TULAMEEN COAL PROPERTY

THESIS - COAL PETROLOGY

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COAL PETROLOGY
OF THE
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by

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ABSTRACT

The Tulameen Coalfield lies in a small, southeast plunging syncline in the Intermontane Belt of the Canadian Cordillera in south central British Columbia. The coal is interbedded with fluvial and lacustrine sediments of the Eocene Allenby Formation of the Princeton Group. The abundance of tephra and bentonite indicates volcanic activity was contemporaneous with coal and sediment deposition.

Although coal occurs on both sides of the basin, its economic importance is currently restricted to a 15-21 meter thick coal seam on the southwestern limb of the syncline. The coal is predominantly vitrain and clarain composed of greater than 90 percent vitrinite. Clean coal has 14 percent ash (mostly kaolinite and quartz) and low sulphur. The coal is interbedded with bentonite, mudstone and shale partings which increase in number from south to north. The partings are montmorillonite and/or kaolinite rich.

Coal rank along the southwestern limb of the basin was determined by measuring the percent maximum reflectance of vitrinite. Vitrinite reflectance increases laterally from .62 in the north to .86 in the south but shows no significant vertical variation. According to the A.S.T.M. classification, coal rank ranges from High Volatile C Bituminous to High Volatile B Bituminous. Field relations indicate partial post-deformation coalification.

Petrographic study of the coal suggests the coal-forming peat developed in a predominantly forest moor swamp environment.

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INTRODUCTION

The Tulameen Coalfield is one of a number of remnant Tertiary structural basins located in south central British Columbia. It lies just east of the Cascade Mountains approximately 50 km north of the United States-Canadian International Boundary. The location of the Tulameen and other coalfields in British Columbia is shown in Figure 1.

Coal along the southwestern portion of the basin was mined from 1919 to 1940 using underground methods and in 1954 using open cast methods. Although 2,364,561 tons of coal were extracted (Dolmage Campbell & Assoc. Ltd, 1975), potential coal resources are still considerable. Currently an extensive study on the economic feasibility of strip mining the main coal seam along the southwest periphery is in progress. Most of the analytical work to date on the coal has been related to economic use. With the exception of Donaldson (1973) little petrographic work has been done on the coal.

The purpose of the present study is to examine the coal petrology of the main seam along the southwest limb of the Tulameen basin. The stratigraphy, petrographic composition and rank of the coal are examined in order to provide a basis for interpreting the coalification history and the environmental conditions that prevailed during coal formation.

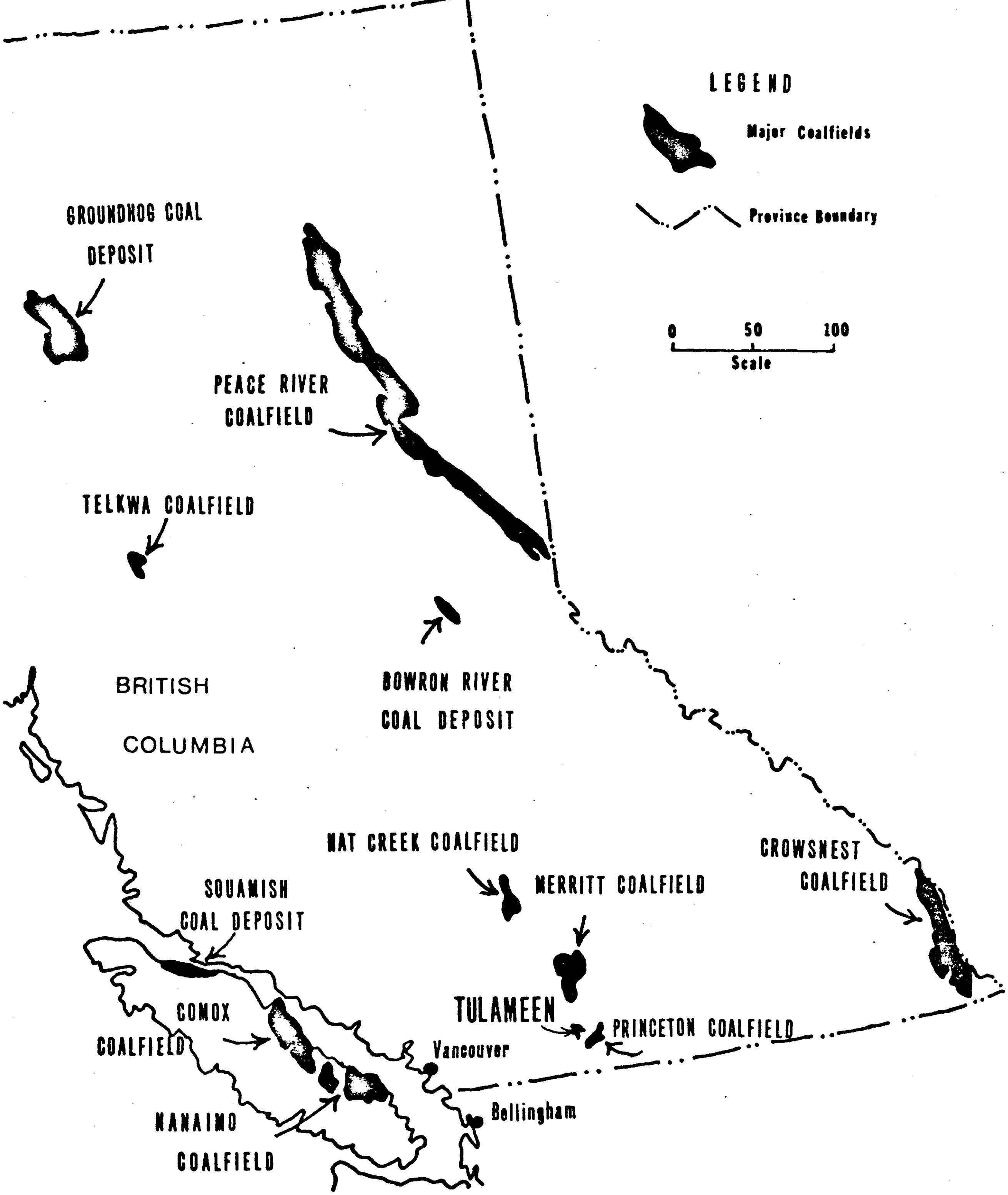

Figure 1. Location of the Tulameen Coalfield and other major coalfields in British Columbia.

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PREVIOUS WORK

The general geology and mineral deposits of the Tulameen area were first described by Charles Camsell (1913) in a series of Canadian government publications from 1906 to 1913. He correlated the coal-bearing sediments of the Tulameen basin with similar Tertiary coal-bearing strata in the Princeton and Hat Creek Coalfields. H.M.A. Rice (1947) published an extensive work which includes a geologic map on the geology and mineral deposits of the Princeton map area.

W.S. Shaw (1952) wrote the first comprehensive report on the Tulameen Coalfield. This publication includes a geologic map of the Tulameen basin as well as a series of stratigraphic columns based on drill core data from the northern limb of the syncline.

The coal petrography of the Blakeburn open pit mine was examined by J. Roger Donaldson (1973). Donaldson's work includes a detailed microlithotype and maceral analysis of a 5½ foot (1.7 meter) column sample as well as some rank determinations based on vitrinite reflectance. In the 1975 publication, Coal Resources of British Columbia, Dolmage Campbell & Associates, Ltd. (1975) describe the coal deposits and mining history of the Tulameen basin. File data from some of the mining companies who have worked in the area is included.

A paper on the Tulameen coal basin by Steve H. Evans (1977) was published in the British Columbia Ministry of Mines and Petroleum Resources report on 1977 geologic fieldwork in British Columbia. Evans' revised field map of the basin reveals the existence of a number of previously unmapped faults.

The most extensive and detailed geologic work to date on the southern limb of the coalfield is found in the 1978 Tulameen Coal Project Report by Tom Adamson of the Cyprus Anvil Mining Corporation. Detailed data contained in his report are included in this thesis.

GEOLOGICAL SETTING

The Tulameen basin rests unconformably on the Upper Triassic Nicola Group. Nicola rocks cover a wide area and are composed of varicolored lava, argillite, tuff, limestone and chlorite/sericite schist. During the Jurassic and Cretaceous, the Nicola was intruded by a series of intrusions ranging in composition from gabbro to granite (Rice, 1947; Adamson, 1978).

Unconformably overlying the Upper Triassic volcanics and Cretaceous granitic intrusives is the Princeton Group (Figure 2). The two main outcrop areas are in the Tulameen and Princeton basins. The Princeton Group is early Tertiary (Eocene) and consists of an unnamed basal volcanic unit unconformably overlain by a thick sequence of clastic sedimentary rocks (Allenby Formation) which in turn are unconformably overlain by an unnamed upper volcanic unit (Eocene-Oligocene?). The basal volcanics consist of a thick section of massive and banded andesitic and basaltic lavas. The overlying Allenby sediments grade upwards from coarse-grained conglomerates to fine-grained shales. The conglomerates have an abundance of granitic cobbles. Feldspar and volcaniclastic fragments are characteristic constituents in the sandstone. The shales contain mostly clay with some quartz and feldspar (Rice, 1947). Coal horizons (some of mineable thickness) and bentonite beds are found interbedded in the sediments. The coal-bearing strata in the Tulameen basin has the same stratigraphic relations as in the Princeton basin and is most likely correlative with the Allenby Formation in the Princeton basin and, therefore, is here extended into the Tulameen basin.

The coal-bearing Allenby Formation forms a sequence more then 800 meters thick in the Tulameen basin. The basal part is 100-150 meters thick and consists of a coarse- to fine-grained sandstone interbedded with siltstone, shale and tephra. Several thin andesitic flows are interbedded with the sediments at the base. The succeeding 130 meter thick section contains shale and minor sandstone interbedded with several coal horizons. The coal is intercalated with numerous shale and bentonite partings. The upper part of the Allenby Formation is over 600 meters thick and is composed of predominantly coarse sandstone and conglomerate. Tuffaceous material is freely dispersed throughout the sediments (Shaw, 1952).

In the southeastern portion of the basin, the Allenby Formation overlaps the basal Princeton Group volcanics and rests unconformably on top of the Nicola Group. The upper volcanic unit of the Princeton Group is absent from the Tulameen basin and, instead, flat-lying Miocene-Pliocene aged volcanics (flood basalts) unconformably cap the sediments. Recent unconsolidated glacial deposits up to 13 meters thick mantle much of the area (Rice, 1947; Shaw, 1952).

In south central British Columbia a number of remnant Tertiary basins are characterized by thick sequences of sedimentary rocks of freshwater origin (Rice, 1947; Cockfield, 1948). The sediments, mostly Eocene, are fluvial and lacustrine and are commonly intercalated with coal and/or carbonaceous shale layers of varying thicknesses. Sediment deposition in the Princeton basin was controlled by block faulting. Paleocurrent data from the sediments indicate a southerly flowing drainage system (Okulitch, et. al., 1977). Major coal deposits are located in the Tulameen and Princeton Coalfields as well as the Hat Creek and Merritt Coalfields (Figure 3). In the Merritt and Hat Creek Coalfields the coal-bearing sediments are assigned to the Coldwater Formation which consists mainly of conglomerate, sandstone and shale. At Hat Creek the Coldwater lies between two Tertiary volcanic units and at Merritt the Coldwater is part of the Kamloops Group. Though discontinuous, the coal-bearing sediments from the four coalfields probably are related, however, no direct correlation between them has been established. Shaw (1952) suggested that a careful reconstruction of Tertiary drainage patterns in the area would help determine whether or not they are correlative.

The Tulameen Coalfield lies in an oval northwest-southeast trending structural basin 5 km long and 3 km wide. Figure 4 shows a geologic map of the Tulameen basin. The basin is an asymmetric fold, with beds on the northeastern side dipping from 40° to 65° to the southwest and beds on the southwestern side dipping from 25° to 49° to the northeast. The fold axis plunges towards the southeast. Shaw (1952) reported two large fault zones and numerous smaller ones in the southern part of the basin and Evans (1977) mapped two probable faults which parallel the trend and run the length of the fold. Folding took place in the interval of time represented between the top of the Princeton Group and the base of the Miocene-Pliocene "flood" basalts.

Although coal crops out on both sides of the syncline, correlation between seams has not been established (Shaw, 1952). Drilling exploration by mining companies along the northeastern limb disclosed a number of irregularly spaced, steeply dipping coal seams characterized

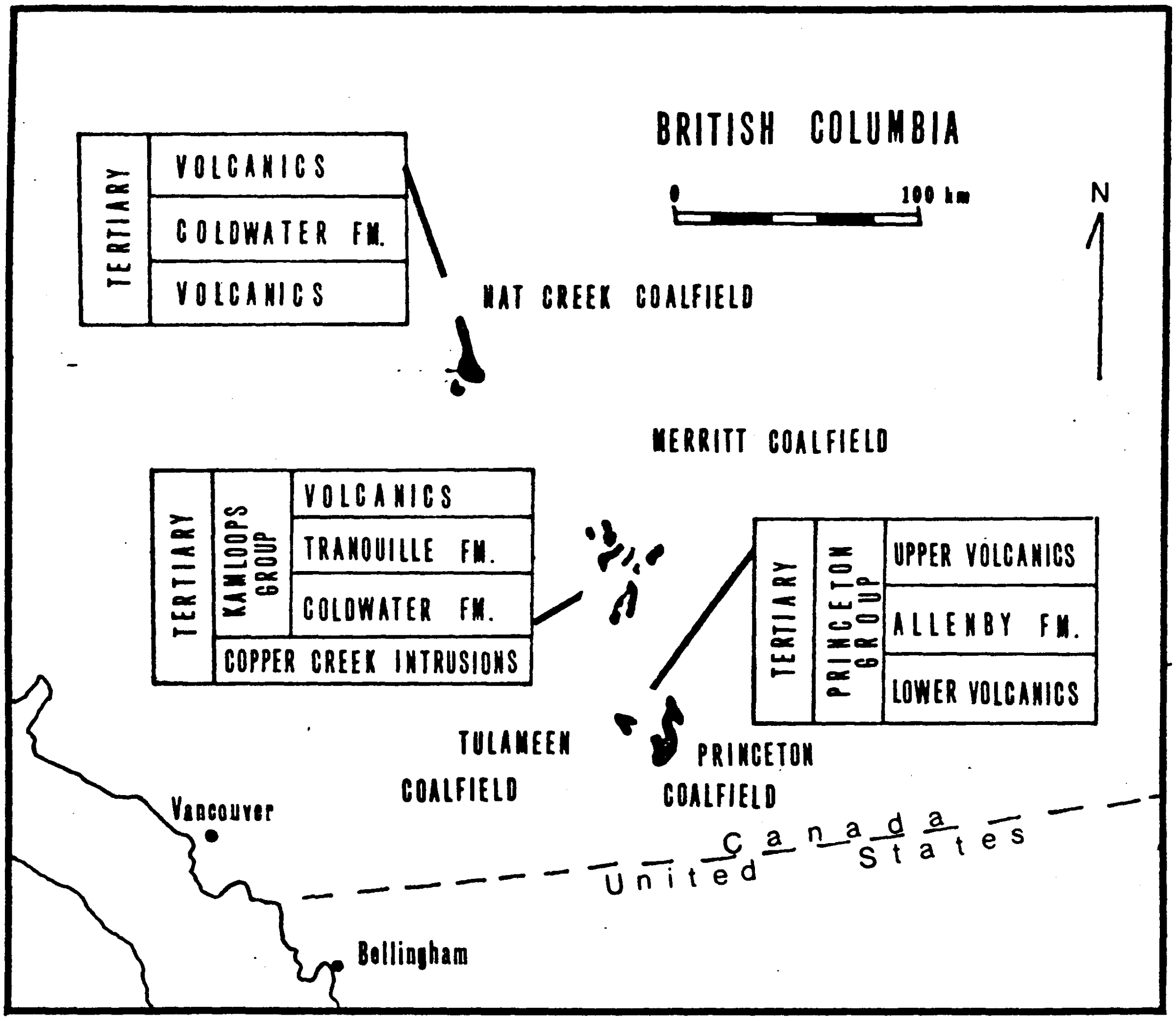


Figure 3. Surficial expression of major coal-bearing formations in the Tulameen, Princeton, Merritt and Hat Creek Coalfields (modified from Dept. of Mines & Petroleum Resources, British Columbia, 1976).

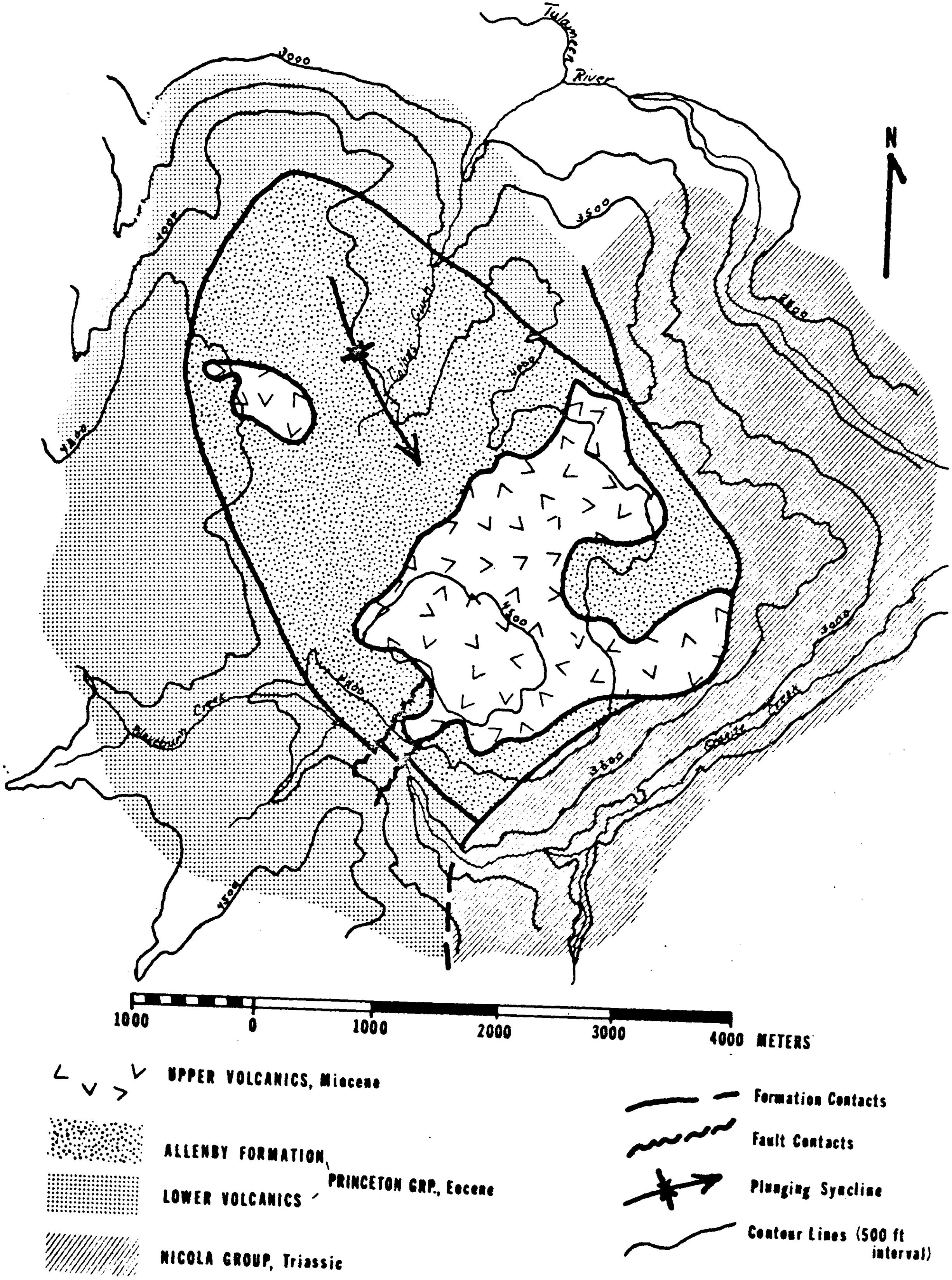


Figure 4. Geologic Map Tulameen basin (modified from Shaw, 1952 and Adamson, 1978).

by highly crushed coal. On the other side of the basin, the coal has shallower dips and is considerably more coherent. Three underground mines followed the main coal seam down dip for over 300 meters and along strike for 2300 meters.

METHODS OF INVESTIGATION

Field investigations were carried out along the southwestern limb of the Tulameen basin during the summer of 1977. The field area encompasses that portion of the coalfield which may be economically feasible to mine. The coal was followed along strike from the Blakeburn open pit in the south of the basin to the extreme northern edge of the basin. Figure 5 shows the configuration of the field area and the location of section and sample sites.

There are a total of 19 sites: the Blakeburn open pit, 6 trenches spaced approximately 300 meters apart and 12 diamond drill holes. The Blakeburn open pit (OP-1) represents the extreme southern border of the field area. The dip of the beds is 25° to 30° to the east. The bottom of the coal zone is not exposed. The trenches (TR 1 through TR 6) are located in the center of the field area where dips range from 28° to 45° . In each trench the entire thickness of the main coal seam, which shows varying degrees of weathering, is exposed. The 12 diamond drill holes were drilled under the direction of the Cyprus Anvil Mining Corporation and are numbered T-77-1 through T-77-12. T-77-1 through T-77-5 were drilled perpendicular to the dip and T-77-6 through T-77-12 were drilled vertically. T-77-10 represents the extreme northern edge of the field area.

Detailed stratigraphic sections of the main coal seam in OP-1 and TR 1 through TR 6 were measured and described (Appendix). Detailed lithologic logs of all of the drill holes were provided by Cyprus Anvil. Over 200 samples of coal and non-coaly interbeds were collected

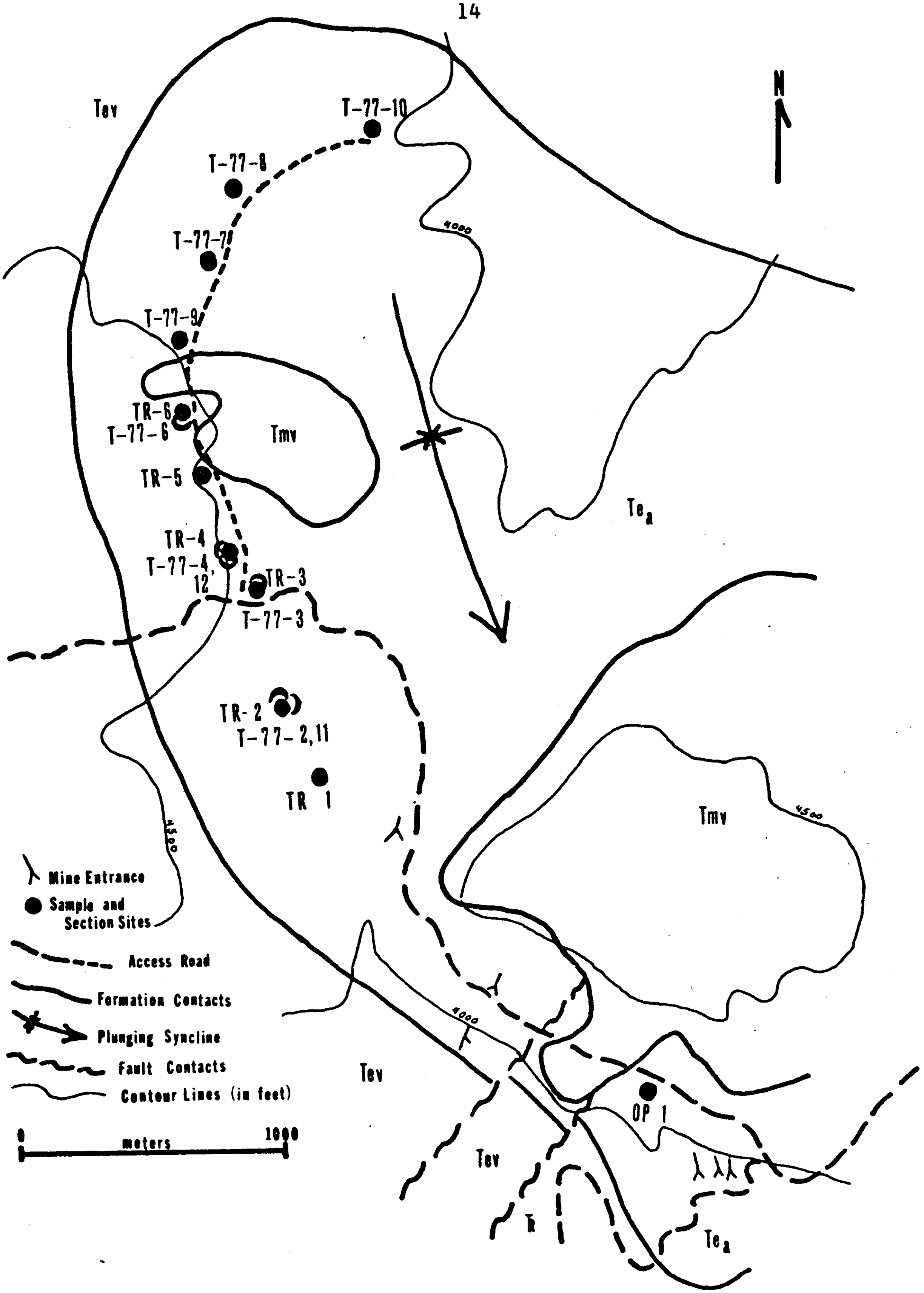


Figure 5. Map showing location of sample and section sites.

from OP-1, TR 1 through TR 6 and T-77-8 through T-77-12. Sampling intervals varied between sites. For the location of each sample see the Appendix.

The organic composition of the coal was examined in reflected light under oil immersion. Twenty-three maceral analyses were made. The percentage of vitrinite, exinite and inertinite was measured by counting 1000 points per sample.

In order to help determine the inorganic mineral composition of the coal, 7 samples ground to pass a 60 mesh screen were oxidized at low temperature (<150°C) in an electronically excited oxygen plasma chamber. One sample was ashed at the Coal Division of the British Columbia Ministry of Mines and Petroleum Resources and the others by the Coal Division of the Illinois State Geological Survey. The ashed products were analyzed on a GE XRD-5 x-ray diffractometer using Cu k radiation. Whole rock and oriented specimens of the $<2\mu m$ fraction of 12 clay and shale partings from TR 4 were also x-rayed. Whole coal analyses on drill cores and bulk samples were provided by Cyprus Anvil.

The rank of 49 coal samples was determined by measuring the maximum percent reflectance ($\bar{R}_o$) of vitrinite. Vitrinite reflectance is an excellent parameter to use for determining rank because it is not appreciably affected by weathering. Therefore, reliable $\bar{R}_o$ values were obtained for the weathered coals in the trench and open pit sites as well as for the relatively fresher drill core samples.

Preparation for rank and maceral analyses involved making the samples into pellets. Each coal sample was crushed and passed through a 20 mesh screen. It was then thoroughly mixed with an equal amount of Buehler Transoptic powder and placed into a Buehler, Ltd., PNEUMAT I mounting press where it was subjected to a pressure of 4500 psi and heated to 140°C. After cooling, the pellet was polished using a five-stage wet polishing technique going from a coarse-grained 240-grit Carbiment paper disc down to a .05 alumina Buehler micropolish. Pellets were allowed to dry for at least 24 hours because moisture influences reflectance values, especially in high volatile coals.

Reflectance was measured using a Leitz 450 photometer at a magnification of x500. Readings were taken on homogeneously appearing vitrinite particles that no longer displayed cellular structure. The vitrinite was viewed in incident light through an oil immersion objective. The stage of the microscope was rotated through 360 and the highest reflectance value was recorded. Fifty readings per sample were taken. Control was maintained by using a glass standard of known reflectance for calibration. The standard was checked after every 25 readings.

STRATIGRAPHY

The coal-bearing middle member of the Allenby Formation in the Tulameen basin is approximately 130 meters thick and consists of interbedded shales, mudstone, tuffs, minor sandstone and coal (Figure 6). Two well defined coal seams are present (Adamson, 1978). The lower seam has an average thickness of 7 to 7.6 meters and can be traced from T-77-11 to T-77-10. It is medium clean to clean banded coal with interbedded bentonite, shale and mudstone. The average percentage of inorganic material intermixed with the coal is high (50-70%).

The upper coal seam has interbeds of bentonite, brown shale and mudstone. The coal is banded, fairly bright bedded coal (Figure 7) with vitrain and clarain predominating. The truly dull coal component consists mainly of durain. Microscopic examination of some of the dull coal samples reveals a large amount of vitrinite and the presence of finely dispersed mineral matter which masks the macroscopic appearance of the coal. This observation also was made by Donaldson (1973). Weathered coal surfaces commonly have a white oxidized coating and iron oxide stain. Clear, amber-colored resin nodules and infrequent, partially coalified wood fragments are scattered throughout the coal. A few small scour channels filled with coal are present. Both calcite and quartz have been identified by x-ray analysis as cleat fillings. In places, the coal exhibits small scale folding and faulting. Finely crushed coal resembling fusain lies along the fault planes. The coal is vitrinite rich throughout the lateral and vertical extent of the coal seam and rank increases slightly from northwest to southeast. The average thickness of the coal in the trench and

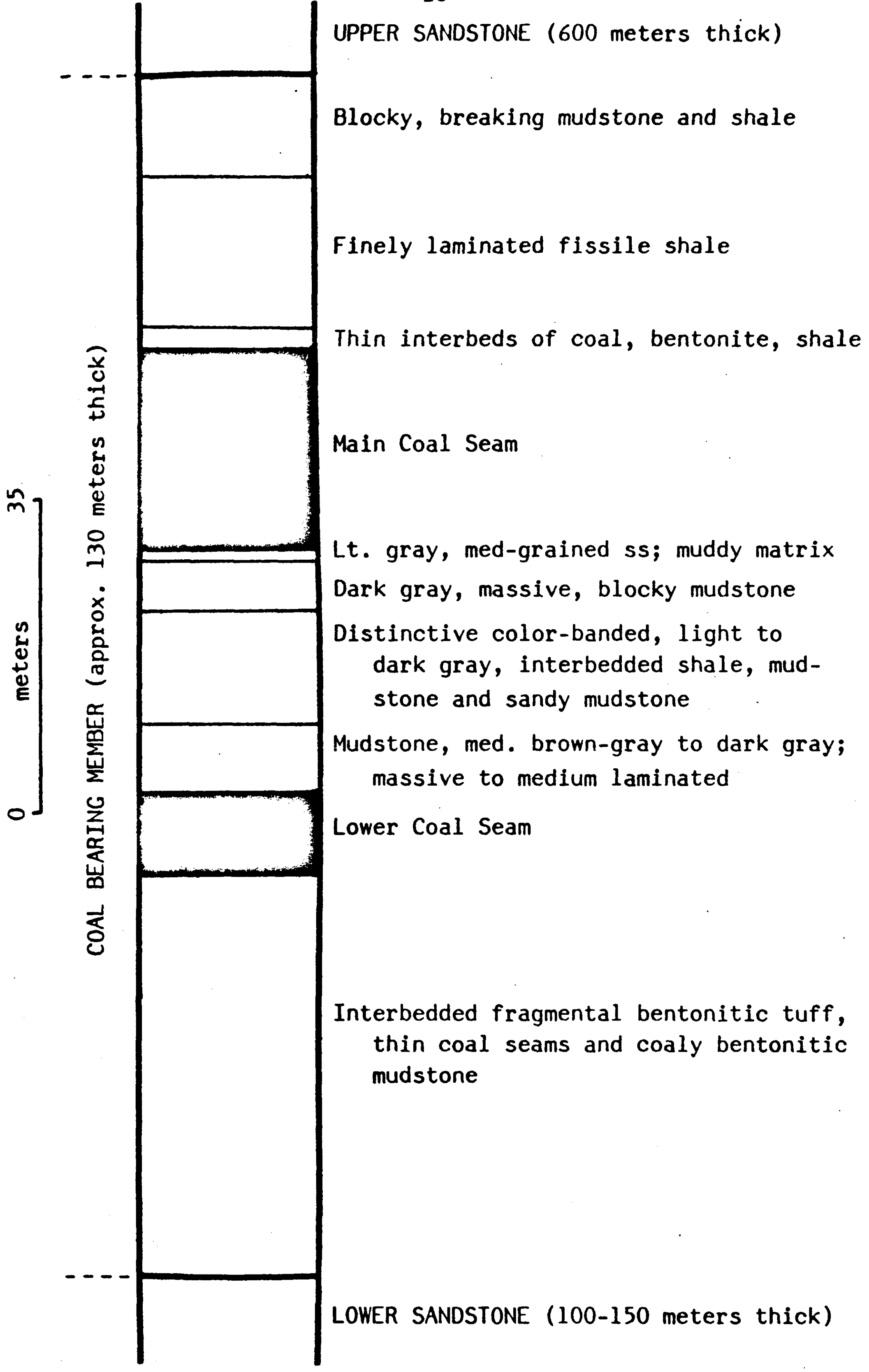


Figure 6. Representative stratigraphic column of the Coal-Bearing Member (approx. 130 meters thick).

Figure 7. South wall of TR 2 showing bright, bedded appearance of coal and thin bentonite, shale and mudstone partings. Photograph taken near the base of the coal section.

drill hole area of the field ranges from 15 to 21 meters. In the Blakeburn open pit (Figure 8) the true thickness of the seam is unknown because the floor of the seam is not exposed. Also, determination of the thickness has been complicated by numerous small faults many of which are subparallel to bedding.

Figure 9 shows a cross section drawn down dip from TR 4 to T-77-4 and Figure 10 shows a series of stratigraphic columns that extend laterally from the extreme northern portion of the field area at T-77-10 to the Blakeburn open pit in the southern portion. The measured sections are based upon the author's field measurements of the Blakeburn open pit and surface exposures in Trenches 1 through 6 and upon detailed lithologic logs from T-77-1 through T-77-12.

The percentage and lithologic character of partings change towards the northern portion of the basin. In the Blakeburn open pit, partings are the least numerous and consist mainly of relatively thin layers of bentonite and mudstone. In the interval between T-77-1 and T-77-5, the coal seam changes from 88 to 82% coal and from 12 to 18% partings. The partings are characterized by bentonite, mudstone and brown shale. Several thin scattered interbeds of a dark, chert-like material are almost pure SiO_2 according to x-ray analysis.

Fifteen partings from TR 4 and roof and floor samples were examined by x-ray diffraction. Table 1 lists their location, physical appearance and mineralogy. A montmorillonitic smectite and "b" axis disordered kaolinite are the two predominant minerals and both are distributed throughout the stratigraphic column. The smectite in bentonite partings consists of almost pure, fully expandable montmoril-

Figure 8. Exposure of main coal seam at Blakeburn open pit (OP-1).

TABLE 1. MINERAL COMPOSITION OF PARTINGS AND ROOF AND FLOOR SAMPLES

Sample #	Macroscopic Appearance	Mineralogy (in size fractions) < 2µm	>50µm
4-70-3	Cream colored B	Almost pure M; minor C	N.D.
4-70-2	Brown coaly Ms	Q and F	N.D.
4-70-1	Cream colored B; Fe stain	Almost pure M	N.D.
4-60-1	Dark brown coaly Ms	Mostly S; K	N.D.
4-45-1	Med. brown colored Ms	S; minor halloysite?	Q,F
4-41-3	Med. buff colored B; Fe stain	Almost pure M; minor C	N.D.
4-34-1	Light brown to buff colored Ms; Fe stained; carbonized plant fragments	K; minor S	N.D.
4-26-1	Med. brown colored Ms; Fe stain; carbonized plant fragments	Almost pure M; minor C; trace Q	N.D.
4-20-1	Brown shaly Ms	S and K	Q
4-18-1	Brown Ms; Fe stain	S	N.D.
4-14-1	Cream to buff colored Ms	K; minor S	Q
4-9-1	Buff colored Ms; Fe stain	S; lesser K	Q
6-63-1	Black cherty rock found interbedded in coal from TR 6	Pure Q	N.D.
OP-1-15-1	Brown fissile Sh; overlies bentonite and main coal seam; from OP-1	Mostly K and Q; minor S	N.D.
1-0-0	Light colored, blocky, laminated Ms; lies at base of coal; from TR 1	Mostly K and Q; expandable mixed layer clay of smectite group	N.D.

*Samples numbered from 4-9-1 through 4-70-3 are arranged in stratigraphic order and come from TR 4; see Appendix for location of samples.

**B = bentonite; C = cristobalite; F = feldspar; K = kaolinite; M = montmorillonite; Ms = mudstone; Q = quartz; S = smectite; Sh = shale.

lonite showing fairly sharp, high intensity peaks indicating good crystallinity (Roberson, 1964). Admixtures of kaolinite and smectite in varying proportions are common in the dark brown mudstones. Some of the partings contain small carbonized plant fragments. All of the kaolinite-bearing partings contain quartz. Kaolinite-rich sediments with quartz and minor amounts of smectite occur both above and below the coal seam.

Between T-77-6 and T-77-10 partings become markedly more numerous. The percentage of coal decreases from south to north from 71% at T-77-6 to 41% at T-77-10. Most of the partings have a volcanic origin and are characterized by tuffs (multi-colored and welded), fine-grained siliceous (sometimes pyritic) rock, very-fine-grained and slightly vesicular flows and bentonitic mudstone. Contacts between the coal and the volcanics are mainly sharp and well-defined (Adamson, 1978).

Occurring near the top of the coal section is a continuous bentonite bed up to 1 meter thick. The bentonite is light gray to cream colored (Figure 11). X-ray diffraction of the $< 2\mu m$ size fraction shows montmorillonitic smectite to be the predominant clay mineral. Small carbonized plant fragments are dispersed throughout the bed. The bentonite can be traced from the Blakeburn open pit northwards to TR 6. The bed does not appear in the T-77-9, T-77-7 and T-77-8 lithologic logs. However, the T-77-10 lithologic log describes a 76 cm thick bentonite bed which may belong to the key unit. Other partings show little correlation between sites.

Figure 11. South wall of TR 4 showing main bentonite bed (thick, light colored bed in center of photograph) and other partings in the upper half of the main coal seam. The coal is weathered and shows iron staining.

COAL COMPOSITION

Macerals

The microscopic organic constituents of coal are called macerals. There are three maceral groups: vitrinite, exinite and inertinite. Table 2 shows the percentage maceral composition of 23 main seam samples (Appendix) covering the lateral and vertical extent of the field area. The results show a uniformly large percentage of vitrinite and relatively small amounts of exinite and inertinite. Exinite is slightly more abundant than inertinite. Donaldson's (1973) maceral analysis also shows a correspondingly large amount of vitrinite. The abundance of the vitrinite imparts the characteristic macroscopic bright appearance of the coal.

Much of the vitrinite is formed from the woody bark and tissue of trees and shrubs. The vitrinite is mostly undifferentiated and has a uniform "homogeneous" appearance (Figure 12). Although the color of vitrinite in a sample usually varies from medium to light gray, samples from T-77-8 and T-77-10 are generally darker and samples from OP-1 lighter. Some samples contain vitrinite differentiated into telinite and collinite (Figure 13). Most differentiated vitrinite fragments show deformation by folding or compression into microlayers parallel to bedding (Figure 14). The brittleness of vitrinite is shown by numerous microfractures in some samples. Exinite and inertinite macerals and mineral matter are mostly enclosed within vitrinite.

Exinite generally has a black to dark gray appearance. Some of the exinite is difficult to identify (Figure 15). Most samples include minor amounts of resinite, cutinite and sporinite. The resinite often

TABLE 2. RESULTS OF MACERAL ANALYSES ON SELECTED SAMPLES

Sample Site*	Sample No.**	Maceral Composition % Vitrinite	% Exinite	% Inertinite
OP-1	OP-1-43-1	95.0	3.9	1.1
OP-1	OP-1-15-1	95.0	3.2	1.0
OP-1	OP-1-11-1	92.8	6.9	0.8
OP-1	OP-1-1-3	96.1	2.8	1.1
TR 1	1-1-1	99.8	0.2	-
T-77-11	DC 11-Q***	97.4	2.0	0.6
TR 3	3-9-2	93.8	0.7	0.9
T-77-12	DC 12-ss	97.2	2.7	0.1
T-77-12	DC 12-pp	98.8	2.2	1.0
T-77-12	DC 12-hh	98.2	1.4	0.4
T-77-12	DC 12-bb	97.8	1.3	0.9
T-77-12	DC 12-y	97.4	2.0	0.6
T-77-12	DC 12-s	96.1	3.8	0.1
T-77-12	DC 12-j	98.7	0.8	0.6
T-77-12	DC 12-a	98.4	0.7	0.9
TR 5	5-81-1	97.7	1.6	0.7
T-77-9	DC 9-B***	99.2	0.5	0.3
T-77-8	DC 8-E***	94.8	4.9	0.3
T-77-8	DC 8-D***	98.2	1.5	0.3
T-77-8	DC 8-C	98.1	1.3	0.6
T-77-8	DC 8-B	97.6	2.1	0.3
T-77-8	DC 8-A***	99.1	0.5	0.4
T-77-10	DC 10-X	99.4	0.4	0.2

*See Figure 5 for location of sample sites.

**See Appendix for location of samples

***Pyrite-rich samples

Figure 12. Undifferentiated vitrinite (1) lacking visible cell structure. Polished surface, oil immersion, x500.

Figure 13. Cell structure in well differentiated vitrinite; telinite (1) represents cell wall tissue and collinite (2) cell fill material. Polished surface, oil immersion, x500.

Figure 14. Structured vitrinite divided into telinite (1) and collinite (2); cell structure highly compressed in lower half of figure. Polished surface, oil immersion, x500.

Figure 15. Deformed piece of exinite (1)--resinite? (2) filling thin-walled telinite? (3)--surrounded by vitrinite (4). Polished surface, oil immersion, x500.

displays orange internal reflections. Most of the resinite (Figure 16) occurs as isolated elongated or spherical shaped bodies and in some cases as cell lumen fillings. Isolated resinite bodies not altered to vitrinite are seen in a few samples. Thin-and thick-walled cutinite commonly show folded and sometimes toothed structure (Figure 17 and 18). Selective decomposition has formed some concentrated layers of thin-walled untoothed cutinite. Sporinite, sometimes occurring in groups, is present in small quantities in most of the samples. It is formed from the resistant perines and exines of pollens and spores. The sporinite is compressed and in some cases is filled with vitrinite (Figure 19). Microscopic cracks which pass through vitrinite often stop abruptly at sporinite which is very tough and resistant (Figure 20).

Inertinite has a light gray to bright white color and a correspondingly high reflectance. Sclerotinite and semifusinite are the two most abundant inertinite macerals in the coal. Though not abundant, sclerotinite occurs in most samples. The sclerotia (Figure 21) are generally rounded or elliptical and some are multicellular. Cavities are usually empty but some show resinite, vitrinite or pyrite fillings. Concentrated clusters of compressed teleutospores in vitrinite (Figure 22) occur, especially in samples from OP-1. Little semifusinite and rare fusinite are found in trench and drill core samples, but are more common in OP-1 samples. Semifusinite has poorly preserved structure, shows varying degrees of fusinization and is often deformed (Figure 23). Plastically deformed degradofusinite (Figure 24) and pyrofusinite with well preserved cell structure (Figure 25) appear in several samples from OP-1. One piece of macrinite? was identified in

Figure 16. Elongated resin bodies (1) in vitrinite; thin-walled telinite (2) with resinite fillings (3); light colored resinite bodies altered into vitrinite (4); finely disseminated pyrite (5) in vitrinite. Polished surface, oil immersion, x500.

Figure 17. Folded, thick-toothed cutinite (1) in vitrinite; rounded light gray objects represent vitrinized cell fillings (2). Polished surface, oil immersion, x500.

Figure 18. Thin-walled cutinite (1) in clarite with sporinite (2), vitrinite and inertinite (3). Polished surface, oil immersion, x500.

Figure 19. Compressed sporinite (1) in clay-rich (2) clarite; microspores filled with vitrinite (3). Polished surface, oil immersion, x500.

Figure 20. Sporinite (1) in clarite with cutinite (2) and inertinite (3); toughness of sporinite shown in top of figure where microscopic crack (4) passes through brittle vitrinite and stops at sporinite (5). Polished surface, oil immersion, x500.

Figure 21. Isolated multicelled sclerotia (1) with resinite (2) filled cavities; vitrinite groundmass with vitrinized cell fillings (3) surrounded by clay (4). Polished surface, oil immersion, x500.

Figure 22. Concentrated layers of compressed teleutospores (1) in fractured vitrinite (2). Polished surface, oil immersion, x500.

Figure 23. Deformed semifusinite (1) in dirty vitrinite; finely disseminated pyrite crystals (2) in vitrinite; aggregate of pyrite crystals (3). Polished surface, oil immersion, x500.

Figure 24. Plastically deformed degradofusinite (1) with poorly preserved cellular structure; thin-walled toothed cutinite (2) and resin bodies (3). Polished surface, oil immersion, x500.

Figure 25. Pyrofusinite (1) with well preserved cellular structure in trimacerite. Polished surface, oil immersion, x500.

in a sample from OP-1 (Figure 26).

Microlithotypes

Characteristic associations of macerals are called microlithotypes. The dominant microlithotype of the main coal seam is vitrite. Clarite with minor interbands of trimacerite (clarodurite) and durite are also present. Donaldson's (1973) microlithotype analysis shows vitrite to represent 72.5% and clarite 10.8% of the 5½ foot column that he studied. Figure 27 shows vitrinite, flattened sporinite, sclerotinite and semifusinite in trimacerite (duroclarite). Vitrinite, cutinite and <5% semifusinite are shown in Figure 28 in clarite.

Proximate and Ultimate Analyses

Bulk and drill core analyses (Adamson, 1978) show clean coal has the following specifications:

Proximate Analysis (As Received)

Total Moisture	12.0%
Ash	14.5
Volatile Matter	30.2
Fixed Carbon	43.3
	100.0%
Sulphur	00.6%
Calorific Value	10,000 B.T.U./lb

Ultimate Analysis (As Received)

Ash	13.80%
Carbon	62.73
Hydrogen	4.90
Nitrogen	1.36
Sulphur	0.63
Oxygen	16.57
	99.99%

Figure 26. Inertinite--macrinite? (1)--in clay-rich (2) vitrinite (3). Polished surface, oil immersion, x500.

Figure 27. Trimacerite with sclerotinite (1), semifusinite (2), resinite (3), cutinite (4) and vitrinite (5); the large resilient sclerotinite resists compression. Polished surface, oil immersion, x500.

Figure 28. Clarite with exinite (1) and vitrinite (2); clarite interlayered with vitrite (3). Polished surface, oil immersion, x500.

Figure 29. Diffuse clay layers (1) of variable width in vitrinite (2). Polished surface, oil immersion, x500.

The ultimate analysis, which determines the major component elements of coal, shows a relatively large amount of hydrogen and small amount of oxygen because of the large vitrinite content.

Mineral Matter

Mineral matter refers to all inorganic material in coal. It includes discrete mineral phases and all inorganic elements other than H, N, O and S which may be present in organic compounds (Ward, 1977). Below are results of the mineral ash analysis of clean coal from bulk and drill core samples (Adamson, 1978):

Mineral Ash Analysis

SiO_2	69.51%
Al_2O_3	13.54
Fe_2O_3	6.55
CaO	1.17
MgO	0.44
Na_2O	0.67
K_2O	0.64
TiO_2	0.04
P_2O_5	0.17
SO_3	0.51
	93.24%

During mineral ash analysis, coal is heated to high enough temperatures so that all of the inorganic constituents are converted to oxides (Sehgal and Wong, 1974). The silica to iron ratio in the main seam coal is large and the alkali content small. Amounts of sulphur, phosphorous and titanium are significantly small.

Mineral ash differs from low temperature ash (LTA) in that low temperature ashing removes organic matter by slow oxidation at low enough temperatures so that the resultant inorganic residue is essentially unaltered. Seven coal samples were low temperature ashed and then analyzed on the x-ray diffractometer. Three samples are from the lower, middle and upper portions of the exposed coal section in OP-1 and a fourth from the base of the main seam in TR 2 (Appendix). All four samples were weathered. The remaining three samples are relatively fresh and come from the lower, middle and upper portions of the main coal seam in T-77-10 (Appendix). Samples have quartz, kaolinite and minor amounts of an expandable clay (smectite?). Quartz predominates. Results from OP-1 show a larger concentration of quartz in the upper part of the seam and a greater kaolinite to quartz ratio in the lower and middle parts. The absence of identifiable sulphides and carbonates from OP-1 is, in part, the result of weathering. In addition to showing the presence of quartz and minor kaolinite, results from T-77-10 show a concentration of magnesium-rich calcite in the upper part of the seam and the presence of pyrite in the middle and lower parts. The sample from the middle part of the seam has a larger kaolinite to quartz ratio than the other two samples.

Microscopic mineral matter in the main coal seam is readily observable in reflected light, oil immersion. Clay, the most commonly occurring mineral, has a dark gray or black appearance and usually forms thin irregular layers or lenses, or, less commonly, forms pockets or petrifications filling cell lumens. Figures 29 and 30 show some clay layers interbedded with vitrinite.

Figure 30. Well defined clay (1) layers and lenses interbedded with vitrinite (2). Polished surface, oil immersion, x500.

Figure 31. Spherical aggregates of euhedral pyrite crystals (1); irregular masses of pyrite crystals (2); pyrite replacing cell walls (3); vitrinite groundmass. Polished surface, oil immersion, x500.

Pyrite is a minor constituent and is mostly syngenetic. Although it generally appears as small discrete grains, it sometimes occurs in spherical aggregates of euhedral crystals (Figure 31). In some samples it replaces cell walls and/or fills cell lumens (Figures 32 and 33). Drill core samples from the northern part of the study area generally have a greater abundance (up to 11%) of pyrite than drill core samples in the central part.

Some samples have detrital quartz grains. Quartz, because of its low relief and transparent gray color in reflected light under oil, is difficult to distinguish from void spaces. However, when present, compaction structures are used to identify quartz (Figure 34)(Kemežy and Taylor, 1964).

Several coal samples have a carbonate mineral with a mottled gray appearance (Figure 35). Some carbonate mineral crystals appear to replace vitrinite and others are surrounded by compaction structures. Identification of individual carbonate minerals is difficult in reflected light under oil because of their similar appearance.

A rough correlation exists between the chemical analyses of high temperature mineral ash and mineralogical composition of coal derived from low temperature ash and petrographic analyses (Mitchell and Gluskoter, 1975). The high SiO_2 percentage is derived mainly from quartz and to a lesser extent from kaolinite and smectite?. The Al_2O_3 as well as Ca, Mg, Na and K oxides originate in large part from the clays and the Fe_2O_3 and SO_3 primarily come from pyrite. The titanium and phosphorous probably represent inherent mineral matter in the coal forming plants.

Figure 32. Syngenetic pyrite (1) replacing well defined cell walls in vitrinite. Polished surface, oil immersion, x500.

Figure 33. Syngenetic pyrite replacing cell walls and filling cell lumens (2) in vitrinite; dark splotches in vitrinite caused by finely disseminated clay particles. Polished surface, oil immersion, x500.

Figure 34. Detrital, sub-angular quartz grain (1) in clay (2) and pyrite- (3) rich vitrinite; compaction structures enclose the quartz grain; small gray splotches on quartz grain are water marks. Polished surface, oil immersion, x500.

Figure 35. Carbonate mineral (1) associated with vitrinite (2) and exinite (3); exinite-rich band forms compaction structures (4) around the carbonate. Polished surface, oil immersion, x500.

COAL RANK

The average maximum percent reflectance of vitrinite ($\bar{R}_o$) was measured on 49 coal samples collected from drill cores and from weathered trench and open pit exposures. Forty-five of the samples are from the main seam and four from the lower seam. Table 3 lists the $\bar{R}_o$ per sample at each site in stratigraphic order.

Low $\bar{R}_o$ values from T-77-8 are caused by the abundance of pyrite. In samples with a relatively large quantity of pyrite, vitrinite $\bar{R}_o$ readings are lowered by the high reflectance of pyrite. The larger readings ($\bar{R}_o$ = .63 and .65) from T-77-8 are from two samples that have little pyrite and are, therefore, more representative of coal rank. Badly scratched polished surfaces also lower readings. Scratching was caused by pellets which disintegrated during the polishing process because of mineral matter intermixed with the coal.

With the possible exception of T-77-11 and TR 2, which are closely associated, no significant vertical variation in reflectance exists. T-77-12, upon which the greatest number of readings were taken, shows little stratigraphic variation between values (.62 to .65).

Figure 36 shows the relationship between the average $\bar{R}_o$ of vitrinite per site and the location of sites with respect to one another. Reflectance gradually increases from .62 in the north to .86 in the south. The average $\bar{R}_o$ for the entire study area is .67.

Coals in North America are usually ranked according to the A.S.T.M. (American Society for Testing Materials) system. The degree of coaliification is based upon utilization parameters. High rank coals are classified on a fixed carbon or volatile content calculated on a dry,

TABLE 3: PLOT OF % $\bar{R}_o$ OF VITRINITE AT DESIGNATED SITES (VALUES ARRANGED IN STRATIGRAPHIC ORDER).

		% $\bar{R}_o$ of Vitrinite at Designated Sites										
		OP-1	TR 1	TR 2	T-77-11	TR 3	T-77-12	TR 5	TR 6	T-77-9	T-77-8	T-77-10
Main Coal Seam	U. Section	.90	*	-	-	-	.62	-	-	-	.54	.66
		-	-	-	-	-	.66	-	-	-	-	-
		-	-	.57	.54	.62	.68	.65	.65	*	-	-
		.87	-	.56	-	-	.66	-	-	-	.55	-
	M. Section	-	-	-	-	-	.68	-	-	-	.58	.60
		.87	-	-	-	-	.67	-	-	-	-	-
		-	.80	*	.65	*	-	.68	.71	.63	.65	-
		-	-	-	-	-	.66	-	-	-	-	-
		.79	-	-	-	-	.67	-	-	-	.63	-
	L. Section	.87	-	-	-	-	.67	-	-	-	-	.59
		-	-	.67	-	-	.67	-	-	-	-	-
		.87	.63	.65	.70	.72	.67	*	.71	.64	.52	.64
Avg. % $\bar{R}_o$ =		.86	.71	.60	.63	.67	.66	.67	.69	.64	.58	.62
Lower Seam		-	-	-	-	-	.72	-	-	.72	-	.63
		-	-	-	-	-	-	-	-	-	-	.66

*Pellets so badly scratched that reliable $\bar{R}_o$ values were not possible.

mineral-matter-free (d.m.m.f.) basis. Lower rank coals having a less than 69% carbon content are classified according to their calorific value calculated on a moist, mineral-matter-free (m.m.m.f.) basis Williamson, 1967). In the Tulameen Coalfield main seam analyses and washability tests from T-77-1 through T-77-6 and from bulk samples show the carbon content of the coal to lie below 69% (d.m.m.f.). The calorific values range from 11,707 B.T.U./lb to 12,362 B.T.U./lb (m.m.m.f.) (Adamson, 1978). Calorific values for the lower seam are similar to those of the main seam. Therefore, under the A.S.T.M. system the Tulameen coal with the T-77-1 to T-77-6 interval would be classified as High Volatile C Bituminous. According to Figure 37, which correlates maximum reflectance of vitrinite with the A.S.T.M. classification system, vitrinite reflectance values from the northern half of the basin fall within the High Volatile C Bituminous range and coal from OP-1 within High Volatile B to A Bituminous range.

DISCUSSION

Widespread late Mesozoic and early Cenozoic sedimentary sections in western North America are associated with a continental margin arc-trench system (Dickinson, 1976). Dickinson (1976) constructed paleotectonic maps illustrating the Cordilleran arc-trench system during the Paleocene to Late Eocene and during the Late Eocene to Early Miocene (Figure 38). The Northern Cascade-Okanogan area during the Late Cretaceous and early Tertiary underwent a period of magmatic cessation characterized by post orogenic sedimentation. Arc magmatism resumed during the Eocene 55 to 50 million years ago and occupied a wide belt lying between 126° to 116° W. Longitude (Davis, 1977; Snyder, et. al, 1976). The Tulameen basin which forms a part of the Intermontane Belt of the Canadian Cordillera (Figure 39) lay within the magmatic arc.

Eocene geology of the Intermontane Belt in south central British Columbia was characterized by concomitant volcanism and sedimentation. Regional north-south block faulting was prevalent and extended across the Canadian/United States border from the Cascade Mountains to Montana (Davis, 1977). Thick successions of volcanic and sedimentary rocks were deposited in lakes and valleys associated with north-south trending block faults (Okulitch, et. al., 1977). Block faulting along with volcanism provided possible mechanisms for the formation of poorly drained areas suitable for coal deposition.

The lithology and thick sequence of clastic sedimentary rocks in the Tulameen basin indicate a fluvial-lacustrine origin (Reineck and Singh, 1975; Hendricks, 1977). The sediments are continental and represent a wide range of particle sizes deposited by fluvial processes.

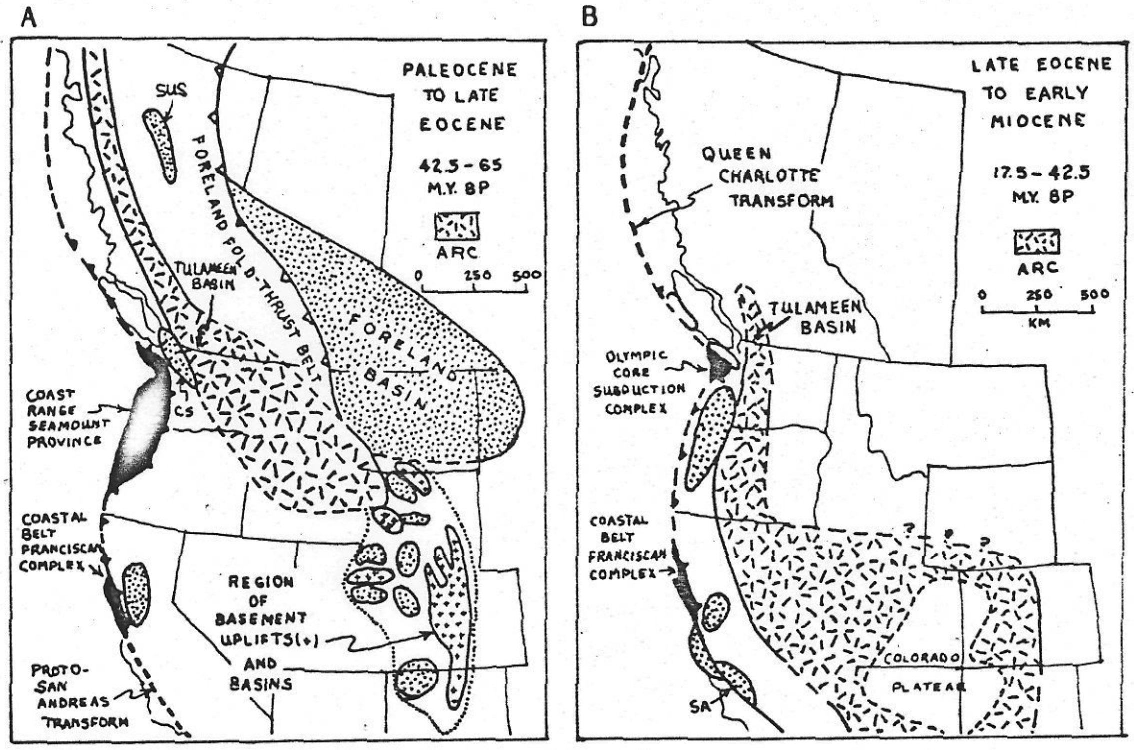


Figure 38. A. Cordilleran arc-trench system in Paleocene to Late Eocene: SUS, Sustat assemblage; CS, Chuckanut Swauk sequence of North Cascades.
B. Cordilleran arc-trench system in Late Eocene to Early Miocene: SA, San Andreas fault. (Dickinson, 1977)

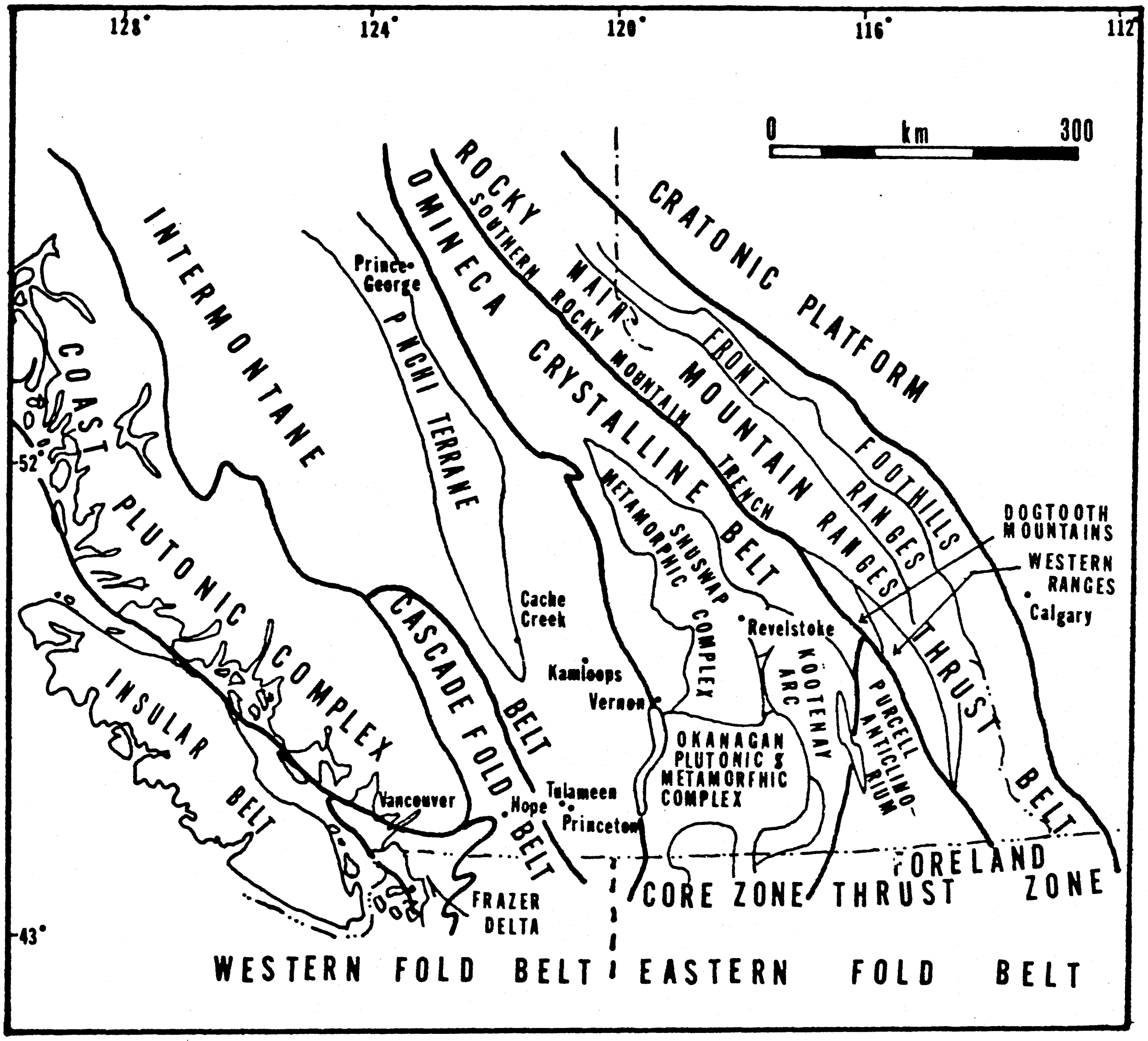


Figure 39. Principal structural subdivisions of the southern Canadian Cordillera (Okulitch, et.al., 1977).

Massive, coarse-grained, feldspathic sandstones and conglomerates were deposited rapidly and were probably derived from a nearby source area. Relatively thick sequences of laminated, fine-grained sandstones, mudstones, fissile shales and intercalated coal horizons represent periods of lower energy environments. The frequent occurrence of tephra and bentonite throughout the sedimentary sequence documents repeated volcanic activity in the area.

Palynomorph assemblages from interior British Columbia imply a warm to subtropical continental climate during Middle and Late Eocene time (Rouse, 1977). Pollens identified from the coal-bearing sediments in the Princeton basin and in four similar locations in interior British Columbia consist of two principle elements: coniferous pollen and deciduous arboreal pollen mainly represented by the Betulaceae and Junglandaceae families (Rouse, 1967). The flora suggests an upland and inland environment. Although interior Eocene assemblages reflect a slightly cooler climate and have different major elements than coastal Eocene assemblages, they have enough similarities to suggest that the present Coastal and Cascade Mountain ranges were much lower during the Eocene than at present (Rouse, 1967).

The mineralogy of the coal determined from LTA and petrographic analyses indicates a fresh water swamp environment. Coals having relatively large quartz and kaolinite contents, as well as little to no carbonate and pyrite, are usually associated with fresh water depositional basins (Millot, 1952; Rao and Gluskoter, 1973). Other Tertiary coal basins in central British Columbia show a similar mineral association (Pearson, personal communication).

Swamp environments are defined on the basis of their predominant type of vegetation. Forest moor environments are dominated by woody trees and shrubs and result in deposits rich in vitrinite (Hacquebard and Donaldson, 1969). The vitrinite concentration and lack of significant petrographic variation in the Tulameen main coal seam indicate that a forest moor environment with a warm, moist climate predominated throughout peat formation. Figure 40 is a schematic block diagram of the Tulameen forest moor swamp as it may have appeared during peat formation.

Poorly drained areas that receive a sufficient inflow of water favor peat development. The type of basin and rate of subsidence help determine the nature of the peat (Hacquebard and Donaldson, 1967; Falini, 1965). Seam thickness and uniform composition (vitrite and exinite-poor clarite) of the Tulameen coal along with numerous thin shale and mudstone partings suggest a relatively high rate of active subsidence (Shibaoka and Smyth, 1972). Alteration of plant material to vitrinite requires anaerobic, reducing conditions with a low pH (Francis, 1961). Such conditions are maintained when the swamp is covered by a moderately high (1 - 1½ meters) stagnating water level (Stach, et. al., 1975). Because forest moor environments promote relatively continuous and rapid accumulation of peat, the groundwater level must steadily rise in order to keep abreast of peat formation. Thin layers of trimacerite and durite, which form subaquatically with increasing oxygenation, record minor periods of a relatively higher water level brought about by an influx of fresh water (Francis, 1961; Stach, et. al., 1975). A too rapid rise in the water level interrupts

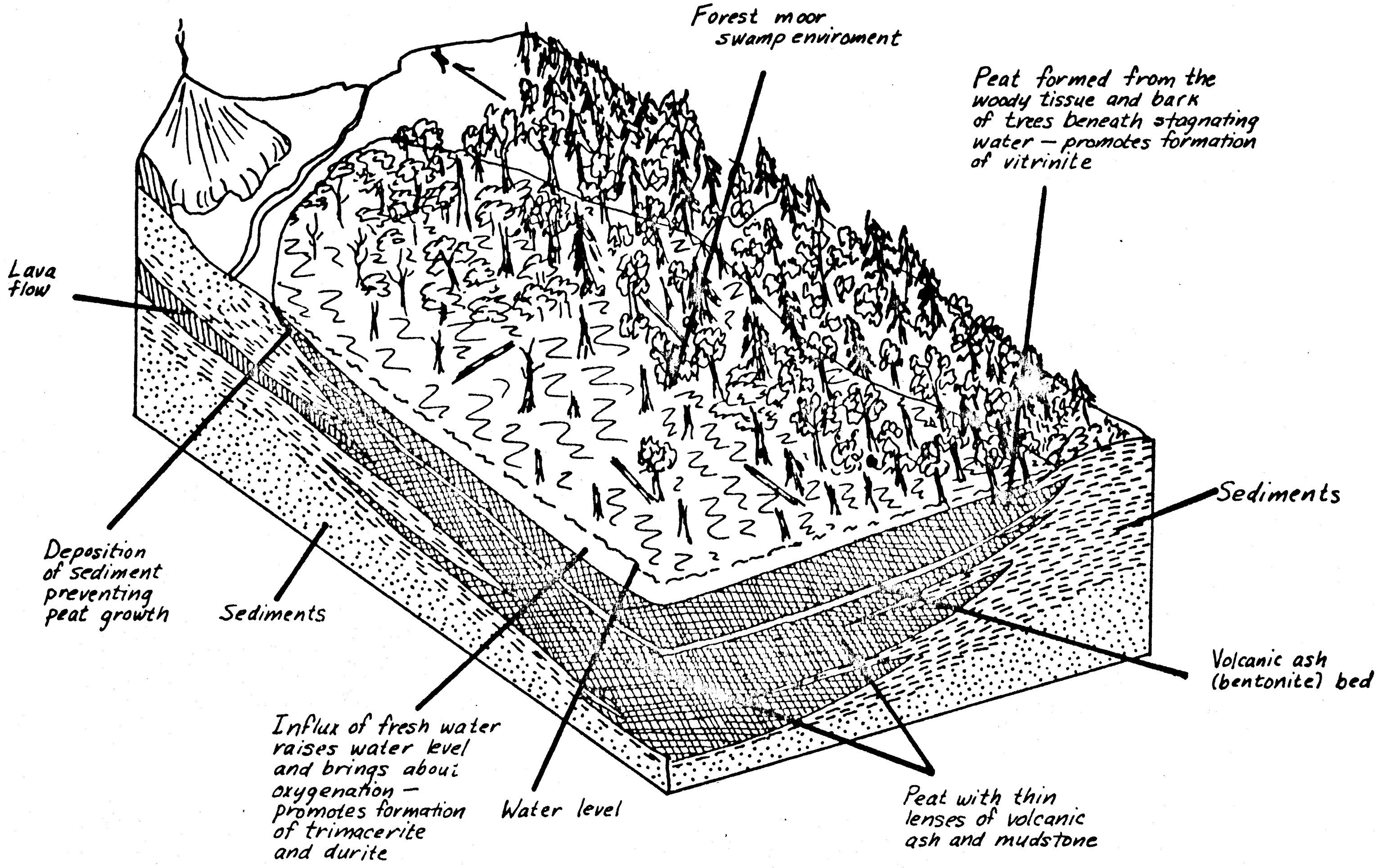


Figure 40. Schematic block diagram of the main seam peat formation in the Tulameen forest moor swamp environment (not to scale).

peat deposition and brings about inorganic sedimentation. Thickness of partings is roughly proportional to the duration of the interruption in peat formation (Falini, 1965). Thin partings in the Tulameen coal indicate short interruptions brought about by small scale flooding. The thick interval of sediments between the lower and main coal seams represents a thick clastic incursion which interrupted peat formation for a long period of time. The lower seam may represent a major split in the main coal seam.

Some tectonic control over subsidence is suggested by the presence of active volcanism. The greater abundance of volcanically derived partings in the northern part of the field area suggests a volcanic source lay north of the basin.

Shale and mudstone partings represent an inwashing of detritus during periods of flooding. Kaolinite, which forms a large percent of the sediments, may have been deposited as a detrital sediment that remained unaltered after deposition (Jansa, 1972) or it may have been deposited as a different material that later was altered to kaolinite by interaction with humic acids (Staub and Cohen, 1978). Montmorillonite also occurs in the same coal seam as the kaolinite. Montmorillonite is an alteration product of volcanic ash which requires an alkaline environment for stability (Keller, 1956; Millot, 1970). Because of the nearly monomineralic nature of the bentonites, the presence of montmorillonite could be explained by instantaneous deposition of an ash fall followed by rapid settling which would isolate the particles from the acidic swamp environment and effectually remove them from the chemical system. The glassy tephra would be altered to montmorillonite after deposition

(Pevear, personal communication). The fact that montmorillonite was not altered to another mineral and coexists with kaolinite in many samples suggests that kaolinite was directly deposited into the swamp rather than forming in place. Kaolinite is a common product of intense weathering in warm to subtropical continental environments and its presence seems to be a general characteristic of a large number of western North American Eocene sediments and coal deposits (Murray and Patterson, 1975). Hopkins (1966) reports a thick kaolinite zone from the Upper Eocene Huntingdon Formation on Sumas Mountain which has been interpreted by Horton (1978) as representing detrital kaolinite brought into the basin as a result of intense weathering. Nearly monomineralic bentonite beds are interpreted as ash falls with minimum reworking, whereas shaly partings containing kaolinite and admixtures of kaolinite and montmorillonite are considered to be reworked kaolinite derived by erosion of low-lying intensely weathered areas.

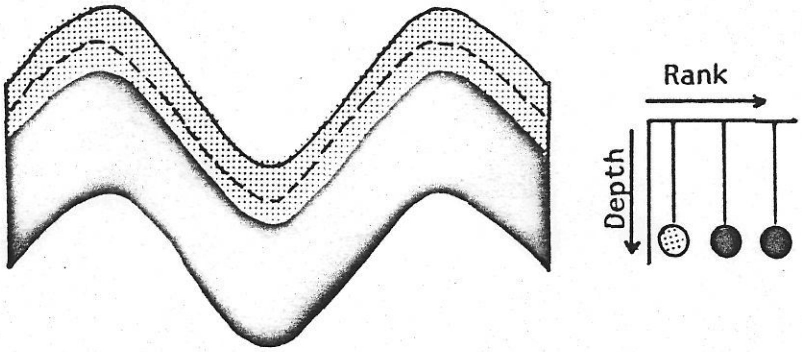
The presence of montmorillonite defines the upper coalification limit of the Tulameen coal. Modifications in clay mineralogy are closely associated with progressive stages of geochemical coalification. Kisch (1968) correlates coal rank and burial-metamorphic mineral facies in terrigenic rocks. Montmorillonite occurs in high volatile bituminous coals and disappears during late diagensis in lower volatile bituminous coals. The degree of coalification is mainly a function of time and temperature (Kaplan, 1971).

Results from the study of Tulameen coal rank show a gradual increase in rank from High Volatile C Bituminous in the northwestern half of the field area to High Volatile B/A Bituminous in the southeastern portion. One possible interpretation for the increase in rank places the Blakeburn open pit area nearer to the center of the coal-forming basin based on the apparent greater thickness of the coal and the presence of fewer partings there in comparison to the northern part of the field area. Using such a model, Donaldson (1973) considered the Blakeburn area as the center and interpreted the higher rank as a result of greater depth of burial in conjunction with an abnormally high geothermal gradient.caused by volcanic activity in the area.

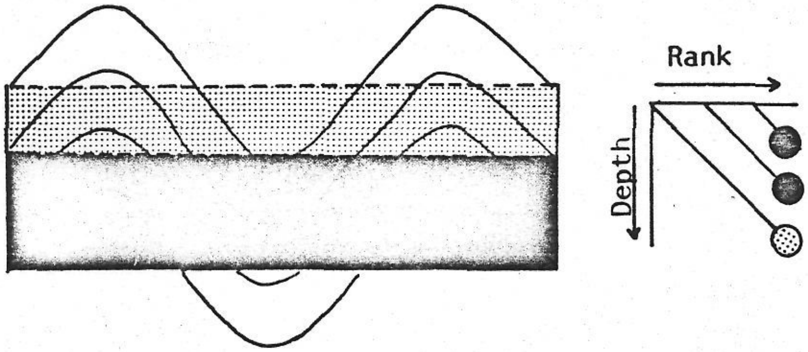
A second possible interpretation for the increase in rank might be the emplacement of an igneous intrusion to the north or east of OP-1. This intrusion would have to be relatively large because the zone of contact metamorphism is highly dependent upon the size of the intrusion (Chakrabarti, 1969; Stach, et. al., 1975). Mining reports on underground workings in the Blakeburn area mention encountering a dike occupying a large fault zone, however, no details on the size, lithology or source of the dike were included (Shaw, 1952).

A deformation model for explaining the increase in coalification is a third possible interpretation. Figure 41 shows the relationship between major bedding planes and isorank lines in three different coalification situations (Pearson and Grieve, 1977). In coalification that occurs prior to folding, isoranks and major bedding planes are parallel. Rank increases vertically with depth and not down dip. Coalification is related to the original depth of burial that existed after deposition but before folding (Hacquebard and Donaldson, 1970). Post-folding coalification, on the other hand, is related to the maximum depth of burial after deformation. Isorank lines are horizontal

A. Coalification All Pre Folding



B. Coalification All Post Folding



C. Coalification Pre Folding and Post Folding

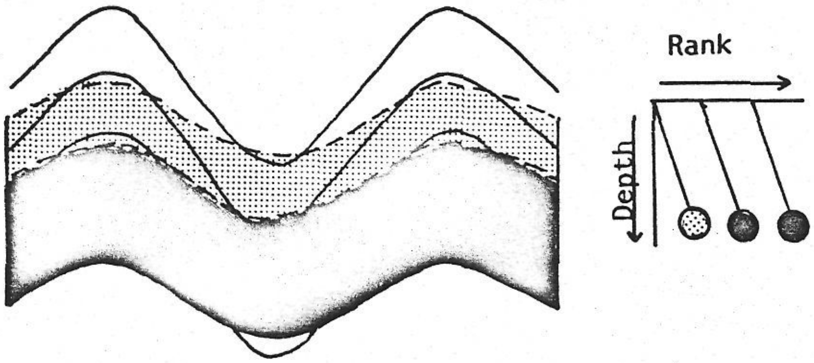


Figure 41. Diagram showing possible configurations between coalification planes (dashed lines) and coal seams in relation to deformation (Pearson and Grieve, 1977).

and rank increases down dip with depth. When postfolding is superimposed on prefolding coalification, isorank lines lie obliquely to major bedding planes (Hacquebard and Donaldson, 1974; Stach, 1975; Pearson and Grieve, 1977). The Tulameen coal deposition basin was folded and tilted prior to deposition of the Miocene volcanics. Although the increase in coal rank follows strike along the southwest limb of the Tulameen basin from northwest to southeast, it parallels the down dip direction of the plunging fold axis. The southern part of the basin, therefore, had a greater maximum depth of burial which suggests some degree of postdeformational influence on coalification.

CONCLUSIONS

The Tulameen Coalfield has a fluvial-lacustrine origin. Fluvial sedimentation was probably controlled by regional north-south block faulting. The coal forming basin developed in a poorly drained, fairly low-lying area near an elevated upland. A warm, moist climate favored formation of a forest moor swamp environment. A relatively high water level and continuous subsidence brought about anaerobic reducing conditions favorable for peat growth. Periodic flooding and active volcanism brought inorganic material into the swamp. With time, biological and physical chemical processes altered the peat into coal. Coalification was partially post-deformational.

The coal is predominantly a bright, bedded coal composed primarily of vitrinite and only minor amounts of exinite and inertinite. Kaolinite and quartz are the major inorganic coal constituents. Interbedded within the coal are numerous thin montmorillonitic bentonite and kaolinite- and/or smectite-rich shale and mudstone partings. The partings not only increase in number towards the northern part of the basin but also their lithology becomes increasingly volcaniclastic.

Vitrinite reflectance measurements reveal an increase in coal rank from High Volatile C Bituminous in the north to High Volatile B/A Bituminous in the south of the field area.

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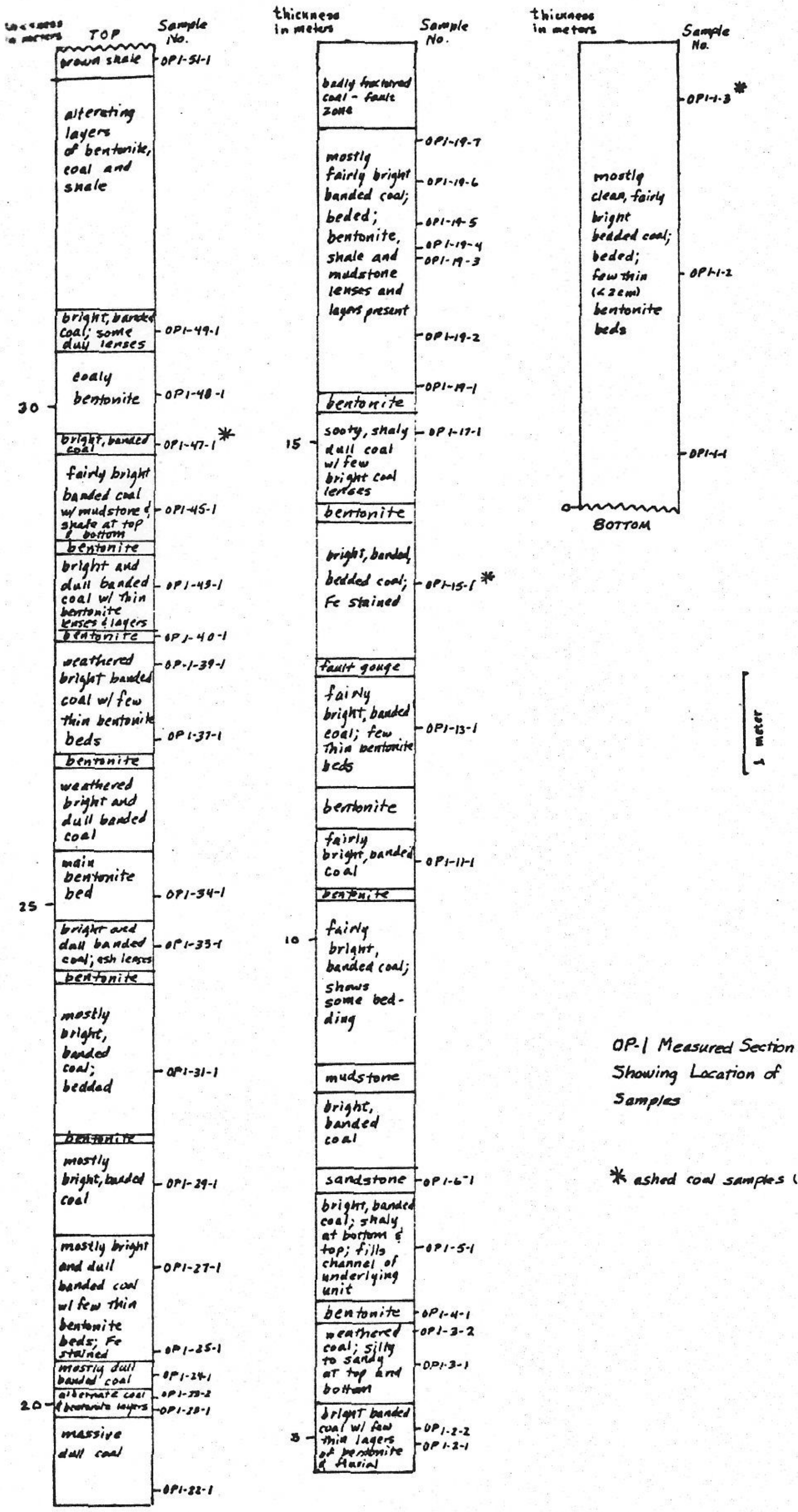
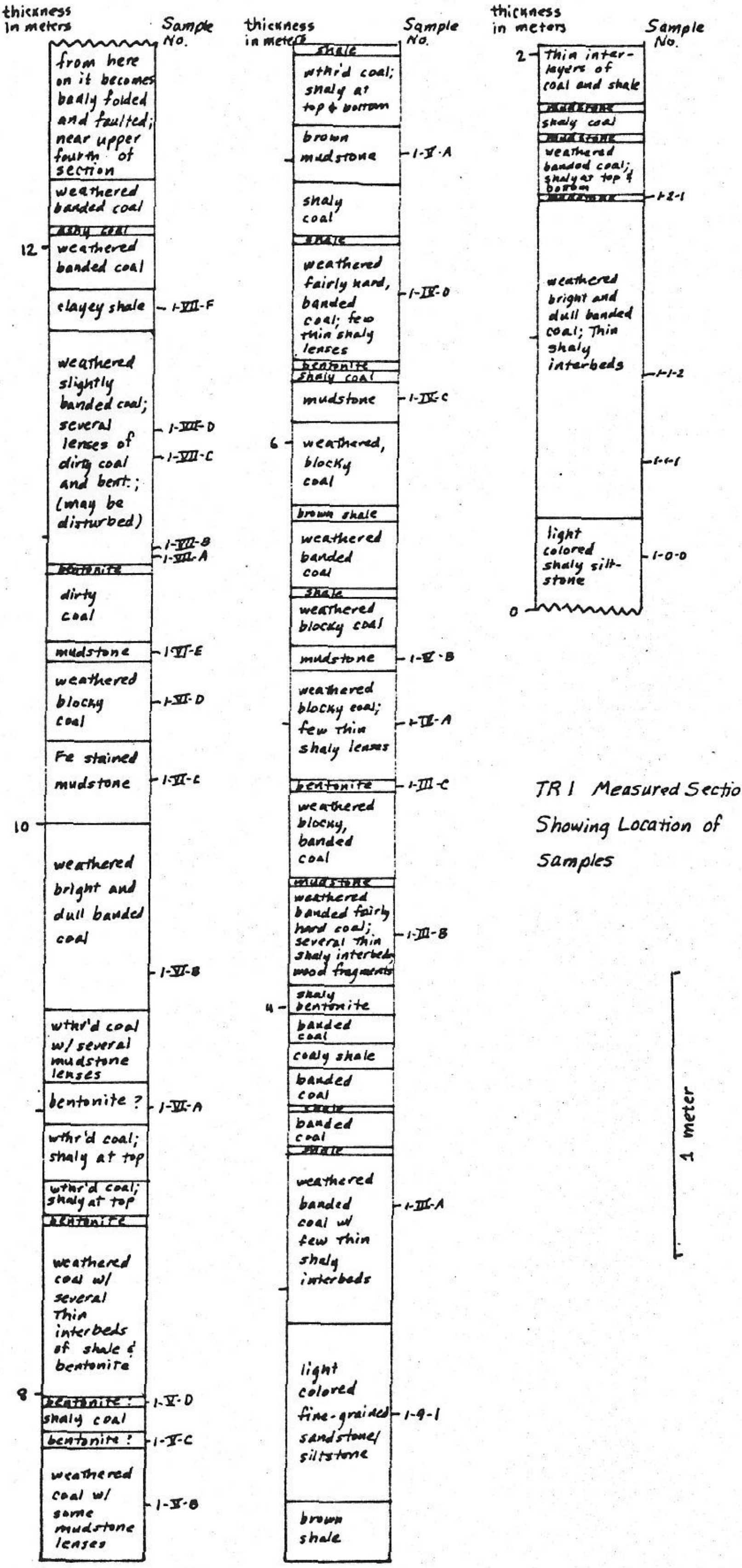
APPENDIX
OF
MEASURED SECTIONS
AND
SAMPLE LOCATIONS

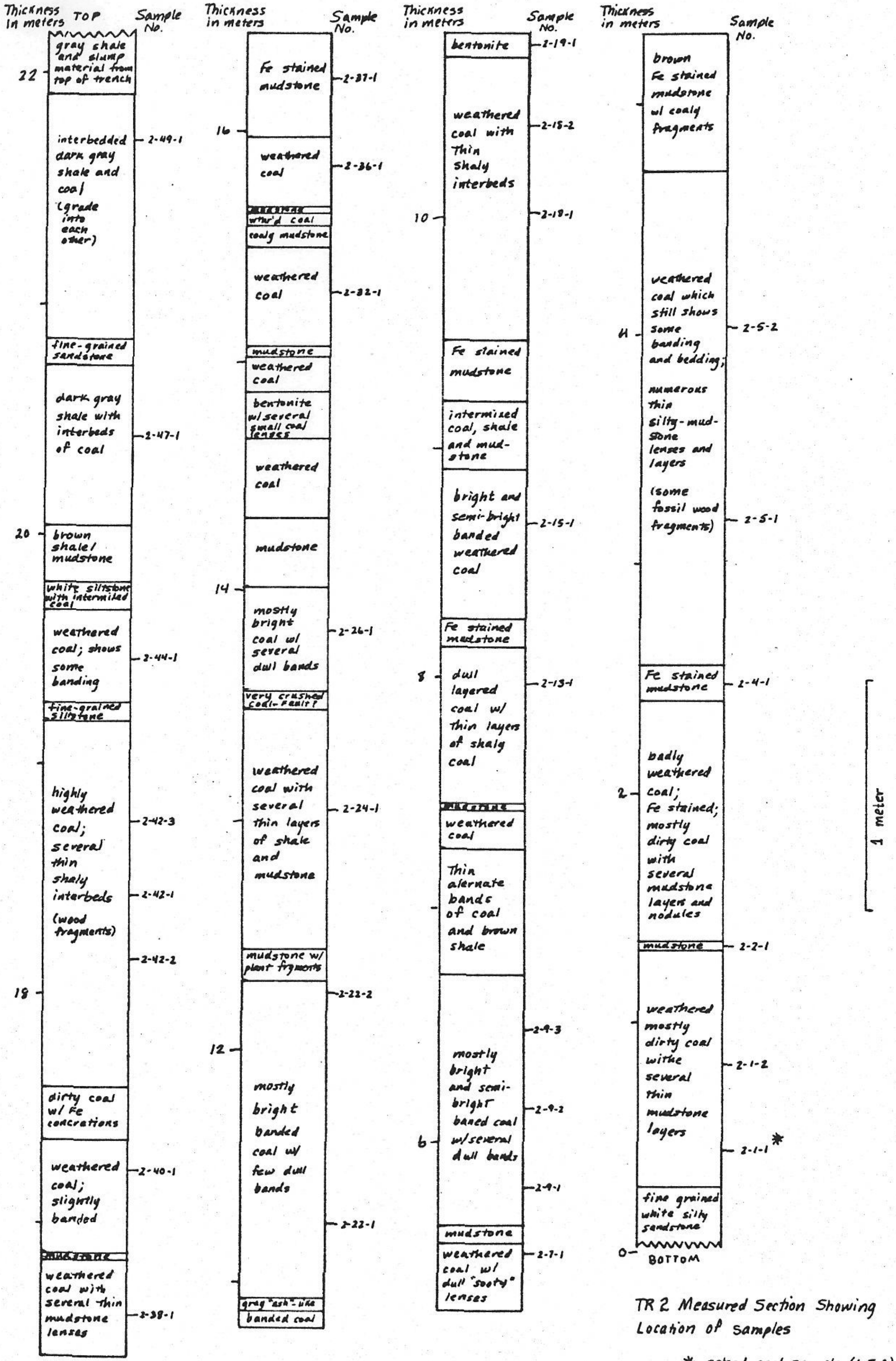


OP-1 Measured Section Showing Location of Samples

* ashed coal samples (L.T.A.)



TR I Measured Section Showing Location of Samples



TR 2 Measured Section Showing Location of samples

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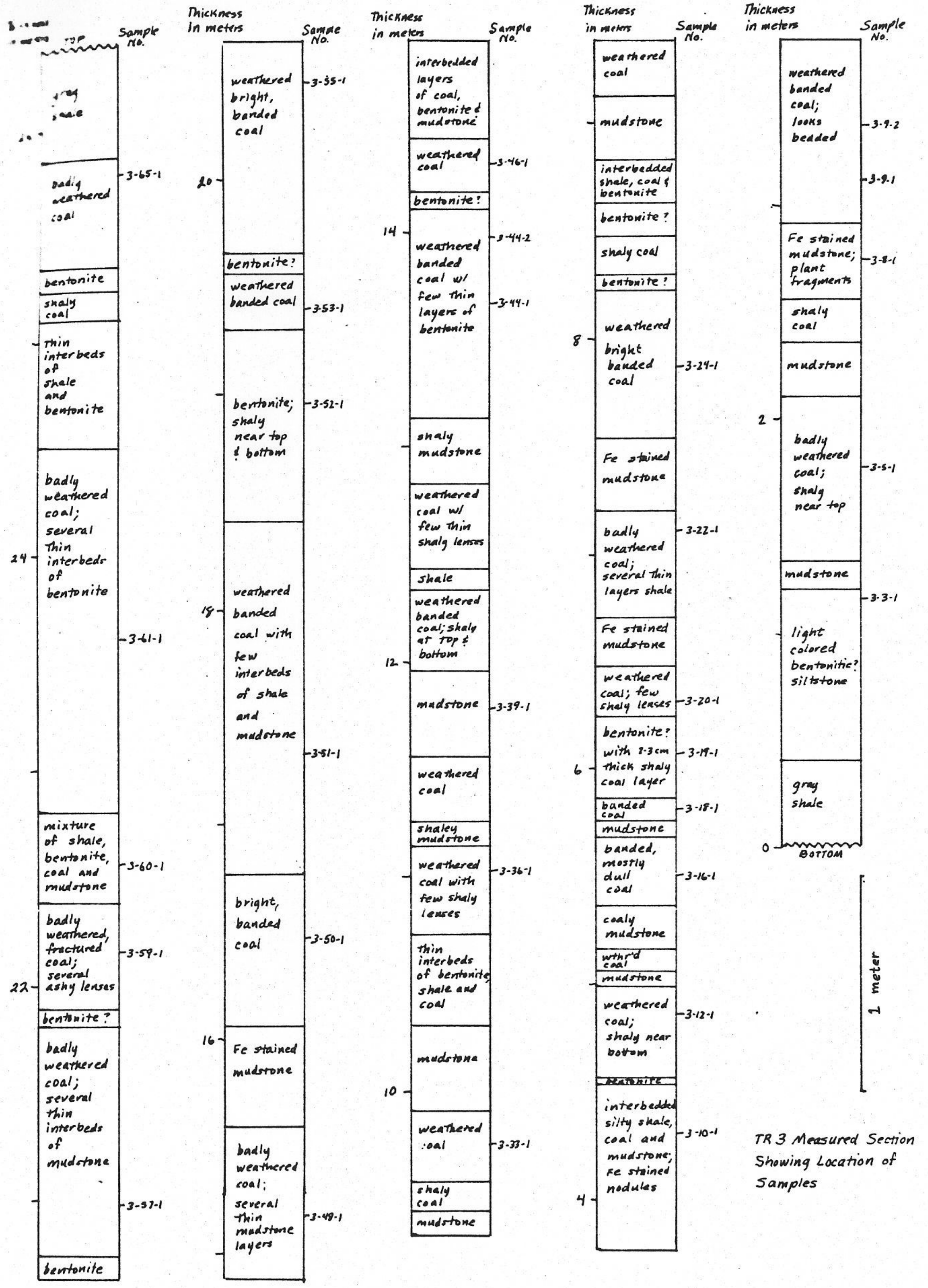

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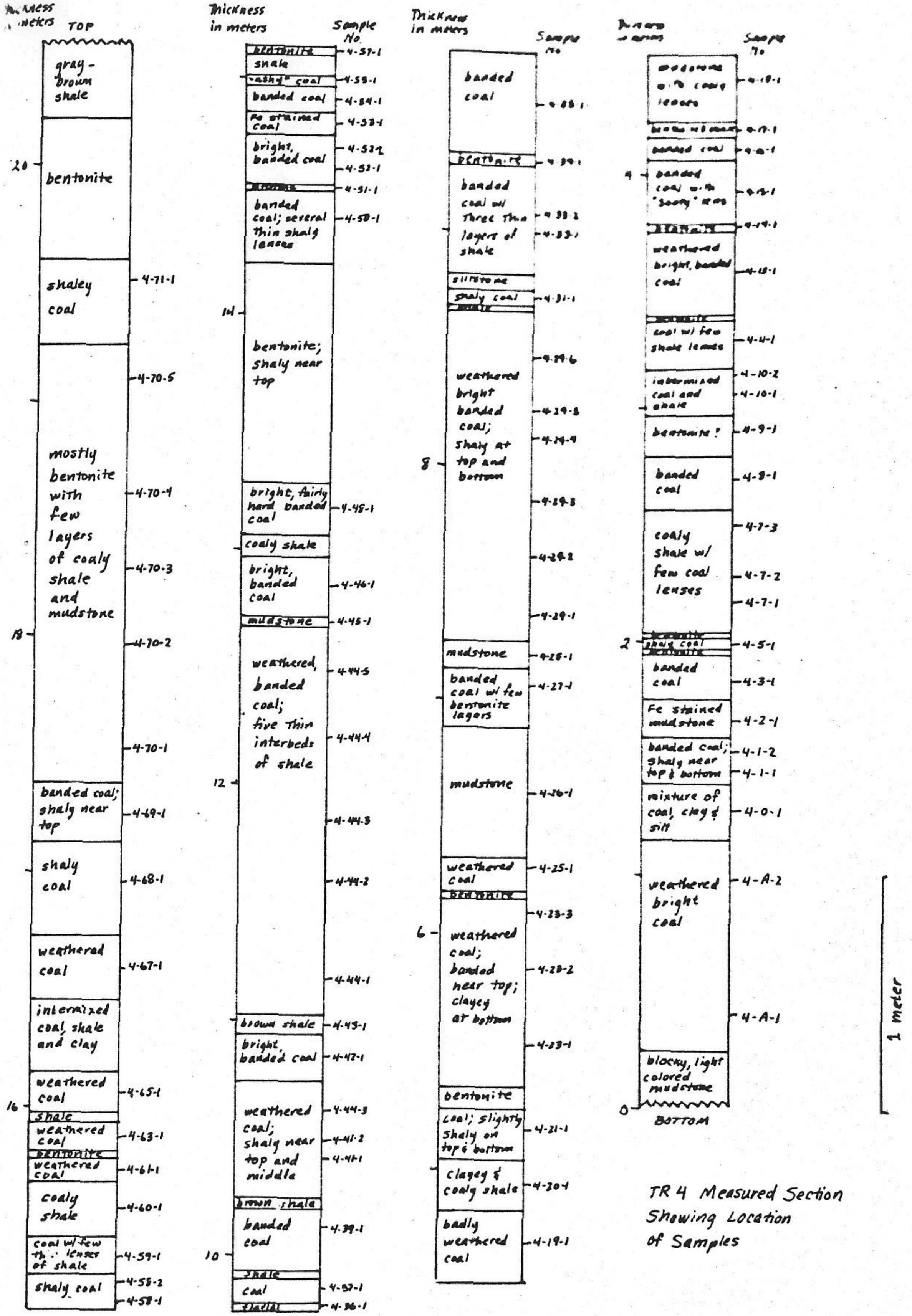

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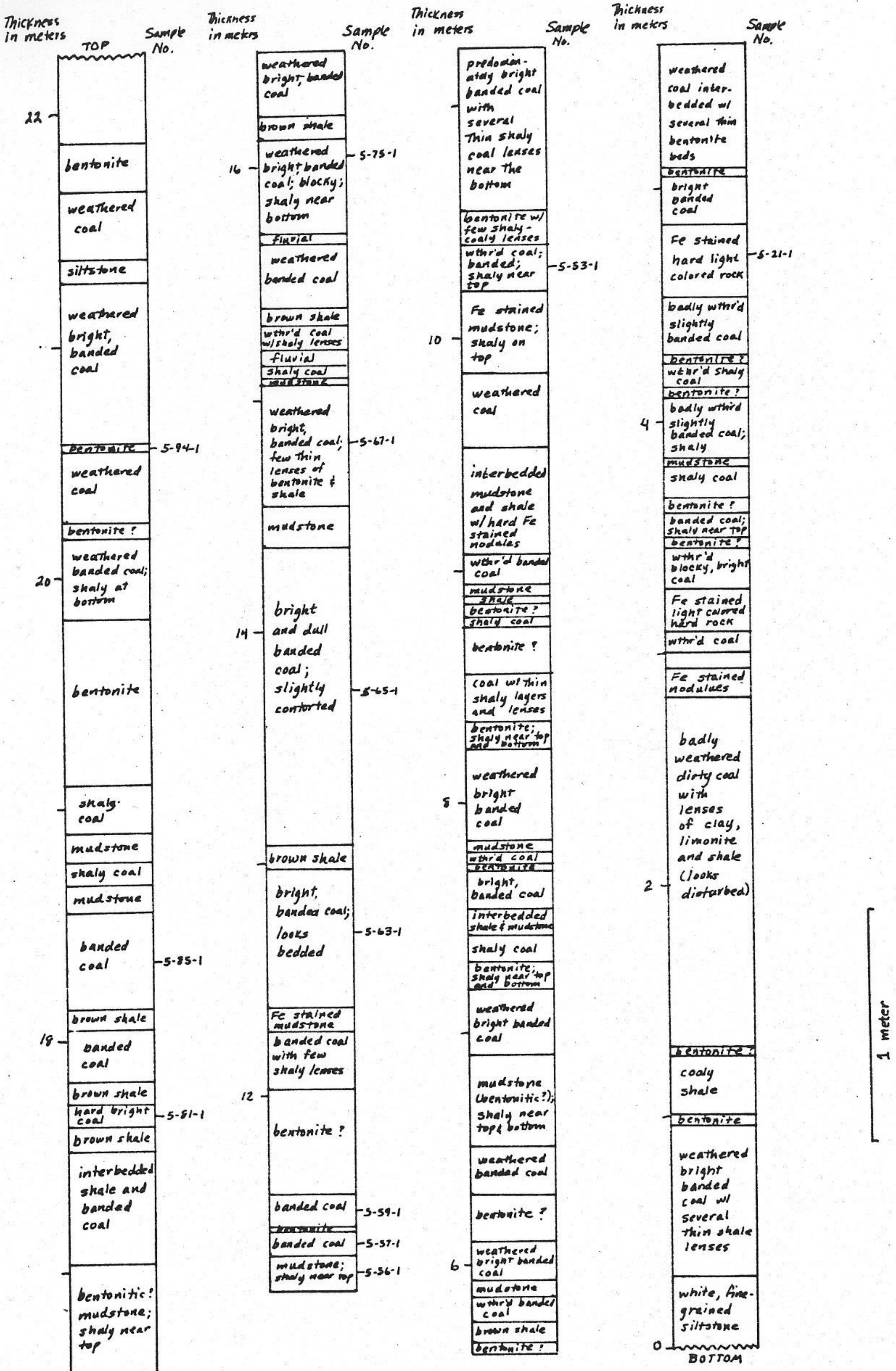
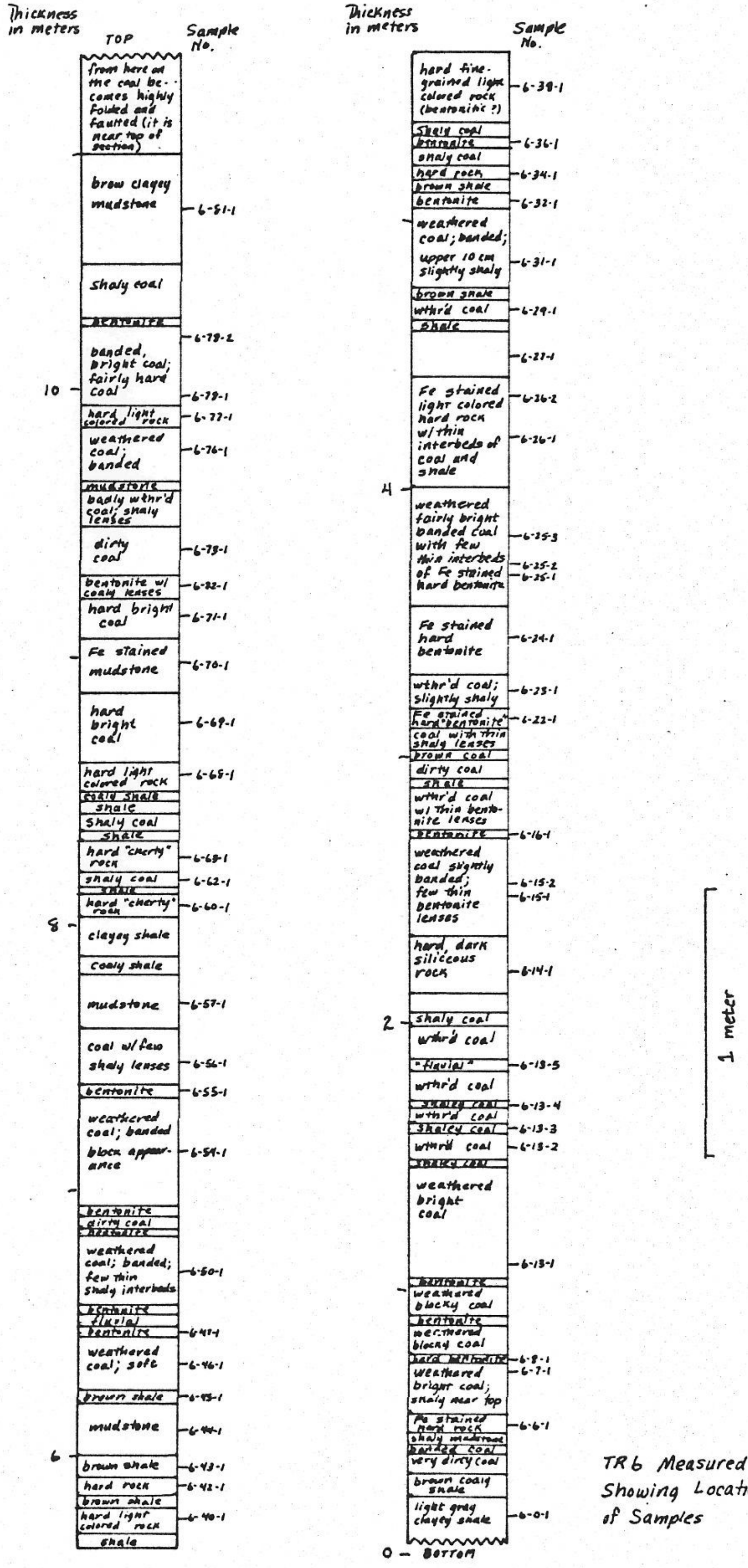


TR 5 Measured Section Showing Location of Samples



TR6 Measured Section
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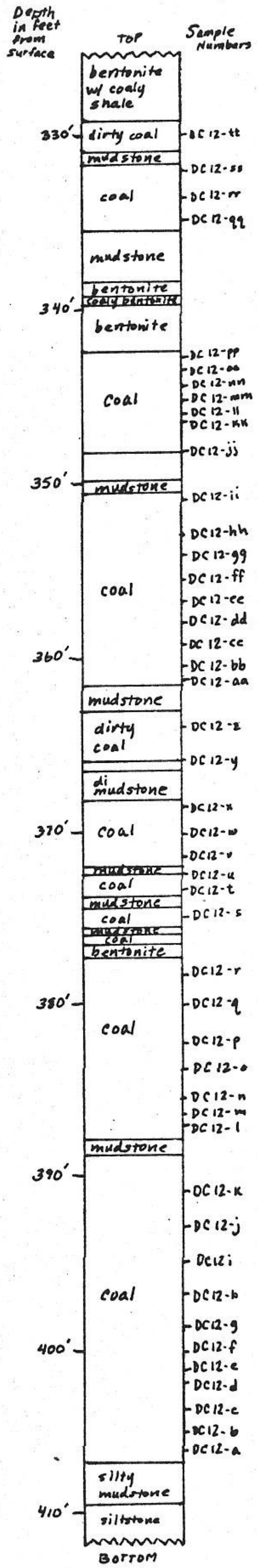
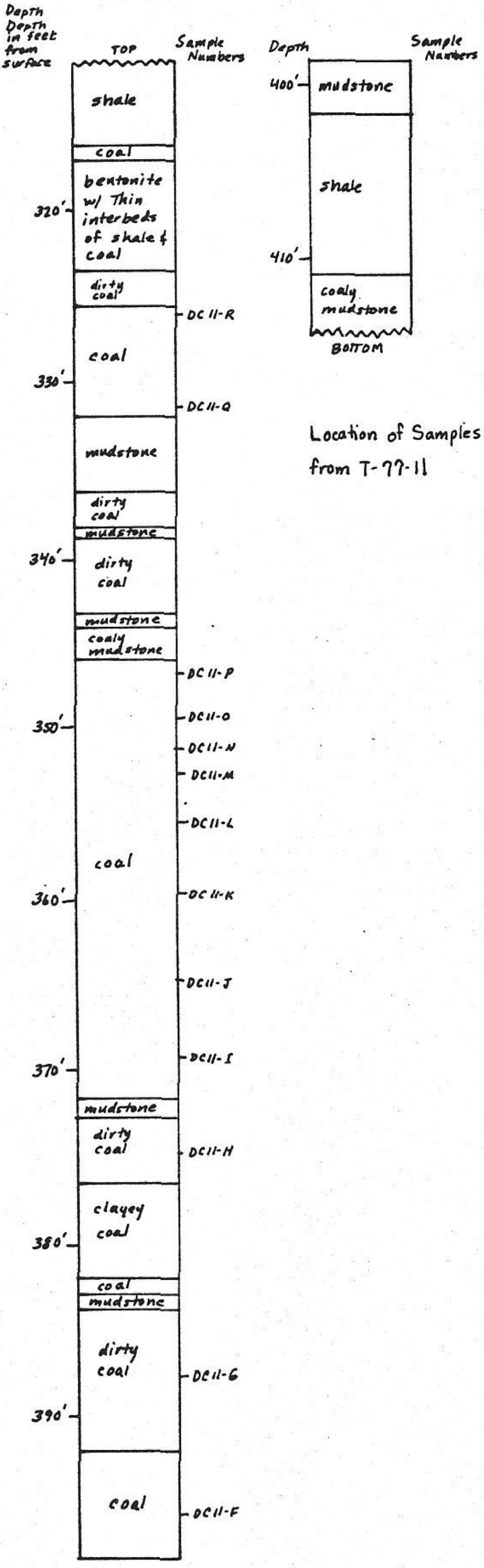
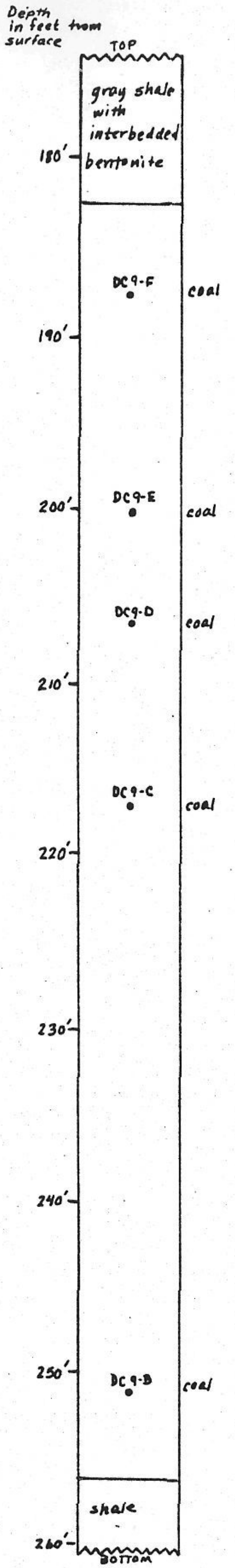


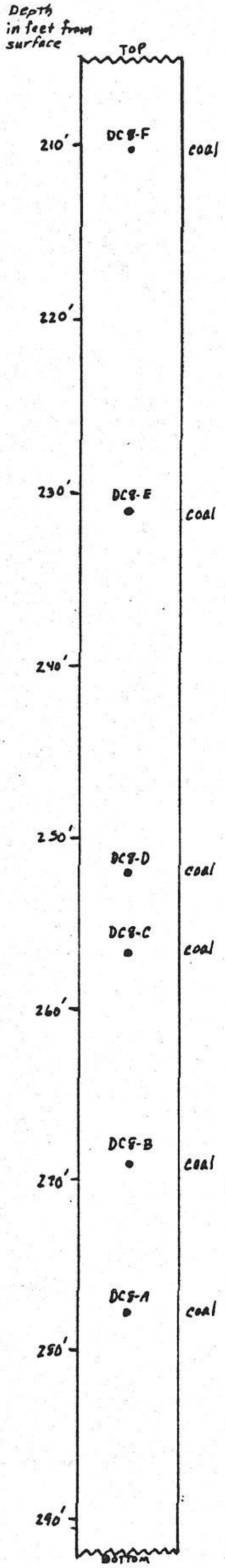
Location of Samples from T-77-12



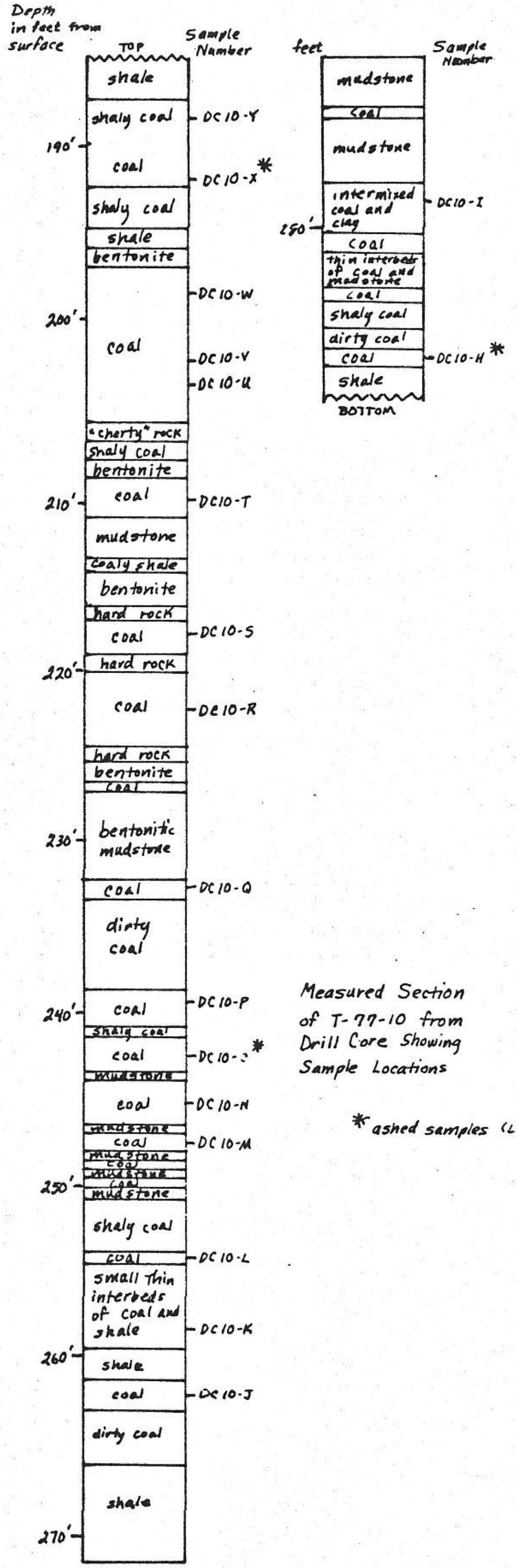
Location of Samples from T-77-11



Location of Samples from T-77-9



Location of Samples from T-77-8



Measured Section of T-77-10 from Drill Core Showing Sample Locations

* ashed samples (L.T.A.)

PRINCIPLES OF COAL PETROGRAPHY

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ABSTRACT

A brief description is given of the terminology and methods of coal petrography especially with reference to the maceral composition of coals. As examples of the differences in the physical properties of macerals, data from the literature are shown for density and reflectance. The former varies from less than 1.2 for exinite to more than 1.5 for fusinite in high volatile bituminous coals while the latter has a value of about 0.2 for exinite to over 5.0 for fusinite in coal of the same rank. As the rank of coal increases, differences for these properties diminish and eventually disappear. Corresponding changes in the hydrogen/carbon, oxygen/carbon ratios for the various macerals also are shown. As an example of the petrographic variation between seams, profiles are shown for two Kootenay Formation coal beds; one with a uniform distribution of macerals from roof to pavement, the other with increased amounts of inertinite toward the base. Increases in Hardgrove grindability indices are shown to be related to a decrease in exinite and an increase in vitrinite. Petrographic analysis of a size fraction series shows an enrichment of vitrinite in the finest fraction. The relationship of coal petrography to coke strength (stability factor) is discussed in some detail. The Schapiro and Gray method for predicting stability factors from petrography appears to be less sensitive for western Canadian coals than for Appalachian coals which may be related to the large amounts of semi-inertinite in the former. A modified stability prediction approach, using the data from a limited number of samples, incorporating elements of the Bethlehem Steel method and considering semi-inertinite as reactive, produced somewhat better correlation between predicted and actual stabilities.

INTRODUCTION

The petrographic composition of coal can be expressed in terms of macerals and microlithotypes. Macerals are the basic constituents of coal and are analogous to the minerals of inorganic rocks. Microlithotypes are distinctive assemblages of macerals and may be considered equivalent to the rock types of inorganic petrology. A microlithotype analysis is useful in giving textural information on the nature of coal as an addition to the overall compositional picture shown by a maceral analysis. For detailed descriptions and conceptual discussions of macerals and microlithotypes the reader is referred to the International Handbook of Coal Petrology and its supplement(1) and to the work of Spackman(2) and Stach(3). This paper will be confined to macerals with discussion of their physical and chemical properties and technological behaviour.

PETROGRAPHIC CLASSIFICATION

Table 1 is a summary of the maceral terms used for bituminous coal. It is not necessary to elaborate on the rather bewildering array of names listed in the macerals column as these have been described in detail in the above mentioned publications. The most important terms are those of the group macerals, namely vitrinite, exinite and inertinite. Individual macerals within these groups will be mentioned and described where necessary. Photomicrographs of a number of macerals are shown in Plate 1.

Vitrinite is the coalified remains of a variety of plant tissues with a large contribution from wood and bark. It normally is the most abundant constituent in coal. In reflected light microscopy vitrinite ranges in colour from dark grey to white depending on rank; it may or may not show cell structure. Exinite comprises a group of macerals derived from spore and pollen grains, cuticles, resins and algae. The exinite macerals are charac-

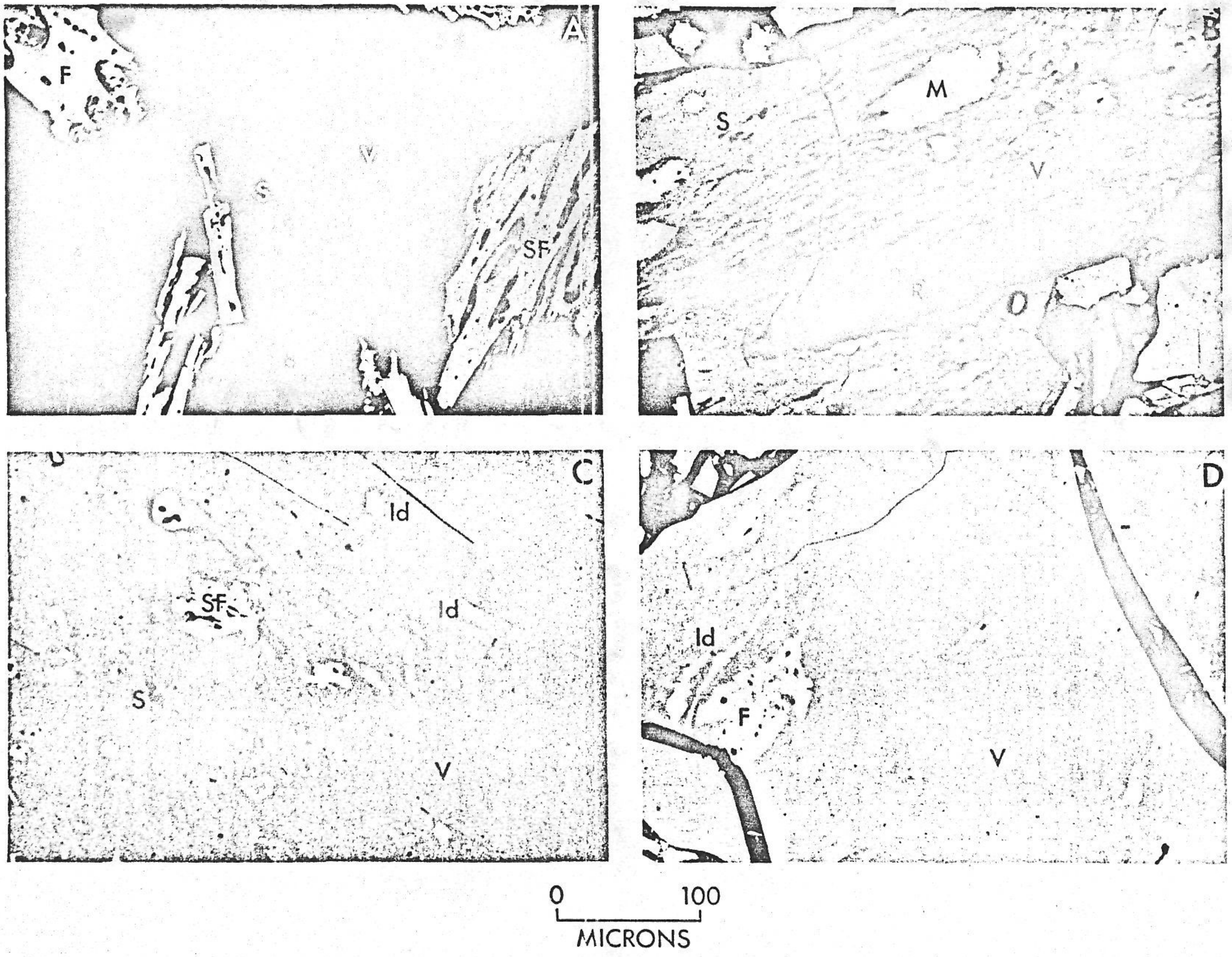
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PLATE I

This plate shows four microphotographs representing four different ranks of Cretaceous coals from western Canada. The plate illustrates two things: 1. Typical photos of the common macerals in coal; 2. The change in reflectance of some of these macerals with increase in rank.

A. Subbituminous coal, Drumheller area, Alberta. Four macerals are depicted. Fusinite (F) with high reflectance and remnants of cell structure; semifusinite (SF) also showing cell structure but with lower reflectance than fusinite; vitrinite (V) dark grey groundmass which constitutes a very large proportion of the particle in the center of the photo; sporinite (S) dark grey, almost black body embedded in the vitrinite matrix.

B. High volatile A bituminous coal; "C" seam, Michel, British Columbia. Four macerals may be singled out: vitrinite (V) forming the groundmass of the particle shown; sporinite (S) thin grey stringers; resinite (R) another exinite maceral occurring here as a large oblong grey body; macrinite (M) with high reflectance relative to vitrinite and no cell structure.

C. Medium volatile bituminous coal; "A" seam, Michel, British Columbia. The maceral vitrinite (V) is again the most abundant constituent; sporinite (S) occurs as small grey bodies; semifusinite (SF) with cell structure and relatively low reflectance; inertodetrinite (Id) which is another component of inertinite is exemplified here by the small (< 15 microns) angular fragments with high reflectance. Small granules (1-2 microns) with high reflectance scattered throughout the coal would be identified as micrinite.

D. Semi-anthracite coal; Wilson seam, Canmore, Alberta. Vitrinite (V), fusinite (F) and inertodetrinite (Id) are shown.

Regarding the influence of rank on the characteristics of some of these macerals note the increasing reflectance of vitrinite from the deeper grey of the low rank subbituminous coal through the intermediate ranks to the light grey in semi-anthracite. Note also the increasing reflectance of the sporinite from the dark grey in the subbituminous coal to the lighter grey in the medium volatile coal and its absence in semi-anthracite. In this latter rank the reflectance of the sporinite is about the same as that of the vitrinite and it is not possible to distinguish these two macerals from one another. It should also be noted that in all these ranks inertinite macerals such as fusinite show little variation in reflectance.

terized normally by distinctive morphographic features and colour which, in reflected light, ranges from very dark grey to white. In most bituminous coals, except those of higher rank, exinite is darker than the associated vitrinite. The inertinite group of macerals have the common characteristic of having higher reflectance than the associated vitrinite. They are carbon-rich, hydrogen-poor materials derived from a wide variety of plant components. In effect, they may be much higher in "rank" than the vitrinite and exinite with which they are associated and this difference in their chemical and physical properties is due mainly to varying conditions of degradation in the peat swamp and to post-burial changes in the peat and low rank coal.

Table 1.

Nomenclature and classification of macerals present in subbituminous and bituminous coals

Group Maceral	Maceral
Vitrinite	Telinite Collinite Vitrodetrinite
Exinite	Sporinite Cutinite Resinite Alginite Liptodetrinite
Inertinite	Micrinite Macrinite Semifusinite Fusinite Inertodetrinite

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Some of the inertinite macerals, especially semifusinite, are transitional between vitrinite and true inertinite and may be more reactive in technological processes than the latter.

Because of the much greater diversity of petrographic characteristics, including structures and texture, to be seen in lignites, another classification system of macerals has been developed to take this into account. This system incorporates an expansion in the terminology used for the precursors of the vitrinite maceral group, designated in lignites as huminite. A great deal of emphasis also is put on the fluorescence properties of the exinite macerals as an identification parameter. The system is described in detail in the Supplement to the ICCP Handbook(1).

MICROSCOPIC METHODS OF COAL EVALUATION

The microscope is the principal tool of the coal petrologist. It is used for determination of macerals and microlithotypes and, in addition, for the evaluation of rank, for measuring fluorescence properties of coal constituents and for determination of microhardness.

Rank is obtained by the measurement of reflectance. The technique is based on the fact that as the rank of coal increases so does reflectance. It is a precise method of determining rank and has the advantage that it can be done on one component, namely vitrinite. The method, equipment and some of the uses of this kind of information have been described in a number of publications(4,5,6 and 7). The fluorescence properties of coal constituents, especially in lignites, appear to hold much potential as an identification parameter for exinite macerals and bitumin-like materials. Special light and measuring equipment are required. The procedure and equipment have been described recently by Ottenjahn, Teichmuller and Wolf(8). Yet another microscopic technique involves measurement of the microhardness of different constituents, and such measurements depend both on the nature of the constituent and the rank. Data from investigations in this area have been published by Honda and Sanada(9) and Schapiro and Gray(5).

PHYSICAL AND CHEMICAL PROPERTIES OF MACERALS

Macerals differ fróm one another in their physical properties and these differences vary according to the rank of the coal. Figures 1 and 2 illustrate this variation with respect to the properties of density and reflectance. Figure 1 is a plot of the changes in the density with increase in carbon content of fusinite, micrinite plus semifusinite, vitrinite and exinite. The familiar ASTM rank designations have been added to the diagram to allow for comparison with conventional North American rank terminology. On the diagram the maximum difference is shown in the high volatile bituminous rank, with exinite displaying a density of less than 1.2 and fusinite more than 1.5. With increase in rank the densities of the various macerals change, though not all at the same rate. There is a gradual converging until, at a carbon content in vitrinite of 95 percent, they have merged into what is essentially one value.

In Figure 2 a similar pattern is reproduced for reflectance. In this figure reflectance is plotted as a function of the carbon content of the vitrinite as well as the volatile matter of the whole coal. Two different terms appear on this figure which has been modified from a diagram by Alpern, Durand, Espitalié and Tissot(10). One of these terms is huminite which has been mentioned previously. The other is pyrofusinite describing a highly reflecting variety of fusinite thought to be formed by fire in the peat swamp. Again the extremes in reflectance are on the low rank side of the diagram, in this case on the left side of the figure where they are represented by exinite and (pyro) fusinite. With increase in carbon content the reflectances of the various macerals other than fusinite increase until they eventually merge with that of fusinite at a carbon content of 95 percent. A rather interesting phenomenon is that above this point there appears to be an inversion in reflectance relationships with fusinite being the lowest reflecting material. It should be noted also that the reflectivity of exinite merges with that of vitrinite at a carbon content of 90 percent. This occurs in the low volatile bituminous rank stage and above this point exinite can no longer be distinguished from vitrinite. Plate I shows photographically the variations in reflectance with rank.

The above described variations in the physical properties of the macerals are related to changes in their chemical compositions. Investigations on the chemical composition of macerals have been carried out in several laboratories, and results reported in a number of publications(11, 12). The results show that, in the lower ranks of coals, exinite has the highest hydrogen and volatile matter contents while inertinite macerals have the lowest. With increase in rank the differences become smaller and eventually disappear in the semi-anthracite - anthracite rank stage. This variation closely parallels the changes in density and reflectivity mentioned earlier.

These changes in chemical properties occur at varying rates for the different macerals and this is shown in Figure 3. In this diagram hydrogen-carbon ratios are plotted against oxygen-carbon ratios for different macerals. For each maceral the trend of increasing rank is from right to left but the rate of loss differs for different macerals. It is

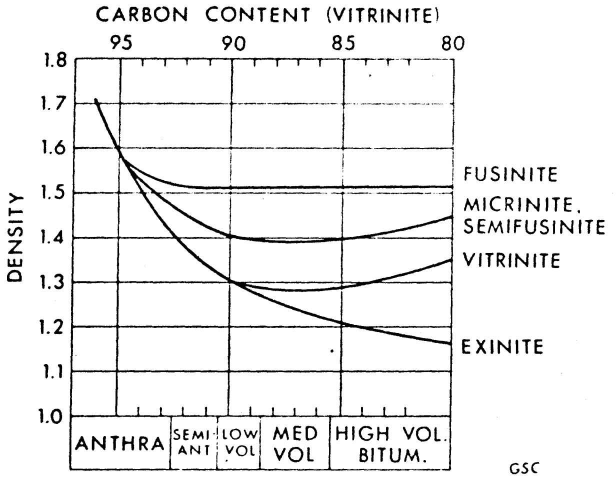

FIGURE 1. Changes in density of macerals with rank (modified from ICCP handbook(1))

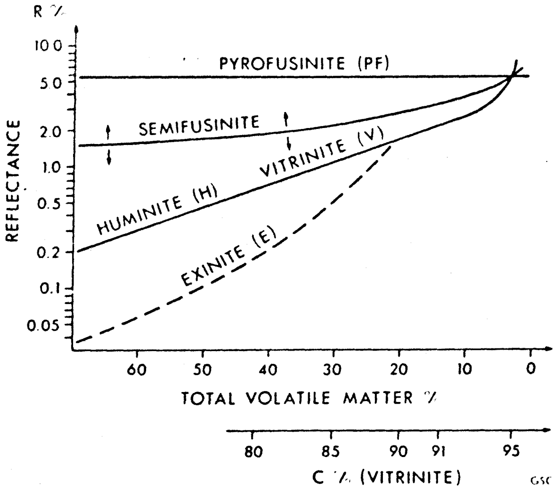

FIGURE 2. Changes in reflectance of macerals with rank (modified from Alpern, Durand, Espitalie, and Tissot (10))

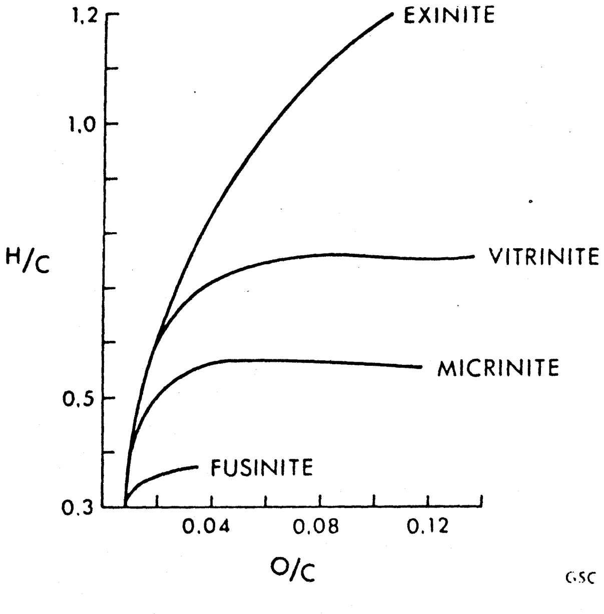

FIGURE 3. Coalification of different macerals based on H/C:O/C atomic ratios (after Dormans et al.(15) and Teichmuller and Teichmuller (14))

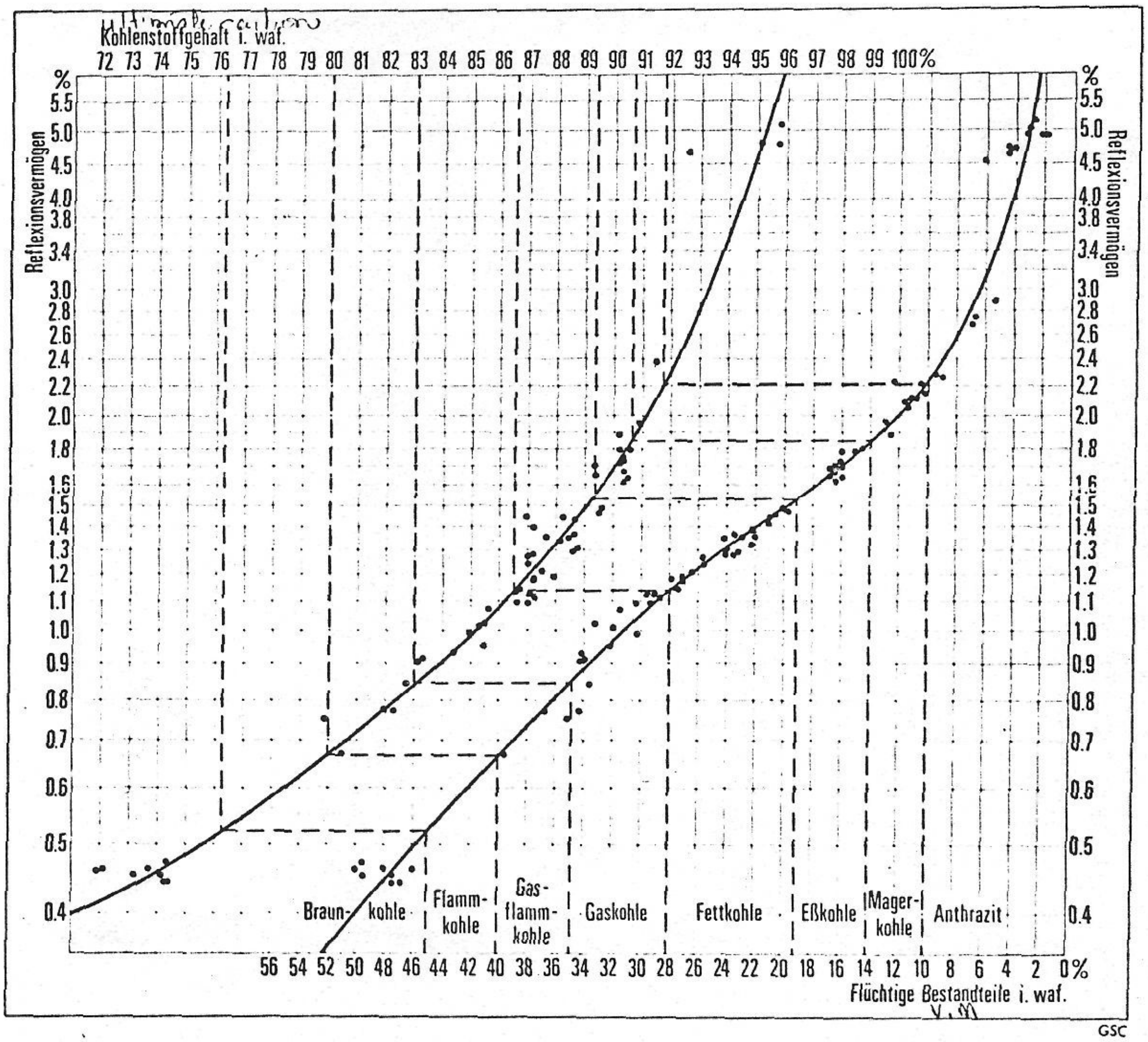

FIGURE 4. Relationship of ultimate carbon (Kohlenstoffgehalt), volatile matter (Fluchtige Bestandteile) and reflectance (Reflexionsvermogen) of vitrinite (after Kotter(13), Hacquebard and Donaldson(7))

for this reason that rank determinations based on reflectance are measured only on one component, the one used is vitrinite because it is the most abundant maceral in coal. The correlation between reflectance values and the ultimate carbon and volatile matter contents of vitrinite is shown in Figure 4, a diagram taken from Kotter(13). Reflectance is less sensitive as a rank indicator in lignites and subbituminous coals than it is in the higher rank coals. In the lower rank coals moisture content and calorific value are apparently more diagnostic(14).

MACERAL DISTRIBUTION WITHIN COAL SEAMS

Coal seams differ from one another because of differences in the depositional conditions of the original peat and differences in the post-depositional geological factors. Therefore, it is logical that the first look at how coal constituents, be they chemical elements, microlithotypes or macerals relate to one another should be within the framework of the coal seam as it occurs in the ground. Figure 5 shows how macerals are distributed in coal seams and how one seam may differ from another in this regard. Here are shown distribution profiles for two seams from the Kootenay Formation. These two seams are of approximately equal thickness and rank and are separated from one another by about 30 feet of strata. The profile for seam B is quite uniform from roof to pavement with all of the seam intervals showing an abundance of vitrinite. However, for seam A that is not the case. The basal part is characterized by a rather large content of inertinite and exinite. Differences like this can be used to distinguish one seam from another and can assist in seam correlation. In addition to the identification of individual seams by this method it is possible to define groups of seams within a certain stratigraphic interval that are characterized by distinctive petrographic traits. Thus, the seams in the bottom part of the Kootenay Formation in the Crowsnest-Elk Valley area of British Columbia and Alberta contain large amounts of inertinite in contrast to the seams in the upper part of the formation which are quite bright; that is they contain large proportions of vitrinite and relatively small amounts of inertinite(16). Such variations may be tied to other sedimentological and stratigraphic data to provide more complete interpretations of the depositional history of coal-bearing rock sequences or to evaluate the types of basins in which peat might accumulate(17). Variations in the distribution of macerals across the vertical profile of a coal seam may be reflected in the amount of energy required to actually mine the coal as was shown by Schapiro, Gray and Eusner(18). These authors showed the amount of power required to operate a continuous miner across the vertical section of a coal seam varied according to the proportions of tough and friable components. Thus dull or splinty coals which tend to be tough would require more energy than bright, vitrinite-rich coals which tend to be friable. It may be economically feasible also to mine separately petrographically dissimilar benches of a given coal seam if the different coal types are shown to have differences in their industrial behaviour. Petrographic and palynological investigations, the latter being the study of fossil spores and pollen, are sometimes carried out together to provide information on environments of deposition and on the nature of the plant assemblages which produced the original peat(19,20).

PETROGRAPHIC COMPOSITION AS RELATED TO TECHNOLOGICAL BEHAVIOUR OF COAL

a) Coal Preparation: The influence of petrographic composition on the technological behaviour of coal is to be expected in view of the differences in physical and chemical properties of macerals to which reference was made earlier. Figure 6 shows an example of the interaction of petrographic composition with what might be termed a preparation property of coal; in this case grindability as expressed by the Hardgrove index. Low Hardgrove values indicate hard, tough coals; higher values indicate softer coals. The index is rank dependant

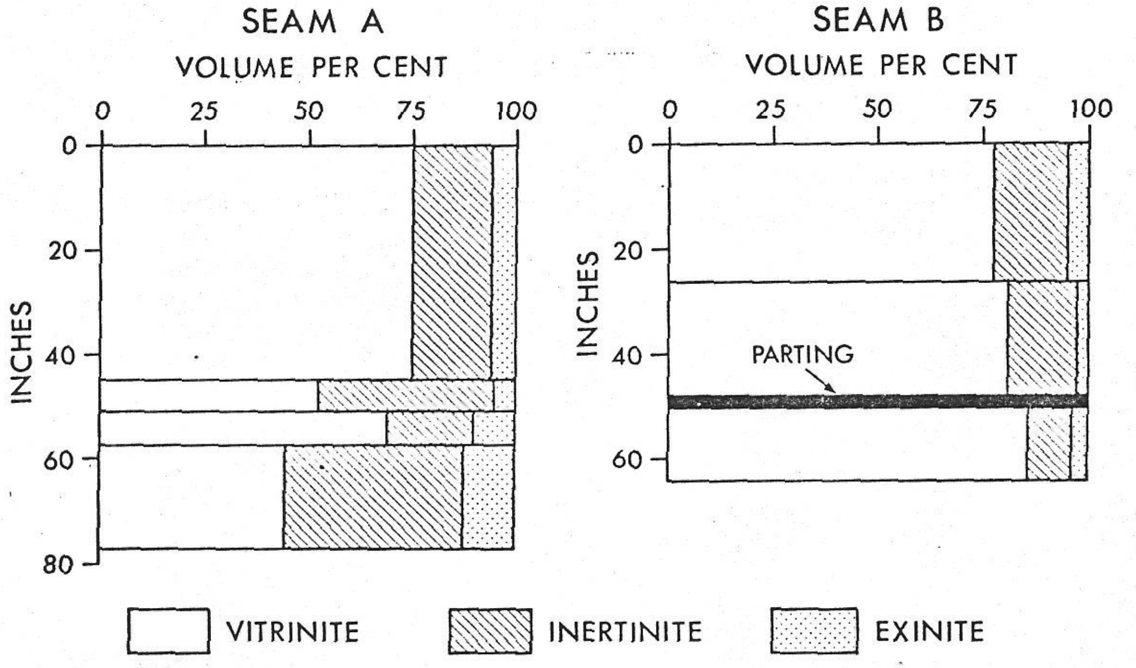

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FIGURE 5. Comparison of maceral profiles for two Kootenay Formation seams

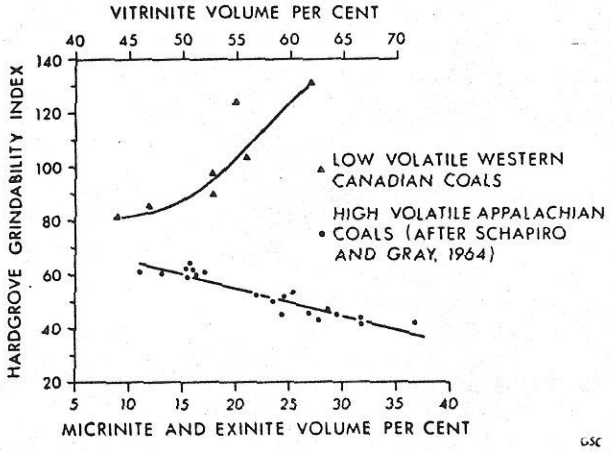

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FIGURE 6. Relationship of petrographic composition to Hardgrove Grindability Index

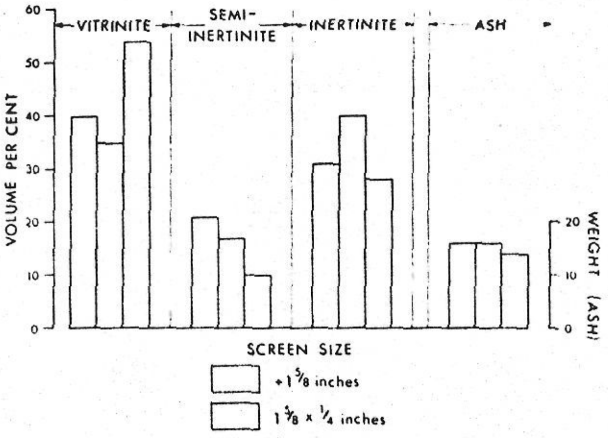

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FIGURE 7. Effect of screening on maceral distribution

but also it is influenced by petrographic composition. Two curves are plotted on this figure. One shows that for high volatile "A" bituminous coals a decrease in Hardgrove index is related to an increase in the content of the tough, non-brittle exinite materials. The other curve, plotted for a series of low volatile coals, shows that an increase in the grindability index is related to an increase in the maceral vitrinite which is a brittle material. Vitrinite may have the same effect in high volatile bituminous coals but it may be obscured by association with exinite. Fusinite which normally is a relatively fragile constituent has the same effect as vitrinite on grindability. Such relationships may be important in the solution of problems relating to the production of fines or the pulverization behaviour of a coal.

Figure 7 illustrates the effect of simple crushing and screening on maceral distribution. The coal is from the Kootenay Formation and is of low volatile bituminous rank. Three sizes are involved; plus 1-5/8 inches, 1-5/8 x 1/4 inches and 1/4 inch x 0. In the finest fraction there is obviously an enrichment in vitrinite with a decrease in combined semi-inertinite and inertinite. Enriching of certain fractions in particular macerals by such methods may be important in the selection of coals for processes such as coking where an enrichment in vitrinite might be desirable.

b) Coking: One of the important areas of applied petrographic research has been in the evaluation of coking properties, especially coke strength. Methods for predicting coke strength from the petrographic analyses of the coal have been developed in Germany(21), the Soviet Union(22), Great Britain(23), Australia(24) and the United States(17,25). The methods differ from one another in detail but they have two principles in common. One is the petrographic constituents of coal can be divided into reactive and inert components signifying their behaviour in the coke oven and the second is that the degree of reactivity varies with rank. These are referred to often simply as reactives and inerts. Vitrinite and exinite are considered reactive while the inerts include most of the macerals grouped under inertinite along with mineral matter. However there are several constituents, the main one being semi-fusinite, which are considered semi-inert and there is some disagreement as to how they should be classified for coke strength calculations. This is of special importance to us because many of our western Canadian coals have high semi-inertinite contents.

The method most used in North America for predicting the ASTM stability factor from a petrographic analysis was developed by Schapiro, Gray and Eusner at United States Steel(17). The method was based to a large extent on coking tests with Appalachian coals and with these coals it has proved quite successful. In this method the semi-inertinite is divided 1/3 to reactive and 2/3 to inerts. Also essential to the calculations are rank data based on reflectance. These are used to divide the vitrinite into so-called "V" types. The V types are identified by numbers which signify reflectance values. Thus V9 includes all the vitrinite with a reflectance of 0.90 to 0.99 percent, while V10 represents vitrinite with a reflectance of 1.00 to 1.09 percent. The number of V types in a given coal may vary from two to four or five. In the Schapiro and Gray method the other reactives are prorated according to the vitrinite V types. Ash content is of importance in the method and the authors have stated that for ash contents greater than 12 percent, stability predictions are less reliable(26).

A modification of the Schapiro and Gray method has been developed at Bethlehem Steel by Thompson and his co-workers and has been used successfully to correct many of the anomalies in strength predictions for a number of the coals used by Bethlehem(25). In the Bethlehem method a portion of the vitrinite (pseudovitrinite) is identified separately from the "normal" vitrinite. A part of the pseudovitrinite is assigned to inerts depending on the degree of difference in the reflectances of the pseudovitrinite and the normal vitrinite.

Figure 8 shows the essential relationships of the Schapiro and Gray method and has been plotted from tables of constants prepared by Bituminous Coal Research, Monroeville,

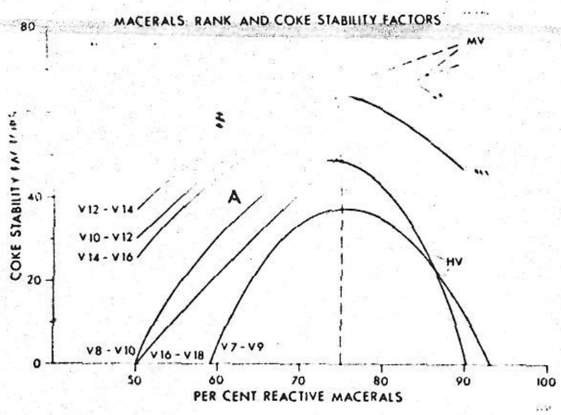

FIGURE 8. Relationship of petrographic composition and rank to coke stability

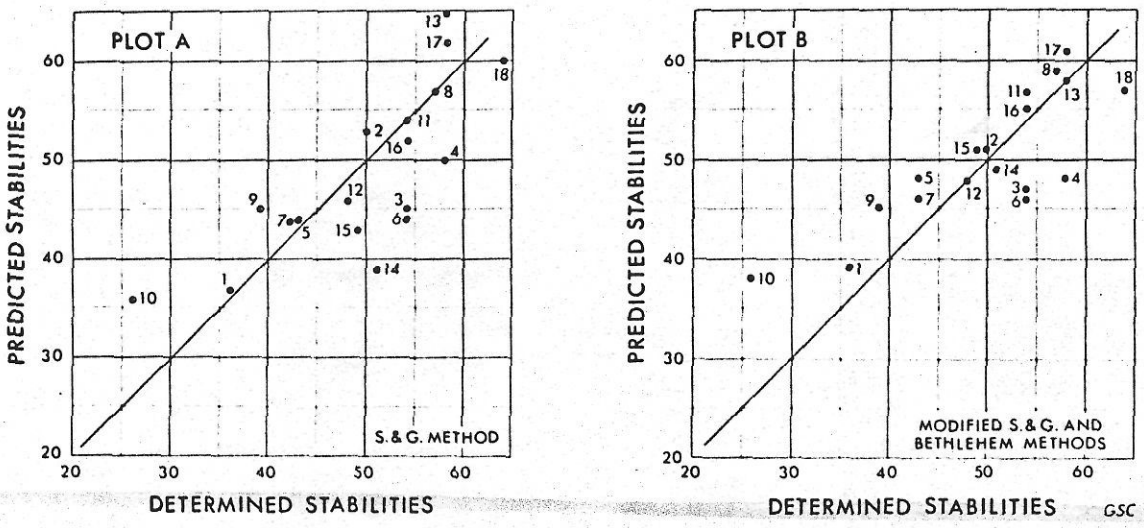

FIGURE 9. Relationship of predicted to determined stabilities by two methods

[illegible] stabilities are [illegible] and these are identified by the ASTM terms and by the "V" types which is a rank index based on reflectance. To interpret this diagram it will suffice to look at two of the curves. Curve A is plotted for a high volatile bituminous coal. It shows that for reactive contents of 50 percent the calculated stability will be 0, with increasing contents of reactives calculated stabilities increase until they reach a maximum at about 70 percent reactives. [illegible] value stabilities can be expected to decrease.

In comparison, Curve B, representing a medium volatile coal, shows a different pattern. According to the Schapiro and Gray model coals of this rank will have stabilities between 30 and 40 even with a reactive content as low as 50 percent. With increasing reactive content the stabilities will increase but unlike the high volatile coal they apparently do not peak at a certain optimum reactive level although it should be pointed out that relationships at the upper end of the curve are not clear-cut as indicated by the dashed line.

If the Schapiro and Gray method is followed this diagram tells us two important things. The first is that high volatile coals cannot be expected to attain stabilities much above 50 regardless of their reactive-inert ratio. The second is that the higher rank coals, that is the medium and low volatiles apparently can tolerate much larger ranges of inert contents and still yield coke with acceptable stabilities.

At the Geological Survey of Canada, coke stability predictions based on petrographic analyses are often made on samples collected by Survey personnel or obtained from mining companies. The Schapiro and Gray method has been used to make the predictions. Among the samples studied have been a number for which coke test data were available from the Mines Branch. These serve as a check on the correlation between calculated stability values and stabilities actually determined on the coke. The correlation between predicted and determined values is far from perfect but suggests that at least a semi-quantitative evaluation of the coking potential of these coals is possible from their petrographic composition.

Plot A of Figure 9 is a comparison of the predicted or calculated stabilities vs the values determined on the actual cokes for 18 coals, fifteen of which are from western Canada. The diagonal line represents perfect correlation between predicted and determined values; the farther the plotted points lie off the line, the greater is the discrepancy. The difference between predicted and determined values varies from 0 to 12 points for these 18 samples with a mean difference of 4.8. Compositional data for these coals are given in Table 2.

Examination of the petrographic data for these 18 coals showed trends which may be significant. The samples which showed good correlation between predicted and determined values (± 2 or less) tended to have the lowest inertinite and semi-inertinite contents. In addition the samples which gave predicted values lower than the determined values had the highest inertinite and semi-inertinite contents and the samples which gave predicted values higher than the determined stabilities tended to have higher pseudovitrinite contents. These trends suggested that some of the reactives and inerts in the Schapiro and Gray method might not be as reactive or inert as was first thought. The studies of Thompson and Benedict have suggested that a certain part of the vitrinite belongs in the inert category. B. N. Nandi(27) has expressed the opinion that some of the semi-inertinite is probably more reactive than originally supposed. With such considerations in mind the coke stabilities were recalculated for the above mentioned 18 samples and different procedures for the assignment of vitrinite and semi-inertinite were used. A part of the pseudovitrinite was included in the inerts following the procedure of Benedict and Thompson, and all of the semi-inertinite was placed in the reactives. The stability calculations were then carried out according to

Table 2. Petrographic and chemical compositions of coals used in study (stability predictions made by Schapiro and Gray method)

Sample	Volume Per Cent										Wt. Per Cent		
	"Normal" Vitrinite	Pseudo-vitrinite	Exinite	Semi-inertinite	Inertinite	Mineral Matter(1)	Total Reactives(2)	Total Inerts(3)	Predicted Stability	Determined Stability	Ash db(4)	Sulphur db	Volatile Matter db
1	46.8	6.3	8.8	2.9	32.5	2.7	62.9	37.1	37	36	4.6	0.73	34.6
2	54.1	13.3	-	6.2	22.9	3.5	69.5	30.5	53	50	6.6	0.70	18.0
3	51.5	7.8	0.2	9.4	27.9	3.2	62.6	37.4	45	54	5.8	0.37	19.8
4	45.7	14.0	-	9.1	27.6	3.6	62.7	37.3	50	58	6.5	0.42	19.8
5	63.1	9.6	8.6	2.3	12.6	3.8	82.1	17.9	44	43	6.4	1.14	35.5
6	43.4	6.7	0.1	9.9	35.3	4.6	53.5	46.5	44	54	8.3	0.35	22.2
7	60.6	6.2	3.7	3.1	21.1	5.3	71.5	28.5	44	43	9.6	0.46	28.0
8	62.4	5.8	1.0	5.1	20.7	5.0	70.9	29.1	57	57	9.0	0.39	24.4
9	52.0	7.6	-	7.2	26.4	6.8	62.0	38.0	45	39	12.5	0.32	20.3
10	51.1	4.9	0.4	6.6	30.9	6.1	58.6	41.4	36	26	11.1	0.46	19.4
11	63.5	6.4	2.0	7.6	14.6	5.9	74.4	25.6	54	54	10.6	0.69	26.9
12	66.8	10.9	1.5	3.5	13.1	4.2	80.4	19.6	46	48	7.5	0.63	29.2
13	53.4	19.7	0.3	7.0	15.6	4.0	75.7	24.3	65	58	7.2	0.56	22.2
14	38.7	8.6	1.3	15.2	32.0	4.2	53.7	46.3	39	51	7.6	0.33	22.1
15	44.2	7.1	1.8	12.0	30.1	4.8	57.1	42.9	43	49	8.6	0.56	24.5
16	62.7	13.6	2.9	4.3	12.0	4.5	80.6	19.4	52	54	7.9	0.79	26.7
17	53.0	14.4	1.3	10.8	18.4	2.1	72.3	27.7	62	58	3.7	0.29	22.4
18	49.2	14.7	0.4	10.6	20.7	4.4	67.8	32.2	60	64	8.0	0.20	21.3

1. Mineral Matter determined from ash and sulphur by Parr's formula and converted to volume percent.
2. Reactives include total vitrinite, exinite and 1/3 semi-inertinite.
3. Inerts include 2/3's semi-inertinite, inertinite and mineral matter.
4. db = dry basis.

Table 3. Petrographic parameters used for calculating stabilities by the modified Schapiro and Gray and Bethlehem methods

Sample	Mean Max. (1) R_o on total Vitrinite	Mean Max. R_o on "normal" Vitrinite	Mean Max. R_o on Pseudo-vitrinite	Volume Per Cent					Predicted Stability	Determined Stability
				Pseudo-vitrinite Content	Pseudovit. Assigned to Reactives	Pseudovit. Assigned to Inerts	Total Reactives(2)	Total Inerts(3)		
1	0.96	0.95	1.03	6.3	4.8	1.5	63.3	36.7	38	36
2	1.59	1.57	1.62	13.3	8.4	4.9	68.8	31.2	52	50
3	1.58	1.57	1.64	7.8	4.3	3.5	65.4	34.6	48	54
4	1.53	1.52	1.55	14.0	8.8	5.2	63.6	36.4	49	58
5	1.00	0.98	1.07	9.6	7.0	2.6	81.0	19.0	47	43
6	1.35	1.34	1.40	6.7	1.9	4.8	55.3	44.7	46	54
7	0.92	0.90	1.03	6.2	2.3	3.9	69.7	30.3	44	43
8	1.09	1.07	1.19	5.8	2.4	3.4	70.9	29.1	58	57
9	1.57	1.56	1.61	7.6	4.6	3.0	63.8	36.2	45	39
10	1.59	1.56	1.65	4.9	2.3	2.6	60.4	39.6	39	26
11	1.06	1.05	1.13	6.4	4.3	2.1	77.4	22.6	55	54
12	1.00	0.98	1.06	1.09	8.3	2.6	80.1	19.9	47	48
13	1.33	1.31	1.35	19.7	6.5	13.2	67.2	32.8	58	58
14	1.22	1.19	1.26	8.6	4.1	4.5	59.3	40.7	49	51
15	1.19	1.17	1.21	7.1	3.8	3.3	61.8	38.2	51	49
16	1.06	1.05	1.10	13.6	9.5	4.1	79.4	20.6	55	54
17	1.29	1.28	1.31	14.4	5.0	9.4	70.1	29.9	60	58
18	1.38	1.36	1.40	14.7	5.1	9.6	65.3	34.7	58	64

1. R_o = Per cent maximum reflectance in oil.

2. Reactives include "normal" vitrinite, exinite, total semi-inertinite and a varying proportion of the pseudovitrinite.

3. Inerts include inertinite, mineral matter and the remainder of the pseudovitrinite.

the Schapiro and Gray method with the "normal" vitrinite and exinite prorated according to the V types of the normal vitrinite and the semi-inertinite prorated according to the V types of the semifusinite. The results of the modified method are shown on Plot B of Figure 9 where again the predicted stabilities are plotted against the determined stabilities. Table 3 gives some of the data used for this calculation. The scatter about the line has been reduced to some extent and a measure of this reduction is that the mean difference between predicted and determined stabilities in Plot B is 3.7 while in Plot A it is 4.8.

Not all the factors which affect coke strength have been included in these calculations. Paramount among those not included is oxidation which is difficult to evaluate quantitatively especially in its early stages. Another factor is the effect of variations in grain sizes among coal charges and the distribution of inerts according to grain size. This may be particularly important with our western coking coals, many of which have high inert contents. Yet another factor is ash content and possibly the composition of the ash. Finally, there are the several important coking conditions such as the bulk density of the charge, the coking time and the oven width. In the Schapiro and Gray method these are assumed to be constant but they may vary from test oven to test oven and they certainly vary from test oven to commercial oven.

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Discussion

ROSS LEEDER, MINES BRANCH: I am not certain Dr. Cameron explained that coke stability is a measure of the strength of the coke produced from a particular coking coal or coal blend. I also want to ask some questions. Were the coals identified in your diagrams all Western Canadian coals, or did they also include Eastern coals?

CAMERON: All but three of the 34 coals were from Western Canada.

LEEDER: In which Mines Branch oven were those coals tested?

CAMERON: I believe most of them were tested in Ottawa at the Mines Branch.

LEEDER: But there are several ovens in Ottawa, and results might vary slightly from one oven to another.

CAMERON: That is quite possible. I suspect some of the data were obtained quite a few years ago and were probably obtained in the first oven built in Ottawa.

LEEDER: In my talk tomorrow I intend to deal with some of the factors that may cause test results to show greater scatter than would be expected. Your data may be better than you think.

RUSS HOLDEN, FOUNDATION: In your Figure (9), you presented a linear relationship. I think a curve would have been more appropriate, especially with respect to grain size.

CAMERON: The straight lines were intended to indicate a hypothetical relationship i.e. a coincidence between predicted and experimentally measured stabilities.

QUESTIONER: With respect to Figure (9), you indicated an improved method for determining coke stability and said that you assigned some vitrinite to the inerts. On what basis did you make this assignment?

CAMERON: I followed Thompson and Benedict's method which involves identifying a constituent called pseudo-vitrinite. The reflectance of this material differs slightly from the reflectance of so-called normal vitrinite. It is the pseudo-vitrinite that is assigned to the inerts.

DAVID MORRIS, ROKE OIL ENTERPRISES: I would like to ask what method you used to determine the density of the macerals and what the precision of this method is.

CAMERON: I am afraid I am rather ignorant on that point. I took the density data from the handbook on coal petrology published by the International Commission on Coal Petrology. Unfortunately, they don't define how these densities were measured.

BERKOWITZ: A partial answer to the last question might be that "true" densities of macerals as well as of "whole" coals are best measured by helium displacement in a high vacuum system and then corrected for mineral matter. The resultant values give the density of the solid substance itself. However, unless the sample is sufficiently finely comminuted before measurement even helium may not be able to penetrate into all pores, and the recorded density may be a little low.

D.S. MONTGOMERY: I have not so much a question as a comment. We too are using reflectance measurements for evaluating coking coals, but before attempting to predict a stability factor, we always measure the dilatation and often examine the semi-coke from the Ruhr dilatometer. This offers some additional insurance against going too far out on a limb on the basis of reflectance data. The fact is that oxygen plays an important role in determining the properties of vitrinite, and reflectance measurements don't tell you anything about how well the vitrinite will fuse. Only about 0.1 or 0.2% oxygen introduced by oxidizing ground waters or during exposure to air can substantially change the properties of the coal. What Dr. Cameron is really saying is that reflectance measurements can be used to predict behaviour if the coal behaves normally. If you are not sure of the state of the sample - if it is an exploration sample or something of this type you are well advised to examine other physical properties.

CAMERON: That is a very pertinent comment. I did indicate at the end that oxidation had not been taken into account and I am aware of the difficulty which it may pose. Relevant to the Ruhr dilatometer, some of the discussion in Europe this year indicated that it is possible to have poor Ruhr dilatometer measurements but the coal on which these measurements were made will still yield a fairly good coke. No one test and no one series of parameters will tell us all that we want to know.

QUESTIONER: Dr. Cameron, we have had coals that coke which show no dilatation in the Ruhr dilatometer. In fact, Dr. Beck from Germany is looking at some of our samples now to try to find out why there is no dilatation and yet the coals still coke.

I would like to ask one more question, or suggestion. Would you like to describe how a sample should be taken in the field on an exploration project so that it can be best used for the petrographic analyses.

CAMERON: Well, ideally it should be taken from a fresh face and put into an inert atmosphere of some sort as quickly as possible. With samples from an adit, the farther in (and presumably away from the oxidized zone), the greater are the values until a plateau is reached. This point is, presumably, out of the oxidized zone.