WASHABILITY OF LITHOTYPES FROM A SELECTED SEAM IN THE EAST KOOTENAY COALFIELD, SOUTHEAST BRITISH COLUMBIA (85J/2)

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KEYWORDS: Coal geology, coal quality, Greenhills, washability, degree of washing, washability number, coal petrography, mineral matter, lithotypes.

INTRODUCTION

This study is part of the Coal Quality project, and involves washability characteristics of British Columbia coals. The first two parts of the project involved collection and analysis of washability data from assessment reports (Holuszko and Grieve, 1990; Holuszko, 1991). The washability characteristics of coals from different regions, geological formations and seams were studied using classical washability parameters, together with the washability number and degree-of-washing. The latter were found to be more appropriate for comparing inherent washability characteristics. This part of the study focuses on the analysis of the washability of different lithotype samples, collected from faces at producing coal mines.

During the 1991 field season a number of lithotype samples were collected from two mine sites: Line Creek and Greenhills in southeast British Columbia. All of the seams belong to the Mist Mountain Formation. The sampling was carried out in cooperation with Dr. A. Cameron of the Institute of Sedimentary and Petroleum Geology, Calgary. Samples collected from Greenhills 16-seam were chosen for the washability study using degree-of-washing and washability number parameters.

BACKGROUND

LITHOTYPES AS INDICATORS OF DEPOSITIONAL HISTORY OF THE COAL SEAM

Lithotypes are defined as macroscopically recognizable bands of coal, based on variations in brightness. They are assumed to reflect original contributions of organic material, and the physical and chemical conditions during and after peat accumulation (Kalkreuth and Leckie, 1989). For example, the height of the water table is believed to play an important role (Diessel, 1982; Cohen, 1984). The bright and banded bright coal lithotypes indicate formation in a wet forest mire, while banded and banded dull were formed in a moderately wet forest mire or in an open mire environment with a higher water table (Kalkreuth *et al.*, 1991).

Frequently, both lithotype description and maceral composition are used to provide information on depositional environment (Kalkreuth and Leckie, 1989). Based on maceral composition, a number of indices are derived, and these are used to outline depositional environments with much greater precision (Diessel, 1986).

Detailed studies defining coal facies, using lithotype and maceral data, have been completed on coals from the Lower Cretaceous Gates Formation in Western Canada (Lamberson *et al.*, 1989, 1991). For these coals it was found that vitrinite content decreases from bright to dull while inertinite and liptinite increase in parallel with mineral matter. The most variation in petrographic composition is associated with dull lithotypes. Macroscopically similar dull coal bands show significant differences in their microscopic composition.

Generally, the petrographic composition of the individual lithotypes has been proved to be consistent for various coal seams (Hower *et al.*, 1990; Lamberson *et al.*, 1991; Kalkreuth *et al.*, 1991).

LITHOTYPES AS INDICATORS OF QUALITY VARIATIONS

The fundamental differences in maceral and lithotype composition account for differences in physical properties of coal (Jeremic, 1980; Stach *et al.*, 1982; Tsai, 1982; Hower *et al.*, 1987; Hower, 1988). This can have an influence on the mining, preparation and utilization of coal.

The density of lithotypes varies significantly, with the bright lithotypes having the lowest density and the dull lithotypes rich in mineral matter the highest. Porosity and mechanical properties such as strength, hardness and friability are also strongly dependent on lithotype composition (Hower *et al.*, 1987, 1990; Falcon and Falcon, 1987; Hower, 1988; Hower and Lineberry, 1988). The relationship between lithotypes and their variation in grindability index (HGI) has also been established (Hower *et al.*, 1987; Hower, 1988; Hower and Linberry, 1988). Differences up to 40 units in grindability index have been observed between lithotypes. Dull lithotypes with a dominance of trimaceral microlithotypes, especially those rich in liptinite, are more resistant to breakage and grinding than those rich in vitrinite and inertinite.

The floatability of lithotypes has been studied, confirming that lithotypes have different responses to flotation, due to varying degrees of hydrophobicity (Horsley and Smith, 1951; Sun, 1954; Klassen, 1966; Holuszko, 1991).

It is also expected that the washability of a whole seam, as derived from density separation, will be influenced by the lithotype composition. Varying ease of washing for different lithotypes is expected due to their varying mineral and maceral composition (Falcon and Falcon, 1987).

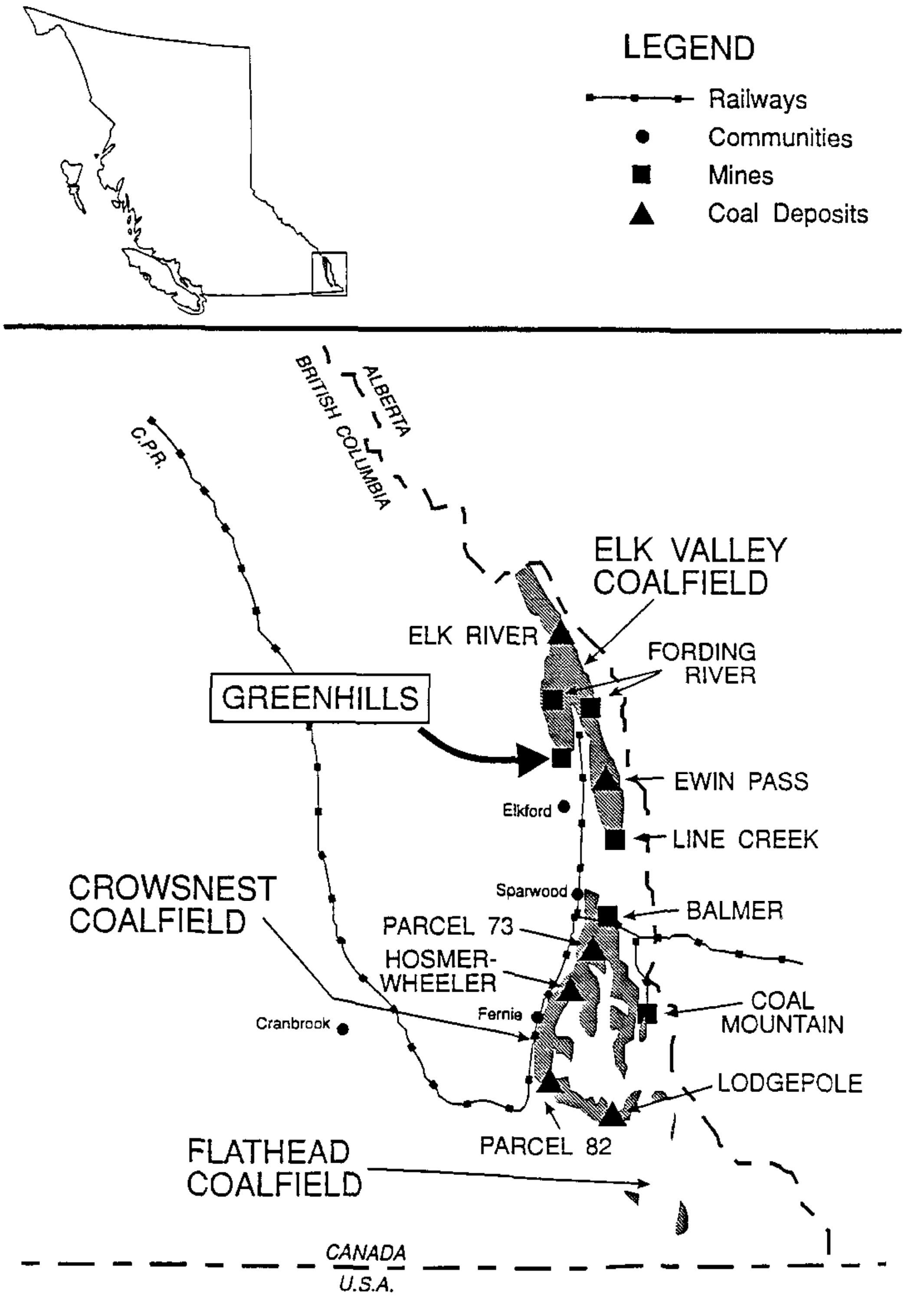


Figure 5-2-1. Location of Greenhills mine.

Factors Influencing Washability and Meaning of Washability Number

The washability of a coal seam is directly related to the amount, type and, most importantly, the association of minerals with the coal. The way in which mineral matter is incorporated in a coal seam is a direct result of the sedimentation conditions that prevailed during its formation. Mineral matter in coal originates from a variety of sources. Some is incorporated in original plant material (chemically bound), some is washed or blown into the mire during peat formation (epiclastic), some is precipitated during the very earliest peat accumulation stage (syngenetic), and some is subsequently introduced by migrating mineral-forming solutions (epigenetic).

Depending on the relative abundance of each type, liberation of these minerals will range from impossible (chemically bound minerals) to easy (epiclastic and epigenetic minerals). The ease of washing will depend on liberation of mineral matter at any given size range of coal. Breaking and crushing during coal preparation leads to separation first of minerals formed along the bedding planes, and successively the syngenetic minerals as the size approaches that of the mineral grains. Liberation of mineral matter from coal is also a function of the physical characteristics of the parent coal, and these are controlled by the lithotype composition (Hower and Lineberry, 1988).

The ease or difficulty of washing is usually related to the yield of clean coal at a particular ash level, and the amount of near-gravity material at the density of separation for a specified coal product. These parameters, however, are coal dependent, and they are not reliable when comparing coals of different origin. Two parameters, degree of washing and washability number, have been established to describe the inherent washability characteristics of a coal (Sarkar and Das, 1974; Sarkar *et al.*, 1977; Sanders and Brooks, 1986; Holuszko and Grieve, 1990; Holuszko, 1991).

The degree of washing, when calculated at each density of separation and plotted against density of separation or yield of clean coal, forms a curve. The maximum on this curve reflects the optimum cut-point for separation. In other words, the maximum advantage in separating coal is expected at this optimum point, giving the highest yield of the cleanest product possible. The ratio of optimum degree of washing to the clean coal ash at this point is the value described as the washability number.

The degree of washing at any specific gravity cut-point is expressed as follows:

$$N = w(a-b)/a$$

where: a = the ash content of the raw coal (feed)

b = the ash content of the clean coal at a given density of separation

w = the yield of clean coal at a given density of separation

The washability number is calculated from the following equation:

$$W_n = 10(N_{opt}/b_{opt})$$

where: b_{opt} = ash content at N_{opt}.

It has been shown that the washability number can be a very useful tool in the study of coal seams as rock units (Sarkar and Das, 1974; Sarkar *et al.*, 1977). The way it is expressed defines the boundary between free (removable) mineral matter and mineral matter associated with coal (fixed) and at the same time it gives an idea of the optimal conditions for separation. According to Sarkar, washability number represents the effect of the depositional conditions on the association of coal with mineral matter. It has been shown by the same authors that washability numbers are higher for coal seams formed under quiescent conditions (autochthonous) as opposed to those formed under turbulent conditions (hypautochtonous). Lateral changes in washability number were used to outline patterns of depositional environment for some Indian and North American coals.

Comparative studies of washability numbers for coal seams in different formations in British Columbia show significant diversity (Holuszko, 1991). Variations in the washability number are also evident among different seams from the same geological formations. For some formations, there is an apparent trend in increasing washability numbers for coal seams higher in the formation, while for others no trend is evident.

The variations in quality within each seam are lithotype dependent, and each lithotype represents a change in the depositional environment. Therefore, it is expected that ease of washing, as measured by washability number, will vary for different lithotypes.

SAMPLES AND PROCEDURES

Lithtoype samples from the Mist Mountain Formation of southeast British Columbia were collected from a number of producing seams. These coals range from high-volatile A to low-volatile bituminous in rank. In general, they are characterized by low sulphur content. Metallurgical products have good to excellent coking properties, while thermal products are also attractive due to their high rank and low sulphur content.

In terms of depositional history, coals of the Mist Mountain Formation were deposited along a broad coastal plain with numerous high-energy wave-dominated deltas (Kalkreuth and Leckie, 1989). The coal seams in the lower part of the formation are believed to have formed in open swamps with free movement of water (Cameron, 1972). Seams from the upper part of the formation were deposited in a fluvial to upper delta plain. These are thinner and vitrinite dominated, which indicates formation under forest bog conditions in stagnant water (Kalkreuth and Leckie, 1989).

Samples of lithotypes from Greenhills 16-seam were chosen for the detailed washability studies. This seam is located in the upper part of the Mist Mountain Formation, and its thickness exceeds 10 metres. This seam has contributed more than 80 per cent of the recent coal production from this property. It is classified as medium-volatile bituminous and is used as metallurgical coal. The location of the Greenhills mine is shown in Figure 5-2-1.

A total of 33 lithotype samples from Greenhills 16-seam were collected. Due to the small size of some of the samples, only 18 samples were used for sink-and-float studies. These represented six lithotypes: bright; banded bright; banded coal; banded dull; dull and sheared coal (Table 5-2-1).

TABLE 5-2-1
LITHOTYPE CLASSIFICATION SCHEME
(modified from Diessel, 1965; Marchioni, 1980)

BRIGHT	subvitreous to vitreous lustre, conchoidal fracture, less than 10% dull coal laminae.
BANDED BRIGHT	predominantly bright coal with 10-40% dull laminae.
BANDED COAL	interbedded dull and bright coal in approximately equal proportions
BANDED DULL	dull coal with approximately 10-40% bright laminae.
DULL	matte lustre, uneven fracture, less than 10% bright coal laminae, hard.
FIBROUS	satin lustre, very friable, sooty to touch.
SHEARED COAL	variable lustre, disturbed bedding, numerous slip/slickenside surfaces, very brittle.

Sampling Techniques

Lithotypes were collected according to the modified Australian classification (Diesel, 1965; Marchioni, 1980). As a general rule, a coal band is considered to be a mixture of bright and dull components, and lithotypes are defined according to the proportions of the basic ingredients. A minimum thickness of 5 centimetres was used to delineate lithotypes, following the procedure of Lamberson *et al.*, (1989). The lithotype profile of 16-seam is reconstructed in Figure 5-2-2.

ANALYSIS

All lithotype samples were processed for proximate, specific gravity and HGI analyses. The chemical and sink-and-float analyses were performed by Loring Laboratory in Calgary. The data in Table 5-2-2 represent analyses of Greenhills 16-seam. The average values were calculated for each lithotype group.

Sink-and-Float Tests

Sink-and-float analyses were performed on the coarse size fraction (0.50 to 9.5 mm) prepared from each lithotype sample, in seven gravity fractions: 1.30; 1.35; 1.40; 1.45; 1.50; 1.60 and 1.70 grams per cubic centimetre. The ash content was determined on the float fractions and the cumulative yield and ash values were computed. These were further used to derive degree-of-washing values at each density of separation and washability number (W_n) at the density corresponding to the optimum degree of washing (N_{opt}).

Maceral Analysis

Maceral analyses were accomplished by counting 500 points on each sample. Petrographic composition on a mineral-matter-free basis was calculated as an average value for each lithotype. The average maceral composition of all lithotypes in Greenhills 16-seam is depicted in Figure 5-2-3.

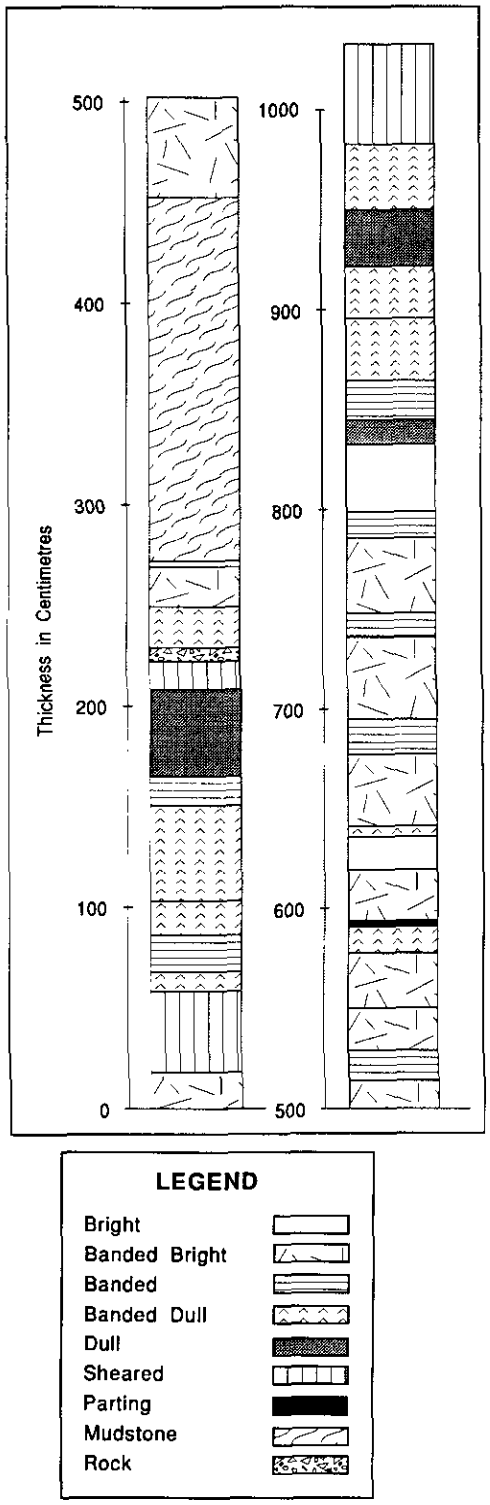
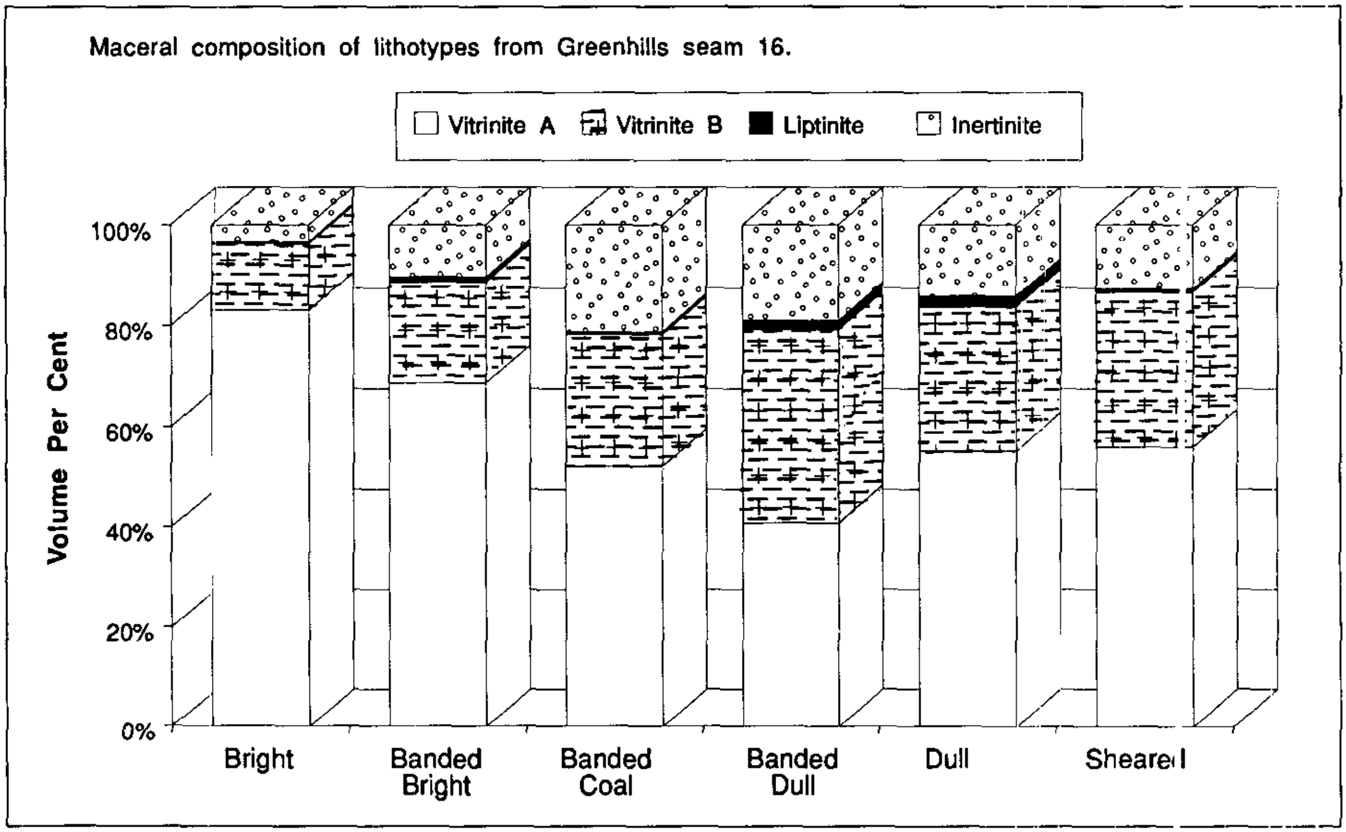


Figure 5-2-2. Profile of Greenhills 16-seam.

TABLE 5-2-2
PROXIMATE ANALYSES, SPECIFIC GRAVITY AND HGI VALUES FOR GREENHILLS 16-SEAM LITHOTYPES

Lithotype	Volatile Matter	Fixed Carbon	Ash	Specific Gravity	HGI
Bright (3)	28.02	68.44	3.53	1.26	99
Banded Bright (9)	28.31	65.21	6.48	1.29	91
Banded Coal (7)	26.61	68.40	4.99	1.29	101
Banded Dull (9)	25.37	61.35	13.28	1.36	90
Dull (3)	28.28	61.46	10.25	1.36	109
Sheared (3)	23.93	52.60	23.47	1.44	125



	Vitrinite A	Vitrinite B	Liptinite	Inertinite
Bright (3)	83.1	13.2	0.4	3.3
Banded Bright (9)	68.3	20.0	1.1	10.2
Banded Coal (7)	52.1	26.1	0.6	21.2
Banded Dull (9)	40.8	38.3	2.0	18.9
Dull (3)	55.2	28.4	2.3	14.1
Sheared (3)	55.9	30.7	0.7	12.7

Vitrinite A = Telinite, Collinite, Telocollinite

Vitrinite B = Vitrininite A + MM or Vitrodetrinite

Figure 5-2-3. Average maceral analyses of lithotypes in Greenhills 16-seam.

RESULTS

Petrographic Analyses

The lithotype profile of Greenhills 16-seam (Figure 5-2-2) shows that it is composed predominantly of banded lithotypes, with banded bright as the most abundant. The base of the seam is rich in banded dull lithotypes, the middle part contains a thick mudstone parting, indicating frequent flooding, and above it the seam becomes predominantly banded bright. In the top of the seam the composition changes gradually to banded dull and dull. Sheared coal is present in the uppermost and lowermost parts of the seam.

On average, bright lithotypes are rich in total vitrinite (vitrinite A plus vitrinite B) reaching 96 per cent by volume (Figure 5-2-3). Vitrinite content decreases from bright to banded dull lithotypes; the average value in banded bright coal is 88.7 per cent, and in banded dull lithotypes its value decreases to 79 per cent. The ratio of vitrinite A to vitrinite B decreases in parallel with the decrease in total vitrinite, with the exception of the dull lithotype. Sheared coal is rich in vitrinite and its ratio of vitrinite A to vitrinite B is similar to that of dull coal. Plate 5-2-1 illustrates examples of macerals found in the lithotypes from Greenhills 16-seam.

The opposite trend is observed for intertinite in various lithotypes, the highest content being associated with the duller bands of coal. The exception again is for the dull lithotype. The liptinite content of these samples is negligible. The highest values, however, occur in banded and dull lithotypes (2.0 and 2.3% respectively).

Chemical Analysis

Proximate analytical values vary between different lithotypes (Table 5-2-2). Volatile matter decreases with decrease in brightness from bright to banded dull, and the lowest value is in sheared coal. Ash content increases from bright to banded dull lithotypes, with a discrepancy for the dull lithotype, and highest ash is associated with the sheared coal. The specific gravities follow a similar pattern of increase in value with decrease in brightness.

The grindability index (HGI) values are somewhat less predictable. The highest grindability is associated with the sheared coal and dull lithotypes, followed by the banded coal and bright lithotypes. Banded dull coal has the lowest grindability.

Washability Characterization

The washability numbers and optimum degree of washing, together with the parameters associated with the optimum cut point, such as density of separation and clean-coal ash at optimum, are presented in Table 5-2-3. For comparison, the average values are also calculated.

The highest washability numbers and the lowest clean-coal ash values (at the optimum) are associated with the bright lithotypes, and equal 289.4 and 1.62 per cent, respectively. The average washability number for the banded bright lithotype is 167.1, with clean-coal ash value of 2.75 per cent. The banded coal washability number is about 110, with the clean-coal ash 3.82 per cent. A significant decrease in washability number is observed in the banded dull lithotype (45.81), with a sharp increase in ash content to 14.82 per cent for the clean coal at the optimum. The washability number for the dull lithotype is much higher than for banded dull, and does not follow the general trend. The sheared coal washability number (79.25 and ash of clean coal at 6.26%) was found to be higher than that for the banded dull lithotype, and lower than for banded coal.

From the analysis of maceral composition and washability numbers (Table 5-2-4), it is evident that washability numbers decrease with decrease in brightness from bright to banded dull lithotypes, and this is accompanied by a decrease in total vitrinite. The ratio of vitrinite A to vitrinite B follows the same trend.

TABLE 5-2-3
WASHABIITY NUMBER, DEGREE-OF-WASHING AND OTHER WASHABILITY PARAMETERS FOR SELECTED LITHOTYPES

Lithotype		Raw Ash	W_N	N_{opt}	d_{opt}	CC_{opt}
Bright		5.16	338.06	55.78	1.35	1.65
		2.88	240.54	39.93	1 35	1 66
		3.01	289.60	45.18	1 35	1 56
	Average	3.68	289.40	46.96	1.35	1.62
Banded Bright		11.69	89.90	43.69	1.35	4.86
		7.71	178.02	52.16	1.35	2.93
		5.70	173.18	47.45	1 35	2.74
		3.40	123.83	29.10	1.35	2.35
		1.76	295.61	33.70	1.35	1.14
		4.02	141.97	35.21	1.35	2.48
	Average	5.71	167.09	40.22	1.35	2.75
Banded Coal		7.30	63.00	28.79	1.35	4.57
		10.19	61.67	30.96	1.35	5.02
		9.18	47.90	27.60	1.35	5.76
		4.07	200.64	42.15	1.35	2.08
		2.45	178.69	30.02	1.35	1.68
	Average	6.64	110.38	31.90	1.35	3.82
Banded Dull		6.79	82.19	30.82	1 35	3.75
		49.04	4.16	5.86	1.70	33.67
		13.55	51 08	35.91	1.40	7.03
	Average	23.13	45.81	24.20	1.48	14.82
Dull		5.92	90.20	31.66	1.35	3.51
Sheared		23.06	79.25	49.85	1.50	6.26

W_N = Washability number
N_{opt} = Degree of washing @ optimum
d_{opt} = Density of separation @ optimum
CC_{opt} = Clean coal ash @ optimum

SUMMARY AND CONCLUSIONS

Examination of washability characteristics of lithotypes collected from Greenhills 16-seam suggests the following conclusions.

The change in brightness of lithotypes is a result of changing maceral composition from vitrinite rich to intertinite rich, and generally the increase in mineral matter content (ash) from bright to dull lithotypes. Bright lithotypes are rich in vitrinite A and the ratio of vitrinite A to vitrinite B decreases with decrease in brightness.

The amount of total vitrinite in the dull lithotype is similar to that of the banded bright lithotype, while the ratio of vitrinite A to vitrinite B is similar to the banded coal category. According to Kalkreuth *et al.* (1991) there are two

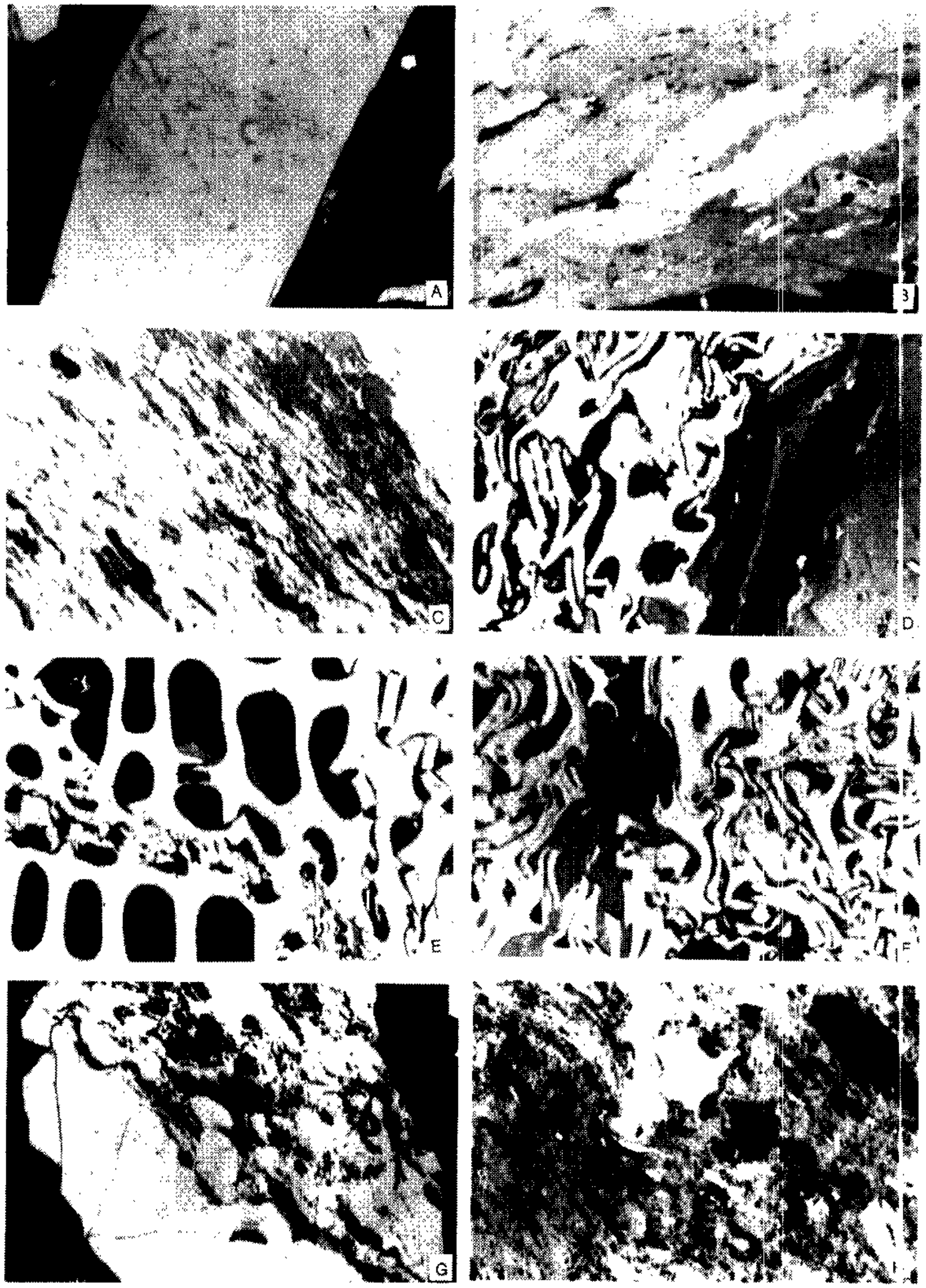


Plate 5-2-1. Macerals in Greenhills seam-16. A) Vitrinite A type. B) Vitrinite B type with semifusinite and liptinite macerals. C) Vitrinite and massive occurrence of liptinite. D) Fusinite (left) and mega-cuticule occurrence and vitrinite (right). E) Fusinite with cell structure preserved. F) Fusinite and resin (dark grey) filling the cavity in fusinite. G) Vitrinite A type with clays. H) Vitrodetrinite (matrix) with inertodetrinite macerals.

TABLE 5-2-4
WASHABILITY NUMBER AND MACERAL COMPOSITION OF SELECTED LITHOTYPES FROM GREENHILLS 16-SEAM

Lithotype		Raw Ash	W_N*	Maceral Composition			
				Vitrinite A	Vitrinite B	Inertinite	Liptinite
Bright		5.16	338.06	86.4	12.4	1.0	0 2
		2.88	240.54	80.8	14.6	4.2	0.4
		3.01	289.60	82.2	12.6	4.6	0 6
	Average	3.68	289.40	81.9	13.0	3.3	0.4
Banded Bright		11.69	89.90	53.6	37.2	7.6	1.6
		7.71	178.02	71.6	25.0	1 8	1.6
		5.70	173.18	73.6	16.2	9.8	0.4
		3.40	123.83	82.4	12.4	4.6	0.6
		1.76	295.61	83.6	3.6	12.2	0 2
		4.02	141.97	78.6	12.2	7.2	2.0
	Average	5.71	167.09	73.9	17.8	7.2	1.1
Banded Coal		7.30	63.00	37.4	34.6	27.2	0.8
		10.19	61.67	46.2	19.2	33.2	1.0
		9.18	47.90	23.0	48.4	27.6	1.0
		4.07	200.64	41.2	35.4	23.0	0.4
		2.45	178.69	91.8	5.4	2.8	-
	Average	6.64	110.38	47.8	28.6	22.8	0.8
Banded Dull		6.79	82.19	38.8	21.2	36 2	0.8
		49.04	4.16	18.4	79.4	1.6	0.6
		13.55	51.08	18.0	56.4	24.4	1.2
	Average	23.13	45.81	25.1	52.3	20.7	0.9
Dull		5.92	90.20	40.2	36.0	22.6	1.2
Sheared		23.06	79.25	80.8	12.4	5.6	0 8

* W_N = Washability number

types of dull lithotypes, one representing a moderately wet forest mire, and referred to as "dry", and the other "wet", indicating high water tables with a strong influence of open mire or marsh environments. In terms of maceral make-up the "wet" dull coal is similar to banded bright and banded coal lithotype composition. It is reasonable to assume that the dull lithotype studied here is the "wet" dull type.

For the dull lithotypes examined for washability, a combination of three factors may have controlled their appearance, as shown in Table 5-2-4. These are: increased inertinite, vitrinite B and, to some extent, liptinite content.

The variation in washability numbers among lithotypes observed here is very wide (Table 5-2-3). The washability numbers associated with the bright lithotypes are the highest, and are accompanied by the lowest ash content in clean coal at the optimum. In general, the variation in washability numbers is narrowest for the bright lithotypes, and this is also true for the ash of clean coal at the optimum. Bright lithotypes are vitrinite rich, with very low ash content. These were presumably formed under quiescent conditions with very little introduction of mineral matter, and this resulted in high washability numbers and low clean-coal ash at the optimum.

For banded bright lithotypes, the range of washability numbers is quite broad, with great variation in raw and clean coal ash content at the optimum. The variation in degree of washing and washability number becomes narrower for the banded coal. However, raw and clean-coal ash values still vary considerably.

The variation in washability numbers is always much greater for banded than for bright lithotypes. For the samples where an increase in raw ash is the probable cause of the dull appearance, the range of variation in washability number becomes narrower. This is because the amount and type of mineral matter (ash) has a major influence on the magnitude of the washability number. It is also important to note that the density of separation at the optimum point, (d_{opt}), is constant and equal to 1.35 grams per cubic centimetre for all lithotypes, except those with high raw ash content, and sheared coal. This may indicate that for these lithotypes, the optimum point occurs at the same density, regardless of their composition. The clean-coal ash, however, increases from bright to banded dull, indicating different associations of mineral matter in different lithotypes.

The mineral matter and its association are the major factors in defining washability characteristics. It is not always the amount of mineral matter (raw ash) but type (association with coal) which contributes to the washability characteristics. For example, two different lithotypes, bright and banded bright, with similar raw ash contents, and similar maceral compositions, have quite different washability numbers (Table 5-2-4). This may indicate that the specific association of mineral matter with coal in one sample makes this coal look duller (due to its disseminated occurrence) and also contributes to the lower washability number, (W_n=123.83 for banded bright, compared to 289.60 for bright lithotype).

Assuming that washability numbers indicate variation in depositional environment, the actual decrease in the magnitude of this number, in conjunction with the decrease in the clean-coal ash at the optimum, suggest that moving towards the duller lithotypes the depositional conditions changed from wet forest mire to open mire. This is also in agreement with the change in maceral compositions, particularly the decreasing ratio of vitrinite A to vitrinite B towards duller lithotypes. Vitrinite A, representing structured vitrinite macerals, indicates a more preserving depositional environment, and reflects deposition conditions with less frequent changes in water level. This results in less mineral matter deposition. Vitrinite B, representing vitrodetrinite and vitrinite associated with mineral matter, indicates macerals of detrital origin, usually characterized by more degraded organic matter and a higher mineral matter content.

Knowledge of the variation in washability with change in lithotype composition may be a useful tool for predicting the washability characteristics of a seam. An attempt was made here to calculate a seam washability number from the washability numbers of component lithotypes. The weighted average washability number of the whole seam is 122.19. This compares with a washability number of 147 from a bulk washability test. The standard deviation of the weighted average value is 50.1.

FUTURE WORK

This paper presents a preliminary attempt to relate the washability characteristics of a coal seam to its lithotype composition. More comprehensive studies are needed to confirm the validity of these findings. This should involve more systematic washability analysis of other seams and linking them with identification of their depositional environments. This may lead to meaningful conclusions regarding the sedimentation patterns and the predictability of washability from lithology. In terms of the statistical significance of the additivity of washability numbers from the respective lithotypes, more samples must be tested.

The next step in this study will be a more precise analysis of the association of mineral matter with macerals. This will be accomplished through microlithotype analysis of lithotype samples. This information will be used to better describe lithotype composition with respect to the original wetland environment and other quality characteristics.

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