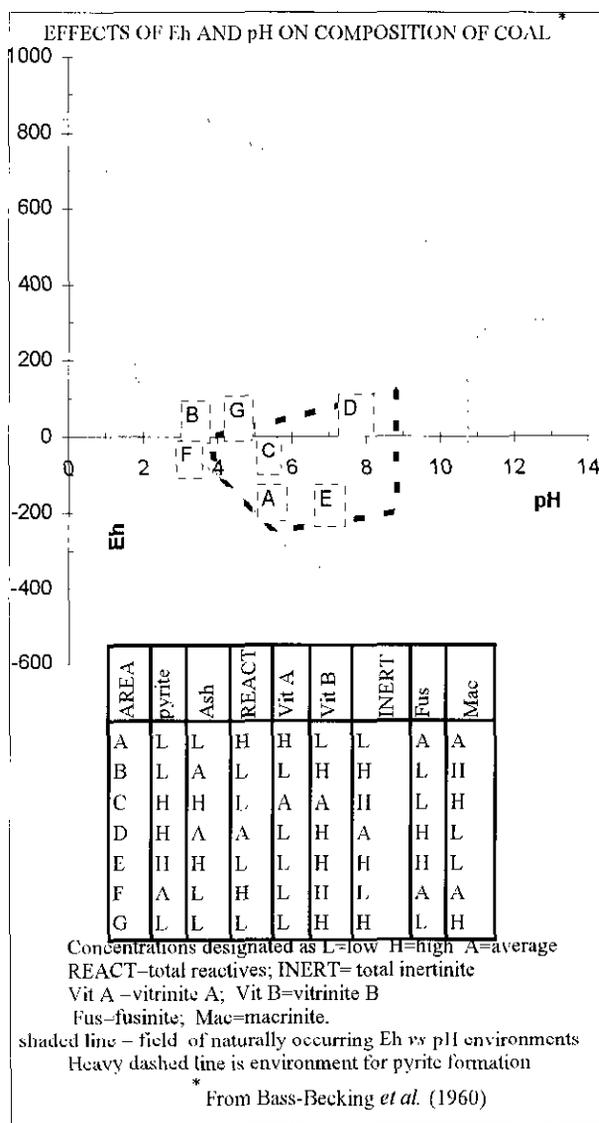

EFFECTS OF Eh AND pH ON COMPOSITION OF COAL*

AREA	pyrite	Ash	REACT	Vit A	Vit B	INERT	Fus	Mac
A	L	L	H	H	L	L	A	A
B	L	A	L	L	H	H	L	II
C	H	H	L	A	A	II	L	H
D	H	A	A	L	H	A	H	L
E	II	H	L	L	H	H	II	L
F	A	L	H	L	II	L	A	A
G	L	L	L	L	H	H	L	H

Concentrations designated as L=low H=high A=average
REACT–total reactives; INERT= total inertinite
Vit A –vitrinite A; Vit B=vitrinite B
Fus–fusinite; Mac=macrinite.
shaded line – field of naturally occurring Eh vs pH environments
Heavy dashed line is environment for pyrite formation
*From Bass-Becking et al. (1960)

Figure 4: Coal formation model adapted from Bass-Becking et al. (1960) adapted to show possible relationships between sulphur and maceral concentrations.

The pH, Eh and water table levels also influence the composition of the ash. Peats deposited in a marine influenced environment often have higher pH values and increased bacterial activity. This results in high concentrations of H, N and S originating from bacterial remains in the coal. Marine influenced coals are also often associated with alkali-rich ashes because clays are less degraded in high pH environments. At low pH values, often associated with limnic environments, montmorillonite is altered to kaolinite, which flocculates at swamp margins and not their interiors.

There is a relationship between the availability of calcium and concentrations of ash and pyrite in seams. The availability of Ca from sea water increases pH values and makes the swamp waters alkaline favouring the activity of bacteria. Pyrite-rich seams are often associated with alkaline floor sediments or penicontemporaneous marls. This may act to balance the ARD potential of high pyrite coals.

Ryan (1996) discussed possible environments for the formation of coals in the Gething Formation from northeast BC, using a pH *versus* Eh diagram derived from Baas-Becking (1960). Many Gething coal seams have low concentrations of pyrite and ash and moderate to high inertinite contents. The inertinite has a high proportion of macrinite, which has lost its cell structure and probably formed from biomass that had previously experienced some humification. Based on these characteristics Gething coals should plot in area F in Figure 4 and branches 13 to 16 (Figure 2). The low pH values inhibit bacterial activity and the formation of pyrite and flocculate clays at the margin of the peat swamp helping to keep waters in the rest of the swamp clear. They would also alter clay minerals to kaolinite. The end result is that the inherent mineral matter will be kaolinite-rich with low base/acid ratios.

Roberts (1988) studied paralic coals from South Africa, which do not have a strong marine influence. He discussed the effects of high and low water tables on the composition of coal. His models are illustrated by branches 9-12 and 21-24 (Figure 2). He found that total sulphur correlated with vitrinite in coals, which probably formed under high water table conditions and moderate pH conditions. Coals formed under low water table conditions, high Eh and low pH values were characterized by high inertinite and low sulphur contents. Inertinite-rich coals of Australian cratonic basins (Hunt, 1989) are characterized by moderate sulphur contents that also correlate with vitrinite content. They may have formed in environments 21-24, Figure 2.

Based on a study of the Upper Freeport coal seams in Pennsylvania, Cecil *et al.* (1979) proposed three environments. the first, an intermittent aerobic peat environment, is characterized by low pH, high ash, semifusinite and macrinite contents and low sulphur concentrations. The intermittent oxidizing conditions inhibit the formation of H_2S and therefore pyrite, but increase the amount of inerts and ash in the coal (branches 9, 10, 23, 24 on Figure 2 and area B on Figure 4).

The second is an anaerobic peat environment with pH values >4.5. This environment is characterized by high ash, sulphur, exinite and micrinite contents. The intermittent pH value is ideal for the production of H_2S and bacterial destruction of vitrinite. Removal of vitrinite increases the percentage of exinite (branches 5 to 8 on Figure 2 and area C on Figure 4).

The third is an anaerobic peat environment with pH values <4.5. The low pH in this environment coupled by the high water table produces a coal with low ash and sulphur contents and high vitrinite contents (branches 9 and 10, Figure 2 and area A, Figure 4).

Renton and Bird (1991) state that the swamp environment plays a large part in defining both the content of pyrite and the maceral composition of the coal. In swamp environments with pHs > 4.5, high ash, pyritic sulphur and exinite concentrations are associated with peat that evolves to coals with low vitrinite contents (branches 5 and 6 in Figure 2 or area D in Figure 4).

The vitrinite will probably be desmocollinite associated with a lot of disseminated mineral matter. Environments where pH is less than <4.5, the resulting coals have low pyrite contents and high contents of bright vitrinite (tellinite and telocollinte) (branches 3 and 4 in Figure 2).

Lamberson *et al.* (1996) suggest that most inertinite is formed by fires, which burn the peat surface when it dries out. Many authors correlate low water tables during peat formation with the increased development of inertinite in coals, but often the exact process responsible for forming the inertinite is not well explained. Lamberson *et al.* point out that it is difficult to find a process other than burning, charring or smoldering that will increase the reflectance of organic material. This method of forming inertinite may make it easier to form inertinite-rich coals that are not associated with a lot of fine mineral matter or sulphur. In this case the inherent mineral matter could be carried away as smoke and the sulphur volatilized as SO_4. It is harder to understand how burning or smoldering in the dried peat bed can produce coals with large amounts of macrinite, which has lost most of its cell structure.
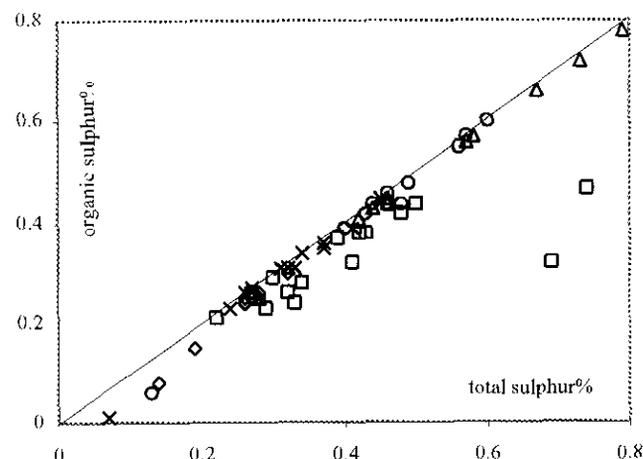

Figure 5: Plot of organic sulphur *versus* total sulphur for a number of Mist Mountain seams. Diamond, Rmax= 1.38 per cent. Triangle, Rmax= 1.36 per cent. Circle, Rmax=1.35 per cent. Cross, Rmax=1.25 per cent. Square, Rmax=0.9 per cent.

SULPHUR FORMS IN COALS OF DIFFERENT RANK

The way organic sulphur is held in coal changes as rank increases, but this is not necessarily associated with a release of sulphur. Hydrogen sulphide gas is not generated from coal below temperatures of above 200°C (Hunt, 1979). As rank increases, so does the aromaticity of the coal so that some of the sulphur bound as thiols is restructured into heterocyclic compounds of thiophene type. If the sulphur is lost from coals, then on average the amount of organic sulphur in coal should decrease as the rank increases. Data from a number of seams from the Mist Mountain Formation (Figure 5) do not reveal any change in the relationship between total sulphur and organic sulphur for seams ranging in rank

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Table 1
ANALYTICAL DATA TENAS CREEK AREA

sample	seam	from	to		ARM	ADM	VM	Ash	FC	TS%	PS%	OS%	1.6 yld	ADM	VM	Ash	FC	TS%	PS%	OS%
TK96-10	C	0	20	HW	4.59	0.61	23.7	13.9	61.8	3.13	1.4	1.62	81.0	0.51	25	9.07	65.4	1.44	0.54	0.82
TK96-11	C	20	40	COAL	4.45	0.69	25	21.5	52.8	1.06	0.3	0.72	70.6	0.66	25.2	14.6	59.6	0.97	0.21	0.73
TK96-12	C	40	72	COAL	4.56	0.61	23.7	18.2	57.5	1.11			77.5	0.71	25.4	11.9	61.9	1.11		
TK96-13	C	72	103	COAL	4.24	0.7	21	36.1	42.2	6.5			30.0	0.47	29	7.19	63.4	1.67		
TK96-14	C	103	132	COAL	7.66	0.6	28.3	6.18	64.9	1.57	0.54	0.98	96.5	0.52	29.2	4.22	66	1.18	0.36	0.78
TK96-15	C	132	160	COAL	6.45	0.59	25.9	7.14	66.4	1.28			98.3	0.5	26.2	6.58	66.7	1.18		
TK96-16	C	160	170	FW	5.77	0.75	25	18.3	55.9	0.91	0.16	0.71	75.1	0.51	26.3	10.2	63	0.89	0.06	0.8
TK96-17	C	MDSTFW rock			3.39	0.76	16.5	69.4	13.3	5.1										
mass wt averages						0.65	23.8	21.3		3.01						9.31		1.09		
Channel	C seam					0.7	24.5	16.6	58.2	1.91										
TK96-1	1 U	0	16	HW	5.31	0.83	24.2	8.54	66.5	1.33	0.45	0.79	94.1	0.64	24	6.2	69.2	1.31	0.44	0.79
TK96-2	1 U	16	28	COAL	3.04	0.68	20.9	30.9	47.5	7.3	3.52	3.62	46.6	0.42	22.8	13.1	63.7	1.21	0.38	0.74
TK96-3	1 U	28	33	MDST	2.45	0.68	16.2	68	15.2	2.49						nd		nd		
TK96-4	1 U	33	58	COAL	5.03	0.51	31.4	6.09	62	1.96			95.5	0.24	31.6	4.32	63.8	1.85		
TK96-5	1 U	58	78	COAL	8.03	0.67	26.8	7.4	65.1	4.43			91.6	0.5	28.3	2.65	68.6	1.4		
TK96-6	1 U	78	94	COAL	6.51	0.64	28.9	4.99	65.5	2	0.61	1.34	96.3	0.45	30	3.77	65.8	1.64	0.42	1.17
TK96-7	1 U	94	117	COAL	6.9	0.53	28.2	3.97	67.3	1.82			96.9	0.41	28.6	3.09	67.9	1.59		
TK96-8	1 U	117	146	COAL	7.96	0.59	24.2	7.7	67.6	1.42			95.6	0.54	24.9	6	68.5	1.3		
TK96-9	1 U	146	180	FW	6.45	0.5	24.4	15.5	59.6	1.19	0.33	0.84	76.9	0.53	25.5	8.96	65	1.11	0.23	0.86
mass wt averages						0.61	24.6	17.85		2.61						6.41		1.39		
Channel	1 Upper					0.6	24.8	14.6	60	2.72										
TRC-05C-15	1	0	4	SLST	3.52	0.86	12.5	80.6	6.07	0.42										
TRC-05C-14	1	4	10	MDST	5.5	0.85	11.8	72.6	14.9	0.51										
TRC-05C-1	1	10	35	COAL	8.72	0.7	23.5	12.8	63	0.71	0.09	0.61	94.5	0.95	23.9	9.59	65.6	0.66	0.05	0.61
TRC-05C-2	1	35	64	COAL	5.8	0.82		15.8		0.57			87.9	0.65	23	10.7	65.8	0.59		
TRC-05C-3	1	64	94	COAL	7.58	0.74		8.17		0.69			95.1	0.96	25.2	5.27	68.6	0.65		
TRC-05C-4	1	94	124	COAL	7.42	0.67		12.5		0.56			93.6	0.87	22.2	9.76	67.2	0.52		
TRC-05C-5	1	124	154	COAL	9.46	0.8	25.5	6.06	67.7	0.76	0.13	0.54	97.3	0.64	25.9	4.69	68.7	0.73	0.12	0.52
TRC-05C-6	1	154	184	COAL	7.43	0.8		10.3		1.05			92.4	0.98	24.4	7.14	67.5	0.92		
TRC-05C-7	1	184	214	COAL	8.15	0.75		16		0.64			86.3	0.93	24.5	9.97	64.6	0.59		
TRC-05C-8	1	214	244	COAL	12	0.77		21.3		0.63			70.0	1.08	26.8	6.27	65.9	0.7		
TRC-05C-9	1	244	274	COAL	9.45	0.78		22.5		0.79			73.7	0.99	25.3	10.6	63.1	0.75		
TRC-05C-10	1	274	304	COAL	7.61	0.86	20.6	29.8	48.7	0.6	0.18	0.4	53.0	1.04	23.1	12.9	62.9	0.72	0.1	0.6
TRC-05C-11	1	304	334	COAL	8.82	0.78		7.82		0.77			94.1	1.03	24.7	5.16	69.2	0.75		
TRC-05-12	1	334	359	COAL	7.61	0.73	22	11.6	65.7	0.6	0.08	0.51	91.3	1.23	22.4	7.84	68.5	0.59	0.05	0.54
TRC-05-13	1	359	369	COAL	7.12	0.75	20.5	19.6	59.1	0.57										
mass wt averages						0.77	22.1	16.59		0.68						8.14		0.67		
Channel	1 Seam					0.9	24.8	14.3	60	1.67										

ARM as-received moisture	FW foot wall	OS organic sulphur	TS total sulphur PS pyritic sulphur
1.6 yld float yield at 1.6 specific gravity	HW hanging wall	AD air-dried moisture	from to in centimetres

from 0.9 % to 1.38 %. It is not clear what happens to the organic sulphur in liptinite when it is progressively destroyed at higher ranks. Any organic sulphur lost during this transformation probably escapes in bitumen that moves out of the coal and leaves behind sulphur-free grains of micrinite.

THE TELKWA COALFIELD

The Telkwa coalfield is in central British Columbia, centered on the town of Smithers. It extends from north of Smithers to south of Telkwa for about 50 kilometres along the Bulkley River (Figure 1). The coalfield contains a potential coal resource of approximately 850 million tonnes (Ryan and Dawson, 1994). The Telkwa coal property, which occupies less than 10 percent of the whole field, is 15 kilometres south of Smithers and is centered on the confluence of the Telkwa River and Goathorn Creek. Coal on the property is generally high-volatile A bituminous and is considered to be an excellent thermal coal with some weak coking coal potential. Exploration in the last few years has been successful in finding more reserves in the southwest corner of the license block near Tenas Creek (Figure 1) and about 21 million tonnes of raw, surface mineable coal have been outlined in this area. This increases the raw coal, surface mineable reserve at Telkwa to about 50 million tonnes which makes the property more attractive for development as a thermal coal mine. At present Manalta Coal Limited is proceeding with development plans and has submitted a report to various ministries of the British Columbia Government as part of the environmental impact assessment process.

The geology of the Telkwa Coalfield is discussed in a number of papers (Koo, 1984, Bustin and Palsgrove, 1997) and is shown on regional geology maps of Tipper (1976), MacIntyre et al. (1989) and Ryan (1993). Coal-bearing rocks belong to the Skeena Group of Lower Cretaceous age and are assigned to the Red Rose Formation of Albian age and possibly also to the older
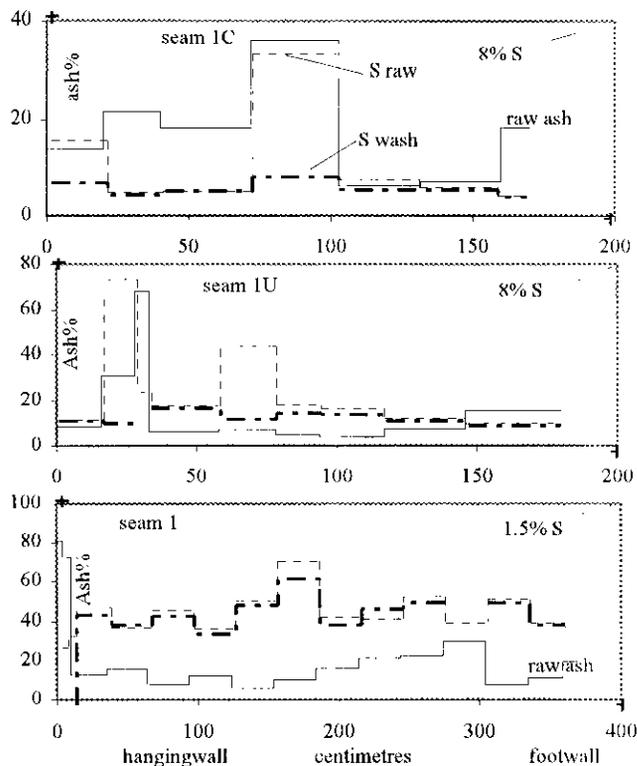
Figure 6: Ash and sulphur striplogs for seams 1, 1U and C. Ash on the left axis and maximum sulphur on the right axis.

Kitsun Creek Formation of Hauterivian age. Coal-bearing rocks outcrop north of Smithers, south of Smithers in the Bulkley River, north of the Telkwa River in the vicinity of Pine Creek, east and west of Goathorn Creek, and at the headwaters of Tenas and Cabinet Creeks (Figure 1). Cretaceous rocks of Hauterivian age outcrop along the northeast edge of the coalfield and contain only traces of coal.

Sulphur in the coal at Telkwa and Quinsam was studied by Holuszko *et al.* (1993). This study continues this investigation at Telkwa, specifically in the Tenas Creek area. In 1996 a test pit was dug in the Tenas Creek area, which is now considered to contain the best mining potential on the property and is expected to be the first area mined. The authors sampled the three mineable seams during the bulk sampling and collected increment and full seam samples. Samples were subjected to a number of analyses, petrographic investigation and scanning electron microscope work.

EXPLORATION HISTORY

There is a long history of exploration and mining in the southern part of the Telkwa coalfield. In the Telkwa area coal seams were mined in 1903 on Goathorn Creek, previously called Goat Creek (Dowling, 1915). From 1913 to 1915 the Transcontinental Exploration syndicate sank a shaft and constructed 2 tunnels in the Cabinet Creek area (previously Cabin Creek), which intersected

five seams of semi-anthracite (Dowling, 1915). During the period from 1930 to 1970, six small underground mines and one surface mine operated in the Telkwa River-Goathorn Creek area and about 480 000 tonnes of coal were mined. More recently a small tonnage of coal was mined in the Goathorn Creek area by Lloyd Gething during the 1970s and early 1980s.

The recent exploration activity at Telkwa is recorded in a number of geological assessment reports submitted to the B.C. Ministry of Energy, Mines and Petroleum Resources (now part of the Ministry of Employment and Investment) and on file in Victoria (Handy and Cameron, 1982, 1983, 1984; McKinstry, 1990 and Ledda, 1992, 1993, 1994). The property was intensively explored in the period 1978 to 1989 by Crowsnest Resources Limited, when over 350 exploration holes were drilled and a large test pit excavated in the area east of Goathorn Creek. In 1992 Manalta Coal Limited acquired the property. Since then it has carried out a number of major programs, which concentrated on the areas north of the Telkwa River, east of Goathorn Creek and east of Tenas Creek. Mineable coal reserves have now been outlined in all three areas.

LOCAL STRATIGRAPHY AND STRUCTURE

The stratigraphy of the Cretaceous Skeena Group on the Telkwa Coal property was divided into four units by Bustin and Palsgrove (1997). The lowest unit, which is 20 to 100 metres thick, rests unconformably on a basement of Lower Jurassic volcanic rocks of the Telkwa Formation, Hazelton Group. The unit is non-marine and is distinguished by an abundance of coarse clastics. It contains a single coal zone composed of up to 12 component coal beds, together referred to as Seam 1, which has a cumulative coal thickness ranging up to 12 metres and averaging 7 metres in the Tenas Creek area (Figure 1).

The coal formed in poorly drained areas adjacent t braided rivers. The combination of basement relief and poorly defined drainage patterns accounts for the variable character of Seam 1. There were occasional influxes of sea water, which periodically flooded, part or all, of the coal swamps causing both lateral and stratigraphic increase in sulphur contents of the Seam 1 coal beds.

Unit 2, which does not contain coal, is composed of from 60 to 170 metres of shallow marine mudstones and siltstones.

The major coal-bearing zone, which comprises seams 2 to 10, is within Unit 3, which averages 85 metres in thickness. The unit was deposited in an esturine mud flat environment that experienced repeated influxes of sea water alternating with regressions and deposition of channel sands. The unit is composed of siltstones, mudstones, sandstones and coal. The seams with higher sulphur contents are generally overlain by

Table 2
Petrography Tenas Creek Area

sample	liptinite	telinite	telocollinite	desmocollinite	detrovitrinite	total reactives	semifusinite	fusinite	macrinite	micrinite	inertodetrinite	total inerts	mineral matter %	ash wt %
C Seam														
TK96-10	3	6	17	25	1	53	13	0	16	0	9	38	9	14
TK96-11	1	10	16	20	3	50	17	0	10	0	12	39	11	17
TK96-12	1	9	19	19	8	57	12	0	10	0	11	33	10	16
TK96-13	1	10	10	24	19	64	3	0	2	0	1	6	29	39
TK96-14	2	8	28	29	2	70	17	1	3	0	8	30	1	1
TK-96-15	2	10	28	32	5	77	6	0	7	0	8	22	2	3
TK96-16	2	7	32	31	1	73	10	1	2	0	4	17	10	16
Av %	2	9	22	26	6	63	11	0	7	0	8	26	10	15
Av mmf	2	10	24	29	6	71	13	0	8	0	8	29		
seam 1 U														
TK96-01	2	7	12	22	4	47	19	0	19	1	12	51	2	3
TK96-02	2	6	17	27	4	57	9	0	7	0	8	24	18	27
TK96-04	1	4	46	29	2	82	8	0	6	0	1	16	2	3
TK96-05	1	3	34	14	6	58	22	0	11	0	6	39	3	5
TK96-06	3	2	31	25	4	66	14	1	12	0	4	32	2	3
TK96-07	2	4	30	26	2	66	14	0	14	0	4	33	1	2
TK96-08	2	5	16	19	5	47	20	0	17	2	11	50	3	5
TK96-09	1	2	29	19	5	56	19	0	11	1	6	37	8	12
Av %	2	4	27	23	4	60	16	0	12	0	7	35	8	8
Av mmf	2	6	35	30	5	79	21	0	16	1	9	46		
seam 1														
TRC-05-02	3	8	22	20	7	60	12	0	10	1	11	35	6	9
TRC-05-03	1	6	28	25	2	62	14	1	13	0	7	35	2	4
TRC-05-04	5	5	8	22	2	42	18	0	16	1	14	49	8	13
TRC-05-06	2	9	19	28	4	62	12	0	10	0	8	30	8	12
TRC-05-07	2	8	18	31	7	66	13	0	6	0	7	26	8	13
TRC-05-08	1	3	28	33	1	67	13	0	4	0	5	22	11	18
TRC-05-10	2	6	21	22	8	59	10	0	5	0	6	21	20	29
TRC-05-11	2	7	18	31	2	60	18	1	15	0	5	39	1	2
TRC-05-12	3	11	9	15	5	42	20	3	19	0	10	52	6	9
TRC-05-5	1	10	20	29	2	62	14	1	11	0	9	35	3	5
TRC-05-1	2	8	21	24	7	61	11	1	8	0	11	30	9	14
TRC-05-9	0	6	29	27	3	66	9	1	5	0	4	19	16	24
Av %	2	7	20	25	4	59	13	1	10	0	8	33	8	13
Av mmf	3	10	27	34	6	79	18	1	14	0	11	44		

SG coal 1.3   SG rock 2.5   ratio min matter/ash=1.2

northeast. Folding in the Late Cretaceous (Evenchick, 1991) has produced open folds that trend northwest with shallow plunges, shallow-dipping west limbs and steeper-dipping east limbs.

The Tenas Creek area, which is underlain by Unit 1, is folded into an open northwest trending syncline. Dips on the west limb range from 9° to 22° and those on the east limb are steepened up to 45°. The resource in the area is contained in Seam 1, which contains a number of coal beds, three of which feature in the mine plans. The lowest bed (1 seam) averages 3.45 metres in thickness and is overlain by a siltstone parting, which attains a maximum thickness of 2.5 meters. 1 Upper seam, which averages 1.9 metres in thickness, overlies the siltstone split. The upper-most C seam averages 1.5 metres and is separated from 1 Upper seam by 13 metres of interbanded sandstone and mudstone. Open pit mineable reserves at Tenas Creek are estimated to be 21 million tonnes based on data from 187 drillholes, which provide a hole spacing of about 150 metres (Manalta Coal Limited, 1997).

The quality of coal from Unit 1 has been studied in the Goathorn Creek- Telkwa River and Pine Creek areas, but not in the Tenas Creek area. In 1989 Matheson (Matheson and Van Den Bussche, 1990) drilled a number of short holes, 6 of which intersected 1 seam near the Telkwa River and Goathorn Creek. In 2 of the holes sulphur contents range from 0.23 to 3.52 and increase towards the hangingwall but for the rest of the seam are less than 0.5 %.

Holuszko et al., (1993) studied 9 samples of coal from Hole GSB89-1 (Matheson and van Den Bussche, 1990) now considered to have penetrated unit 1 coals. The sulphur content averaged 3.53 % and reached 9.7 % in the hangingwall coal. The upper part of the seam was enriched in vitrinite (94.6 %), which was associated with increased amounts of coarse pyrite. The size and amount of pyrite decreased downwards through the seam in conjunction with the vitrinite content, which averages 65 % in the lower parts. More of the data collected as part of the 1989 drill program is described in Matheson et al. (1994). Holes GSB89-3 and GSB89-4, which intersected splits of 1 seam, both have low sulphur contents of 0.42 % and total reactives contents of 76 % and 84 %.

sandstone. The cumulative coal thickness in unit 3 averages 20.5 metres in areas considered for development.

Unit 3 is overlain by the sandstone-rich unit 4, which is over 100 metres thick, contains no economic coal and represents a major shallow marine transgression.

Outcrop on the Telkwa coal property is sparse and an understanding of the structural geology and seam stratigraphy has evolved as information from drilling and a number of geophysical surveys have became available. Bedding generally dips shallowly southeast or east and is disrupted by at least two generations of faulting. The first generation of faults occurred in the Late Cretaceous and are represented by east-dipping thrusts and reverse faults, that offset the east dip of the sediments east of Goathorn Creek. The younger Tertiary, steep-dipping faults trend northwest or

SAMPLING PROGRAM

Samples were collected from the three major seams (C Seam, 1 Upper and 1 Seam) in the Tenas Creek area. Seven samples were collected from C seam, nine from 1 Upper, and fourteen from 1 Seam. Sampling increments averaged about 30 centmetres. In addition full seam channel samples were collected. Raw and samples washed at 1.6 specific gravity were subjected to proximate and sulphur form analyses (Table 1). The petrographic compositions of most of the samples were measured using polished samples and an oil immersion lens. Three hundred grains per sample were identified, which is sufficient to provide an estimate of trends in petrography (Table 2). The major macerals were
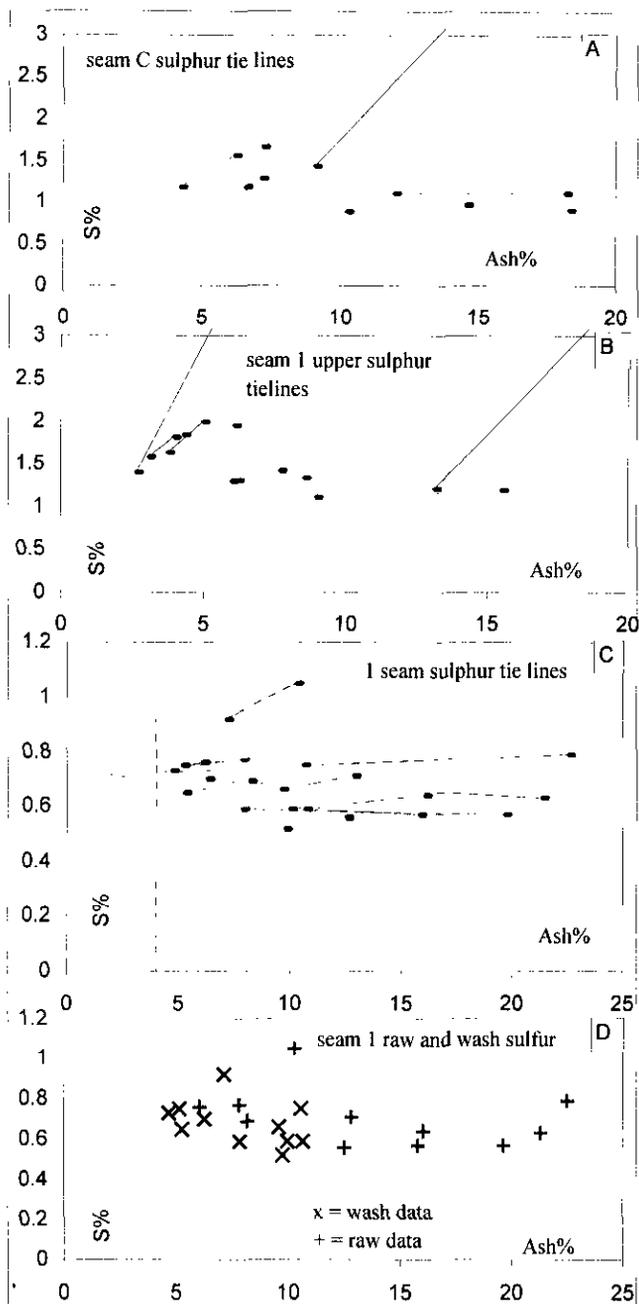
Figure 7: Sulphur *versus* ash tieline plots for seams 1, 1U and C. Lines join raw and 1.6 specific gravity wash data points.

characterized by high sulphur in the hangingwall coal and a rock split (Figure 6). Sulphur in 1 Upper is concentrated above a rock split and sulphur in 1 seam, which is the thickest seam, correlates with low ash increments. The striplog pattern indicates that the two upper seams each experienced influxes of sulphur from the hangingwall and associated with deposition of a mudstone split.

The weighted average sulphur content of all the C seam samples is 1.91 % compared to a channel sample value of 3.01 %. The difference probably indicates the difficulty of collecting a representative sample of the seam because it contains irregularly distributed concentrations of coarse pyrite. The total sulphur content of C Seam is higher in hangingwall coal, indicating that there was some marine influence. Also the organic sulphur content is higher than in 1 seam (Table 1) indicating some hydrogen sulphide in seams C and 1U was generated in the coal swamp below the mudstone split, but that there was insufficient iron available to combine with all the H_2S as pyrite. The coarse pyrite in the hangingwall coal and associated with the split is easily removed (Figure 6).

The weight averaged sulphur content of 1 Upper is 2.61 % using the increment samples, which agrees quite well with the single full channel result of 2.71 %. The highest sulphur content (7.3 %) occurs just above a mudstone split. If the 28 centimetres of coal and 5 centimetre mudstone split are removed then the average seam sulphur drops to 1.9 %. The high sulphur above the split indicates that a lot of sulphur has percolated downwards through permeable hangingwall rocks into the upper part of the seam after it was buried. The mudstone split isolated the lower part of the seam from the sulphate-rich waters. The hanging wall portion of the coal could be mined separately, but the high raw sulphur values are deceptive because a lot of it is coarse pyrite that is easily washed out. In fact in this case the float sulphur for the increment samples (heavy dashed lines, Figure 6) above the mudstone are no higher than float sulphur values below the split and separate handling of the upper part of the seam would not effect the clean coal sulphur content.

The channel sample of 1 seam has sulphur content (1.67 %) higher than for the average of the increment samples (0.68 %) suggesting that there is some coarse pyrite in the seam. Sulphur contents are not higher in the hangingwall coal consequently there is no evidence of marine sulphate percolating downwards into the seam. Sulphur contents (Figure 6) are only slightly reduced by washing.

Raw and wash total sulphur data from drill cores is of necessity used to predict the sulphur contents of planned product coal from a wash plant. This introduces the problems of size consist and specific gravity (SG). Drillcore is washed at a top size of about 10 millimetres and experiences better liberation than coal entering a wash plant, which is usually crushed to a size range of 50-0 millimetres. The second problem results from the fact that the core is washed to a fixed SG whereas a plant

identified included the vitrinite sub macerals tellinite, telocollinite, detrovitrinite and desmocollinite and the inertinite sub macerals semifusinite, fusinite, inertodetrinite and macrinite. No attempt was made to quantify the small quantities of micrinite and gelovitrinite or to subdivide the liptinites.

DATA INTERPRETATION

Coal quality data

The average raw total sulphur contents of the three seams decrease downwards, with C seam being

operates at variable densities to produce a constant ash concentration. The average wash ash concentration of the drillcore data rarely matches the clean coal ash specifications from a wash plant. The average sulphur concentration of the drillcore data, therefore, must be increased to account for the decrease in wash plant liberation and must be adjusted to reflect SG variations between the wash drillcore ash concentration and clean ash specifications for the plant.

Sulphur *versus* ash tieline plots provide one way of adjusting sulphur contents to different ash concentrations and they also give insights into the form of the sulphur. Tieline plots for the three seams (Figure 7 a, b, c) indicate clearly the different washing tracts for sample with coarse pyrite and those with finely dispersed pyrite or organic sulphur. The former form steep lines with positive slope and the latter flat lines some with negative slope. The background sulphur concentrations in seams C, 1 Upper and 1 are about 1.2 %, 1.2 % and 0.7 %. The tielines for seam 1 are projected to lower ash concentrations with dashed lines. An approximate estimate of sulphur at a lower ash concentration could be derived by averaging the projected sulphur intercepts on a vertical ash line in this case 4 % (chosen for the sake of clarity). In comparison Figure 7d is a plot of all sulphur data *versus* ash and estimating sulphur from this diagram would provide a higher sulphur concentration than the technique above. Neither technique is without faults, but the tieline approach may provide a better estimate.

In general the Tenas Creek samples tend to have a lower organic/total sulphur ratio than coals from the Mist Mountain Formation (Figures 5 and 8b). With the exception of two samples with very high organic sulphur contents, there is more organic sulphur in the wash than raw samples (Figure 8a) and organic sulphur contents tend to increase as the ash decreases. The two samples with high organic sulphur are the hangingwall coal from C (1.62 %) and coal above the split in 1U (3.62 %). The organic sulphur contents of both these samples, which also have high pyritic sulphur, are reduced to less than 1 % after washing without extensive loss of coal. This means that some of the coal has very high organic sulphur contents. Removing small quantities of it with the ash does not drastically decrease the yield, but does decrease the total sulphur content of the wash product.

A lot of the coarse pyrite is associated with detrovitrinite and finely disseminated ash (Photo 1). The association of detrovitrinite, fine ash and coarse pyrite could indicate an environment of moderate pH, in which vitrinite formed, followed by generation of H_2S at a fairly high pH with limited introduction of iron and a moderate amount of disruption and biodegradation of the humus.

The pyritic sulphur concentrations of most of the samples increase as the coal is washed (Figure 8a) because most of the pyrite is finely dispersed in vitrinite and is concentrated as the ash is removed. The sulphur content of the ash is low, probably less than 0.2 % and consequently it would be better to wash the coal to a
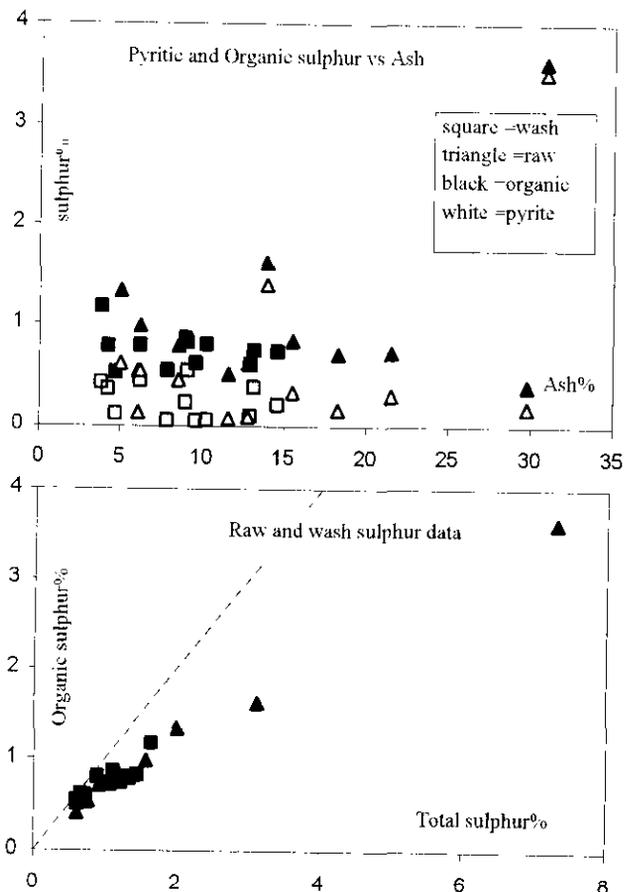

Figure 8: Wash pyrite, raw pyrite and organic sulphur *versus* ash plots for seams 1, 1U and C.

higher ash concentration to maintain clean coal sulphur contents at the 1 % level.

Some useful information about weathering, rank and petrography can be deciphered from inherent or bed moisture content of coal. It is always useful to generate a plot of as-received moisture *versus* ash to see if there are any significant variations in these parameters on a seam by seam basis because this information is always readily available. The predicted as-received moistures at zero percent ash vary from 11 % to 7 % (Figure 9) and decrease to zero at ash values varying from 65 % to 81 %, which is equivalent to about 100 % mineral matter, because of the weight loss that occurs when the mineral matter is ashed. The lower ash at zero moisture for 1 Upper Seam may indicate a more calcareous ash, which often signifies a marine influence and more sulphur, especially pyritic sulphur. The higher moisture in 1 seam at zero ash may indicate that the samples were weathered or that the seam contains a higher proportion of vitrinite. In fact the mineral matter free average total reactives contents of the seams are 79 % for seams 1 and 1U and 70 % for C. The easiest way of separating the effects of petrography from those of weathering is by using an ash *versus* FSI plot (Ryan, 1996) or by doing oxidation tests (the light transmittance test is the best for high-volatile A through medium-volatile bituminous ranks). Another important aspect of as-received moisture is the fact that it can give an indication of the
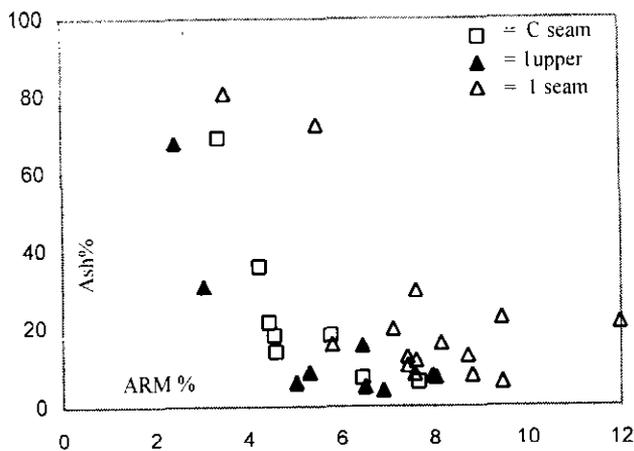
Figure 9: As-received moisture *versus* ash for seams 1, 1U and C.

Run-Of-Mine moisture content of the coal. Based on a 20 % ash and the data in Figure 6, a moisture content averaging about 7 % seems reasonable. This value in conjunction with product moisture specifications should be factored into plant recovery calculations.

Petrography data and relationship to sulphur distribution

The petrographic composition of 6 samples from C seam, 8 samples of 1 Upper seam and 12 samples of 1 seam were measured (Table 2) and the data presented as striplogs for the three seams (Figure 10). The seams are characterized by total reactives contents that range from 70 % to 80 % on a mineral-matter-free basis. A lot of the inertinite occurs as macrinite or inertodetrinite and there is not much semifusinite with well preserved cell structure and very little fusinite. Samples contain moderate to low contents of liptinite considering their rank of high-volatile bituminous.

The striplogs indicate that there are no major variations in petrography through the seams. There is a tendency for the upper part of the seams to be vitrinite poor and this correlates with the presence of coarse pyrite which occurs above the splits in C and 1U seams. There are also some correlations in cross plots that provide hints to the controls of maceral formation. There is a good correlation between semifusinite plus fusinite *versus* total inerts (Figure 11e), which is also apparent in data sets for Mist Mountain coals (Cameron, 1972 and Grieve, 1993). But the proportion of semifusinite+fusinite is higher in the Elk Valley samples (dashes in Figure 11e). The correlation between semifusinite+fusinite in both areas implies a similar origin, or inter-relationship of origins for the formation of structured inertinite and massive inertinite and consequently both may be related to fire, smoldering or charring. There is a similar relationship between the amount of structured vitrinite *versus* total vitrinite (Figure 11a) and the proportion of structured vitrinite increases as the amount of total vitrinite increases. The formation of desmocollinite and inertovitrinite implies a
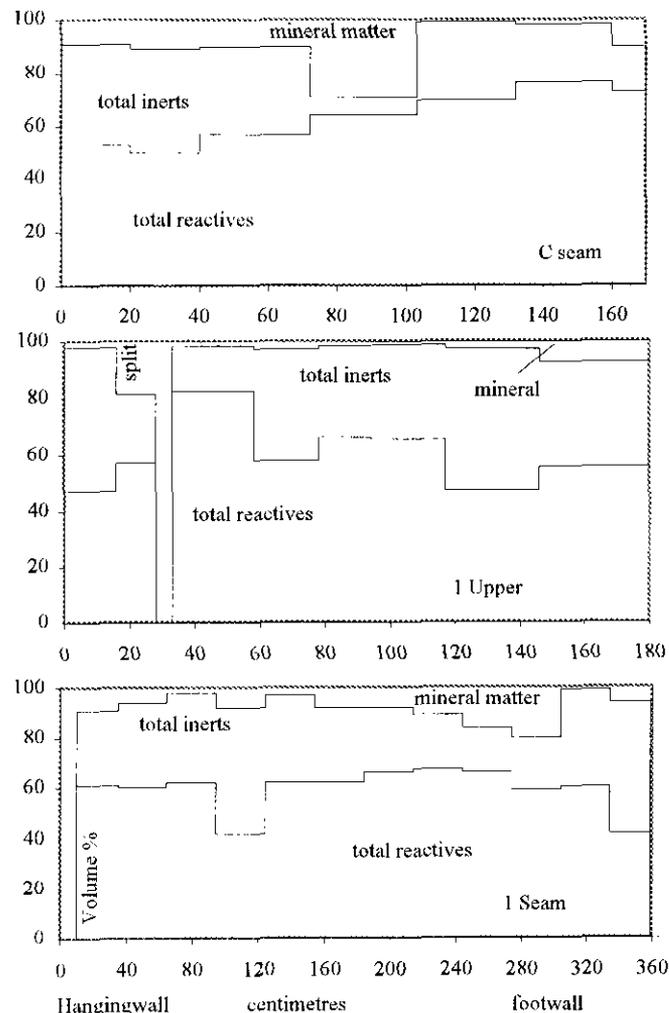

Figure 10: Striplogs of basic petrography for seams 1, 1U and C.

high degree of degradation of humus. There is a weak negative correlation of liptinite with total reactives (Figure 11b) implying that, as observed by other authors, liptinite is more resistant to biodegradation than pre-vitrinite material.

It is easy to recognize the various forms of pyrite in the three seams. Coarse pyrite is concentrated in the upper part of Seam 1 Upper above the split (Photo 3). Below the split the pyrite occurs as fine framboids or euhedral grains usually scattered in vitrinite (Photo 1, 2). The euhedral pyrite fills cavities in desmocollinite or semifusinite and generally the coal does not appear to have compacted around the grains implying a latter origin than framboidal pyrite around which the coal is compacted. There is very little visible pyrite in 1 Seam, which contains some pyrite filling fractures in inertinite

(Photo 4). This is evenly distributed through the seam and was probably the last morphology of pyrite to be implaced. It is difficult to quantify the various forms of pyrite and compare the amounts to changes in petrographic composition. This can be done in an approximate fashion by generating a correlation matrix between macerals proportions and the sulphur analytical
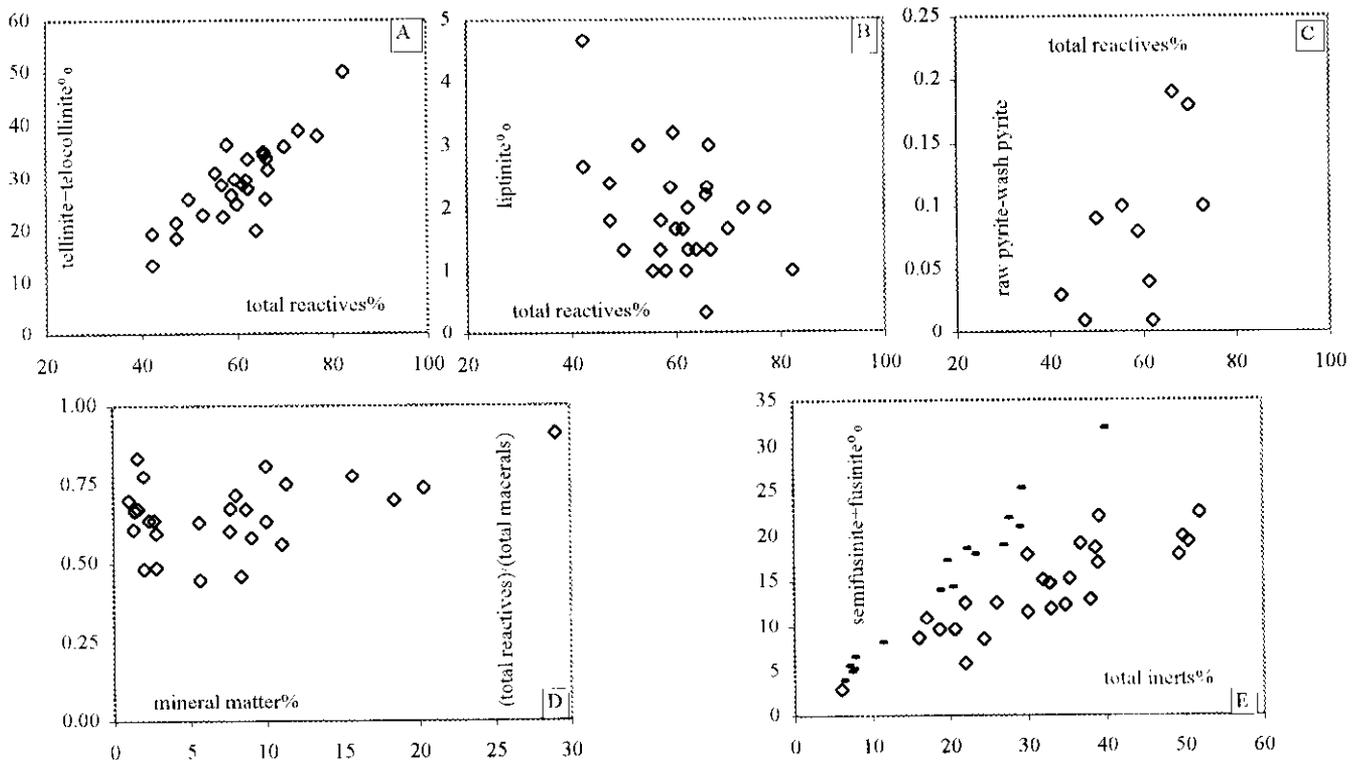
Figure 11: Maceral cross plots for various maceral and sulphur combinations; a/ structured vitrinite *versus* total vitrinite; b/ liptinite *versus* total reactives; c/ easily removed pyrite *versus* total reactives; proportion of total reactives *versus* per cent mineral matter; structured inertinite *versus* total inertinite for Telkwa (diamonds) and Elk Valley coals. Dash data from Grieve, (1993), diamond data from Tenas Creek.

Table 3
Partial correlation matrix for sulphur and petrographic data

	liptinite	telinite	telocollinite	desmocollinite	detrovitrinite	total reactives	semifusinite	macrinite	inertodetrinite	total inerts	mineral matter
					C seam						
TS%R	-0.2	0.1	-0.7	-0.1	0.8	-0.1	-0.6	-0.2	-0.7	-0.6	0.8
PS%R	0.8	-0.6	-0.5	-0.2	-0.4	-0.5	0.0	0.8	0.2	0.6	-0.1
OS%R	0.9	-0.7	-0.4	-0.1	-0.5	-0.4	-0.1	0.7	0.2	0.5	-0.1
VM%W	-0.2	0.2	0.0	0.3	0.5	0.5	-0.3	-0.8	-0.6	-0.6	0.3
Ash%W	-0.4	0.1	-0.3	-0.7	-0.1	-0.7	0.3	0.4	0.5	0.4	0.2
TS%W	0.1	0.0	-0.7	-0.1	0.7	-0.1	-0.5	0.1	-0.5	-0.4	0.6
PS%W	0.7	-0.4	-0.5	-0.2	-0.2	-0.5	0.3	0.7	0.4	0.7	-0.3
OS%W	1.0	-1.0	0.3	0.6	-1.0	0.3	-0.7	0.1	-0.6	-0.3	-0.1
					1 upper seam						
TS%R	-0.1	0.1	-0.1	0.1	0.2	0.0	-0.4	-0.5	0.1	-0.4	0.8
PS%R	-0.1	0.4	-0.4	0.8	-0.6	0.1	-0.9	-0.7	0.1	-0.7	0.9
OS%R	-0.1	0.3	-0.3	0.8	-0.5	0.2	-0.9	-0.7	0.0	-0.8	0.9
VM%W	-0.1	-0.5	0.9	0.2	-0.3	0.8	-0.2	-0.4	-0.9	-0.5	-0.6
Ash%W	-0.1	0.3	-0.5	0.2	0.1	-0.3	-0.3	-0.2	0.4	-0.1	0.9
TS%W	0.1	-0.1	0.7	0.5	-0.6	0.8	-0.5	-0.3	-0.7	-0.5	-0.6
PS%W	0.9	0.6	-0.5	0.6	-0.7	0.0	-0.3	0.5	0.4	0.2	-0.3
OS%W	0.6	-0.7	0.8	0.0	0.5	0.8	0.0	0.0	-0.8	-0.1	-0.6
					1 seam						
TS%R	-0.5	0.3	0.2	0.4	-0.2	0.4	-0.3	-0.1	-0.3	-0.2	-0.1
PS%R	-0.1	-0.7	0.6	0.3	0.4	0.5	-0.7	-0.7	-1.0	-0.8	0.7
OS%R	-0.5	0.5	0.0	0.3	-0.4	0.2	0.2	0.2	0.9	0.3	-0.7
VM%W	-0.8	-0.3	0.7	0.8	-0.6	0.8	-0.3	-0.5	-0.7	-0.6	-0.1
Ash%W	0.4	-0.2	-0.1	-0.5	0.8	-0.1	-0.5	-0.4	0.1	-0.3	0.8
TS%W	-0.6	0.1	0.4	0.5	-0.1	0.5	-0.4	-0.3	-0.5	-0.5	0.1
PS%W	-0.5	-0.2	0.5	0.7	-0.3	0.6	-0.4	-0.4	-0.6	-0.5	0.1
OS%W	0.3	-0.8	0.5	-0.1	0.9	0.3	-0.7	-0.7	-0.2	-0.7	0.7

data (Table 3). This reveals some weak correlations between pyritic and organic sulphur and the various macerals. This is probably because there is not a lot of sulphur form data and there is not a lot of variation in the maceral data.

Organic sulphur in high sulphur seams C and 1U tends to correlate with liptinite content whereas in the low sulphur 1 seam there are no consistent correlations. Coarse pyrite, which is a large component of the raw pyrite contents in seams C and 1U, does not appear to correlate consistently with any particular maceral. A better measure of coarse pyrite is the difference between wash and raw pyrite and this value does tend to correlate with total reactives (Figure 11c). Fine pyrite, which is probably well represented by the wash pyrite contents in seams C and 1U, correlates with liptinite and other reactive macerals in seam 1U.

Washability data

The washing characteristics of the three seams at Telkwa are estimated using a plot of wash ash *versus* coal recovery (Figure 12), which gives an indication of the relative ease of washing. Coal recovery is calculated as:

coal recovery =

yield x (100-wash ash x R)/(100-raw ash x R)

where R=wt mineral matter/wt ash.

Data for easy washing seams plots in the top left corner of the diagram and seams that are more difficult to wash plot in the lower right. It is apparent that
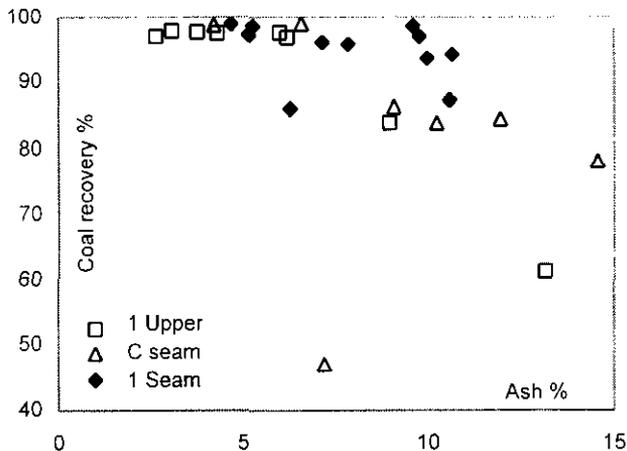
Figure 12: Wash ash *versus* coal recovery data for seams 1, 1U and C.

relative ease of washing of the three seams is 1 Upper > C > 1 Seam. This sequence agrees with the ash *versus* yield plots from full washability data for the seams (Figure 13). Coal recovery correlates positively with the inert macerals and negatively with detrovitrinite probably because of the association of finely disseminated mineral matter with this maceral.

Full seam samples of the three seams were subjected to size analysis and washability incorporating 11 SG fractions. Samples were crushed and screened at top sizes of 9.6 , 6.0, 0.6 and 0.15 millimetres. Sulphur data for the three seams indicates that there is some liberation of pyrite into the finer sizes, but only from the 6.0 to 0.15 millimetre size range (Table 4). The 9.6 to 6.0 millimetre size material experienced a net pyrite gain, because there was little liberation of pyrite into finer sizes and some pyrite-free fine coal or ash particles ended up in finer sizes after the crushing and screening process. Pyrite is liberated from the 6.0 to 0.6 millimetre size range and this pyrite is pushed into the 0.15 to 0.0 millimetre size range.

It is possible to estimate the amount of coarse and fine pyrite in the samples using the washability data. For example, the total sulphur of seam 1 for the upper 9.6 to 6.0 millimetre size range is 3.13 % and this is easily reduced to about 1.65 % (Figure 13), probably by the removal of coarse pyrite. The organic sulphur content of this sample is 0.95 % so that 1.65% - 0.95% = 0.7% is an estimate of the amount of fine pyrite in the sample. Table 4 documents the sulphur form and liberation data interpreted from the washability data. The 1 Upper seam contains more coarse than fine pyrite, whereas C seam contains about equal amounts of coarse and fine pyrite. The 1 seam, which contains low concentrations of both coarse and fine pyrite, is the easiest to wash. The coarse pyrite is concentrated in the 9.6 to 6.0 millimetre size fraction of all three seams.

The form, association and size of pyrite grains in the Telkwa seams are all critical to estimating how easy it will be to remove the pyrite and lower the sulphur concentration of the clean coal. It is important to know the sulphur concentration that can be achieved by practical washing methods. It can be uneconomic to crush coal to a fine size-consist, or to intensely wash it with a low recovery, to obtain a low sulphur product. It might be more practical to remove the sulphur during the end use of the coal, for example by scrubbers in modern coal power plants.

The sulphur is distributed in the coal as organic sulphur, fine pyrite (framboidal or euhedral) and coarse pyrite. The fine pyrite is enclosed by vitrinite and will be difficult to liberate it tends to occur through out the seam. The coarse pyrite, which is concentrated in the hangingwall coal, appears to be easily liberated and occurs detached grains in the petrographic mounts.

ACID ROCK DRAINAGE IMPLICATIONS

This paper does not address the issue of acid rock drainage (ARD) at Telkwa. There are a number of consultant reports covering the ARD included in the Telkwa Coal Project Report (Manalta Coal Limited, 1997). However because the title does include the two words sulphur and Telkwa it is appropriate to emphasize some very general points.

Mining disturbs much larger volumes of interburden rock than coal seams. It is therefore important to concentrate acid rock drainage studies more on the interburden rock rather than on the coal. Sulphur in coal occurs in organic and pyritic forms. The organic sulphur does not oxidize and does not take part in acid forming reactions. Pyrite can oxidize to form sulphuric acid and ferrous iron hydroxides This is the basis of the acid rock drainage problem

When coal seams are mined, they produce three controlled product streams; the clean coal, which leaves the site; the coarse refuse and the fine tailings material. Only pyrite is that is easily washed out of the coal stays on the mine lease, either in tailing material (fine framboidal or euhedral pyrite) or in the coarse rejects (coarse pyrite).

Different forms of pyrite are more or less susceptible to oxidation under similar conditions. Framboidal pyrite composed of many very small crystals has the highest surface area to volume ratio and therefore can oxidize rapidly. The rapid generation of acid can overwhelm the natural neutralizing capacity of surrounding rock even if on a stockiometric basis it contains sufficient capacity to do the job. Luckily most of the framboidal pyrite will end up in the tailings and can therefore be placed in a non-oxidizing environment.

Coarse pyrite oxidizes slower than fine pyrite and therefore places less stress on the neutralizing capacity of the surrounding rocks. This type of pyrite is most likely to end up in the coarse rejects. When determining a safe ratio of neutralizing potential to acid generating potential it is important to consider the relative percentages of the various forms of pyrite. This can be estimated for coal, either from core samples, or from bulk samples using sulphur form data and wash sulphur concentrations (Table 4).
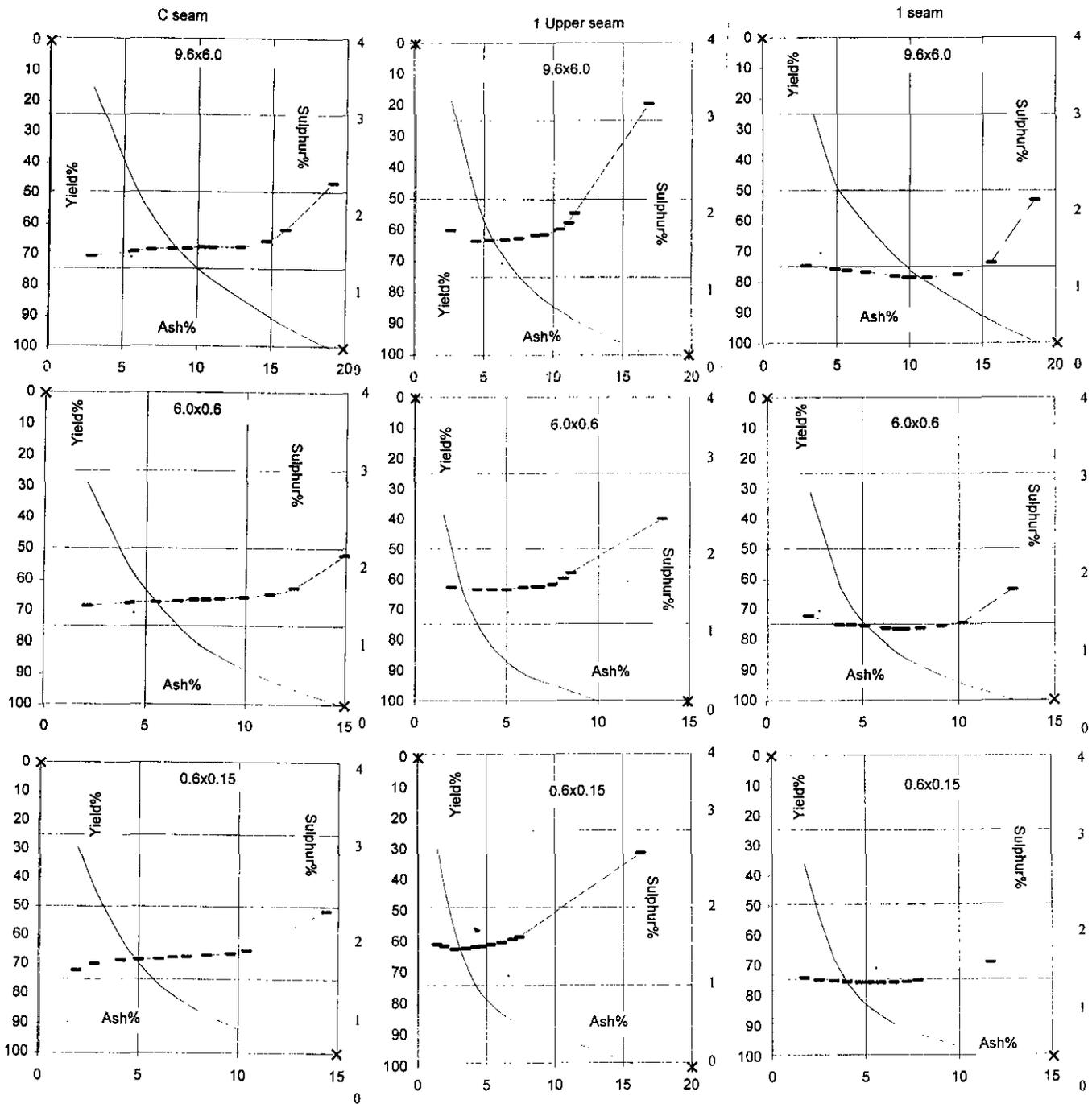
Figure 13: Washability data for seams 1, 1 Upper and C. Sulphur and ash *versus* yield data is illustrated for three size ranges.

Often it is hangingwall rock material that contains elevated concentrations of pyrite. Some of this material is mined as hangingwall dilution and is trucked with the raw coal to the plant where it will be rejected at the breaker and can then be handled separately from general interburden rock.

CONCLUSIONS

The average sulphur contents of the three seams sampled at Telkwa vary from 0.7 % to 3 % on a raw basis and 0.6 % to 1.4 % on a 1.6 SG float basis. The C

seam is moderately enriched in marine sulphur, which with available iron has formed framboidal and euhedral pyrite through out the seam. The limited supply of iron has resulted in high concentrations of organic sulphur in hangingwall coal.

The upper part of 1 Upper seam is enriched in marine sulphur and coarse pyrite, indicating an influx of brackish water soon after burial. The formation of the coarse pyrite post dates formation of the framboidal and euhedral pyrite because it is external to the macerals and often associated with detrovitrinite. The organic sulphur content is moderately high through out the seam

indicating a marine influence during accumulation of the vegetation in an environment lacking a ready source of iron but suitable for the generation of H_2S.

The lowest 1 seam, which is the thickest, has the lowest concentration of sulphur. Pyrite concentrations are low and occur as fracture filling in inertinite, indicating crystallization after some amount of coalification.

The hangingwall rock lithology may well be a good indication of how much coarse pyrite exists in 1 Upper. Unfortunately there may be no field clues as to variations in the organic sulphur content of the seam . Any obvious increase in bright lithotypes in 1 seam will probably correlate with an increase in organic sulphur. In the other seams an increase in bright lithotypes may correlate with an increase in framboidal and euhedral pyrite, both of which are difficult to wash out.

Coarse pyrite is moderately easy to wash out of the coal. Other forms of pyrite are more difficult to wash out because they are associated with the coal. It is better to wash the coal to a higher ash content rather than to force coal into the reject stream in order to achieve minor reductions in sulphur concentrations.

Table 4

Sulphur liberation and sulphur form data

I Upper Seam						
size mm	A	TS	PS	OS	WS	CP	FP
9.5 x 6.0	9.1	3.13	2.14	0.95	1.65	1.48	0.7
6 x 0.6	-13.2	2.41	1.57	0.82	1.6	0.81	0.78
0.6 x 0.15	-0.2	2.62	1.77	0.81	1.6	1.02	0.79
0.15 x 0	4.6	3.76	2.99	0.69			

C Seam						
9.5 x 6.0	3.4	2.04	1.33	0.71	1.3	0.74	0.59
6 x 0.6	-2.4	1.86	1.13	0.73	1.35	0.51	0.62
0.6 x 0.15	-0.8	2.01	1.08	0.9	1.35	0.66	0.45
0.15 x 0	2.2	2.69	1.71	0.86			

1 Seam						
9.5 x 6.0	10.6	2.18	1.44	0.72	0.9	1.28	0.18
6 x 0.6	-8.1	1.51	0.84	0.66	0.95	0.56	0.29
0.6 x 0.15	-4.9	1.25	0.53	0.71	0.96	0.29	0.25
0.15 x 0	-0.4	1.7	0.89	0.74			

A = pyrite liberation from size as % of total pyritic sulphur
  a minus sign indicates pyrite loss
TS total sulphur   PS pyritic sulphur   OS organic sulphur
WS wash sulphur   CP coarse pyritic sulphur
FP fine pyritic sulphur

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