Province of British Columbia
Ministry of Energy, Mines
and Petroleum Resources
Hon. Anne Edwards, Minister

MINERAL RESOURCES DIVISION
Geological Survey Branch

WASHABILITY CHARACTERISTICS OF BRITISH COLUMBIA COALS

By Maria E. Holuszko, P. Eng.

PAPER 1994-2

ABSTRACT

This paper summarizes the washability study conducted under the Coal Quality project. The aim of the study was to investigate and interpret washability characteristics of British Columbia coals, in order to provide a geological basis of washability and to gain practical information which will be useful in the processing and utilization of these coals. Washability characteristics of many coal seams from various British Columbia coalfields were examined.

The classical washability parameters were used to compare washability characteristics of different seams: yield of clean coal and the amount of near-gravity material close to the density of separation for desired clean coal product. Comparisons were made between seams from different coalfields, geological formations and lithotypes within the same coal seam. Unconventional washability parameters, such as degree of washing and washability number, were also calculated and compared.

Degree of washing and washability number were found to be very useful tools in the study of coal seams as rock units. Washability number defines the boundary between free (removable) mineral matter and mineral matter associated with coal (fixed), and at the same time gives an idea of the optimal conditions for separation. It is reasonable to assume that this number represents the effect of the depositional conditions on the association of coal with mineral matter. Above all, it characterizes inherent properties of a coal, and provides a single numerical measure of the variation in washability characteristics.

Suggestions of possible applications of the washability number to improve various technical procedures (blending, sampling) and coal preparation technologies are also included in this paper.

TABLE OF CONTENTS

ABSTRACT . . . iii

INTRODUCTION . . . 1
Acknowledgments . . . 2

PHYSICAL CHARACTERISTICS OF COAL IN RELATION TO COAL CLEANING . . . 3
Coal Characteristics at the Seam Level . . . 3
Physical Properties of Lithotypes . . . 4
Macerals . . . 7
Mineral Matter and its Influence on Physical Characteristics of Coal . . . 7
Washability . . . 9
Construction of Washability Curves . . . 10
Yield of Clean Coal and Quality of Rejects . . . 11
Predicting the Ease of Washing . . . 11
Degree of Washing and Washability Number . 11

SOURCES OF DATA AND SAMPLES FOR THE STUDY . . . 15
Bulk Samples . . . 15
Samples for Detailed Study . . . 15
Sampling Techniques . . . 15
Sink and Float Tests . . . 15

GEOLOGICAL SETTINGS OF THE STUDIED AREAS . . . 17
Peace River Coalfield . . . 18
East Kootenay Coalfields . . . 18
Merritt Coalfield . . . 19
Klappan Coalfield . . . 19
Comox Coalfield . . . 20

WASHABILITY CHARACTERISTICS OF BRITISH COLUMBIA COALS . . . 21
Washability of Coal Seams from Different Geological Formations . . . 21
Mist Mountain Formation . . . 21
Gates Formation . . . 25
Gething Formation . . . 26
Wapiti Formation . . . 26
Comox Formation . . . 26
Merritt Coalfield . . . 27
Klappan Coalfield . . . 27
Washability of Lithotypes . . . 27
Washability of Lithotypes from Greenhills and Quintette . . . 27

DISCUSSION AND CONCLUSIONS . . . 31

TECHNOLOGICAL APPLICATIONS OF WASHABILITY NUMBER AND ASSOCIATED PARAMETERS . . . 33

REFERENCES . . . 35

FIGURES

1. The relationship between seam composition, lithotypes, microlithotypes and macerals . . . 3
2. Type of mineral association and its possible effect on the washability . . . 7
3. Washability characteristics: ash *versus* clean coal yield curve for different size fractions for two coal seams from British Columbia . . . 9
4. Example of classical washability curves for a British Columbia coal seam . . . 10
5. Graphical representation of washability number . . 12
6. The effect of size reduction on increase in yield of clean coal and washability number . . . 12
7. Location of coalfields in British Columbia . . . 17
8. Stratigraphic relationships and relative coal seam positions in the Peace River coalfield . . . 18
9. Stratigraphic positions of the seams in southeast British Columbia . . . 19
10. Yield of clean coal for seams from: (a) Mist Mountain; (b) Gates Formations; (c) Gething Formation; (d) Wapiti Formation; (e) Comox Formation; (f) Klappan coalfield; (g) Merritt coalfield . . . 22
11. Variations in the ease of washing for seams in the Mist Mountain Formation . . . 25
12. Variations in the ease of washing for Gates Formation seams seams . . . 25
13. Correlation between washability numbers and amount of near-gravity material for 10% ash clean coal . . 31

TABLES

1. The correlation between Australian and ICCP lithotype classification . . . 4
2. Types of mineral matter in coal and their amenability to physical separation . . . 9
3. Example of sink-and-float data from southeast B.C. coal seam . . . 10
4. Industrial classification of "ease of washing" . . . 11
5. Washability data for seams from different geological formations . . . 23
6. Washability Number and associated parameters for seams from different geological formations . . . 24
7. Washability data for Mist Mountain Formation seams; southern part of the coalfield . . . 25

8. Washability data for Mist Mountain Formation seams; northern part of the coalfield 26

9. Washability number, degree-of-washing and other associated parameters for selected lithotypes from Greenhills and Quintette seams 31

PLATES

1. Fording mine operation - view to the west 1

2. Elkview operation, formerly Balmer mine - coal loading 4

3. Quintette coal preparation plant 5

4. Examples of macerals from southeast British Columbia coal seams. 6

5. Examples of mineral matter from British Columbia coals 8

6. Line Creek seams - coal bearing strata exposed in the highwall 20

7. Sampling lithotypes at Quintette 27

8. Sampling lithotypes at Greenhills 31

TABLE OF CONTENTS

	Page
ABSTRACT	iii
INTRODUCTION	3
Background and Current Status	3
Location and Physiography	3
Previous Work	3
Objectives of the Study	7
Regional Geological Setting	9
Structure	9
Stratigraphy	10
Fernie Formation (Jurassic)	10
Kootenay Group (Upper Jurassic to Lower Cretaceous)	10
Blairmore Group (Lower Cretaceous)	10
Alberta Group (Upper Cretaceous)	11
Coal Petrography	11
Rank	11
Composition	11
Predicted Quality	11
Computer Modelling Technique	14
Gridded-surface Technique	14
Grid-surface Design	15
Gridded-surface Construction	15
Model Format and Analysis	15
PARCEL 73	17
Structure	17
Stratigraphy of the Lookout Thrust Sheet	17
Coal Quality	18
Adit Samples	18
Rank Distribution	19
Predicted Coal Quality	20
Deposit Model	20
Objectives	20
Grid Specifications	20
Data Sources	20
Grid Construction	21
Modelling	22
Analysis	22
Resource Calculations	23
Mining Method and Logistics	23
PARCEL 82 - FLATHEAD RIDGE	25
Structure	25
Stratigraphy	25
Coal Quality	26
Washability	26
Steel Mill Tests	26
Rank Distribution	27
Predicted Coal Quality	28
Deposit Model	29
Objectives	29
Grid Specifications	29
Data Sources	29
Grid Construction	29
Modelling and Analysis	31
Resource Calculations	32
Mining Methods and Logistics	33
PARCEL 82 - MOUNT TAYLOR	35
Structure	35
Stratigraphy	35
Coal Quality	36
Washability	36
Other Analyses	36
Rank Distributions	36
Predicted Quality	37
Deposit Model	37
Objectives	37
Grid Specifications	37
Data Sources	37
Grid Construction	38
Modelling and Analysis	38
Resource Calculation	39
Mining Method and Logistics	40
CONCLUSIONS	41
Acknowledgments	41
REFERENCES	43
APPENDIX 1	45
Program Manual	45
Introduction	45
Grid Survey (G-SURV)	45
Operation	45
Example	45
Program Output	45
Grid Plotter (G-PLOT)	45
Operation	45
Example	45
Grid Edit (G-EDIT)	46
Operation	46
Example	46
Grid Calculator (G-CALC)	46
Operation	46
Example	46
Trim Grid	47
Grid-standard Function	47
Example	47
Grid-to-grid Function	47
Example	47
Digital Model Description	47
APPENDIX 2	49
Diskette Use	49

FIGURES

Page

1. Location of the East Kootenay coalfields 4
2. Coal tenure map of Crowsnest coalfield 5
3. Topography of Parcel 73, Dominion Coal Block, with outline of model grid superimposed 6
4. Topography of Flathead Ridge in Parcel 82, Dominion Coal Block 7
5. Topography of Mount Taylor in Parcel 82, Dominion Coal Block 8
6. Former coal licences in Parcel 73 9
7. Former coal licences in Parcel 82 9
8. Generalized geology of the Crowsnest coalfield (modified after Price, 1962) 9
9. Distribution of coal rank in Crowsnest coalfield 11
10. Predicted volatile matter for Crowsnest coalfield 12
11. Predicted FSI for Crowsnest coalfield 12
12. Predicted dilatation for Crowsnest coals 12
13 Predicted fluidity for Crowsnest coals 13
14. Predicted ASTM coke stability for Crowsnest coals 13
15. Predicted coking coal groups for Crowsnest coals 13
16. Positions of coking coal groups listed in Table 1 relative to reflectance and inert contents 14
17. Geology of Parcel 73 18
18. Generalized measured stratigraphic section from Parcel 73 with coal rank values 19
19. Isometric diagram of the surface topography of Parcel 73 with coal seams and reflectance values displayed 20
20. Plots of poles to bedding in Parcel 73 (Wulff projection) with associated eigenvectors and eigenvalues 21
21. Distribution of waste-to-coal ratios over Parcel 73 22
22. Geology of Parcel 82 (modified after Ollerenshaw, 1981b) .... (in pocket)
23. Generalized measured stratigraphic section from Flathead Ridge in Parcel 82 26
24. Isometric diagram of the surface topography of Flathead Ridge in Parcel 82 28

Page

25. Plot of poles to bedding on Flathead Ridge in Parcel 82 (Wulff projection) 29
26. (a) Down-plunge projection profile of B-seam data and selected outcrop orientation data; (b) B-seam structural contour grid; (c) Residual grid; (d) Final B-seam position grid 30
27. Areal distribution of seams used in the digital deposit model 31
28. Distribution of waste-to-coal ratios over Flathead Ridge in Parcel 82 32
29. Stratigraphic section from Mount Taylor, Parcel 82 with coal rank values 35
30. Isometric diagram of the surface topography of Mount Taylor in Parcel 82, selected coal seam traces and reflectance values 37
31. Plots of poles to bedding on Mount Taylor (Wulff projection) 38
32. Distribution of waste-to-coal ratios over Mount Taylor in Parcel 82 39

TABLES

1. Characteristics of Coking Coal Groups 14
2. Summary of Test Results on Parcel 73 Adit Samples 17
3. List of Grids in the Parcel 73 Model 21
4. Potential Coal Resources in Parcel 73 23
5. Individual and Cumulative Waste-Coal Ratios, Parcel 73 23
6. Combined Results of Float-Sink Tests of B-Seam Flathead Ridge 26
7. Summary of Clean B-Seam Test Results at Japanese Steel Mills 27
8. Summary of Clean A-Seam Test Results at Japanese Steel Mills 27
9. List of Grids in the Flathead Ridge Model Parcel 82 31
10. Reserves and Resources, Flathead Ridge, Parcel 82 32
11. Mount Taylor U2-Seam Washability 36
12. Mount Taylor M-Seam Quality 36
13. Mount Taylor U2-Seam Quality 36
14. List of Grids in the Mount Taylor Model Parcel 82 38
15. Potential Coal Resources , Mount Taylor Parcel 82 39

INTRODUCTION

Washability is an important factor in the economic evaluation of a coal seam. It provides practical information on those characteristics of coal that affect recovery, beneficiation and final use. In general, washability analyses are carried out to determine how much coal, of what quality, can be produced from a given coal seam.

The evaluation of the economic viability of any coal seam requires consideration of factors related to geological conditions for mining, and parameters related to the seam characteristics. Amongst seam characteristics, the most important the yield and the quality of coal which can be produced. The price of coal, as compared to other mineral commodities, is relatively low, therefore the costs of mining, processing and transportation to market are critical factors in the economics of the project, and must be offset by the quality of mined coal.

Coal is an organic sedimentary rock made up of organic matter (macerals) and inorganic components (minerals associated with coal). The quality of coal is assessed according to its type, rank and grade. Rank and type are related to the quality of organic matter composing the coal, whereas grade refers to the quality of coal in terms of size and mineral matter content (ash).

In order to be a saleable commodity, a coal must be prepared into a clean, graded and consistent product suitable for its intended market. This is accomplished by "coal preparation". Following preparation, coal can be used as a fuel, a reducing agent in metallurgical processes, or as feed to conversion processes (liquefaction or gasification).

Most cleaning processes rely on the physical differences between coal particles and associated minerals (minerals form the ash during combustion of coal). Parameters derived from washability tests, such as yield of clean coal at preselected ash levels, yield of rejects and their quality, and amount of near-gravity material, indicate the ease or difficulty in washing of a particular seam.

Mineral matter content is practically the only characteristic of the coal that can be controlled during coal preparation. The coal quality requirements may be different, however, for various coal utilization purposes. Depending on the rank of coal, the allowable amount of ash in a thermal coal product may vary from as much as 30% for use in a minesite power station, to 10 to 15% for export to other markets. For coals used to produce coke, ash content may be required to be as low as 5% when used by Canadian steel companies and generally in the range of 9 to 10% for western Canadian metallurgical coals exported to Japanese and Korean steel mills. Plate 1 shows mining operation at Fording.

Size distribution and sink-and-float data are the basic information required to evaluate cleaning alternatives and ancillary operations. It is important to ensure that correct

Plate 1. Fording mine operation - view to the West.

information is used in the designing of a coal preparation plant and that the inherent characteristics of coal are taken into consideration. For example, the partition curves derived from washability data serve to predict efficiency in the performance of various types of coal cleaning equipment (Leonard, 1979; Butcher, 1985; Laskowski and Walters, 1987).

From the environmental point of view, extraction of any mineral is a process leading to the disturbance of the natural environment and production of waste material, as a result of both mining and processing. Coal preparation produces reject material, in the form of rock and middlings, which is accumulated as waste. The characteristics of waste material can easily be predicted from the washability parameters. This information can be useful in decision making about possible utilization of waste products during the environmental impact assessment.

ACKNOWLEDGMENTS

I wish to express my gratitude to all colleagues in the Coal Unit and support staff from the Geological Survey Branch of the Ministry of Energy, Mines and Petroleum Resources, who contributed their moral support and cooperation to the Washability Project and preparation of this paper.

Special thanks are due to Dave Grieve for his valuable discussions and guidance throughout the duration of the project and in preparing this paper. Ward Kilby is acknowledged for his help in the first stage of the project and for providing computer programs used in the study.

Many thanks are given to the geology staff at all the province's coal mines for their cooperation, especially the staff of Greenhills, Line Creek, Quintette and Quinsam for their assistance in the sampling programs. Valuable discussions with many geologists and engineers during the scientific exchange meetings in Tumbler Ridge and Sparwood during the summer of 1992 are greatly appreciated.

Mike Fournier provided technical assistance in preparation of graphs and sketches. Linda Hitchen and Anna Peakman typed many pages of washability data tables. Their help is also very much valued.

PHYSICAL CHARACTERISTICS OF COAL IN RELATION TO COAL CLEANING

COAL CHARACTERISTICS AT THE SEAM LEVEL

Many physical characteristics of coal are directly related to the coal rank and type, as well as the minerals associated with it. These can be considered at various levels of coal composition. For example, each coal seam represents a geological entity comparable to an orebody, which is characterized by a number of physical characteristics, such as thickness, continuity, density and lithological composition; and by properties resulting from its composition, for example, strength, hardness, abrasiveness and friability. These may be different, however, for a broken lump of mined coal and the same piece of coal in-place in the seam.

Coal is formed from plant material accumulated during peat formation. Peat is deposited in swamps and marshes from different plant communities with distinct sets of biological characteristics and geochemical conditions. The individual ecosystems control the formation of various mixtures of macerals and minerals, which subsequently form layers of coal types within the coal seam, referred to as lithotypes. The relationship between seam composition, lithotypes, microlithotypes and macerals is illustrated in Figure 1.

Coal, therefore, is a stratified rock composed of lithotypes, and each lithotype is a mixture of macerals and minerals. The lithotype layers in a seam may be only a few centimetres or up to a few metres thick. They also may vary in thickness laterally, which contributes to changes in seam composition over distance. On a microscopic scale, mixtures of macerals and minerals are defined as microlitho-

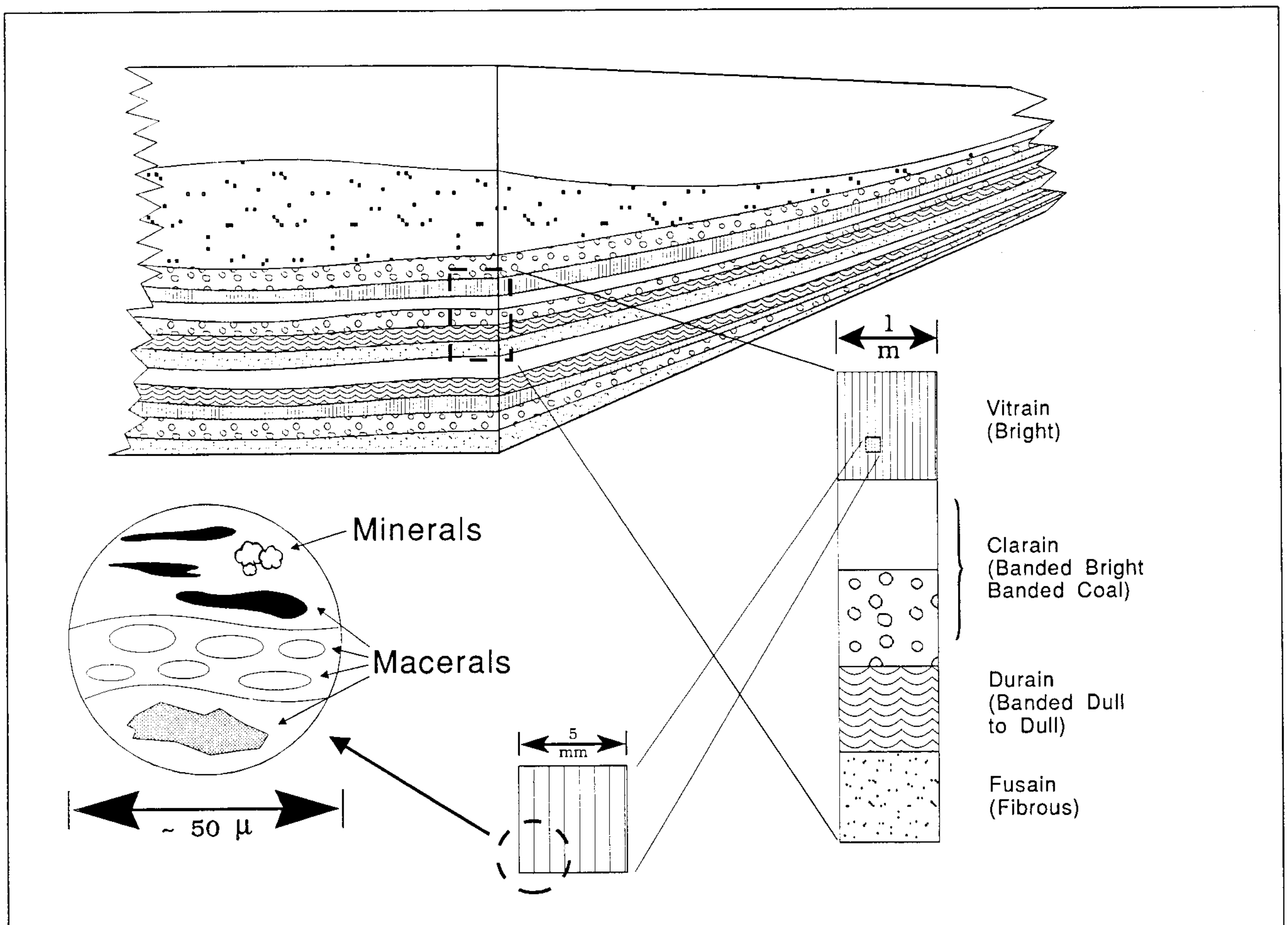

Figure 1. The relationship between seam composition, lithotypes, microlithotypes and macerals.

types (<50 µm), and, conversely, microlithotypes form bands of lithotypes on the macroscopic scale.

The physical characteristics of coal are dependent on lithotype composition, whereas composition of lithotypes is strongly dependent on the maceral composition as well as the association of macerals with different proportions of mineral matter (Diessel, 1965). Depending on the level at which we consider coal, its physical characteristics may vary. At a seam level, for example, the physical properties of coal are determined not only by rank and type of coal, but also by physical properties developed in the seam as a result of geological conditions, for example, overburden pressure, faulting, folding and shearing. These may result in development of cleats, fractures which will subsequently influence the strength, friability and hardness of all or part of a coal seam. Many British Columbia coals are very friable, due to folding and faulting. At this level, the properties of coal affect its mining and the resulting composition of material delivered to the coal processing plant.

The physical characteristics of coal, viewed from the lithotype (macroscopic) and maceral (microscopic) levels, are covered in the next two sections.

PHYSICAL PROPERTIES OF LITHOTYPES

Lithotypes are defined as macroscopically recognizable bands of coal, based on variations in appearance. The Stopes ICCP system (International Commission for Coal Petrology, (ICCP Handbook, 1963) defines four distinct lithotypes, while in the system developed in Australia recognizes six lithotypes. In the Australian approach coal is regarded as a mixture of bright and dull components and defined according to the proportions of these basic ingredients in the layer (Diessel, 1986). The correlation between the two lithotype classifications is given in Table 1.

TABLE 1
THE CORRELATION BETWEEN AUSTRALIAN AND ICCP LITHOTYPE CLASSIFICATIONS

Classification after Stopes (1919)	Australian Classification	Description
Vitrain	Bright coal	Subvitreous to vitreous lustre, or conchoidal fracture, <10 % dull.
	Banded bright coal	Bright coal with some thin dull bands, 10-40 % dull.
Clarain	Banded coal	Bright and dull coal bands in equal proportion, 40-60 % dull.
	Banded dull coal	Dull coal with some thin bright bands, 10-40 % bright.
Durain	Dull coal	Matt lustre, uneven fracture, <10 % bright
Fusain	Fibrous coal	Satin lustre, friable.

As the run-of-mine coal is delivered to the preparation plant, depending on its top size, it usually represents coal at the lithotype level. Plate 2 illustrates loading operations at Elkview mine, formerly Balmer. At this level, the physical properties of coal lumps are strongly dependent on the lithotype composition. It has been shown that many physical properties of coal, related to cleaning, can be predicted from lithotype characteristics. It is known, for example, that different lithotypes are characterized by different density, strength, hardness, grindability and abrasiveness (Falcon and Falcon, 1987; Hower, 1988; Hower and Lineberry,

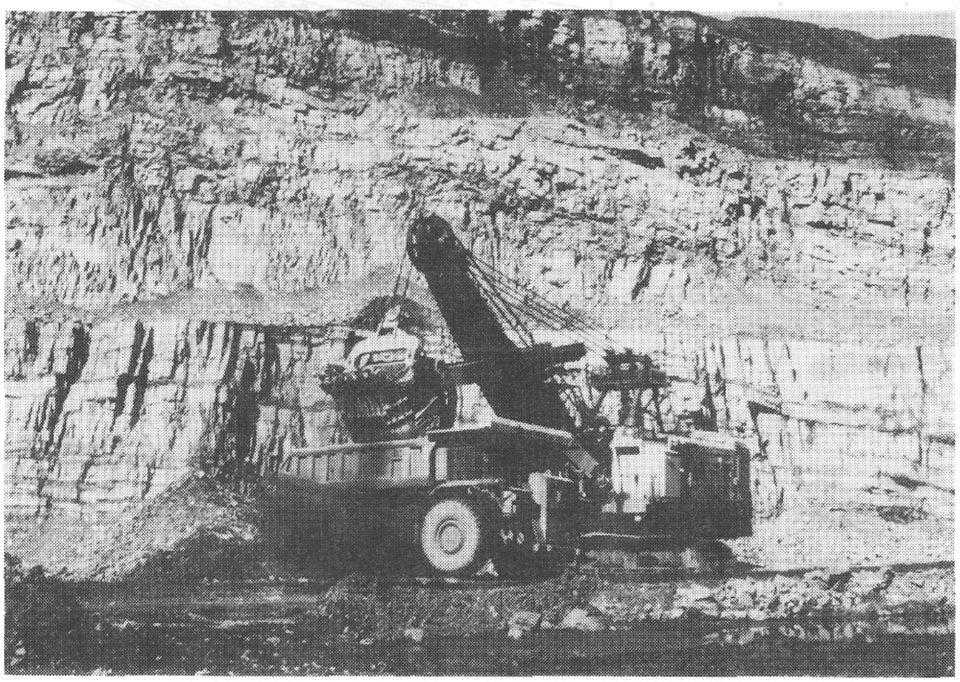

Plate 2. Elkview operation, formerly Balmer mine - coal loading.

1988; Hower *et al.,* 1987; Hsiech (1976) in Hower *et al.*, 1987, 1990). The relationship between lithotypes and their variation in grindability index (HGI) has also been established (Hower, 1988; Hower *et al*, 1987; Hower and Lineberry, 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. Many of these properties have been shown to have profound effect on the processing and handling of coal.

Coal cleaning usually involves breaking, crushing,sizing, gravity separation and flotation. Different properties of coal are exploited in each of these operations. Strength, hardness, grindability and friability are important parameters in breaking and crushing. Sizing leads to segregation of coal particles into different size fractions and these are usually cleaned in separate washing circuits. Depending on the lithological composition of the seam, coal particles segregated into various size fractions may be dissimilar.

In a finely stratified coal seam, lithotype compositions of different size fractions may be very similar. However, for a seam with thicker layers of various lithotypes, segregation during sizing may be more apparent. As a result, durain-rich (dull) coal will usually comprise a coarser size fraction, while clarain and vitrain will be concentrated in the finer sizes (Laskowski, 1948; Mackowsky and Hoffman, 1960). Depending on its petrographic composition, it is also possible for a coal seam to generate a fine size fraction (0.0-0.15 mm) enriched in fusain (McCabe, 1942). In the tectonically sheared coal seams of southeastern British Columbia, for example, the dull durain-rich coals are relatively unsheared compared to clarain and vitrain-rich coals. As a result, coarse coal fractions are usually enriched in durain while fine coal is composed mainly of vitrain (Bustin *et al.*, 1983).

The typical top size of coal treated in preparation plants in British Columbia is 50 millimetres, with a few exceptions. Due to the friable nature of western Canadian coals, the amount of fines in metallurgical (medium-volatile to low-volatile) coals may reach 60%, but usually 30 to 35% of the material is below 0.50 millimetre (28 mesh). In part, the higher content of fines in British Columbia metallurgical coals is related to the rank of coal; medium-volatile coals are characterized by the lowest hardness and highest friability. Medium-volatile and low-volatile coals in the Rocky Mountain region of the province have been subjected to severe geological disturbance, and this has resulted in extensive shearing of coal strata throughout the region. The strongly sheared coals tend to be very friable and produce very high amounts of fines during mining, handling and processing.

In gravity separation, differences in density play a critical role. The density of lithotypes varies quite significantly, with the bright lithotypes (vitrain) having the lowest density, and the dull, mineral matter-rich lithotypes (durain) the highest. It has been shown that during gravity separation there is segregation of lithotypes into various density fractions, and finally into various clean coal products (McCabe, 1942; Falcon and Falcon, 1987).

Most cleaning processes are based on specific gravity differences and are most effective for coal coarser than 0.50 millimetres in size. The most commonly used are: heavy media vessels (treating coal in the size range of 6 to 100 millimetres); jigs (5 to 50 mm or 0 to 8 mm) and heavy media cyclones (0.6 to 6 mm). Due to the fact that coarse fractions in most British Columbia coals are more difficult to clean than coarse fractions elsewhere, less accurate washing devices, such as jigs, are not very suitable to clean these coals (only one preparation plant in British Columbia uses a Baum jig in its operation). While it may be possible to obtain a 10% ash coal product from Carboniferous coals from the eastern United States or Europe using a jig washer, western Canadian coals require more accurate heavy media processes to achieve an equivalent coal product. Fine coal is usually treated in circuits using a combination of water-only cyclones and froth flotation. Plate 3 shows the Quintette coal preparation plant.

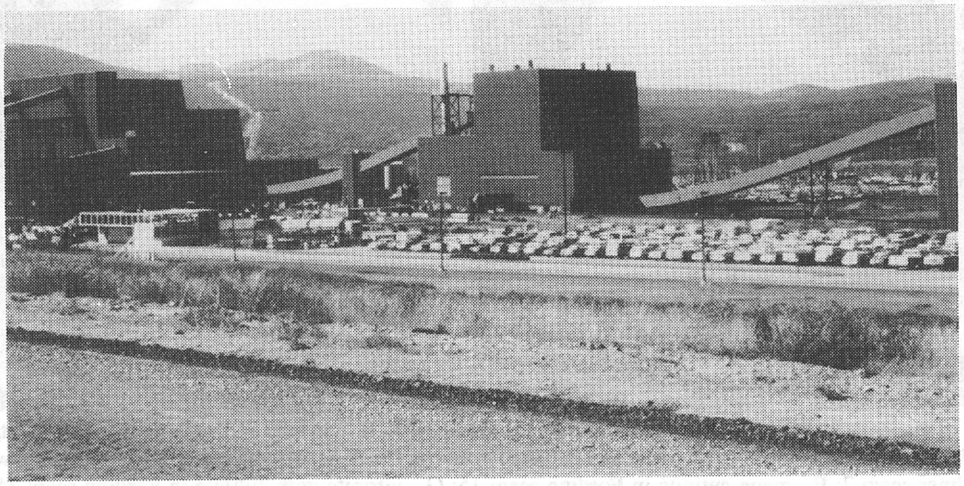

Plate 3. Quintette coal preparation plant.

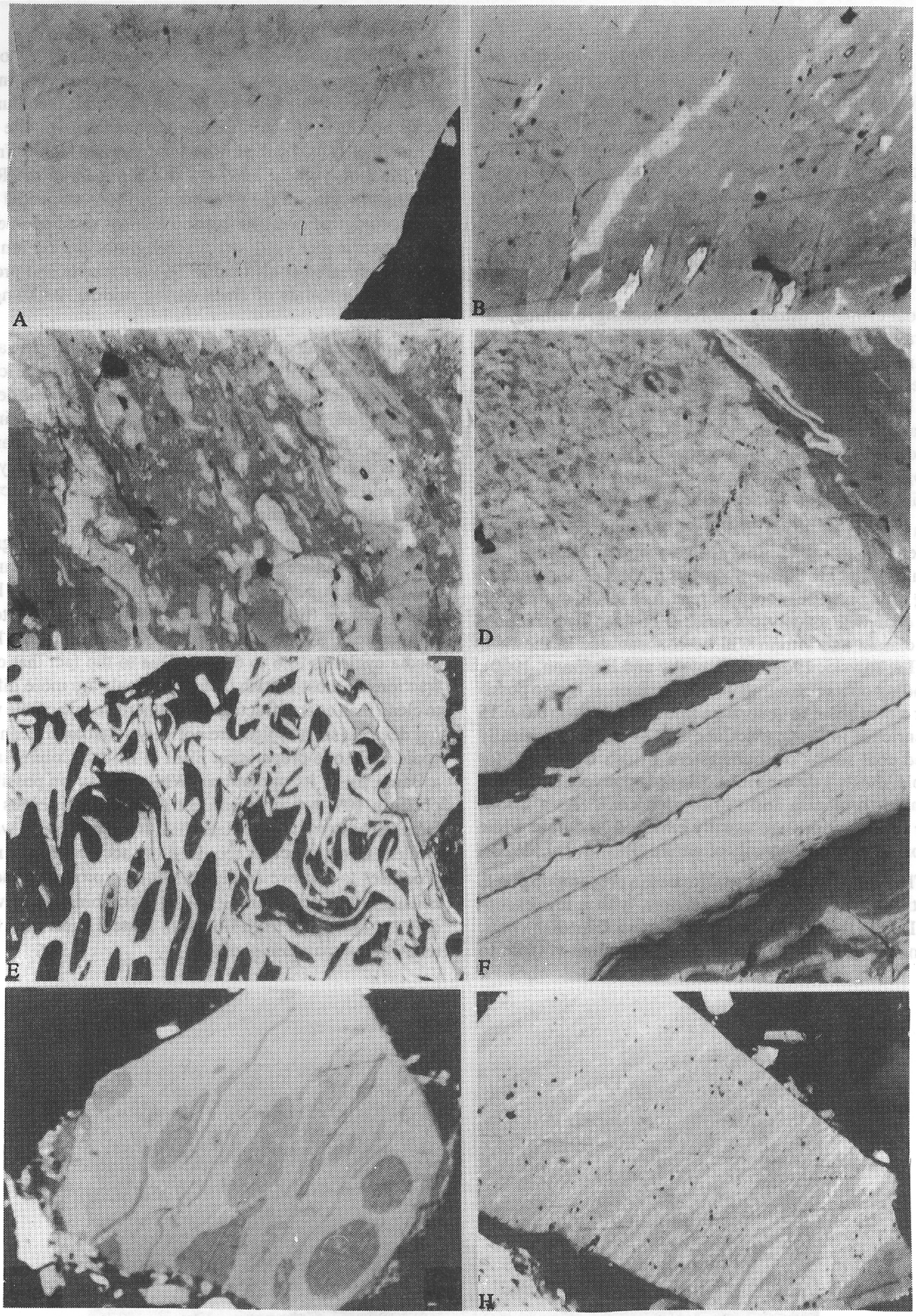

Plate 4. Examples of macerals from southeast British Columbia coal seams: A, B - vitrinite and vitrinite with inertodetrinite in Line Creek seam 9; C - vitrodetrinite (vitrinite with semifusinite and cutinite) in Byron Creek Mammoth seam; D- semifusinite with desmocollinite; E - fusinite in Balmer seam 7; F - mega-cutinite in Fording seam 15; G - vitrinite with cutinite in Fording seam 15; H - vitrinite with micrinite in Line Creek seam 9.

The flotation responses of lithotypes have also been studied, confirming various behaviours during flotation. These was found to be due to varying degrees of hydrophobicity of lithotypes (Horsley and Smith, 1951; Sun, 1954; Klassen, 1966; Holuszko, 1991).

One can assume that, at any level of coal preparation, segregation of coal lithotypes will be accomplished. Different lithotypes will be distributed into various fractions and they will define technological properties and final use of the coal products.

MACERALS

Macerals are the basic organic components of coal. They occur in association with each other and various proportions of mineral matter, and these associations are referred to as microlithotypes on a microscopic scale, and lithotypes on a macroscopic scale. Except for the ultrafine sizes, microlithotypes and macerals are not handled during coal preparation. Examples of some coal macerals from British Columbia coals are illustrated by Plate 4.

Macerals are known to have different chemical compositions and physical properties. For example, they vary in density with rank, and the coal macerals have different densities at any particular rank. Any separation which relies on differences in density will therefore influence distribution of macerals in various products. It has been demonstrated that more consistent maceral partitioning is usually exhibited in the cleaning of fine fractions than coarse fractions.

The concentration of a certain maceral in a particular stream of a coal preparation plant is considered to be a function of its physical properties (Hower *et al.*, 1986; Hower and Wild, 1991; Bustin, 1982; Falcon and Falcon, 1983). Methods of optimizing the ratio of specific macerals during selective size reduction have been developed, for example, the Longway-Burstlein method. Using this method, selective maceral concentration into certain size fractions was accomplished by using combinations of cleaning operations designed to produce the optimum coking coal (Bustin *et al.*, 1983).

MINERAL MATTER AND ITS INFLUENCE ON PHYSICAL CHARACTERISTICS OF COAL

There are three different levels at which minerals can be associated with coal. The first is at the ply and lithotype level; mineral matter occurs as deposits in cracks and cleats in coal, or as discrete bands of rock. The second level of association is observed at the maceral level; mineral matter may be present as stringers or disseminated mineral particles within different macerals, or as open-space fillings in the maceral structure. The third level represents inorganic elements chemically bonded to the coal molecular structure.

During the process of mining, the structure of a seam is destroyed, and, depending on the severity of the mining and handling methods, this results in various levels of mineral and organic matter interrelation in coal particles. This is usually referred to as degree of liberation of coal from minerals. As-mined (run-of-mine) coal usually contains not only components of the coal seam, but also mineral matter from the inclusion of roof or floor rock, as well as the discrete rock bands within the seam. As a result, a large amount of coal and rock is already sufficiently liberated to enable immediate separation even before it enters the coal cleaning circuits.

Type and mode of mineral matter in coal are particularly important to washability. The amount of inorganic matter associated with macerals has a direct influence on the density of composite coal particles, while the type of minerals, and their association with coal macerals, has an impact on the ease of gravity separation.

Minerals deposited in cleats and fissures are relatively easy to remove by means of crushing and washing operations. Liberation of this type of mineral matter is straightforward and results in good separation between coal and shale particles, with very small amounts of "middlings". Minerals which occur either as finely disseminated mineral particles, or as larger species intergrown with coal macerals, are more difficult to separate and larger amounts of middlings are produced.

In western Canadian coals, pyrite occurs predominantly in the latter form, whereas clays are found in both forms. Plate 5 shows examples of mineral matter association with macerals found in British Columbia coal seams. Figure 2 shows the type of mineral association and its possible effect on the washability. Table 2 presents types of mineral phases in coal and their amenability to physical separation.

Coals containing fine-grained syngenetic minerals will produce relatively equal amounts of light clean coal, middlings and high-density rejects, when subjected to gravity separation. In this case liberation of mineral matter can only be achieved by fine grinding. However, liberation of mineral matter is not always desirable. For example, the presence of liberated clays in the fines, especially bentonite clays, can render the cleaning process almost impossible. These clays

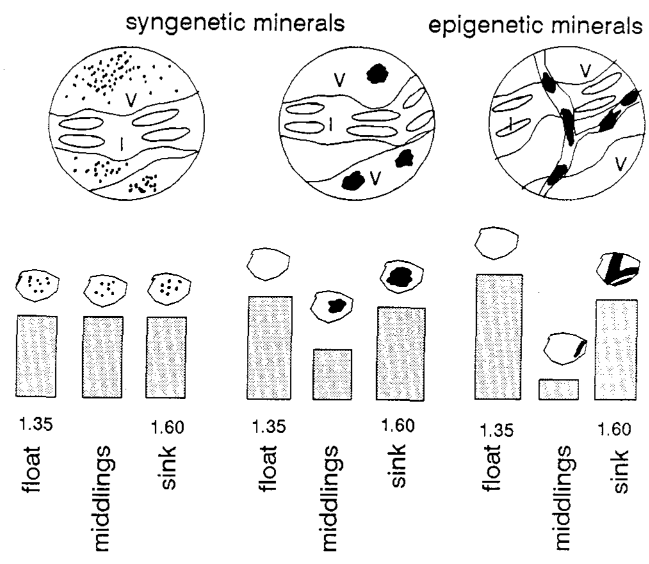

Figure 2. Type of mineral association and its possible effect on the washability.

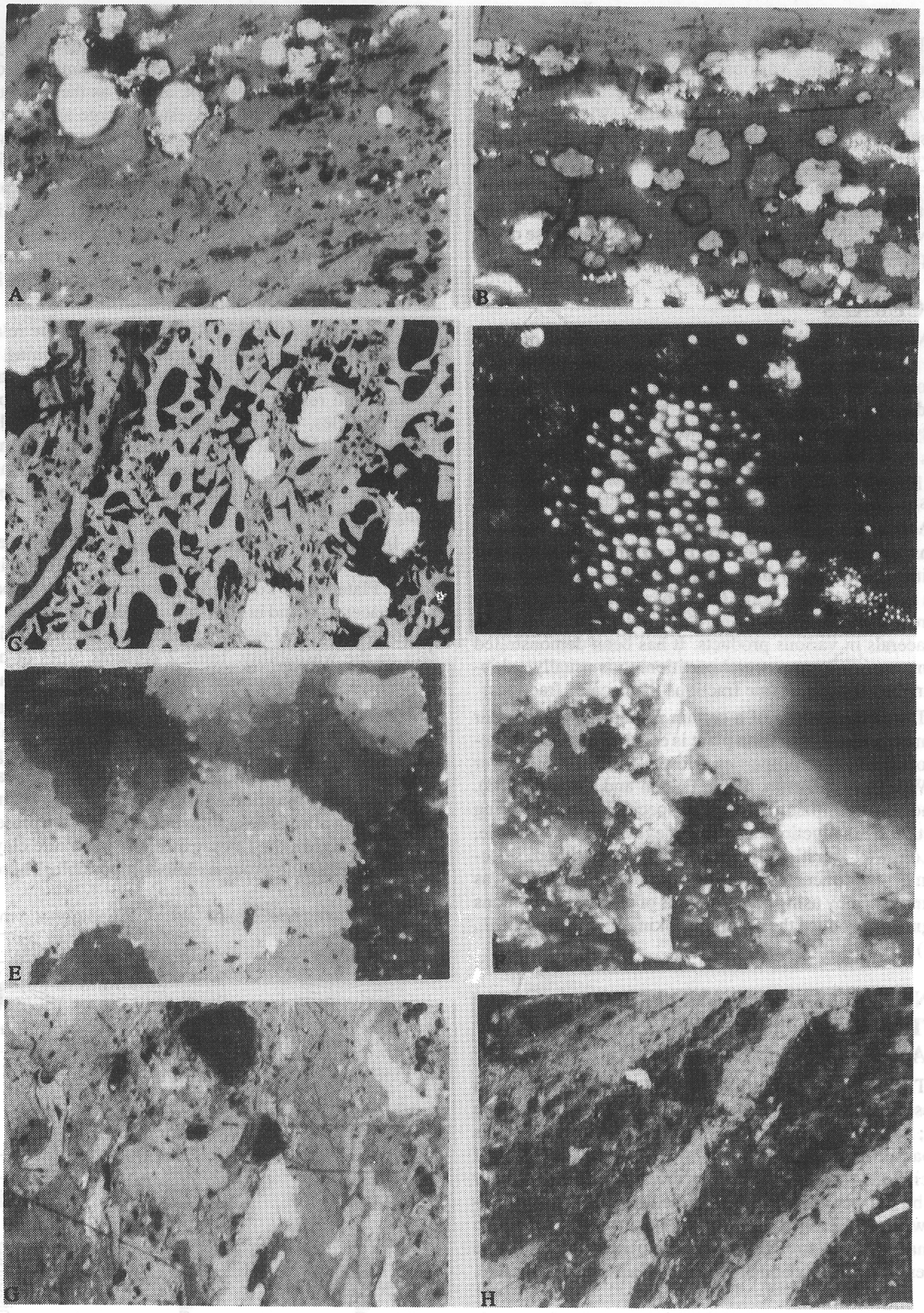

Plate 5. Examples of mineral matter from British Columbia coals: A - framboidal pyrite in Bowron coal; B - pyrite with siderite in Bowron coal; C - irregular euhedral pyrite in Quinsam coal; D - dendritic pyrite from Bowron; E - carbonate minerals from Bullmoose coal; F - quartz with clays in Bullmoose coal; G - quartz (black) in Bullmoose coal; H - clays in Bullmoose coal.

TABLE 2
TYPES OF MINERAL MATTER IN COAL AND THEIR AMENABILITY TO PHYSICAL SEPARATION

Type	Origin	Examples	Physical Separation
Strongly chemically bonded elements	From coal-forming organic tissue material	Organic sulphur, nitrogen	No.
Absorbed and weakly bonded groups	Ash-forming components in pure water, absorbed on the coal surface	Various salts	Very limited.
Mineral matter			
a. Epiclastic	Mineral washed or blown into the sea during coal formation	Clays, quartz	Partly separable by physical methods.
b. Syngenetic	Incorporated into coal from the very earliest peat-accumulation stage	Pyrite, siderite, some clay minerals	Intimately intergrown with coal macerals.
c. Epigenetic	Stage subsequent to syngenetic; migration of the mineral-forming solutions through coal fractures	Carbonates, pyrite, kaolinite	Vein = type mineralization; epigenetic minerals concentrated along cleats, preferentially exposed during breakage; separable by physical methods.

After Cook (1981).

when mixed with water form a gel-like suspension, which is difficult to settle, and in many cases tends to cover coal surfaces, impairing cleaning processes.

Coarser syngenetic minerals are easier to remove. Better washing characteristics are mainly due to a greater degree of liberation of coarse minerals.

WASHABILITY

Washability of a given coal is estimated from a set of washability curves. These are constructed from sink-and-float analysis of a representative coal sample, carried out under ideal conditions, and characterized by ash content and yield at each density of separation. As the specific gravity of coal is closely related to its mineral matter content in raw coal (expressed as ash), gravity separation will divide coal into ranges of different impurity content. The washability curves provide the best possible prediction of theoretical results for gravity-based coal preparation processes.

In order to investigate the washability characteristics of raw coal it is necessary to determine the amount and distribution of the mineral matter, expressed as ash, in a representative sample. Due to the fact that sample is composed of coal material varying in size, and, at the same time, each size fraction has a different composition (mineral matter as well as petrographic), it is necessary to examine certain size ranges for washability characteristics separately. Figure 3 presents varying washability characteristics (as predicted from the ash *versus* clean coal yield curve) for different size fractions for two British Columbia coal seams.

The washability determined for any coal seam is very much dependent on the top size of its representative sample. Liberation of coal from mineral matter is usually achieved by reducing the size of coal by breaking or crushing. During breakage coal particles separate from epigentic minerals, usually along the bedding planes. The way in which coal separates from ash-forming minerals depends on the type

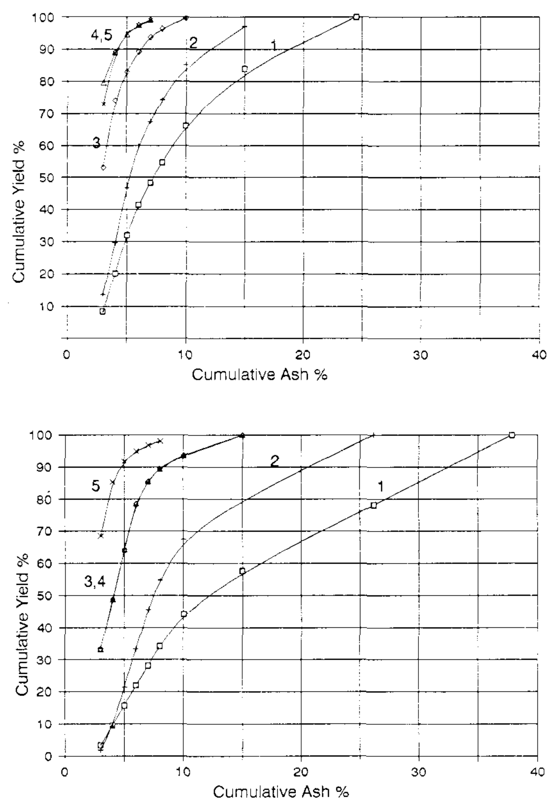

Figure 3. Washability charactertistics: ash versus clean coal yield curve for different size fractions for two coal seams from British Columbia. For those coals size fraction 1 = 50-19 mm, 2 = 19-6.3 mm, 3 = 6.3-0.6 mm, 4 = 0.6-0.3 mm and 5 = 0.3-0.15 mm.

and mode of occurrence of the minerals as well as the type of coal.

As discussed in the previous chapter, the easiest to separate are the epigenetic minerals, while epiclastic and syngenetic minerals are more difficult to remove by physical separation (Cook, 1981; Falcon and Falcon, 1983). Epigenetic minerals are easily liberated when the size is reduced and this results in an increase in the yield of clean coal. Epiclastic and syngenetic minerals (clays, quartz, pyrite, siderite) are not usually liberated during the coarse coal crushing.

Depending on the size of coal particles or the severity of the reduction process (crushing or grinding), a part of the mineral matter will be impossible to separate from coal. From a practical point of view, the terms "extraneous" and "inherent" mineral matter are usually used to distinguish between ash-forming mineral matter which is separable by physical methods, and that which is not. Extraneous mineral matter invariably refers to epigenetic minerals, whereas the term "inherent" may be applied to syngenetic or epiclastic minerals. What the so-called "inherent" mineral matter actually represents is questionable. It does reflect, however, the amount of mineral matter intergrown with the coal in a particular size fraction. Recent research shows that even mineral matter as fine as 1 micron in size can be separated if liberated by fine crushing and grinding. In this context, inherent mineral matter represents only inorganic elements which are confined to the coal molecular structure and which can only be removed by chemical treatment.

At the top size of each size fraction of a coal sample there is a ratio of inherent to extraneous mineral matter content which characterizes the sample in terms of the ability to clean the particles within the given size range. There is also a critical top size below which further reduction leads to deterioration in the quality of the coarse fractions in the sample. Coarser fractions are enriched in composite particles (coal intergrown with mineral matter) and these are more difficult to clean. Reducing the top size below the critical level deteriorates the quality of coarse fractions, while cleaner coal particles are concentrated in fine fractions. This may not be desirable from the cleaning point of view: coarse fractions will have to be cleaned with more accurate devices while circuits treating fine coal will be overloaded.

In practice, coal preparation treats raw coal according to size. For thermal coal, only two circuits may be employed (coarse and fine), whereas three or four are commonly used for metallurgical coal. In this respect it is important to know the washability characteristics of various size ranges within the coal sample.

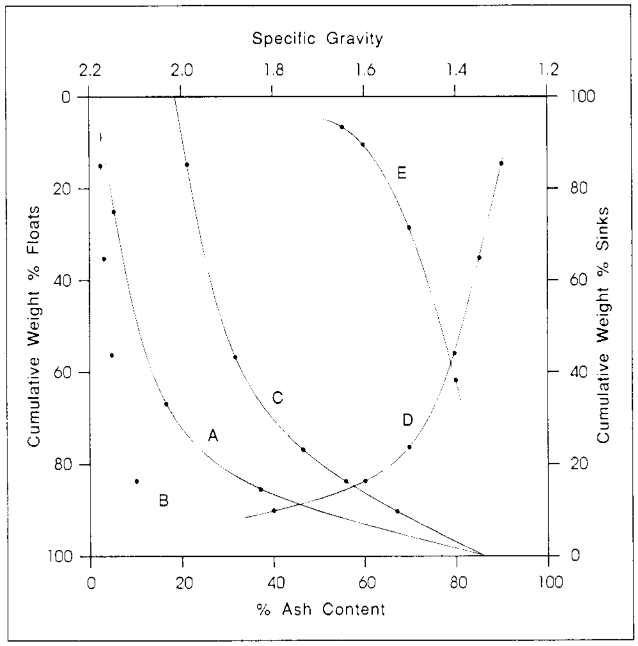

Figure 4. Example of classical washability curves for a British Columbia coal seam. A- primary curve, B - clean coal curve, C - cumulative sink curve, D - density distribution curve, E - near-gravity material within ± 0.1 s.g.

CONSTRUCTION OF WASHABILITY CURVES

In coal preparation, results of coal cleaning are expressed as yield of concentrate, which is the clean coal, together with the grade expressed as ash content. Points defined by yield and ash content at each step of density separation in sink-and-float tests are used to construct washability curves. An example of sink-and-float data is presented in Table 3 and the resulting washability curves are illustrated in Figure 4.

The primary curve (A) is obtained by plotting incremental ash content at each separation density *versus* incremental yield on the cumulative yield scale. The clean coal curve (B) is obtained by plotting cumulative ash content at any given density *versus* cumulative yield. The cumulative sink curve (C) predicts ash content of the sinks at any yield of clean coal. The cumulative density distribution is plotted

TABLE 3
EXAMPLE OF SINK-AND-FLOAT DATA FROM A SOUTHEAST B.C. COAL SEAM, SIZE >0.15 mm

Specific Gravity	Direct Weight %	Direct Ash %	% Weight of Ash of Total	Cum. Weight of Ash %	Cum. Floats Weight %	Cum. Floats Ash %	Sink Weight of Ash %	Cum. Sinks Weight %	Cum. Sinks Ash %	± 0.1 S.G. Distribution S.G.	± 0.1 S.G. Distribution Weight
-1.30	14.96	1.90	0.28	0.28	14.96	1.90	17.36	85.04	20.41		
1.30-1.35	20.51	5.65	1.16	1.44	35.47	3.32	16.20	64.53	25.10	1.40	62.15
1.35-1.40	20.86	10.08	2.10	3.54	56.33	5.82	14.10	43.67	32.29		
1.40-1.50	20.78	16.20	3.37	6.91	77.11	8.62	10.73	22.89	46.88	1.50	27.43
1.50-1.60	6.65	25.94	1.73	8.64	83.76	10.00	9.00	16.24	55.42	1.60	10.39
1.60-1.80	6.23	37.31	2.32	10.96	89.99	11.87	6.68	10.01	66.73	1.70	6.23
+1.80	10.01	66.70	6.68	17.64	100.00	17.37					
	100.00		17.64								

as density *versus* yield (D). The near-gravity material curve (E) indicates the amount of material within ±0.1 specific gravity of separation and is derived from plotting density of separation *versus* the amount of material within the specified range of densities (Leonard, 1979; Laskowski and Walters, 1987).

YIELD OF CLEAN COAL AND QUALITY OF REJECTS

Theoretical yield of clean coal is predicted from the clean coal curve as described above. For example, if the clean coal product has to meet market requirements of 10% ash, then the yield of this product is obtained from the clean coal curve. The higher the yield at the lowest ash content, the better the quality of the coal for a given seam. Cumulative ash% *versus* cumulative yield% are usually plotted separately for coarse and fine fractions and then combined to plot the total curves if necessary. However, sink-and-float-derived washability data cannot be used to predict fine coal flotation yields, as these two processes are based on different principles.

The quality of rejects is measured by ash content. The ash content of rejects can also be used as a measure of the efficiency of the coal cleaning processes. In a case where the ash content of rejects is not sufficiently higher than ash of the feed sample, combustibles will be lost into the discard. Either the process of separation is not efficient, or liberation of coal from mineral matter is not adequate. In the latter case, crushing or grinding will be required to liberate interlocked coal particles.

PREDICTING THE EASE OF WASHING

The "ease of washing" generally describes the way in which a given coal seam responds to gravity separation. The difference in density between clean coal particles and mineral matter when liberated is sufficient to achieve complete separation. The difficulty in washing is encountered with particles of composite nature. Given a density for coal between 1.2 and 1.4, and of mineral matter between 2.3 and 5.0, composite particles will generally have a density between 1.4 and 2.3. These particles will contribute to the difficulty of cleaning by gravity methods.

From the washability curves, the shape of the primary curve and yield of clean coal curve can indicate whether coal is easy or difficult to clean. A comparison of the yields of clean coal at selected ash levels, and the quality of their sinks, can also be used to estimate the ease of washing. A relatively low ash content of the sinks, at low separation densities, indicates the presence of middlings material, but it is not a quantitive measure of the ease of washing.

The amount of material in the range ±0.1 of the density of separation is considered to be a more quantitive measure for comparing relative "ease of washing" between different coal samples. The near-gravity material curve (E) is shown in the upper right corner in Figure 4. The ±0.1 specific gravity range approach assumes that all material within this range contributes to difficulties in washing. This range was chosen to measure the difficulty of obtaining the theoretical results when cleaning with jigs. This assumption may not be accurate for washing by more efficient separators, operating within much narrower ranges (*e.g.*, ±0.05 specific gravity). It is extremely important to determine the amount of near-gravity material at the cut points for the required quality of clean coal. Depending on the amount of near-gravity material within the ± 0.1 specific gravity range, a coal sample may be classified into one of six different categories: simple, moderate, difficult, very difficult, exceedingly difficult and formidable (Leonard, 1979). Table 4 presents values of near-gravity material and their assignments to different categories. This parameter, however, appears to have mainly technological implications rather than being related to the inherent properties of coal.

TABLE 4
"EASE OF WASHING" CLASSIFICATION ACCORDING TO THE AMOUNT OF NEAR-GRAVITY MATERIAL WITHIN ± -0.1 OF DENSITY OF SEPARATION FOR DESIRED PRODUCT

Amount of near gravity wt % (+0.1 s.g. range)	Degree of Difficulty
0-7	simple separation
7-10	moderately difficult
10-15	difficult
15-20	very difficult
20-25	exceedingly difficult
Over 25	formidable

after Leonard (1979)

DEGREE OF WASHING AND WASHABILITY NUMBER

Washability takes into account a number of parameters such as ash, yield of clean coal and amount of rejects, and amount of near-gravity material. The ease or difficulty in 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, as discussed above. Additionally, all of these parameters are coal dependent and not reliable when comparing coals of different origin. As discussed by some authors (Sarkar and Das, 1974; Sanders and Brooks, 1986; Holuszko and Grieve, 1991) it is useful to have washability parameters which include most of the washability variables and reflect inherent properties of coal. For that purpose, Sarkar and Das (1974) introduced the "degree of washing" and, resulting from it, the "washability number", as additional measures.

The degree of washing (N) was defined and calculated according to the expression:

$$N = \frac{w(a-b)}{a}$$

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

For a given coal sample, depending on the rank, type and mineral matter associated with the coal, there is always a density of separation which maximizes the yield of the cleanest product possible. The optimum degree of washing (N_{opt}) is then obtained by plotting degree-of-washing values (N) *versus* the density of separation, and finding the maximum value.

The ash content of the clean coal at the optimum degree of washing has specific significance in characterizing a

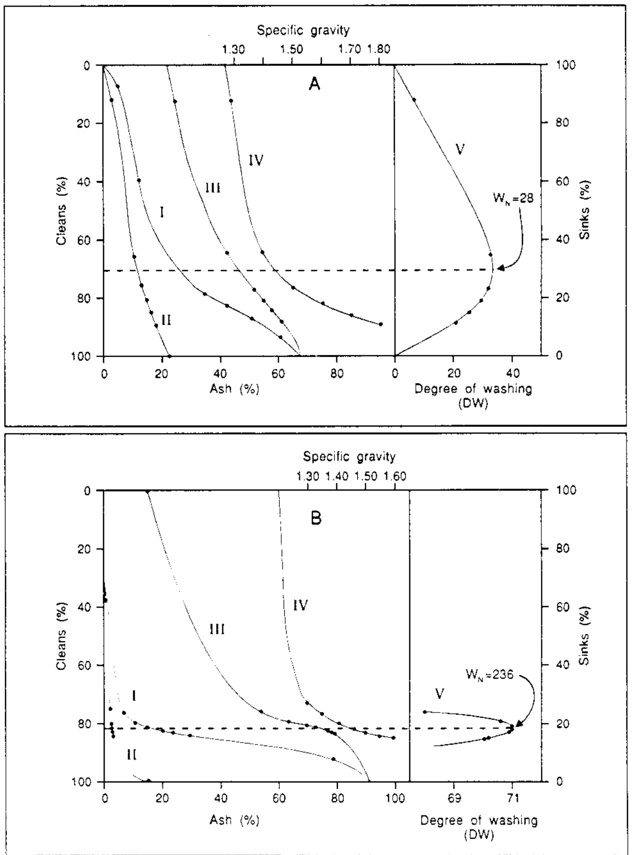

Figure 5. Graphical representation of washability number: Coal A with washability number Wn = 28, difficult to wash characteristics; Coal B with washability Wn=236, easy to wash characteristics. I - primary curve, II - clean coal curve, III - sink curve, IV - density distribution curve, V - degree of washing curve.

given coal sample. It is advisable to express the washability number as the ratio of the degree of washing to the clean-coal ash at the optimum level (Sarkar and Das, 1974; Sarkar *et al.*, 1977; Sanders and Brooks, 1986). The washability number can be expressed as follows:

$$W_n = \frac{10(N_{opt})}{b_{opt}}$$

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

The degree of washing and washability number take into account the ash content of the raw coal, yield and ash of clean coal at each density of separation, and ash of clean coal at the optimum of washing. These two parameters describe characteristics that pertain to inherent properties of coal. The graphical representation of degree of washing for two coals of significant difference in ease of washing is presented in Figure 5.

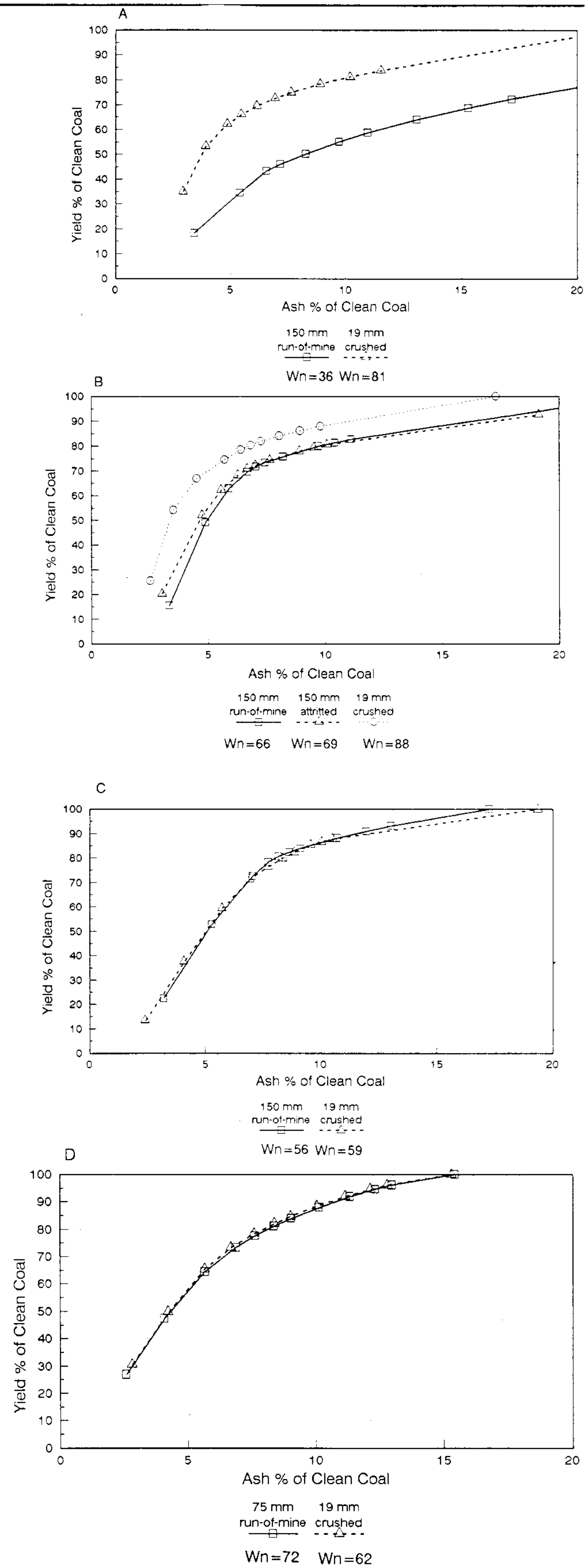

Figure 6. The effect of size reduction on increase in yield of clean coal and washability number in four different coals from the Gates Formation of northeast British Columbia.

It has also 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). 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). Changes in washability number within a single seam were used to outline lateral changes in depositional environment for some Indian and North American coals.

Comparisons of washability numbers from a number of countries around the world allow conclusions to be drawn about the global pattern in washability characteristics (Sarkar and Das, 1974; Sarkar *et al.*, 1977). Carboniferous coals of Europe and North America have the highest washability numbers, ranging from 96 to 157, with the lowest ash at the optimum degree of washing (between 3 and 6%), while Mesozoic coals have lower washability numbers (ranging from 25 to 95) with the ash from 4 to 12% at the optimum. The lowest washability numbers are found in Gondwana coals of Permian age, with washability numbers near 20 and ash at the optimum varying from 8 to 16%, indicating their inherent difficulty in washing.

This shows that the environmental conditions during the formation of these coals may had been significantly different. The Carboniferous coals of the northern continents were presumably deposited under quieter swamp conditions, leading to formation of more heterogeneous coal deposits with less mineral matter incorporated within the seam. Gondwana coals are more allochthonous, which leads to the difficulty in cleaning them.

It is generally known that the size of coal influences its washability characteristics. As discussed earlier, this is related to the liberation of mineral matter during size reduction. It is expected that a reduction in the top size of a coal will increase the value of its washability number until the critical top size for the coal sample is reached, below which there is no increase in clean coal yield. Figure 6 illustrates this effect.

Reducing the top size of the samples from seams A and B improves the recovery of clean coal while reduction in size in seam C sample has no positive effect on the yield of clean coal. Crushing to a smaller size does not increase the yield of clean coal from seam D, and, as indicated by the washability number, leads to an increase in difficulty in washing. This also may imply that washability is more sensitive in detecting changes in ease of washing than the curve for yield of clean coal.

SOURCES OF DATA AND SAMPLES FOR THE STUDY

Two types of washability data were used to study washability characteristics of coal seams from British Columbia: bulk sample data derived from coal industry exploration assessment reports filed with the Ministry of Energy, Mines and Petroleum Resources and data from analysis of samples collected from selected coal seams.

The study of the washability number as a parameter in the evaluation of sedimentological conditions during deposition required examination of coal seams and coal deposits in much greater detail and in a more systematic and comprehensive way. This aspect of the study compared the washability characteristics of various coal deposits in the context of their host formations. Care was taken to follow a standard procedure in choosing representative coal samples and to ensure that the top size of the samples was more or less uniform.

BULK SAMPLES

Washability data on bulk samples from across the province are available in the form of sink-and-float analysis results. Analyses on bulk samples are frequently performed on several size fractions. To obtain washability curves for the composite sample, the sink-and-float data for different size fractions combined and calculated. These calculations were performed using a computer program written in Basic. In-house software was used (Kilby, unpublished) to plot the set of washability curves.

The following selection criteria were applied to bulk samples:

- only bulk samples representing run-of-mine coal were used;
- washability data on attrited samples were preferred to data on crushed samples;
- the top size of the sample was restricted to the range 50 to 150 millimetres; a lower size limit of 0.5 millimetre was applied to all samples.

SAMPLES FOR DETAILED STUDY

Lithotype samples were collected from producing seams in the Mist Mountain Formation (southeast British Columbia) and Gates Formation (northeast British Columbia). Samples from selected seams were characterized on the basis of their macroscopic appearance and lithotype classification.

SAMPLING TECHNIQUES

Lithotypes in the seam were identified according to the modified Australian classification (Diessel, 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 these basic ingredients. A minimum thickness of 5 centimetres was used to delineate lithotypes, following the procedure of Lamberson *et al.*, (1989). Each lithotype band was channel sampled separately.

SINK-AND-FLOAT TESTS

Sink-and-float analyses were performed on the coarse size fractions (0.50 to 9.5 mm or 0.5 to 6 mm) prepared from each lithotype sample, in at least three, and usually 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}).

GEOLOGICAL SETTINGS OF THE STUDIED AREAS

Coals in British Columbia range from lignite to anthracite, with most of the present production in the bituminous rank. Coal production in the province usually exceeds 20 million tonnes per year. More than 90% of coal production is from two major coalfields: Peace River (northeast coalfield) and East Kootenay (southeast coalfield). These coal deposits account for all of the metallurgical coal in the province, as well as substantial amounts of thermal coal. One mine in the Comox coalfield is producing thermal coal.

Coal deposits in British Columbia range from Late Jurassic to Tertiary in age, and occur in three of the six major tectonic belts: the Insular, Intermontane and Foreland (Rocky Mountain) belts. The Upper Cretaceous Vancouver Island coals are within the Insular Belt; the Jurassic and Cretaceous coals in the northwest and Tertiary coals of south-central British Columbia are within the Intermontane Belt. The Foreland Belt includes the mainly Cretaceous coals of the Peace River coalfield, and the Jurassic-Cretaceous coals of the Kootenay coalfields (Grieve, 1992). Locations of coal deposits in British Columbia are shown in Figure 7.

Coal-bearing strata throughout the province were deposited in both paralic and limnic settings, mainly in deltaic and alluvial plain environments. Tectonism associated with mountain building has resulted in strongly faulted and folded coal measures in some coalfields.

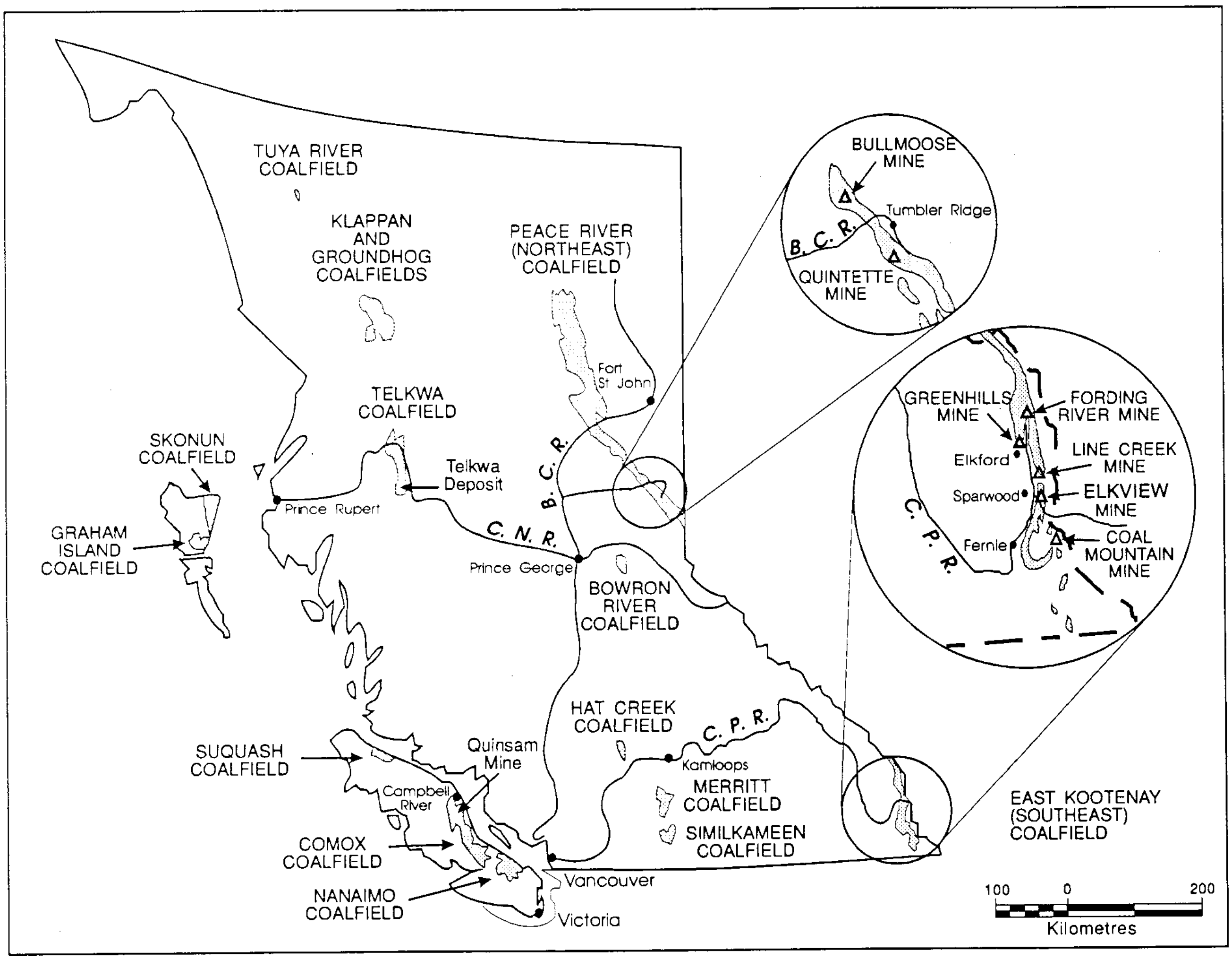

Figure 7. Location of coalfields in British Columbia.

PEACE RIVER COALFIELD

Coal deposits of the Peace River coalfield underlie the northern Inner Foothills belt, which extends northwestward for more than 300 kilometres from the Alberta - British Columbia border east of Prince George (Figure 7). The coal deposits occur in four different geological formations, but the major coal measures of the region are in the Lower Cretaceous Gething Formation and Gates Formation. Stratigraphic relationships and relative positions of coal seam are shown in Figure 8. The Gates Formation contains 70% of the commercially attractive coal measures (Smith, 1989) and accounts for all the current production. Coals of the Jurassic-Cretaceous Minnes Group and the Upper Cretaceous Wapiti Formation are currently considered economically unattractive.

Structurally, the area is characterized by folding and thrust faulting, resulting in thickening of some of the coal seams. The least structural deformation is observed in the coal seam in the Wapiti Formation. In terms of coal quality, most of the seams in the region are classified as medium-volatile bituminous with excellent coking characteristics and low sulphur. The rank of coals in the Gates and Gething formations is in the range high-volatile A to low-volatile, whereas the Wapiti Formation coal is much lower rank, high-volatile C bituminous.

Lower Cretaceous Gates Formation seams are characterized by relatively low vitrinite and high inertinite contents with negligible liptinite (Lamberson *et al.*, 1991; Kalkreuth *et al.*, 1991). The lithotype composition of coal seams is highly variable, reflecting various depositional conditions during peat formation. In some seams, banded lithotypes are predominant, in others brighter lithotypes are the most abundant, but generally banded lithotypes are characteristic of the Gates coals. The dull appearance of some lithotypes is due either to the presence of mineral matter, or an abundance of inertodetrinite and mineral matter, particularly quartz (Kalkreuth *et al.*, 1991) or close proximity to clastic partings. According to Lamberson *et al.* (1991) differences in lithotype stratigraphy are due to variations in groundwater level as well as differences between wetland types. These lithotypes represent a continuous range in depositional environment from forest swamps (dry and wet) to dry, herbaceous or shrubby marshes.

Coal seams in the upper part of the Lower Cretaceous Gething Formation are in general composed predominantly of bright lithotypes. The reported maceral analysis for these seams shows that they are rather low (mean 66%) in vitrinite content and high in inertinite macerals, mainly semifusinite and micrinite. The mineral matter content is exceptionally low. Carbonate minerals (mostly calcite) occur in cleats and fill cavities in semifusinite and fusinite; clays occur more rarely and are associated with massive vitrinite (Cook, 1972).

The coal at the base of the Upper Cretaceous Wapiti Formation is the only seam in this formation with possible economic potential. However, it contains large amounts of mineral matter both from the dirt bands (partings) and inherent in the coal.

EAST KOOTENAY COALFIELDS

The economic coal-bearing strata in southeast British Columbia (Figure 7) are confined to the Mist Mountain For-

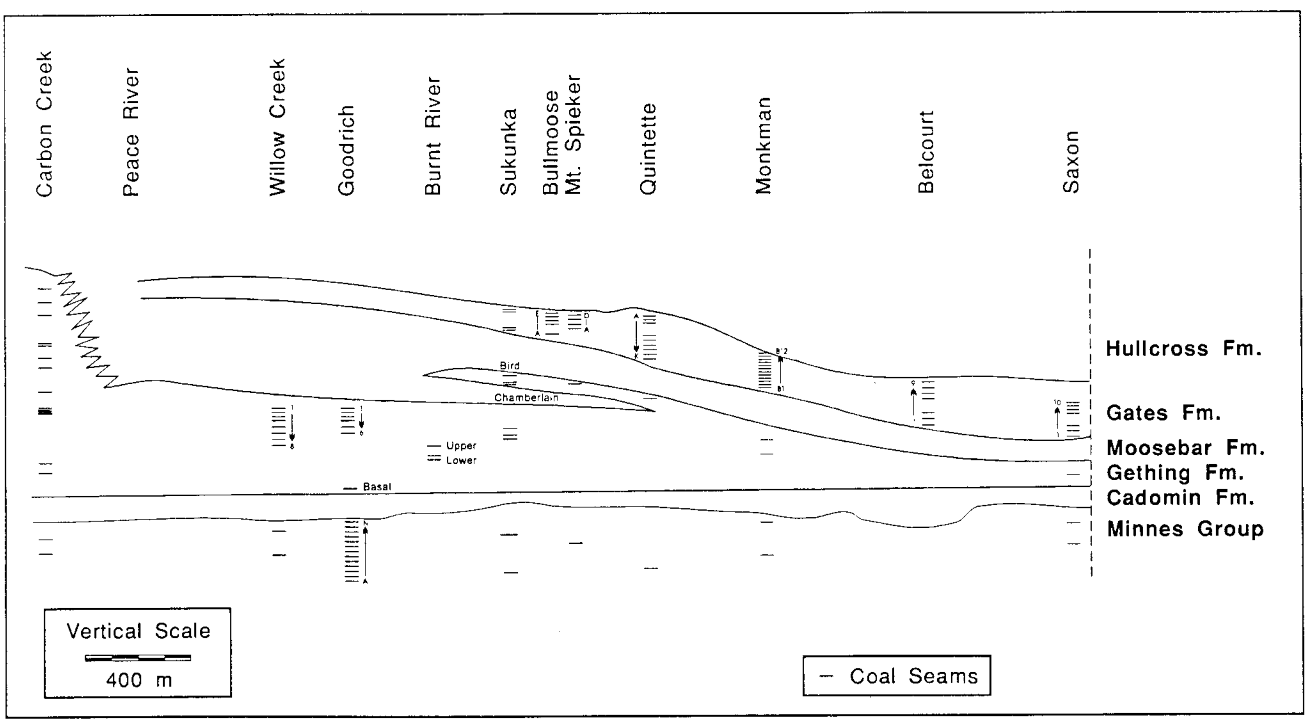

Figure 8. Stratigraphic relationships and relative coal seam positions in the Peace River coalfield.

mation of the Jurassic-Cretaceous Kootenay Group. Stratigraphic positions of the coal seams at some locations within Mist Mountain Formation are illustrated in Figure 9. Mist Mountain coals are between high and low-volatile bituminous in rank (Smith, 1989). Coal beds comprise 8 to 12% of the stratigraphic thickness of the formation (Grieve, 1985). Coal seams in the lower part of the formation tend to be thicker and more continuous, and in some instances structural deformation has resulted in substantial thickening of seams (Grieve, 1985; Smith, 1989).

In terms of coal quality, most of the coals produced in southeast British Columbia are medium-volatile bituminous in rank, and all of the coal products are low in sulphur. Structural deformation of coals in the Mist Mountain Formation has also influenced mining. Faulting and folding have created many problems in terms of correlation of the seams, and in many cases discontinuity of the seams has complicated mine planning and development. Line Creek coal-bearing strata exposed in the highwall are shown in Plate 6. The washing characteristics of many coal seams have deteriorated, as a result of shearing (Bustin, 1982).

Petrographic composition of the Mist Mountain coals varies from inertinite rich to vitrinite rich, from the base to the top of the formation (Cameron, 1972; Grieve, 1985). This reflects a systematic variation in depositional environment, changing from a lower to an upper delta plain up-section (Cameron, 1972). In terms of lithotype composition, this accounts for a brightening-upward (increasing bright lithotypes) tendency in these coals.

MERRITT COALFIELD

The Merritt coalfield is located about 100 kilometres south of Kamloops and occupies an area of 11 by 5 kilometres (Figure 7). The Tertiary coal measures are preserved in a basin underlain by Triassic volcanics (White, 1947) and the stratigraphy of the coal measures is very variable due to lateral variation in rock types, faulting and folding. In some places, five to eight seams occur within 230 metres of strata, while in others six seams are contained in 140 metres of section (White, 1947; Grieve, 1992).

Coal rank in the Merritt coalfield ranges from high-volatile C bituminous to high-volatile A bituminous (Smith, 1989). Some of the seams have fairly good coking properties, but the majority are more suitable for use as fuel for power generation.

The coal is interbedded with shale and sandstone. The depositional environment ranged from back-barrier lagoons to sand and mud flats parallel to low and moderate energy areas with variable current rates. Petrographic analyses of some Merritt coal seams indicate that these coals are vitrinite-rich.

KLAPPAN COALFIELD

The Klappan coalfield is located near the north end of the Bowser Basin in northwestern British Columbia, about 250 kilometres northeast of Prince Rupert (Figure 7). Coal measures at Klappan occur mainly in Upper Jurassic strata; up to 25 seams are present in some sections (Grieve, 1992).

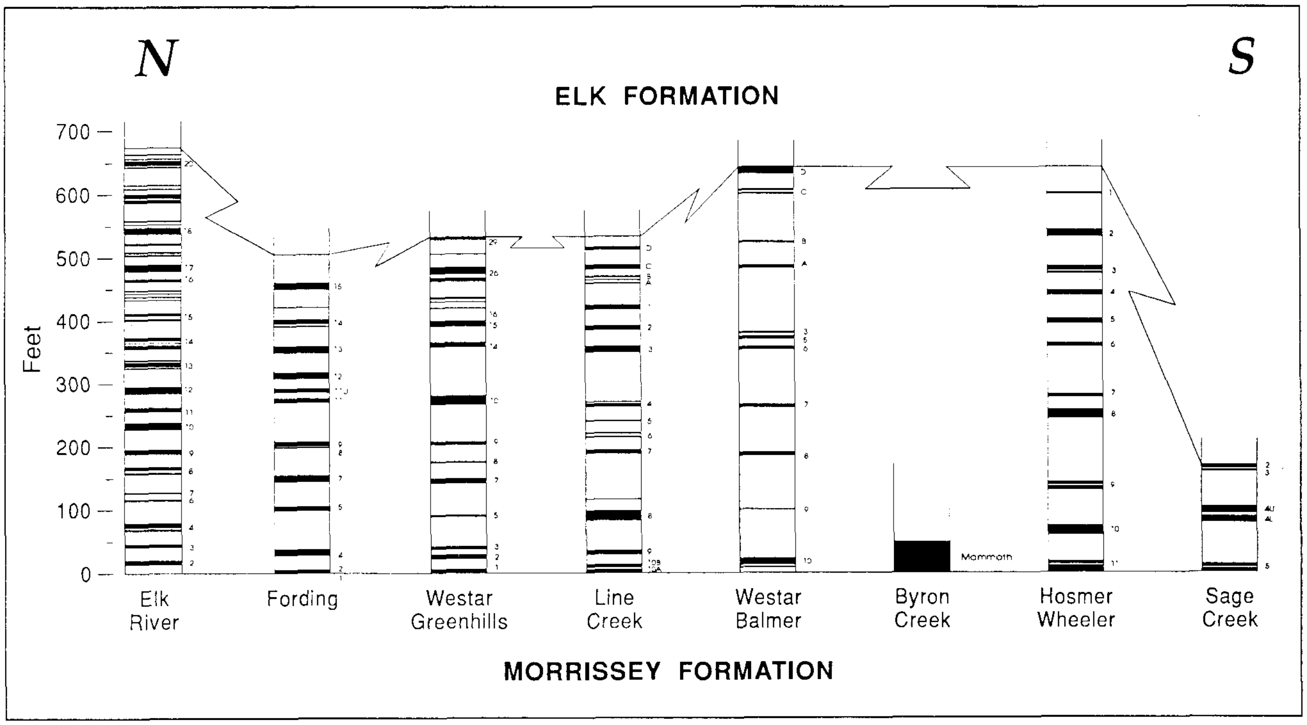

Figure 9. Stratigraphic positions of the seams in southeast British Columbia.

Plate 6. Line Creek seams - coal- bearing strata exposed in the highwall.

Subsequent folding and thrust faulting have severely deformed the coal-bearing strata.

Coal seams considered here are from Hobbit-Broatch and Lost-Fox deposits on the Klappan property. The coal is anthracitic in rank and the ash content in raw coal ranges from 14 to 42%, with an average of 29.5%. The coals are moderately hard, with an average grindability index of 54.

COMOX COALFIELD

The Comox coalfield is on the east side of Vancouver Island (Figure 7). The coals are within the Cumberland and Dunsmuir members of the Comox Formation, which is part of the Upper Cretaceous Nanaimo Group. Commercially, the most attractive coal measures are in the Quinsam basin, site of the Quinsam mine. Four coal zones are recognized here (Kenyon *et al.,* 1991). The two lowermost zones, (1 and 2) occur in a succession of siltstones of the Cumberland Member. The No.1 zone consists of the No.1 seam, with an average thickness of 2.3 metres, and a rider seam with a thickness of 0.40 metre. In zone 2, coal bands are 0.20 to 0.50 metre in thickness (Matheson, 1990; Kenyon *et al.*, 1991). Coal zone 3 is in the Dunsmuir Member and is nearly 35 metres above zone 2. This zone contains seams locally up to 3 metres thick (Smith, 1989). Coal zone 4, with a thickness of 1 metre, is the uppermost coal bed and occurs only locally. Current Quinsam coal mine production is mainly from seam No.1 (Grieve, 1992).

Coals in the Comox coalfield are predominantly high-volatile A and B bituminous in rank (Smith, 1989). Quinsam coal mine produces thermal coal with 13.5% ash and 1.0% sulphur (Grieve, 1992). These coals are relatively hard (average Hardgrove Grindability Index = 48).

Quinsam coals are of semibright to bright composition. No.1 seam is very hard, banded dull to banded bright coal with inclusions of coaly mudstone and finely disseminated pyrite (Kenyon *et al.*, 1991). In places, 1-seam coal produced from the open pit does not need to be washed due to its inherently low ash content. These coals also produce very few fines due to their relative hardness.

WASHABILITY CHARACTERISTICS OF BRITISH COLUMBIA COALS

Classical washability parameters were used to compare washability characteristics of different seams: yield of clean coal, corresponding yield of rejects, and the amount of near-gravity material for a desired clean coal product. For the comparison, 10% ash in the clean coal was chosen as the grade of the coal product. The comparisons were done between different coalfields, geological formations, seams and lithotypes.

Degree of washing and washability numbers were also compared for coal seams belonging to the same and different formations within one coalfield, and between seams from different coalfields. Washability of lithotypes within the same seam related to their petrographic composition and, whenever possible, linked to the changes in depositional environment during the seam formation.

In British Columbia, metallurgical coal must be beneficiated to remove mineral matter and produce a high-quality, uniform and saleable coal product. The higher rank of thermal coals produced from some British Columbia coalfields allows for less cleaning.

The geological settings of most of the coal seams in British Columbia are complex. Coal seams from mountainous regions are especially difficult to mine and process. The most common problem encountered during the handling and processing of these coals is their tendency to disintegrate. Size degradation of bituminous coals has been attributed to the natural fissuring and fracture structure in these coals (Mikhail and Patching, 1980). Fractures and fissures have been caused mostly by tectonic movements, leading to compression and tension, and resulting in shearing.

Sheared seams are usually more difficult to wash, especially when the shear plane is in contact with the coal seam. Dissemination of floor or roof rock through the coal seam makes it difficult to distinguish between sheared rock and coal. Very often the mineral matter is intimately intermixed with coal, and as a result is very difficult to remove during cleaning (Bustin, 1982).

Difficulty in washing British Columbia coals is related to the middling-stype quality of coarse fractions produced from these coals. Large amounts of fines also contribute to difficulty in cleaning as there are fewer and less efficient methods to clean fines as compared to coarse coal. These factors significantly increase the overall cost of a coal cleaning operation.

WASHABILITY OF COAL SEAMS FROM DIFFERENT GEOLOGICAL FORMATIONS

Washability variations are very common in coal seams from British Columbia coalfields. The range of variation in yield of clean coal for a number of seams from different formations is presented in Figure 10. Figures 10a and 10b show seams from the Mist Mountain and Gates formations; Figures 10c,d,e,f and g present clean coal data for the remaining formations and coalfields.

Comparison of yields of clean coal at a preselected ash level (10% ash) for a number of seams in British Columbia can be made from the data in Table 5. In the table seams are listed in stratigraphic order for each property (A to O), in 100 or 200-metre intervals. Thin lines separate seams from different properties within stratigraphic positions which are marked by thick lines. Mist Mountain and Gates formations are the most represented among all geological formations and are the most productive. Other formations are represented by seams from random stratigraphic positions.

Yield of clean coal at selected ash levels is influenced by the mineral matter within the coal, but also by the rock material from the floor and roof of the seam introduced during mining or sampling. Low yield of clean coal at a particular ash level is not synonymous with difficult washability characteristics. The amount of near-gravity material at the density of separation for a specific clean coal product is believed to be a practical indicator of ease of washing, and these values are also included in Table 5.

The best indicators of inherent washing characteristics are washability number and the parameters associated with it, as discussed earlier. These data are presented in Table 6, grouped the same way as in Table 5.

MIST MOUNTAIN FORMATION

A number of coal seams in the Mist Mountain Formation were examined for their washability characteristics (Tables 5 and 6). A total of 33 seams have been studied; some of the bulk samples represent current producing seams, while other data were obtained from exploration reports. Raw ash content for these seams varies from 8.37 to 51.12%, with an average of 28.91%. Yield of clean coal at 10% ash ranges from 23.94 to 100%, with an average of 68.16%.

The average amount of near-gravity material at the density of separation for clean coal at 10% ash, is 8.92%. The highest values are for seams at the bottom of the formation, with some as high as 56.9% (Table 5). This trend is also evident in the data presented on Figure 11. It is apparent that seams at the bottom of the formation must be cleaned at a lower density, with larger amounts of near-gravity material,

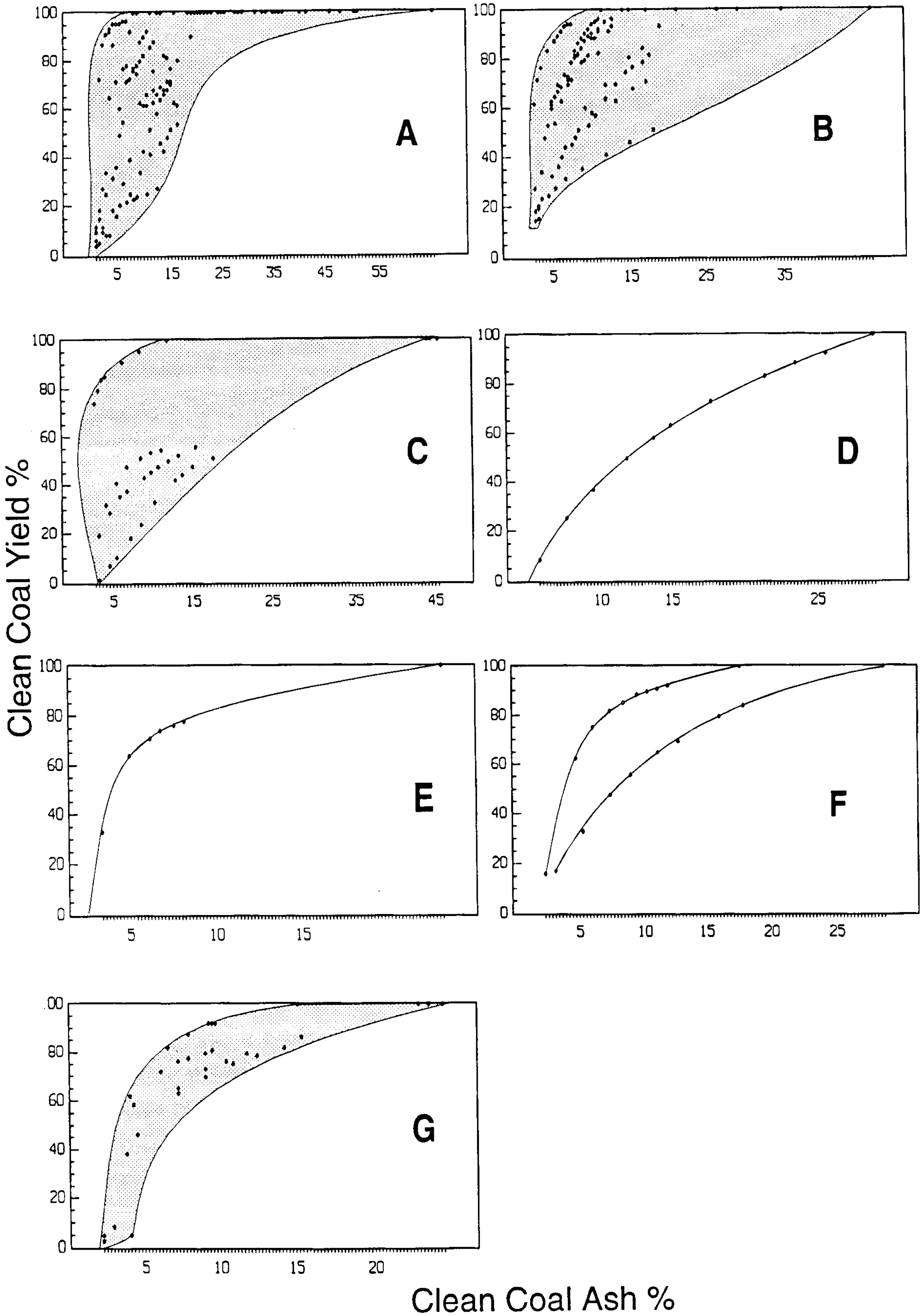

Figure 10. Yield of clean coal for seams from: (a) Mist Mountain; (b) Gates Formations; (c) Gething Formation; (d) Wapiti Formation; (e) Comox Formation; (f) Klappan coalfield; (g) Merritt coalfield.

TABLE 5
WASHABILITY DATA FOR SEAMS FROM DIFFERENT GEOLOGICAL FORMATIONS

Formation/ Coalfield	Yield at 10% Ash	Raw Ash	*d (10)	Near gravity % material	Ash of rejects at 10% ash in CC	Property
MIST MOUNTAIN						
Bottom	42.24	40.10	1.52	11.00	66.97	A
	74.91	22.04	1.46	17.10	80.60	
	74.84	28.45	2.00	0.00	80.68	
	80.76	20.55	1.68	5.10	61.43	B
	34.54	26.14	1.43	56.90	29.73	C
	71.87	24.39	1.53	24.70	53.33	
	85.34	19.66	1.80	8.00	69.91	
	65.39	23.57	1.52	32.10	43.00	
100 metres	88.27	16.21	1.57	8.20	57.54	D
	69.07	27.85	1.55	14.50	63.71	A
	46.25	41.41	1.53	12.10	64.98	
	76.11	25.59	1.78	4.50	72.67	
	61.62	36.59	1.76	4.30	77.65	B
	62.99	35.33	1.54	15.10	64.78	E
200 metres	58.13	34.89	1.54	15.00	63.60	
	79.03	24.95	1.98	2.00	77.91	A
	46.18	46.22	1.74	5.25	75.80	
300 metres	84.83	19.25	1.75	3.80	68.20	D
	42.81	51.12	1.72	3.40	80.71	A
	40.92	50.64	1.68	5.50	77.20	
	97.17	11.98	1.90	2.00	76.06	B
	94.86	13.42	2.00	1.50	72.46	D
400 metres	86.10	18.60	2.00	2.00	67.93	
	48.31	33.95	1.59	5.80	55.86	A
	65.67	36.04	1.95	2.50	82.88	
	54.17	35.43	1.61	7.80	64.08	B
	77.45	22.52	1.78	5.30	63.47	
	73.56	23.00	1.62	7.90	57.37	
500 metres	84.10	21.12	2.10	0.00	75.05	D
	63.34	36.10	1.93	3.45	79.10	A
	100.00	8.37	2.50	0.00	66.00	B
	94.58	13.05	1.72	4.00	62.98	D

Formation/ Coalfield	Yield at 10% Ash	Raw Ash	*d(10)	Near gravity % material	Ash of rejects at 10% ash in CC	Property
GATES	99.44	10.35	2.00	0.00	69.69	G
	90.49	19.79	1.70	9.59	55.55	
	100.00	9.00	2.00	0.00	58.39	
	50.06	44.56	1.80	4.30	77.50	
	97.49	11.82	1.48	16.00	79.28	H
	87.64	15.42	1.65	7.80	48.65	
	86.38	17.26	1.74	6.30	59.18	I
	53.61	35.19	1.56	13.00	60.68	
200 metres	80.56	19.13	1.91	0.10	76.39	
	89.02	17.41	1.79	1.47	75.26	J
	91.65	14.46	1.70	5.04	58.27	
	56.61	35.84	1.53	15.00	66.51	
	56.28	29.55	1.49	25.10	50.52	
	80.27	21.36	1.72	4.20	65.15	K
	92.04	14.85	1.79	5.50	64.32	
	61.03	26.52	1.51	20.63	48.10	
	37.08	46.91	1.52	13.10	65.74	
300 metres	75.12	26.84	1.70	5.00	73.91	
GETHING	31.78	45.65	1.53	27.50	56.77	E
	98.89	12.00	1.80	0.50	68.44	
	52.77	44.17	1.71	3.60	80.73	
WAPITI	39.13	28.55	1.46	49.70	36.23	L
COMOX	79.32	23.39	2.00	3.40	71.49	M
MERRITT	72.00	24.59	1.54	10.50	56.49	N
	74.77	22.83	1.54	9.20	56.02	
	80.99	23.53	1.86	2.90	79.76	
	92.44	15.22	1.82	0.50	77.75	
KLAPPAN	59.07	28.75	1.65	23.02	49.82	O
	88.54	17.61	1.95	3.28	72.61	

*d (10) - density of separation to obtain 10% ash product
CC - clean coal

TABLE 6
WASHABILITY NUMBER AND ASSOCIATED PARAMETERS FOR SEAMS FROM DIFFERENT GEOLOGICAL FORMATIONS

Formation/ Coalfield	Raw Ash	d (opt)	N (opt)	Ash (opt)	WN	Property
MIST MOUNTAIN						
Bottom	40.20	1.70	38.80	13.08	29.66	A
	22.04	1.50	54.22	6.35	85.39	
	28.45	1.60	51.41	8.01	64.18	
	20.55	1.50	43.85	9.05	54.34	B
	26.14	1.50	29.60	13.76	21.51	C
	24.39	1.50	42.59	9.40	45.31	
	19.66	1.50	45.76	8.24	55.50	
	23.57	1.50	37.68	9.74	38.69	
100 metres	16.21	1.40	39.64	7.16	39.64	D
	27.85	1.55	44.28	9.97	44.41	A
	41.41	1.70	36.75	13.65	26.92	
	25.59	1.50	49.44	6.95	71.45	
	36.59	1.60	45.31	7.70	58.84	B
	35.33	1.60	41.58	11.36	36.60	E
200 metres	34.89	1.60	41.97	10.95	38.33	
	24.95	1.50	52.39	6.39	81.99	A
	46.22	1.50	36.42	11.06	32.93	
300 metres	19.25	1.45	48.23	6.46	74.66	D
	51.12	1.70	34.43	9.87	34.90	A
	50.64	1.70	32.93	10.60	31.10	
	4.98	1.35	52.52	3.57	147.10	B
	13.42	1.40	47.97	5.27	91.00	D
400 metres	18.60	1.45	52.63	4.91	107.20	
	33.95	1.55	34.24	9.15	37.40	A
	36.04	1.60	49.89	6.17	80.90	
	35.43	1.60	38.89	9.96	39.00	B
	22.52	1.50	49.44	6.36	77.70	
	23.00	1.45	43.87	7.71	57.00	
500 metres	21.12	1.50	53.69	5.57	96.40	D
	36.10	1.60	47.69	6.69	71.00	A
	8.37	1.35	54.43	2.94	185.10	B
	13.05	1.50	34.69	7.94	43.70	D
GETHING	45.65	1.80	31.64	17.46	18.10	F
	12.10	1.40	56.73	3.46	164.00	
	44.17	1.70	40.83	9.95	41.00	
GATES	10.35	1.45	37.46	5.79	64.70	G
	19.79	1.45	47.98	5.41	88.70	
	9.00	1.35	42.63	3.87	110.20	
	44.56	1.80	38.82	10.71	35.70	
	11.82	1.40	52.50	3.70	141.90	H
	15.42	1.40	40.82	5.66	72.10	
	17.26	1.45	43.29	7.74	55.90	I
	35.19	1.60	38.77	10.87	35.70	
200 metres	19.13	1.50	46.12	6.68	69.00	
	17.41	1.45	43.17	8.06	53.60	J
	14.46	1.40	40.35	6.00	67.30	
	35.84	1.60	41.14	11.02	37.30	
	29.55	1.55	38.10	11.89	32.00	
	21.36	1.5	45.86	8.21	55.9	K
	14.85	1.45	44	5.92	74.3	
	26.53	1.5	37.97	9.65	39.3	
	46.91	1.7	30.95	15.24	20.3	
	26.84	1.5	51.93	5.75	90.3	
WAPITI	28.55	1.55	30.32	13.56	22.3	L
COMOX	23.39	1.5	51.49	6.32	81.5	M
MERRITT	24.59	1.4	43.97	7.21	61	N
	22.83	1.4	43.99	7.29	60	
	23.53	1.4	53.21	6.12	87	
	15.22	1.5	45.99	7.92	58.1	
KLAPPAN	28.75	1.7	39.21	11.20	35	O
	17.61	1.6	48.2	6.23	77.4	

d (opt) - density at optimum
N (opt) - degree of washing at optima
Ash (opt) - ash content at optimum
WN - washability numbers

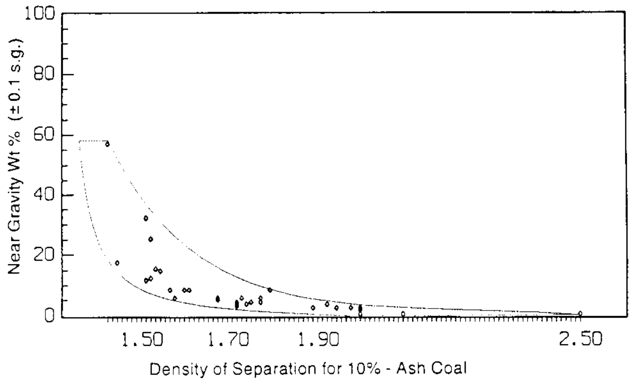

Figure 11. Variations in the ease of washing for seams in the Mist Mountain Formation; density of separation for 10% ash *versus* near-gravity material at the cut point.

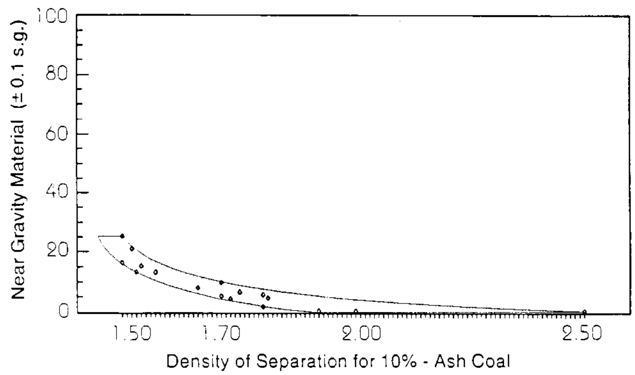

Figure 12. Variations in the ease of washing for Gates Formation seams; density of separation for 10% ash *versus* near-gravity material at the cut point.

to obtain a 10% ash product. The large amount of near-gravity material contributes to the difficulty in cleaning of these coals. An improvement in ease of washing is especially obvious in seams located above 200 metres from the base of formation.

The variations in washability characteristics of Mist Mountain coal seams are not only stratigraphic but also lateral. Washability data for two stratigraphic sections of the formation, 75 kilometres apart, are shown in Tables 7 and 8. There is a more obvious trend in improving ease of washing for seams towards the top of the formation in the southern part of the coalfield. There is very little indication of correlation in washability characteristics between these seams. In effect, seams at the same stratigraphic position have different washability characteristics. Generally, washability of seams from the property in the southern part of the coalfield is much better than seams in the northern part. The average washability number for all seams in the formation from the southern property is 75.4, with near-gravity material at the density of separation at 10% ash equal to 3.3%. For seams from the northern property, the washability number is 50.6, and near-gravity material is 6.44%. Whether this represents a regional trend is not known at this time.

GATES FORMATION

Coal seams in the Gates Formation are usually thick and continuous. The formation reaches up to 350 metres in thickness at the southeast end of the Peace River coalfield, and thins to about 60 metres to the northwest. Commercially important coal seams occur in the southern part of the coalfield and extend to north of the Bullmoose mine (Figure 8; Grieve, 1992). Eighteen Gates coal seams were examined in this study, representing the entire stratigraphic section from throughout the coalfield. Classical washability data for Gates coals are presented in Table 5. Coal seams on property G are from the southeast end of the coalfield; whereas property K is located at the northwest end.

Raw ash in these seams varies from 9 to 46.9%, with an average of 23.13%. Yield of clean coal at 10% ash ranges from 37.08 to 100%, and averages 76.4%, with the average amount of near-gravity material near the cut point at 8.45%.

Variation in the ease of obtaining 10% ash for raw Gates coals is illustrated in Figure 12. The density of separation

TABLE 7
WASHABILITY DATA FOR MIST MOUNTAIN FORMATION SEAMS - SOUTHERN PART OF THE COALFIELD

Stratigraphic location of seams (m above base)	Yield at 10% Ash	Raw Ash %	d_{10}*	Near-gravity Material (±0.1 s.g.)	Ash of Rejects	W_N**
0-100	88.27	16.21	1.57	8.20	57.54	39.6
100-200	33.89	47.76	1.45	29.70	60.59	20.4
200-300	84.83	19.25	1.75	3.80	68.20	74.7
300-400	94.86	13.42	2.00	1.50	72.46	91.0
	86.10	18.60	2.00	2.00	67.93	107.2
400-500	84.10	21.12	2.10	0.10	75.05	96.4
500-600	94.58	13.05	1.72	4.00	62.98	43.7

*d_{10} = density of separation for 10% Ash, clean coal product.
**W_N=Washability number.

TABLE 8
WASHABILITY DATA FOR MIST MOUNTAIN FORMATION SEAMS - NORTHERN PART OF THE COALFIELD

Stratigraphic location of seams (m above base)	Yield at 10% Ash	Raw Ash %	d_{10}*	Near-gravity material % (±0.1 s.g.)	Ash of rejects	W_N**
0-100	42.24	40.10	1.52	11.00	66.97	29.7
	74.91	22.04	1.46	17.10	80.60	85.4
	74.84	28.45	2.00	0.00	80.60	64.2
100-200	69.07	27.85	1.55	14.50	63.71	44.4
	46.25	41.41	1.53	12.10	64.98	26.9
	76.11	25.59	1.78	4.50	72.67	71.4
200-300	79.03	24.95	1.98	2.00	77.91	82.0
	46.18	46.22	1.74	5.25	75.80	32.9
300-400	23.94	65.62	1.72	3.00	82.33	16.2
	42.81	51.12	1.72	3.40	80.71	34.9
	40.93	50.64	1.68	5.50	77.20	31.1
400-500	48.31	33.95	1.59	5.80	55.86	37.4
	65.67	36.04	1.95	2.50	82.88	80.9
500-600	63.34	36.10	1.93	3.43	79.10	71.0

*d_{10} = density of separation for 10% ash, clean coal product.
**W_N = Washability number.

varies from 1.50 to 2.00, and near-gravity material varies from 0 to about 23%. Coal seams from the base of the formation, in the southeasternmost part of the coalfield, are considered to be the easiest to wash in terms of their amount of near-gravity material (*see* values for property G in Table 5), and seams become progressively more difficult to wash towards northwest.

The lowest three seams on properties J and K, in the upper part of the formation (above 200 m), representing the same stratigraphic sequence, have very similar washability characteristics (Table 5); this is even more evident when their washability numbers are compared (Table 6). Variation in washability numbers for Gates coals is significant, with values ranging from about 20 to 141, with an average of 64.1. There is no significant correlation between washability numbers and stratigraphic position in the formation. Variation between adjacent seams can be as great as that between widely separated seams. Only in one instance is correlation possible between seams in the same stratigraphic position, based on very similar washability characteristics (the lowest three seams on the J and K properties; Table 6).

GETHING FORMATION

The Gething Formation is also a major coal-bearing unit in the Peace River coalfield. It varies in thickness from 100 metres in the southeast, up to 1000 metres in the Carbon Creek area in the northwest. Three Gething Formation coal seams were examined for washability, two from the upper and one from the lower part of the formation. The upper seams are a part of the upper formation, which pinches out in the Sukunka area; the third seam is at the top of the bottom coal measures, north of Sukunka (Figure 8).

Washability characteristics of the seam from the lower part of the formation are very different from those of the two upper seams (Tables 5 and 6). The former has a very low yield of clean coal at 10% ash, and high amounts of near-gravity material at the density of separation. This is confirmed by the very low washability number (18.1). High ash content at the optimum density of separation indicates a very high content of unseparatable mineral matter. The two other seams have much better washing characteristics their washability number values are 164 and 41.

WAPITI FORMATION

Coal from the Wapiti Formation is generally unaffected by the structural complications so common in coals in the Peace River coalfield. However, the major seam at the base of the formation has very difficult washability characteristics. Despite having relatively moderate ash content in raw coal, yield of clean coal at 10% ash is low and near-gravity material is very high (Table 5). The washability number is also very low, with high ash at the density for optimum washing (Table 6). The difficult washing characteristics are due to large amounts of mineral matter intimately intermixed with the coal.

COMOX FORMATION

Washability of one coal seam from the Comox Formation was evaluated. This seam appears to have quite good characteristics: relatively high yield of clean coal at 10% ash and a low amount of near-gravity material at the density of separation. Washability number and ash at optimum also indicate good inherent washing properties (Tables 5 and 6).

MERRITT COALFIELD

Four coal seams from Merritt were examined, and they represent almost the entire stratigraphic section of the coal-bearing formation (Tables 5 and 6). Raw ash in these seams varies from 15.2 to 24.59%, with an average of 21.54%. The average yield of clean coal at 10% ash is equal to 80.05%, and the average amount of near-gravity material is 5.77% at the density of separation. There is an improvement in the ease of washing towards the top of the formation. Washability numbers indicate less visible improvement in the washing characteristics towards the top of the coal sequence. This may imply that it may be easier to obtain a 10% ash product from the upper seams, but difficulty will be encountered when a lower ash product is needed.

KLAPPAN COALFIELD

Two seams from the Klappan coalfield were studied. They are from the middle part of the anthracite-bearing sequence, but they account for almost 70% of the mineable reserves identified to date. Despite the fact that these seams are close together stratigraphically, the washability of one is far superior to the other (Tables 5 and 6). The washability number for one seam is higher by a factor of two. The seam with the lower washability number has quite a high ash content at the optimum cut point, and this contributes to the difficulty in cleaning this coal. Klappan coals are anthracitic; the higher density of anthracite requires cleaning at a higher specific gravity.

WASHABILITY OF LITHOTYPES

Variation in coal quality, and consequently washing characteristics, are related to the lithological composition of each seam. Testing washability characteristics of coal lithotypes may be used as a predictive tool in assessing the ease of washing of the whole seam. Lithotypes represent changes in depositional conditions, and as expected ease of washing, as measured by washability number, is significant parameter for relating the lithology of a seam to washing characteristics.

WASHABILITY OF LITHOTYPES FROM GREENHILLS AND QUINTETTE

Lithotype samples were collected from producing seams in the Jurassic-Cretaceous Mist Mountain Formation of southeast British Columbia, and the Lower Cretaceous Gates Formation of northeast British Columbia. Plates 7 and 8 show sampling from seams at Quintette and Greenhills mines. The seams selected were Greenhills 16 seam and Quintette D and E seams. A total of 18 lithotype samples from Greenhills and 15 samples from Quintette were analyzed. These represented six lithotypes: bright; banded bright; banded coal; banded dull; dull and sheared coal.

Washability numbers and associated parameters for these lithotype samples are presented in Table 9.

Greenhills seam 16 is composed predominantly of banded lithotypes, with banded bright the most abundant. The base of the seam is banded dull, but not until the middle of the seam does the coal change from being predominantly banded bright to predominantly banded dull. Dull lithotypes are common near the top. Quintette seams D and E are also composed of predominantly banded lithotypes. Lithotype composition of seam E changes from banded bright at the

Plate 7. Sampling lithotypes at Quintette.

Plate 8. Sampling lithotypes at Greenhills.

bottom, to mainly dull and banded dull in the middle, to banded bright and banded coal, becoming duller and sheared near the top. A similar trend is observed in Quintette seam D; the base of the seam is composed predominantly of banded bright and banded coal, then becomes duller towards the middle. The seam brightens up again towards the top, but becomes duller and sheared in the uppermost part of the seam.

The highest washability numbers and the lowest clean-coal ash values (at the optimum) are associated with the bright lithotypes in all three seams. There is an evident trend in the decrease of washability numbers from bright to dull lithotypes. This is accompanied by an increase in ash at optimum, and this is more consistent for lithotypes from Quintette seams. The average washability numbers for all lithotypes from Greenhills 16 seam are much higher than for the same lithotypes from Quintette D and E seams. The average washability number for bright lithotypes for Greenhills samples, for example, is three times greater than for Quintette seams, with the clean coal at optimum values significantly lower.

Sheared coal in the Greenhills seam has a degree-of-washing value similar to that of bright coal, but with a much higher ash of clean coal at the optimum, and a washability number between that of banded coal and banded dull. For Quintette seams, the washability number of sheared coal is similar to that of banded dull, while degree of washing corresponds to the banded bright lithotype. The raw ash content for the sheared coal from Greenhills and Quintette is the

TABLE 9
WASHABILITY NUMBER, DEGREE-OF-WASHING AND OTHER ASSOCIATED PARAMETERS FOR SELECTED LITHOTYPES FROM GREENHILLS AND QUINTETTE SEAMS

Lithotype	Raw Ash %	Wn	N (opt)	d (opt)	CC (opt)
Property: Greenhills Seam 16					
Bright (3)	3.68	289.40	46.96	1.35	1.62
Banded Bright (6)	5.71	167.09	40.22	1.35	2.75
Banded Coal (5)	6.64	110.38	31.90	1.35	3.82
Banded Dull (3)	23.13	45.81	24.20	1.48	14.82
Dull (1)	5.92	90.20	31.66	1.35	3.51
Sheared (1)	23.06	79.25	49.85	1.50	6.26
Property: Quintette Seams D and E					
Bright (1)	3.90	107.80	28.34	1.30	2.63
Banded Bright (1)	8.13	78.30	35.78	1.40	4.57
Banded Coal	7.14	40.34	19.83	1.42	4.77
Banded Dull (6)	9.60	36.50	21.35	1.48	6.26
Dull (2)	12.95	24.10	18.88	1.45	9.07
Sheared (2)	25.22	34.40	37.14	1.55	10.39

WN - Washability Number
N (opt) - degree of washing at optimum
d (opt) - density of separation at optimum
CC (opt) - clean coal ash at optimum
( ) - numbers of samples analyzed

highest. However the clean coal at optimum value is much higher for the Quintette seams.

The variations in brightness of lithotypes in these seams is a result of changing maceral composition, from vitrinite rich (bright) to intertinite rich (duller), and generally an increase in ash content from bright to dull lithotypes (Lamberson *et al.*, 1991; Holuszko, 1992). Due to the fact that mineral matter (ash) has a major influence on the washability number, lithotypes having a dull appearance as a direct result of a higher mineral matter content show more dramatic changes in washability numbers than those whith a dull appearance that is due to a change in petrographic composition. It is not always the amount of mineral matter (raw ash), however, but its association with the coal that contributes to the change in washability characteristics. Two different lithotypes with very similar petrographic compositions and ash contents were found to have different washability characteristics. In one lithotype, mineral matter was disseminated throughout the coal, whereas in the other it was epigenetic. The disseminated occurrence of mineral matter made one lithotype look duller and contributed to the difficulty in washing.

Assuming that washability numbers indicate variation in depositional environment, the actual decrease in the magnitude of this number, in conjunction with the increase in clean-coal ash at the optimum in moving towards the duller lithotypes, indicates a change from a wet forest swamp to an open marsh environment (Lamberson *et al.*, 1991; Kalkreuth *et al.*, 1991). This trend is usually evidenced by changes in maceral composition and the amount of mineral matter associated with coal. An interesting maceral trend was observed in lithotypes from Greenhills seam16: the ratio of vitrinite A to vitrinite B decreases toward duller lithotypes. Abundance of vitrinite A, representing structured vitrinite macerals, indicates a more preserving depositional environment, and reflects depositional conditions with less frequent changes in water level. This environment is characterized by less mineral matter deposition. Vitrinite B, represented by vitrodetrinite and vitrinite associated with other macerals and mineral matter, indicates coal of detrital origin, usually characterized by more degraded organic matter and a higher mineral matter content.

Comparisons of lithotypes from the Greenhills and Quintette seams show that washability numbers for the same lithotypes are much higher for Greenhills 16 seam than for Quintette D and E seams. This may indicate that the Greenhills seam was deposited in less turbulent conditions than the Quintette seams. According to Cameron (1972) for example, seams in the upper part of the Mist Mountain Formation (Greenhills seam 16), were accumulated in an upper delta plain environment. Coal seams in the Gates Formation are believed to have formed in depositional settings ranging from coastal swamp to upper delta plain (Kalkreuth *et al.*, 1991). The coastal swamp coals are characterized by variable lithotype sequences (brightening-up, dulling-up). Seam D from Quintette, however, was formed on a coastal plain, more open to clastic influx than seam 16 at Greenhills (Kalkreuth *et al.*, 1991). This resulted in a higher content of mineral matter intermixed with coal, and contributed to more difficult washing characteristics.

DISCUSSION AND CONCLUSIONS

A number of coal seams from various coalfields and geological formations in British Columbia were examined in terms of their "ease of washing". In general, the washability characteristics of British Columbia coal seams are considered to be moderately difficult to difficult compared to other coals. For some coals a density of separation of around 1.5 is necessary to obtain a clean coal product (*e.g.*, 10% ash); for others higher densities can be used to obtain the same quality coal product. For coals which require a lower density of separation, higher amounts of near-gravity material are usually encountered, and this leads to technical difficulties in their cleaning. The average values of near-gravity material, close to the density of separation for a 10% ash product, for Mist Mountain and Gates Formation coals are about 9%. For Gething coals the average amount of near-gravity material is 10.5%; for Merritt 5.77%; for Klappan 13.15%; for Comox 3.40%; and for Wapiti as much as 49.70%. Accordingly, Comox and Merritt coals are categorized as simple to wash, Mist Mountain and Gates Formation coals are moderately difficult, coals from the Gething Formation and Klappan coalfield are difficult to clean and coals from the Wapiti Formation are formidable to wash. For situations where a lower ash product is required (*e.g.*, 7% ash or less) more difficulty in cleaning is likely, as many of these coals would have to be washed at even lower densities.

In the Mist Mountain Formation, the most difficult coals to clean, in terms of ease of washing, are seams at the bottom of formation, with near-gravity material up to 57% in one case. Only three other seams studied fall into the same category (formidable to wash). These are: a seam from the top of the Gates Formation; a seam from the lower part of the Gething Formation and the one from the Wapiti Formation. In other seams, ease of washing ranges from simple to exceedingly difficult.

The trend in improving ease of washing toward the top of the formation is observed in the Mist Mountain Formation and in the Merritt coalfield. In Gates coals the opposite trend is apparent; coal seams become more difficult to wash upwards in the formation, albeit in an iregular manner. Lateral changes in washability characteristics over 75 kilometres were noted in Mist Mountain coals. Seams on a property in the southern part of the coalfield have better washing characteristics than those in the north. Moreover, the upward trend of improving ease of washing is more persistent for coals on the southern property. For Gates coals, difficulty in washing appears to increase from southeast to northwest.

In general, the lowest washability numbers, with highest ash at optimum, are for coals which are the most difficult to clean in terms the amount of near-gravity material. The correlation between washability numbers and the amount of near-gravity material at density of separation for 10% ash coal for all tested coals is illustrated in Figure 13. It shows that a decrease in washability number is accompanied by an increase in the amount of near-gravity material. Most coals, however, fall into a washability number range of 30 to 100, and these correspond to the range of 0 to 10% of near-gravity material.

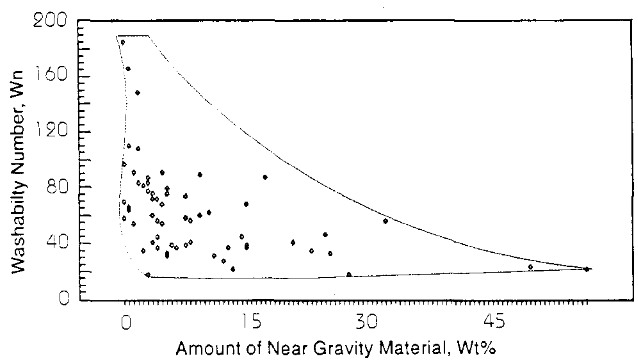

Figure 13. Correlation between washability numbers and amount of near-gravity material for 10% ash clean coal for all examined coal seams from British Columbia.

For the most difficult to clean coals, washability numbers range from about 18 to 30. The lowest numbers are for seams in the lower part of the Gething Formation (18.1) and the Wapiti Formation (22.3); the highest for seams in the middle and uppermost parts of the Mist Mountain Formation (147, 107 and 185), the upper part of the Gething Formation (164) and two lower seams in the Gates Formation (110.2 and 141.9). Variation in washability numbers between seams in very close proximity may be equally high; two seams in the Gething Formation have values of 164 and 41. The average washability number for all coal seams examined is about 63.5, with an average degree of washing of 43.19, a clean coal at optimum equal to 8.22% ash and a 1.53 density of separation at optimum. Among the different formations the highest average washability number, 74.7, is derived for Gething Formation coals and the lowest value, 23, represents the Wapiti Formation. The other formations have washability numbers in the range of 56 to 66. In this comparison, however, only the Mist Mountain and Gates formations are well represented.

It has been shown that the washability characteristics of a coal seam are strongly dependent on its lithological composition. There is a strong correlation between washability number and relative brightness. The bright lithotypes consistently have the highest washability numbers with lowest ash at optimum, and washability numbers decrease considerably towards duller lithotypes. However, where the duller appearance is related to varying petrographic composition, there is little evidence of change in washability characteristics.

It is also evident that it is not the amount of mineral matter, but rather its association with the coal, that determines the washing characteristics of a particular seam. The disseminated occurrences of mineral matter usually affect both the appearance of the coal as well as its washability characteristics. This is why there is a strong correlation between lithology and washability characteristics of the seam. The same lithotypes from different coals may, however, display different washability characteristics, due to different sedimentary origins of the coal. Washability number and parameters associated with it can also be related to indices derived from maceral composition, leading to conclusions about the depositional environment of the coal.

Washability number defines inherent washability characteristics and, as such, may be used as a valuable index in many technological applications, as discussed in the following chapter.

TECHNOLOGICAL APPLICATIONS OF WASHABILITY NUMBER AND ASSOCIATED PARAMETERS

Use of the washability number extends the scope of application of standard coal quality data, especially in aspects related to coal processing. In fact, it was suggested by Grounds (in Sarkar and Das, 1974) that washability number should be included in the list of indices used to characterize coals (*e.g.*, caking index, shatter index or Hardgrove index).

The washability number is often a good parameter for correlation of coal seams in accordance with their washability characteristics, for developing sedimentation patterns for coalfields, and even for prediction of coal quality (ash distribution patterns, etc.; Sarkar *et al.*, 1977).

Washability analyses are costly and time consuming, and the ability to predict washability from small samples or lithological descriptions of coal seams is a very attractive feature of washability number. Estimating washability of coal seams from small samples using washability number was discussed by Ryan (1992). Prediction of seam washability from washability of lithotypes has also been discussed by Holuszko, (1992).

For every coal within a specified size range, there is an optimal density cut point for separation, which distinguishes free from fixed mineral matter. Degree of washing and washability number represent this optimal condition for separation. Theoretically, the maximum advantage could be expected for separation at this point. In practice, however, the separation at optimum may not necessarily correspond to the level of ash in clean coal which is required by commercial specifications.

It has been shown that the size of coal generally influences washability characteristics. Therefore, washability number, degree of washing and ash at the optimum of separation vary with the top size of crushing. For some British Columbia coals a decrease in the top size of coal during crushing usually increases the washability number, and lowers the ash in the clean coal at the optimum density of separation. For others, reducing the top size leads to deterioriation in washability characteristics, as discussed in earlier sections. This results from reaching the critical top size below which there is no advantage in further crushing.

Other studies show that systematic calculation of washability numbers and corresponding ash of clean coal at optimum degree of washing at various levels of size reduction can help in assessing the mode of association of mineral matter with coal (Sarkar and Das, 1974). It may be practical to use the ratios of the washability number of the coarse coal (of specified top size) to the washability numbers at various levels of crushing, as a valuable parameter characterizing coal or even performance of size reduction equipment. The ratio of washability number at any particular level of crushing to that of the critical top size should be significant in describing coal liberation characteristics, and also should correlate with grindability index.

In any processing operation where inherent washability properties of coal are important, use of washability number will be of great benefit. With blending, for example, where raw or clean coals are mixed in order to ensure consistency in coal quality, it is necessary to take into account a number of coal quality parameters which affect either the washability or the eventual product specification. For thermal coals it is the ash content and the heating value of the desired product, while for metallurgical coals, ash and swelling and plastic properties are critical. Due to the fact that conditions for obtaining desired ash-level products do not necessarily correspond to the optimum conditions of separation, defining the blending ratios based on these parameters is not always the best approach.

Coals which are easy to wash usually have high yields of low density material, very little middlings and some amount of liberated or free impurities. For these coals, low-density material usually has a very low ash content and, as a result, achieving a certain ash level (*e.g.*, 10%) leads to a situation where rock material must be added to meet product specifications. Using the washability number as a blending parameter allows the use of the least amount of the best quality coal in the most beneficial way in composing the blends.

From a knowledge of variability in washability numbers it may be possible for the coal process engineer to make decisions on the size of crushing, method of blending and even on designing specific cleaning operations for a particular coal. There are probably other useful applications of washability number in coal processesing and utilization, which should be explored in the future.

REFERENCES

Bustin, R.M. (1982): The Effect of Shearing on the Quality of Some Coals in the Southeastern Canadian Cordillera; *Canadian Institute of Mining and Metallurgy,* Bulletin, Volume 75, No. 841, pages 76-83.

Bustin, R.M., Cameron, A.R., Grieve, D.A. and Kalkreuth, W.D. (1983): Coal Petrology - Its Principles, Methods and Applications; *Geological Association of Canada,* Short Course Notes, Volume 3.

Butcher, S.G. (1985): Economic Impact of Coal Preparation Problems; *Canadian Institute of Mining and Metallurgy,* Bulletin, Volume 78, No. 881, pages 47-51.

Cook A.C. (1972): Report on Samples of Coal from Sukunka, Canada; *Clifford McElroy and Associates Pty. Ltd.*, unpublished internal report, January 1972

Cook, A.C. (1981): What Are We Trying to Separate?; *Separation Science and Technology,* Volume 16, No. 10, pages 1545-1569.

Cameron, A.R. (1972): Petrography of Kootenay Coals in the Upper Elk River and Crowsnest Areas, British Columbia and Alberta; *Research Council of Alberta,* Information Series No. 60, pages 31-45

Diessel, C.F.K. (1965): Correlation of Macro and Micropetrography of some New South Wales Coals; *in* Proceedings, Volume 6, *8th Commonwealth Mineralogical and Metallurgical Congress,* Melbourne, Woodcock, J.T., Madigan, R.T. and Thomas, R.G., Editors, pages 669-677.

Diessel, C.F.K., (1986): The Correlation between Coal Facies and Depositional Environments. Advances in the Study of the Sydney Basin; *in* Proceedings, 20th Symposium, *The University of Newcastle, New South Wales*, pages 19-22.

Falcon, L.M. and Falcon, R.M.S. (1983): The Application of Coal Petrography to Certain Beneficiation Techniques on South African Coal; *Geological Society of South Africa,* Special Publication 7, pages 137-148.

Falcon, L.M. and Falcon, R.M.S. (1987): The Petrographic Composition of Southern African Coals in Relation to Friability, Hardness and Abrasive Indices; *South African Institute of Mining and Metallurgy,* Journal, Volume 87, pages 323-336.

Grieve, D.A. (1985): Rank Variation, Coallfication Pattern and Coal Quality in the Crowsnest Coalfield, British Columbia; *Canadian Institute of Mining and Metallurgy,* Bulletin, Volume 78, No. 881, pages 39-46.

Grieve, D.A. (1992): British Columbia Coal Quality Catalogue; *B.C. Ministry of Energy, Mines and Petroleum Resources,* Information Circular 1992-20.

Holuszko, M.E. (1991): Wettability and Floatability of Coal Macerals as Derived from Flotations in Methanol Solutions; unpublished M.A.Sc. thesis, *The University of British Columbia.*

Holuszko, M.E. (1992): Washability of Lithotypes from a Selected Seam in the East Kootenay Coalfield, Southeast British Columbia; *in* Geological Fieldwork 1992, Grant, B. and Newell, J.M., Editors, *B.C. Ministry of Energy, Mines and Petroleum Resources,* Paper 1993-1, pages 517-525.

Holuszko, M.E. and Grieve, D.A. (1991): Washability Characteristics of British Columbia Coals; *in* Geological Fieldwork 1990, Grant, B. and Newell, J.M., Editors, *B.C. Ministry of Energy, Mines and Petroleum Resources,* Paper 1991-1, pages 371-379.

Horsley, R.M. and Smith, H.G. (1951): Principles of Coal Flotation; *Fuel,* Volume 30, pages 54-63.

Hower, J.C. (1988): Additivity of Hardgrove Grindability: A Case Study; *Journal of Coal Quality,* Volume 7, pages 68-70.

Hower, J.C. and Lineberry, G.T. (1988): The Interaction of Coal Lithology and Coal Cutting on the Breakage Characteristics of Selected Kentucky Coals; *Journal of Coal Quality,* Volume 7, pages 88-95.

Hower, J.C. and Wild G.D. (1991): Maceral Partitioning for Selected Eastern Kentucky Coals; *Journal of Coal Quality,* Volume 10, No. 4, pages 159-163.

Hower, J.C., Esterle, J.S., Wild, G.D. and Pollock, J.D. (1990): Perspectives on Coal Lithotypes Analysis; *Journal of Coal Quality,* Volume 9, No. 2, pages 48-52.

Hower, J.C., Grease, A.M. and Klapheke, J.G. (1987): Influence of Microlithotype Composition on Hardgrove Grindability for Selected Eastern Kentucky Coals; *International Journal of Coal Geology,* Volume 7, pages 68-70.

Hower, J.C., Trinkle, E.J. and Wild G.D. (1986): Maceral Partitioning through Beneficiation of Illinois Basin Coals; *International Journal of Coal Preparation,* Volume 2, pages 149-164.

International Committee for Coal Petrology (ICCP) (1963): International Handbook of Coal Petrology, 2nd Edition; *Centre Nationale de la Recherche Scientifique*, Paris

Kalkreuth, W.D., Marchioni, D.L., Calder, J.H., Lamberson, M.N., Naylor,R.D. and Paul, J. (1991): The Relationship between Coal Petrography and Depositional Environments from Selected Coal Basins in Canada; *International Journal of Coal Geology,* Volume 19, pages 21-76.

Kenyon, C., Cathyl-Bickford, C.G. and Hoffman, G. (1991): Quinsam and Chute Creek Coal Deposits (NTS 92F/13, 14); *B.C. Ministry of Energy, Mines and Petroleum Resources,* Paper 1991-3.

Klassen W.I. (1966): Flotation of Petrographic Components; *in* Flotacja Wegla, *Slask,* Katowice, Poland.

Lamberson, M.N., Bustin, R.M., Kalkreuth, W. and Pratt K.C. (1989): Lithotype Characteristics and Variation in Selected Coal Seams of the Gates Formation, Northeastern British Columbia; *in* Geological Fieldwork 1989, *B.C. Ministry of Energy, Mines and Petroleum Resources,* Paper 1990-1, pages 461-468.

Lamberson, M.N., Bustin, R.M. and Kalkreuth, W. (1991): Lithotype (Maceral) Composition and Variation as Correlated with Paleo-wetland Environments, Gates Formation, Northeastern British Columbia, Canada; *International Journal of Coal Geology,* Volume 18, pages 87-124.

Laskowski, T. (1948): Problem of Processing of Fines in the Polish Coal Industry; *in Biuletyn Instytutu Naukowo-Badawczego Przemyslu Weglowego,* (Polish National Science Foundation and the Department of the Interior Bulletin), No. 23, pages 1-82.

Laskowski, J.S. and Walters, A.D. (1987): Coal Preparation; *in* Encyclopedia of Physical Science and Technology, Volume 3, *Academic Press,* pages 37-61.

Leonard, J.W. (1979): Coal Preparation, 4th Edition; *American Institute of Mechanical Engineers,* New York.

Mackowsky, M.-Th. and Hoffman, E., (1960): Coal Preparation; *in* Textbook of Coal Petrology; *Gerbruder Borntraeger,* Berlin, Stuttgart, 3rd Edition, pages 415-419.

Marchioni, D.L., (1980): Petrography and Depositional Environment of the Liddell Seam, Upper Hunter Valley, New South Wales; *International Journal of Coal Geology,* Volume 1, No. 1, pages 35-61.

Matheson, A. (1990): Subsurface Coal Sampling Survey, Quinsam Area, Vancouver Island, British Columbia; *in* Geological Fieldwork 1989, *B.C. Ministry of Energy, Mines and Petroleum Resources,* Paper 1990-1, pages 439-443.

McCabe, L.C. (1942): Practical Significance of the Physical Constitution of Coal in Coal Preparation; *Journal of Geology,* Volume 50, pages 407-410.

Mikhail, M.W. and Patching, T.H. (1980): Size Degradation of Bituminous Coal from Western Canada; *Canadian Institute of Mining and Metallurgy,* Volume 73; No. 817, pages 105-110.

Ryan, B. (1992): Estimation of Coal Washability Using Small Samples; *Journal of Coal Quality,* Volume 11, No. 1-2, pages 13-19.

Sanders, G.J. and Brooks, G.F. (1986): Preparation of the "Gondwana" Coals. 1. Washability Characteristics; *International Journal of Coal Preparation,* Volume 3, pages 105-132.

Sarkar, G.G. and Das, H.P. (1974): A World Pattern of the Optimum Ash Levels of Cleans from the Washability Data of Typical Coal Seams; *Fuel,* Volume 53, pages 74-84.

Sarkar, G.G., Das, H.P. and Ghose, S. (1977): Sedimentation Patterns: Do They Offer Clues to Coal Quality?; *World Coal,* August 1977, pages 10-13.

Smith, G.G. (1989): Coal Resources of the Rocky Mountain Front Ranges and Foothills; British Columbia and Alberta; Coal Resources of Canada, *Geological Survey of Canada,* Paper 89-4, pages 50-68.

Stopes, M.C. (1919): On the Four Visible Ingredients in Banded-Bituminous Coals, *Proceedings of the Royal Society,* Series B, 90, page 470.

Sun, S.C. (1954): Hypothesis for Different Floatability of Coals, Carbons, and Hydrocarbon Minerals; *American Institute of Mining Engineers,* Transactions, Volume 199, pages 67-75.

White, W.H. (1947): Report on the Merritt Coalfield; *in* Report of the Minister of Mines 1946, *B.C. Ministry of Energy, Mines and Petroleum Resources,* pages A250-A279.

Queen's Printer for British Columbia©
Victoria, 1994