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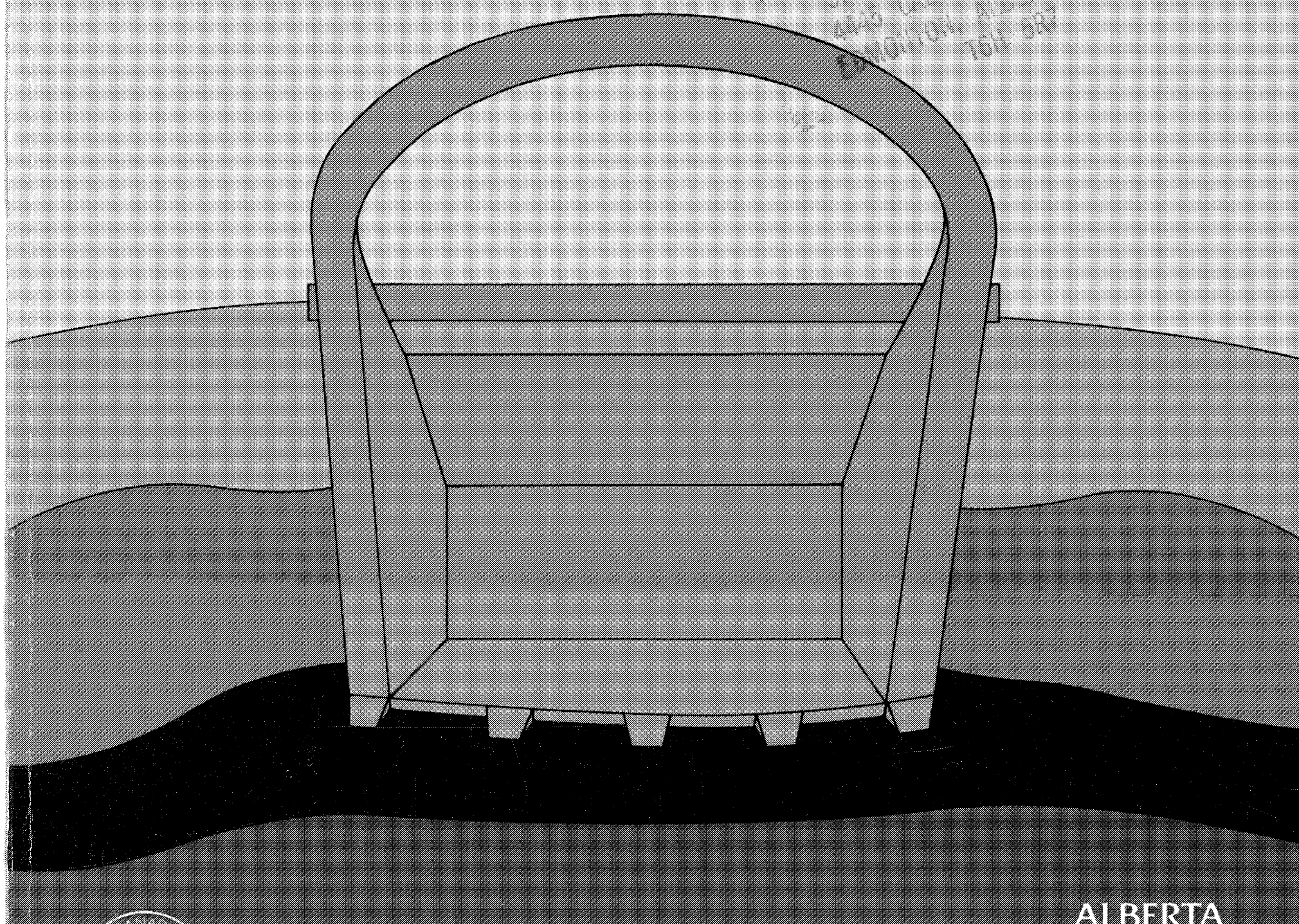
Advances in Western Canadian Coal Geoscience – Forum Proceedings



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ALBERTA RESEARCH COUNCIL

Alberta Geological Survey

Alberta Research Council Information Series No. 103

Advances in Western Canadian Coal Geoscience – Forum Proceedings

Edmonton, Alberta
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W. Langenberg

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FOREWORD

The Western Canada Coal Geoscience Forum is held periodically to exchange information on recent advances in coal geoscience. The first conference of this kind was held in Edmonton in 1971. Coal in western Canada is an important natural resource with well established, growing markets. However, proper development of this resource is dependant on a thorough understanding of the geological setting of the coal deposits and of resulting coal quality. The 1989 Forum shows how government agencies, industry and academic institutions are progressing in this understanding.

The papers published in these proceedings are the oral presentations of the technical program of the Forum. The authors were requested to submit camera-ready manuscripts and to have the papers reviewed by at least one colleague. The contents of the papers have been divided into four different themes, which are: 1) Geology of coal-bearing strata, 2) Geological controls on coal utilization, 3) Geological controls on coal composition, and 4) Geological techniques and models. These four themes constitute the four sessions of oral presentations given during the Forum. In addition, the abstracts of the posters presented during the conference are included in this volume.

The contributors to the technical program are thanked for submitting manuscripts. We believe that the proceedings give a good insight into recent advances in geoscience related to western Canadian coals. We also thank the hosting agencies for providing time, facilities and finances towards the organization of the Forum. Our corporate sponsors are acknowledged for their financial assistance. We thank Dale Hite for help in the publication of these proceedings.

Dennis Nikols — Alberta Geological Survey
Grant Smith — Geological Survey of Canada
Ward Kilby — B.C. Geological Survey Branch

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A PRELIMINARY ANALYSIS OF THE STRATIGRAPHY AND SEDIMENTOLOGY OF THE COAL BEARING WAPITI GROUP, NORTHWESTERN ALBERTA

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ABSTRACT

Coal-bearing sediments of the Wapiti Group outcrop in northwestern Alberta and northeastern British Columbia. Palynological studies indicate that these sediments range from Late Campanian to Early Paleocene in age. Two, major, coal-bearing sequences within the upper third of the 1700 m thick Wapiti Group have been identified. These intervals are both approximately 100 to 150 m thick and contain numerous coal seams up to 6 m thick. Thin, discontinuous coal horizons up to 2 m thick are occasionally present in the lower interval of the Wapiti Group. It appears that a correlation between the Wapiti Group strata and the Saunders Group to the south is possible, however, further work is required to substantiate this possibility. Future work for the Wapiti project will encompass regions south and east of the Smoky River, and north into northeastern British Columbia.

Résumé

Les sédiments riches en charbon du Groupe de Wapiti sont exposés au nord-ouest de l'Alberta et au nord-est de la Colombie Britannique. Des études palynologiques ont démontré que l'âge de ces sediments va du Campanien supérieur au Paleocène inférieur. Deux séquences contenant du charbon ont été identifiées dans les deux tiers supérieurs du Groupe de Wapiti, l'épaisseur duquel est de 1700 m. L'épaisseur approximative de ces séquences varie de 100 à 150 m, et chaque séquence contient des niveaux de charbon variant de 2 à 6 m d'épaisseur. De plus, des horizons ne dépassant pas les 2 m d'épaisseur sont parfois observés dans la partie inférieure du Groupe de Wapiti. Il semble qu'il soit possible de corréler les strates du Groupe de Wapiti avec celles du Groupe de Saunders plus au sud. Cependant, de plus amples travaux sont requis pour confirmer cette hypothèse. Les futurs travaux du projet Wapiti couvriront les régions au sud et à l'est de la rivière Smokey, et plus au nord, au nord-est de la Colombie Britannique.

INTRODUCTION

The Wapiti study area extends from northeastern British Columbia to the Berland River in north-central Alberta, paralleling the Rocky Mountains to the west. Although the study is interprovincial, only the region bounded by the sixth meridian to the east and the British Columbia border to the west has been examined to date. This initial phase of the study (1988-89), extends from the Smoky River in the south to north of Grande Prairie, encompassing an area of approximately 600 square km (Figure 1).

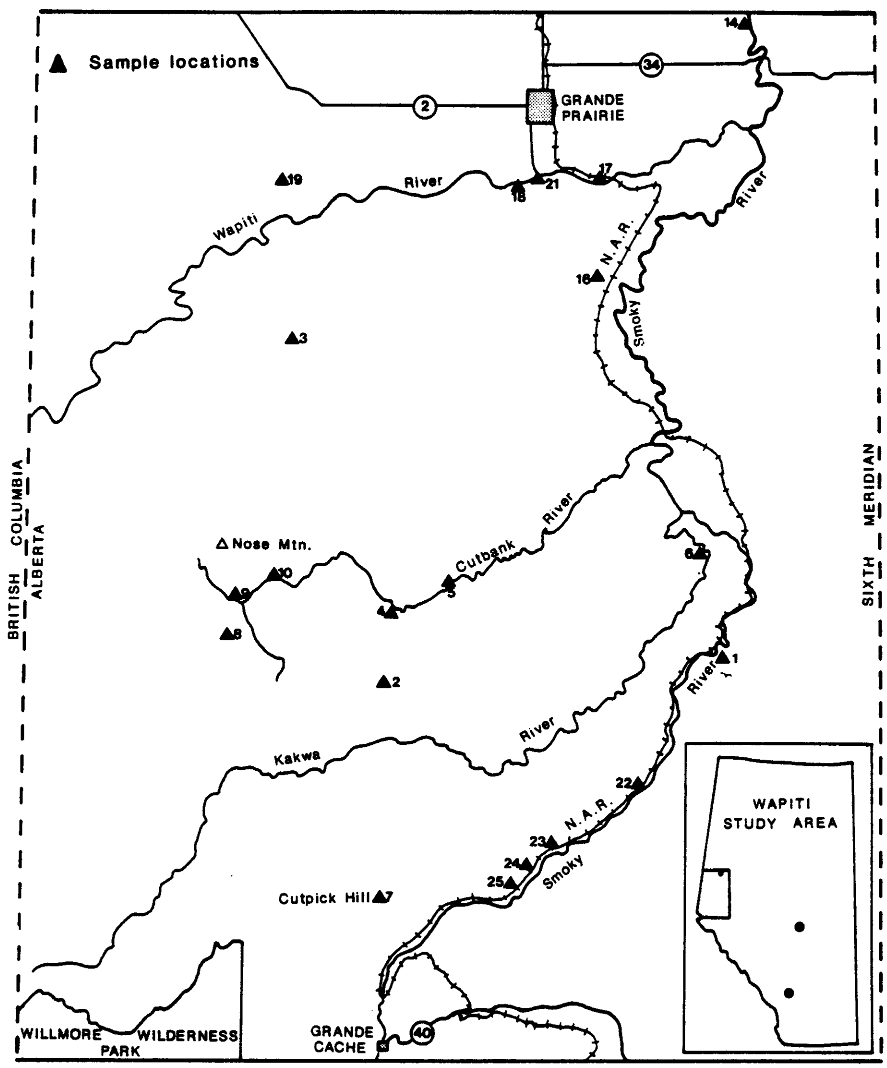

Figure 1. Location map and sample locations, Wapiti Project.

The Geological Survey of Canada's present project was undertaken to examine all available data for the Wapiti Group and establish a geological framework upon which coal characterization and resource assessment can be made. This paper presents the preliminary results of the investigations conducted during the summer of 1988 and outlines a stratigraphic framework upon which future studies can be based.

REGIONAL STRATIGRAPHY

The Wapiti Group consists of nonmarine sandstones, siltstones and mudstones with coal-bearing intervals. This group was defined for rocks outcropping in the Peace River area overlying the dark grey marine Smoky River shales, (Dawson, 1881). According to McLearn (1919) the base of the Wapiti Group may be correlative with the base of the Foremost Formation of the southern plains. Rutherford (1930) and Allan and Rutherford (1934) considered the Wapiti Group in the Grande Prairie area to be correlative to the Belly River and Bearpaw and Edmonton formations. Allan and Carr (1946) divided the Wapiti Group in the Wapiti-Cutbank rivers area into five members. The lowermost member A, 350 to 400 m thick, was considered to be correlative to a part of the Belly River Formation. The overlying four members (B-E), totalling approximately 1200 m in thickness and containing numerous coal beds, are younger, but no attempt was made to establish their age. Fresh water invertebrate fossils (pelecypods and gastropods), terrestrial vertebrates (dinosaur remains) and plants (Bell, 1949) found in the Wapiti strata did not provide sufficient material for biostratigraphic dating. Kramers and Mellon (1972) established a correlation utilizing the nomenclature for the Upper Cretaceous and Tertiary from the Alberta plains.

Samples of mudstone and coal were collected for palynological studies to assist in the biostratigraphic dating of the Wapiti strata (Figure 2). An age range of Late Campanian to Early Paleocene has been determined for the Wapiti Group.

PALYNOLOGY

The basal part of the Wapiti (section location 14, Figure 1) contains a palynoflora comparable to the "early loranthaceous suite" of Norris et al (1975) of early late Campanian age (Nichols and Sweet, in press). This pollen suite has also been observed in the lower part of the Brazeau Formation of the central Alberta foothills (Braman and Sweet, in press) suggesting the timing of the initiation of a continental clastic wedge was more or less contemporaneous throughout central and north-central Alberta.

The palynoflora of the Red Willow coal measure is referrable to the **Cranwellia** suite of Norris et al. (1975) which they found to span the latest Campanian Bearpaw Formation and contiguous strata. Samples from this interval yield both species typical of the latest Campanian **Aquilapollenites clairireticulatus** Samoilovich, 1965; **A. trialatus** Rouse, 1957 and **Mancicorpus calvus** (Tschudy & Leopold) Tschudy, 1973 and **Kurtzipites andersonii** Srivastava, 1981 which has been considered to be restricted to the earliest Maastrichtian. The Campanian-Maastrichtian boundary therefore probably occurs within or immediately contiguous to this interval. A similar assemblage was found to occur associated with cyclothem I and

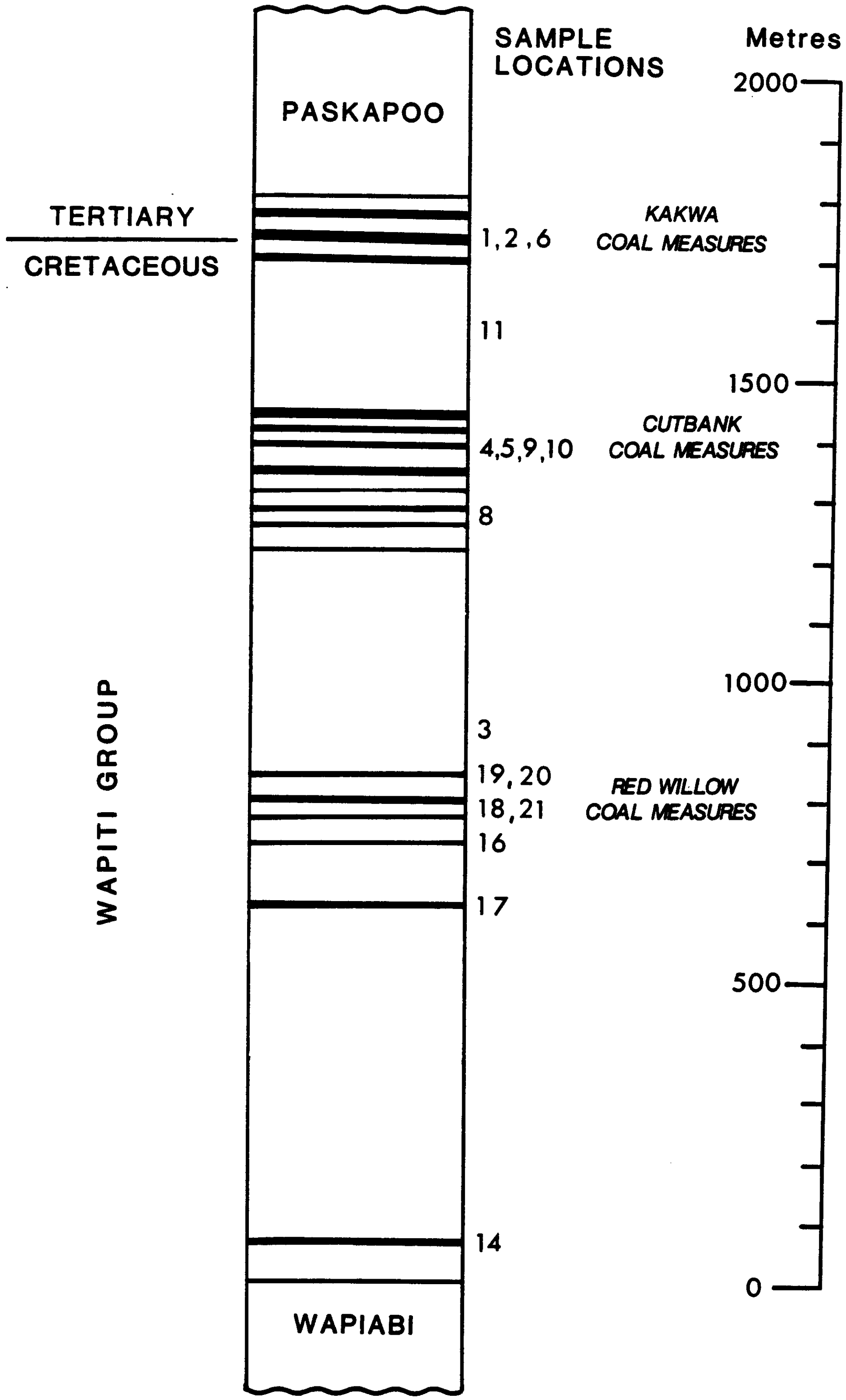

Figure 2. Generalized stratigraphic section, Wapiti Group.

IIa of the Brazeau Formation in the Blackstone River section and in the basal beds of the St. Mary River Formation (Jerzykiewicz and Sweet, 1988).

The early Maastrichtian interval between the Red Willow and Cutbank coal measures has yet to be fully analyzed palynologically. The Cutbank coal measure yield a distinctive palynological assemblage characterized by **Scollardia trapaformis** Srivastava, 1967 which typically occurs in association with abundant specimens of the longer ranging species **Aquilapollenites augustus** Srivastava, 1969, **A. delicatus** var. **delicatus, A. quadrilobus** Rouse 1957, **Liliacidites complexus** (Stanley) Leffingwell 1971 and **Orbiculapollis lucida** Chlonova, 1961. **Scollardia trapaformis**, the main index fossil for the mid Maastrichtian **Scollardia trapaformis** zone of Srivastava (1970), spans the Thompson coal to Whitemud Formation interval of the central Alberta plains (Srivastava, 1970). This same assemblage occurs within the coal-bearing beds at the top of the Brazeau Formation (Jerzykiewicz and Sweet, 1988) and therefore provides the means of correlating the Cutbank coal measure to both the upper part of the Brazeau and Horseshoe Canyon formations.

Although the lower part of section 8 (Figure 2) contains **Scollardia trapaformis** its uppermost part appears to range into the late Maastrichtian based on the combined presence of **Aquilapollenites bertillonites** Funkhouser, 1961 and **Wodehouseia spinata** Stanley, 1961. The late Maastrichtian is otherwise poorly represented in the currently available samples.

The entire interval of the Kakwa coal measure appears to be of early Paleocene age in that they contain a low diversity assemblage dominated by gymnosperm pollen of the Taxodiaceae-Cupressaceae complex and **Laevigatosporties.** Occasional specimens of **Paraalnipollenites alterniporus** (Simpson) Srivastava, 1975, **Azolla schopfii** Dijkstra, 1961 and more infrequently **Wodehouseia fimbriata** Stanley, 1961 lend support to an exclusively early Paleocene age for this uppermost coal measure. The Kakwa coal measure are therefore correlative to the Ardley coal zone of the central Alberta plains and the coal-bearing part of the Coalspur Formation of the central Alberta foothills.

SEDIMENTOLOGY

Sedimentological observations of the surface sections indicate that coal forming swamps originated in a floodplain and marginal lacustrine depositional setting. The lower part of the Wapiti strata (base of the Wapiti to the top of the Red Willow coal measure in Figure 2) represents a mainly alluvial plain environment, probably drained by numerous, large, high sinuosity, meandering channels. Fining-upward units of point bar origin are the most common type of sedimentary sequence. The lower members of these sequences are built up with low angle inclined beds of sandstones, laterally infilling large broad channels. The upper is composed of alternating mudstones and very fine grained sandstones. This type of inclined heterolitic stratification illustrated by Thomas et al. (1987, Figure 15),(Plate 1), is attributed to mixed to suspended-load meandering rivers of markedly fluctuating discharge (Stewart, 1981). Coals occur in the overbank sediments along with mudstones that are usually dark grey, organic rich and nonlaminated. Upright rootlets, root casts and root burrows indicating autochthonous origin of coal are common.

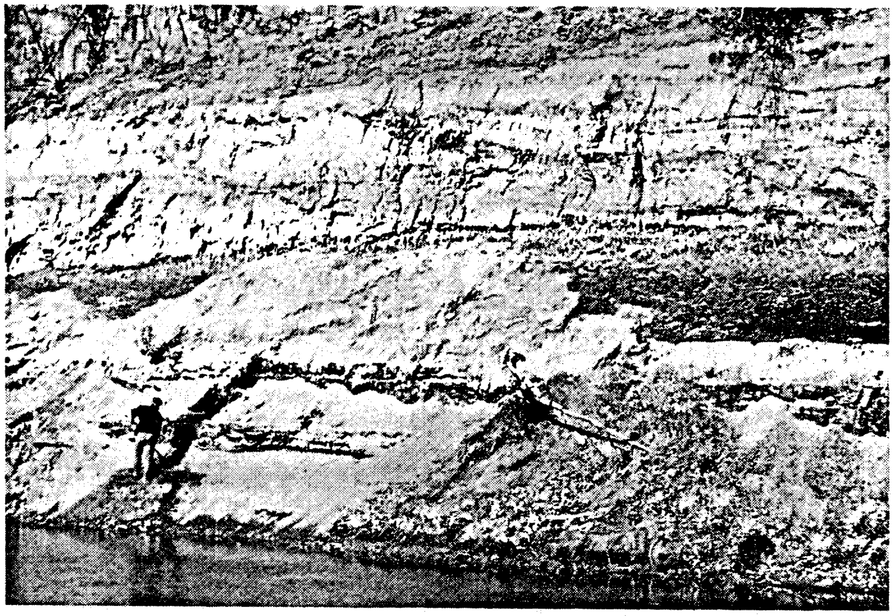

Plate 1. Low angle inclined beds laterally infilling a large broad channel (IHS), above coal seam; Location 3.

The lacustrine component of the floodplain depositional environment is pronouced in the upper part of the Wapiti strata (top of the Red Willow coal measure upward, Figure 2). Laminated mud-shales and siltstones, which are interpreted in terms of lacustrine rhythmites, are very common. The coals are often associated with the rhythmites, suggesting that the coal forming swamps developed in a lake margin depositional setting.

A variety of meandering and braided channel types occur in the upper Wapiti strata, but the nonchannelized, flat bounded sandstone bodies with wavy bedding, which are associated with the rhythmites, represent a lacustrine environment.

REGIONAL STRUCTURE

Wapiti strata within the project area have gentle dips in the east varying to more moderate dips along the western margin. A broad synclinal structure trends northwest through the eastern half of the project area. This structure may be the northward extension of the Alberta Syncline to the south. Dips of the strata are generally less than 10 degrees on either limb of the fold. Along the western margin of the project area, near the deformed belt of the Foothills, are a series of anticlinal and synclinal folds with dips up to 25 degrees. A structural contour map of the base of the Wapiti Group indicates that these folds trend to the northwest. Immediately to the west, a high angle reverse fault has thrust Upper Cretaceous strata of the Alberta Group upon the Wapiti strata. This fault delineates the western margin of the project. There does not appear to be significant faulting east of this feature into the core of the Alberta Syncline. Minor folds and faults with limited displacement probably exist; however, no surface expressions have been recognized to date.

COAL DISTRIBUTION

Coal zones have been recognized in outcrop as well as the subsurface throughout most of the stratigraphic succession of the Wapiti Group. The thickest zones occur in two major intervals (Kakwa and Cutbank coal measures) within the upper third of the section (Figure 2). In the lower two thirds of the Wapiti Group, repetitive cycles of medium to coarse grained sandstone overlain by a fine grained sequence of mudstone with minor coal contain multiple thin coal zones (up to 2 m thick). Outcrops along the Smoky and Wapiti rivers indicate that at least three cycles of coarse grained and fine grained units are present in the lower Wapiti strata. The coals (Red Willow coal measure) that occur in this strata (Figure 2), appear to be widely variable in thickness and limited laterally to isolated deposits with an areal extent of approximately 5 to 10 km.

The first major coal-bearing interval (Cutbank coal measure) lies approximately 1300 m above the base of the Wapiti Group. These strata contain up to 6 coal zones over an interval of approximately 100 to 150 m. Coal zones up to 6 m thick have been observed in outcrop and exploration boreholes. Sample localities 4,5,8,9 and 10 represent coal seams within this interval (Plate 2). This coal-bearing sequence is correlative with the Brazeau coal zone of the Saunders Group in west-central Alberta and the Thompson coal zone of the Alberta Plains.

Approximately 190 to 250 m above the Cutbank coal measure is another thick sequence of coal bearing strata similar to the lower interval. Informally defined as the Kakwa coal measure, the interval is approximately 100 to 150 m thick. Up to to seven individual coal zones have been observed, with zone thickness' ranging from 1 to 6 m. Sample locations 1,2 and 6 were measured within this interval. Preliminary biostratigraphic data indicate that the Cretaceous-Tertiary boundary probably lies at or near the base of this coal measure. A subsurface correlation of coal exploration data based upon this coal interval has been undertaken.

COAL CHARACTERISTICS

During the 1988 field season, 31 coal samples were collected from outcrops along the river valleys (Figure 1). These samples represent most of the coal zones within the Wapiti Group (Figure 2). The coal zone sections were measured at the

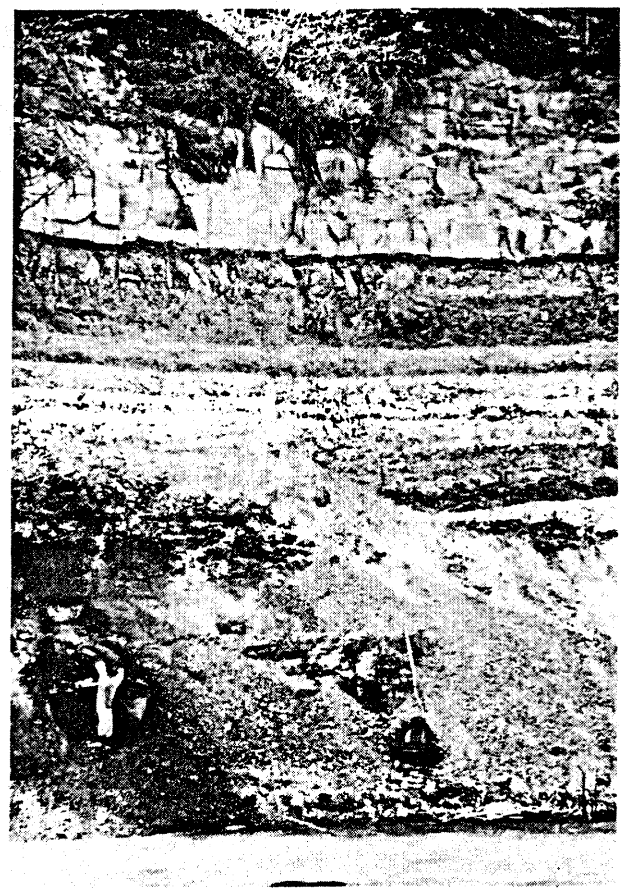

Plate 2. Coal associated with lacustrine facies, Location 4.

outcrop, and the coal seams and interseam partings were sampled in detail. Only the coal samples were analysed by proximate and ultimate analyses, and by petrography (rank and petrographic composition). Preliminary data indicate that the coal averages high volatile C and B bituminous in rank. The rank of the coal at location 9 (Figure 1) is high volatile A bituminous, possibly due to the proximity of the tectonic influence along the western margin of the project area. Conversely, at location 14 (Figure 1) along the eastern margin of the study area, the coal is subbituminous C in rank (Dawson and Kalkreuth, in press).

In the southern part of the study area, the Kakwa coal measure appears to have a slightly lower reflectance level than the Cutbank coal measure, perhaps reflecting depth of burial. In samples collected from the Red Willow coal measure, which were mainly collected in the northern part of the study area (Figure 1), there is a trend of decreasing reflectance values from the southwest to the northeast, possibly reflecting the increased subsidence associated with the Laramide uplift to the southwest on the rank of the coals. Further sampling of Wapiti Group coals is required to understand the regional rank variations with respect to depth of burial of the strata and the effect of Laramide deformation (Kalkreuth and McMechan, 1988).

The coals of the Upper Cretaceous Wapiti Group are high in vitrinite content, markedly different from the Lower Cretaceous Gates Formation coals of the same area. Many of the Gates coals accumulated in coastal swamps (Kalkreuth and Leckie, in press), in which relatively low water tables allowed the enrichment of inertinite macerals semifusinite and fusinite, indicative of oxidizing conditions . The preliminary results on maceral distribution in the Wapiti coals (Dawson and Kalkreuth, in press) and corresponding gelification and tissue preservation indices (Diessel, 1986), suggest that these coals accumulated in a more fluvial depositional environment, thus supporting the sedimentological interpretations.

SUMMARY

The Wapiti project area extends from northeastern British Columbia southeast to the Berland River in western Alberta. Phase 1 of the study examined the coal potential of the region from Grande Prairie to Grande Cache, west of the sixth meridian. Thick coal seams, (up to 6 m) have been observed within two coal bearing intervals within the upper third of the Wapiti Group. Preliminary studies indicate the coals to be bituminous to subbituminous in rank. Further work is required to delineate the stratigraphic framework in which these coals are found, as well as extend the boundaries of study to the north and the southeast.

ACKNOWLEDGEMENTS

The authors are appreciative to G. Smith and W. Kalkreuth for reviewing and providing comments on this paper.

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COAL GEOLOGY AND RESOURCE POTENTIAL OF THE LUSCAR GROUP IN WEST CENTRAL ALBERTA*

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ABSTRACT

The Luscar project was initiated to compile and synthesize existing geological data and gather new data where required, in order to assess the coal resource potential of the region bounded by the Clearwater and North Saskatchewan rivers in the Foothills of western Alberta. Preliminary results of this project indicate that the main coal bearing sequence lies within the Grande Cache Member of the Gates Formation of the Luscar Group. Up to six coal zones are present, of which two appear to be of potentially mineable thickness. The rocks have been highly folded and faulted, giving rise to a series of linear trends of coal bearing strata trending parallel to the front ranges of the Rocky Mountains. This paper presents the geological framework upon which the coal resource potential of the Luscar Group will be determined.

Résumé

Le projet Luscar fût initié dans le but de compiler et d'intégrer des données géologiques existantes et de recueillir de nouvelles données là où elles étaient requises. Ce travail fût effectué dans le but d'évaluer les ressources possibles en charbon de la région définit par les rivières Clearwater et Saskatchewan dans les Foothills de l'ouest albertain. Les résultats préliminaires indiquent que la principale séquence houillère repose au sein du membre de Grande Cache de la Formation Gates, laquelle appartient au Groupe de Luscar. Jusqu'à six zones riches en charbons sont présentes, deux desquelles semblent posséder des épaisseurs exploitables. Ces roches ont été fortement plissées et faillées, résultant en une série de bandes linéaires charbonneuses, orientées parallèlement au front des Montagnes Rocheuses. Cet article présente le canevas géologique à partir duquel les ressources possibles en charbon du Groupe de Luscar seront évaluées.

* Paper was first published in Contributions to Canadian Coal Geoscience, Geological Survey of Canada, in press.

INTRODUCTION

Coal resources of Lower Cretaceous age outcrop within the disturbed belt of the Foothills of western Alberta. The main coal-bearing strata belong to the Gates Formation of the Luscar Group, which extends within the inner foothills from the Bow River northward into British Columbia. The Luscar project was initiated in 1988 to examine the coal potential of the Luscar Group, from the Clearwater River in the south, to the North Saskatchewan River in the north (Figure 1). The rocks have been highly faulted and folded as a result of the Laramide Orogeny, producing near surface coal resources which are restricted to narrow bands of outcropping Luscar strata that parallel the Front Ranges of the Rocky Mountains, (Figure 2).

The Luscar project entails the compilation and synthesis of subsurface and surface exploration data, coupled with gathering of new data where required, to provide the basis upon which an assessment of the coal resource potential and coal quality characteristics can be made. Existing subsurface information is very limited, and the lithostratigraphic data collected during the 1940's is outdated. Geological mapping was undertaken during the summer of 1988 to upgrade the existing geological information and provide greater data control within the coal bearing areas.

PREVIOUS WORK

Coal has long been known to occur in the Foothills of western Alberta. G.M. Dawson (1886) was the first to assign geological names to the coal bearing sequences in this region. It was not until the early 1900's (Malloch, 1911), that the coal resource potential of the region from Nordegg south to the Clearwater River was examined. In the 1940's, the Geological Survey of Canada undertook a regional mapping program in the region. Maps produced by MacKay (1940), Erdman (1945), Henderson (1945), and Crombie (1946) have provided the mainstay of geological information for the area. From the 1950's to the present, much of the geological work conducted in the Foothills of Alberta has been concentrated in the regions to the north of Nordegg, toward Hinton and Grande Cache. Geologists such as Douglas (1956), Irish (1965), Mellon and Wall (1961,1963), McLean (1982) and Langenberg and McMechan (1985) have examined in detail the Lower Cretaceous strata farther to the north, perhaps due to better outcrop exposure, or to the significant coal resources that are present in these regions. The examination of the Lower Cretaceous strata within the Foothills region from the North Saskatchewan River southward to the Clearwater River has been ignored.

During the 1970's, several coal companies recognized the coal resource potential within the region and undertook numerous exploration programs throughout the area. Consolidation Coal Company and Hudbay Coal Company were the major firms involved in

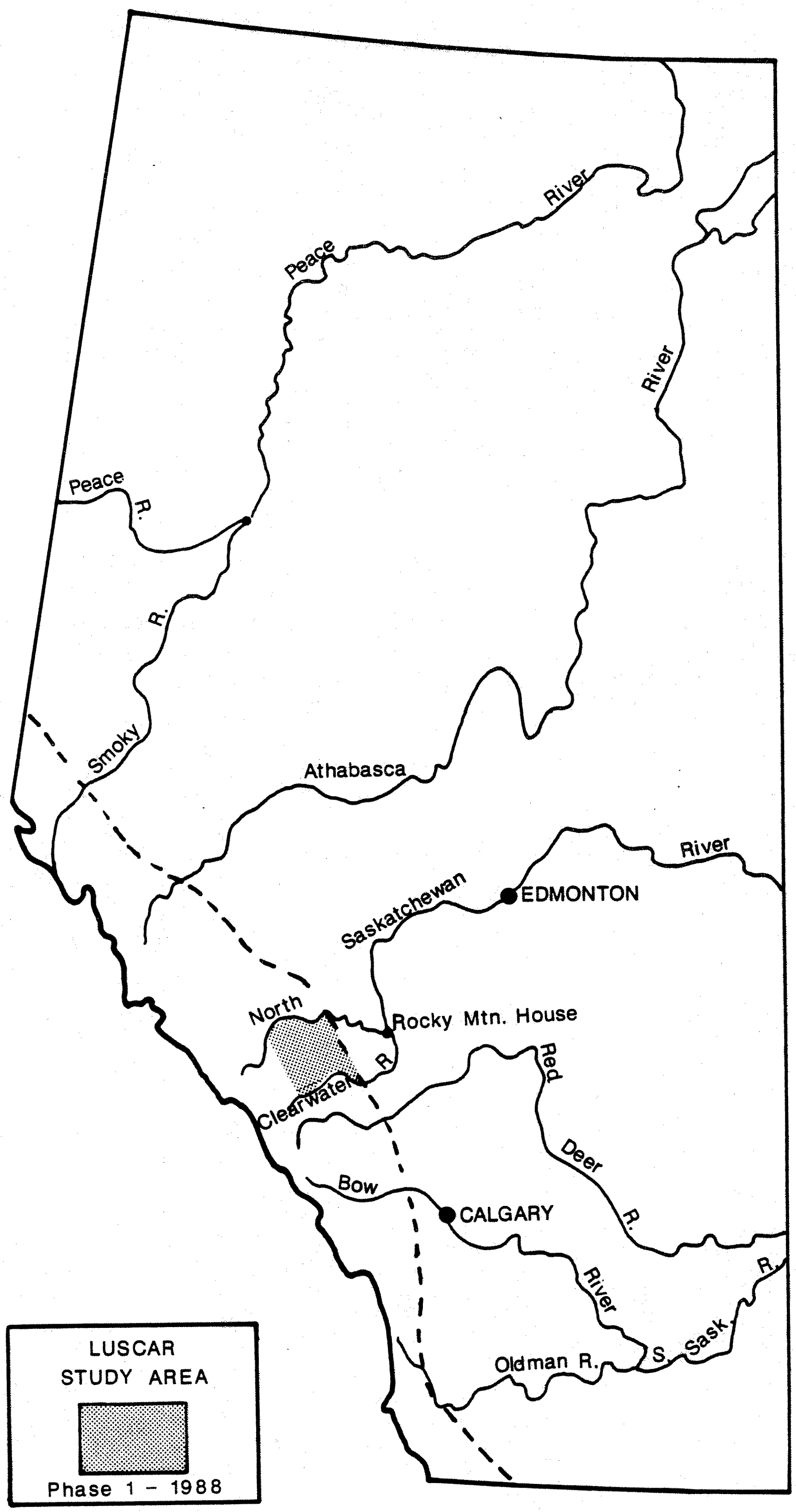

Figure 1. General location map of Luscar Project area.

this effort, with smaller programs conducted by Clearwater Coal Company and Brascan Resources Limited. Most of the exploration consisted of geological mapping, followed by the drilling of numerous coal exploration boreholes.

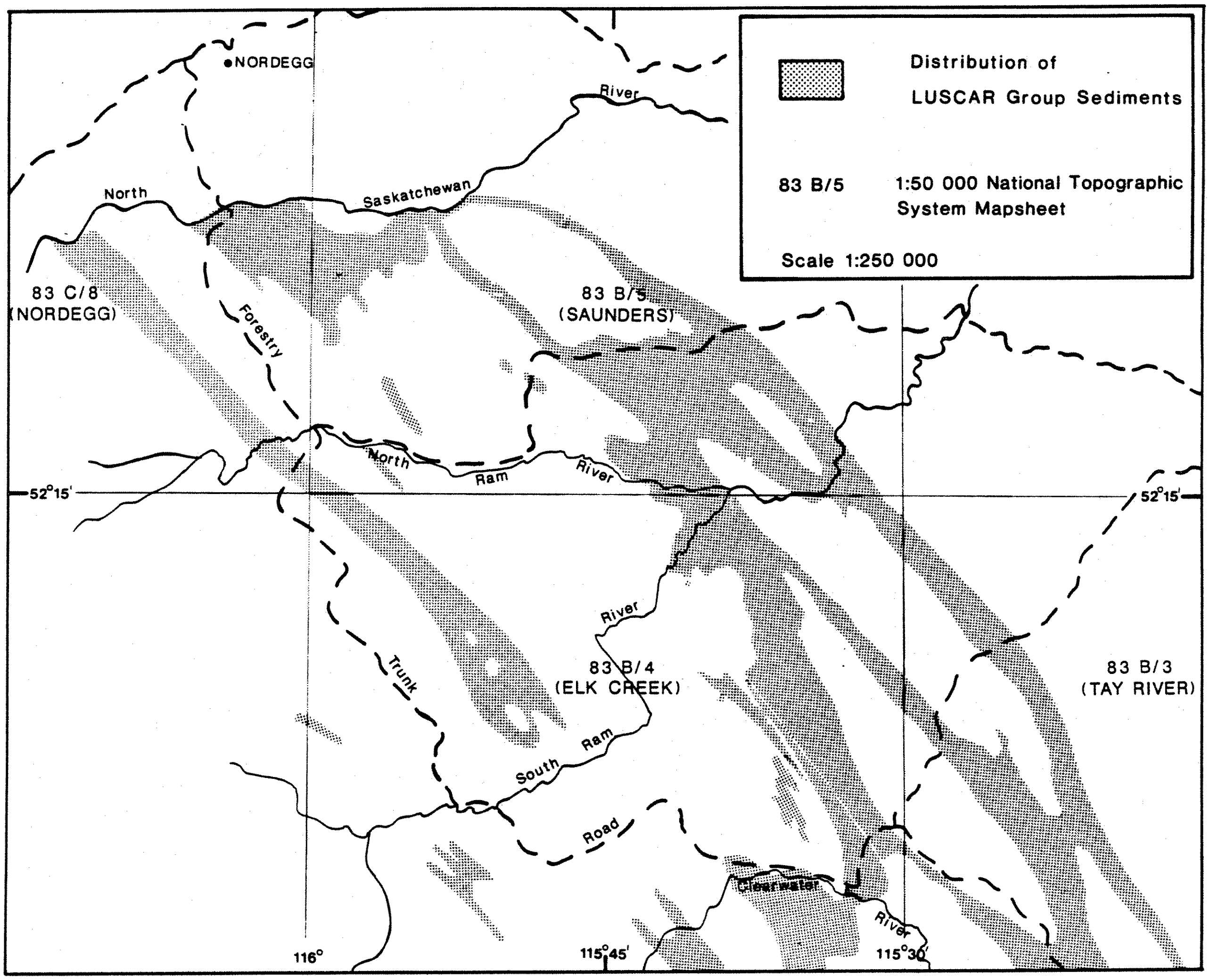

Figure 2. Distribution of Luscar Group strata.

Recently Rosenthal (1988b), has examined the Luscar Group stratigraphy in the region, however, this study was directed toward the hydrocarbon potential in the subsurface east of the Foothills belt.

STRATIGRAPHIC NOMENCLATURE

The Lower Cretaceous Luscar Group contains marginal marine to non marine strata derived from the Columbian orogenic uplift during the Early Cretaceous. In west central Alberta, the Luscar Group is approximately 400 m thick and can be divided into several, distinctive, mappable formations, as defined by Langenberg and McMechan (1985), (Figure 3).

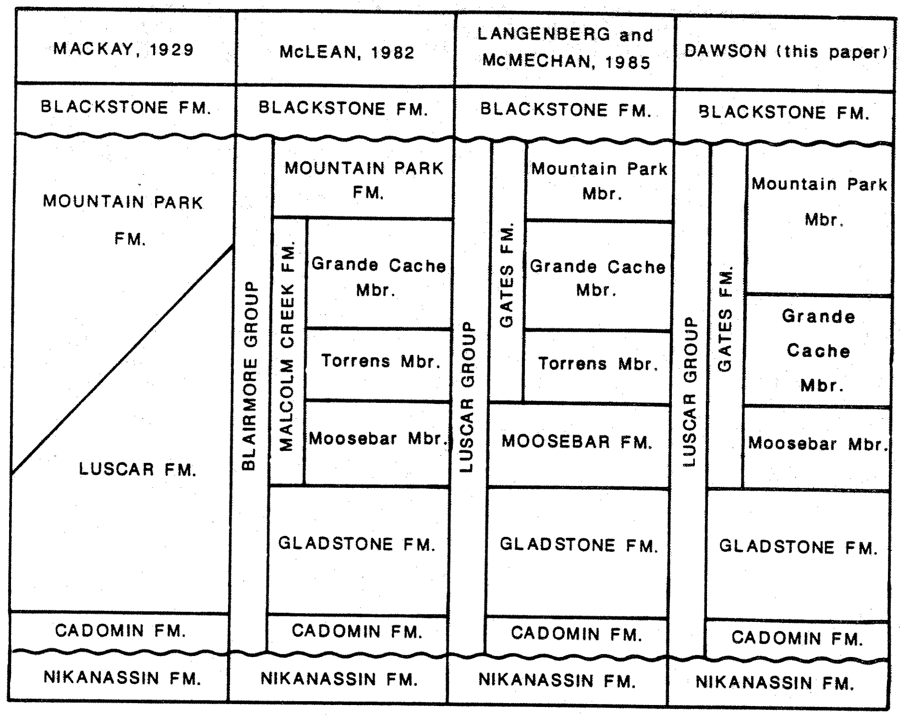

Figure 3. Stratigraphic nomenclature for Luscar Group strata.

The base of the Luscar Group is represented by the Cadomin Formation. This unit consists of interbedded coarse grained quartzitic sandstone and chert and quartz rich pebble conglomerate. The Cadomin Formation varies from 5 to 15 m in thickness in the project area, and forms a distinctive resistant unit in outcrop. The base is sharp and lies unconformably on the interbedded sandstones and mudstones of the Nikanassin formation.

Lying conformably above the Cadomin Formation are interbedded sandstones and mudstones of the Gladstone Formation (Figure 4). This formation is approximately 75 m thick and consists of dark grey, quartzitic, fine grained sandstones, and dark grey mudstones. Thin, carbonaceous shale or coal beds are present throughout. The sandstone beds are resistant in outcrop and are distinctive by the quartz sheen of weathering. The top of the Gladstone Formation is gradational with the overlying Moosebar Member of the Gates Formation, (Figure 3). The strata that overlie the Gladstone Formation consist of dark grey to black mudstones and siltstones of marine to marginal marine origin. Pelecypods, gastropods and ostrocodes are abundant throughout the sequence. In northeastern British Columbia and northwestern Alberta, this interval has been defined as the Moosebar Formation (Langenberg and McMechan, 1985), and is greater than 200 m thick. Within the study area, the Moosebar equivalent strata are less than 65 m thick and represent a gradational sequence with the overlying sediments. For this paper, in the Foothills of west central Alberta, the Moosebar

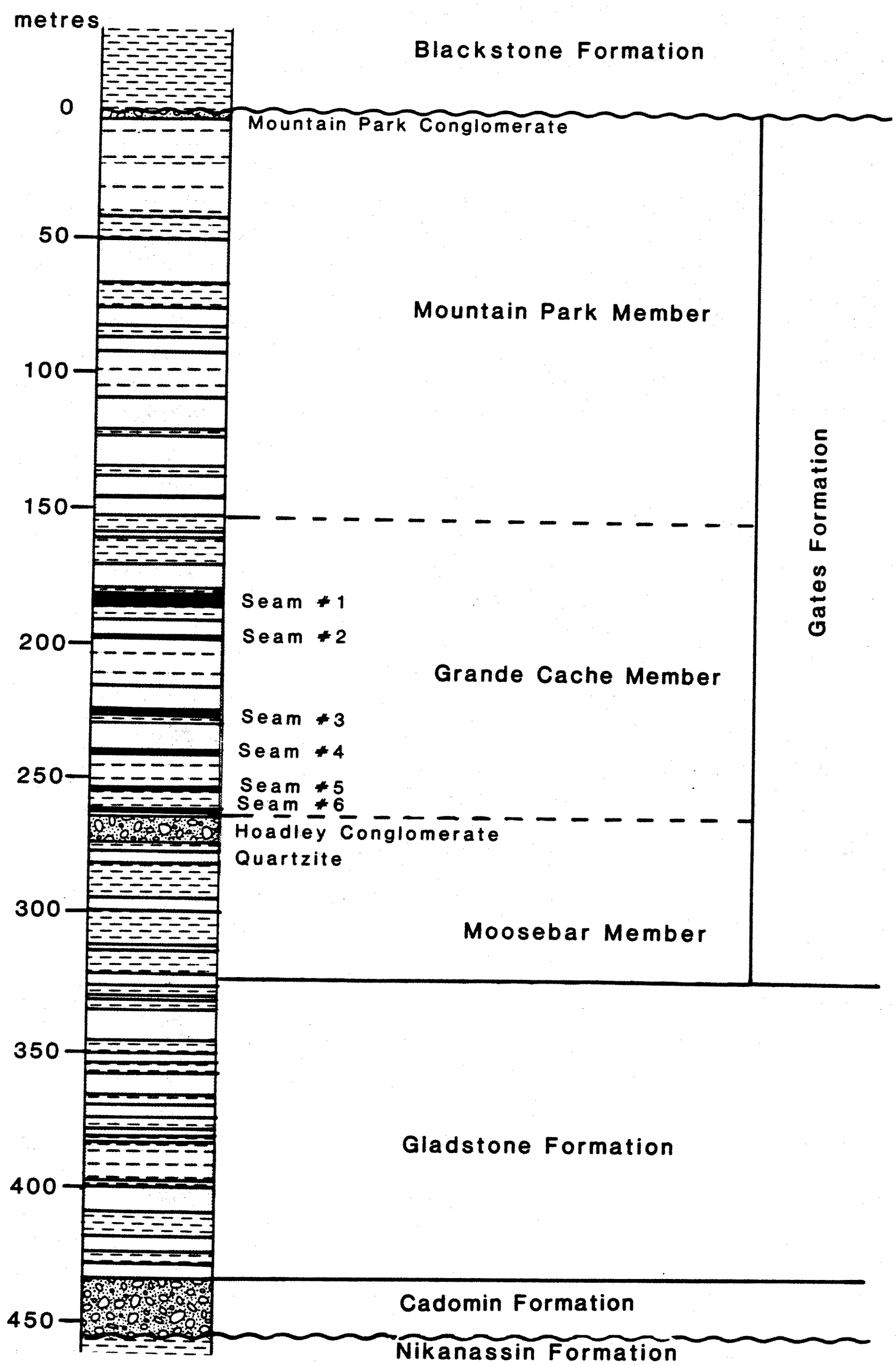

Figure 4. Composite section of the Luscar Group.

interval has been defined as a member of the overlying Gates Formation, and is interpreted as representing the marginal marine facies of the sequence. The Moosebar Member is correlative with the Ostracode zone of the Mannville Group in the subsurface of the Alberta Plains (Rosenthal, 1988). The top of the Moosebar member is represented by a thin mudstone unit immediately lying above a conglomeratic sequence approximately 15 to 20 m in thickness, (Figure 4).

This conglomerate is equivalent to the subsurface Hoadley complex (Rosenthal 1988a) of the Alberta Plains, a series of beach deposits associated with the progradation of the clastic sediments of the Mannville Group into the Moosebar sea during Early Cretaceous time. The Hoadley units, where present, signifies, for mapping purposes, the base of the overlying coal bearing sequence. The Hoadley strata consist of quartzitic sandstone, approximately 3 to 5 m thick, overlain by a thin (1-2 m), recessive mudstone unit. Immediately above is a predominantly coarsening upward sequence of fine to medium grained, light grey sandstone and clast supported pebble conglomerate (Rosenthal, 1988a). The Hoadley conglomerate is very similar lithologically to the Cadomin Formation. The unit is usually capped by a mudstone or thin coal zone (seam #6). The conglomeratic beach facies of the Hoadley complex appears to be limited laterally to a predominantly east-west trend, and pinches out rapidly to the north and south, whereas the underlying quartzite unit is more widely distributed.

Lying conformably above the Moosebar Member are the main coal bearing rocks, defined as the Grande Cache Member of the Gates Formation (Langenberg and McMechan, 1985). Strata consist of interbedded, fine grained, orange to brown weathering sandstone and orange to dark brown mudstone and siltstone. The rocks are highly feldspathic, significantly different from the siliceous pre-Moosebar strata. This difference can be utilized in the surface mapping of isolated outcrops. The Grande Cache Member is approximately 110 m thick and contains up to six coal zones, of which two, (zones 1 and 3), appear to be of potentially mineable thickness. Zone 3 lies approximately 35 m above the Hoadley complex, and zone 1 a further 40 m above. Both coal zones are widely variable, with thicknesses up to 4.5 m being reported.

Above the Grande Cache Member is a thick sequence of interbedded, fine grained sandstone and mudstone, with minor carbonaceous beds, defined as the Mountain Park Member of the Gates Formation. These rocks usually display a distinctive greenish grey colour, which can be attributed to their high feldspar content. The Mountain Park Member is predominantly barren of coal, with only minor carbonaceous beds near the top. Occasionally channel deposits, up to 40 m thick, downcut into the underlying Grande Cache Member. The Mountain Park Member is approximately 150 to 200 m thick, and the base is usually represented by a thick, massive, greenish grey, cliff forming sandstone. The top of the Mountain Park Member is sharp and unconformable with the overlying marine strata of the Blackstone Formation. This contact is frequently represented by a pebble conglomerate varying in thickness from 10 cm up to 6 m. The matrix of the conglomerate is predominantly mudstone and is easily distinguishable from the conglomeratic units of the

Moosebar Member and the Cadomin Formation.

The overlying marine Blackstone Formation comprises up to 530 m of dark grey, fissile mudstone and siltstone with occasional bright orange weathering concretionary beds (Stott, 1963). The Blackstone Formation is usually recessive; the only complete exposures occur along the South Ram River.

Middle to Upper Cretaceous strata exposed within the study area belong to the Cardium, Wapiabi and Brazeau formations. The former two are of marine origin, while the Brazeau Formation is of continental origin. Thin coal zones of the middle Brazeau Formation have been exploited in the Alexo-Saunders region along the North Saskatchewan River.

COAL STRATIGRAPHY

The major coal development within the Lower Cretaceous Luscar Group is restricted to the Grande Cache Member of the Gates Formation. Minor carbonaceous beds have been observed within the Gladstone Formation and the upper section of the Mountain Park Member of the Gates Formation; however, these beds are very thin and poorly developed. Six separate coal zones are present over an interval of approximately 80 to 110 m. Of these, zones 1 and 3 appear to have the greatest thicknesses and widest distribution. Zone 3 may be correlative with the Medicine River coal in the subsurface to the east of the study area (Rosenthal, 1988). Thicknesses vary from 0.5 to 4.0 m. Zone 1 lies approximately 30 to 40 m above zone 3 and ranges is thickness from 1.0 to 4.0 m. The other coal zones, 2,4,5 and 6, appear to be less than 1.0 m thick and are much more discontinuous.

Regionally, the coals of the Grande Cache Member appear to thin to the west. Coal exposures along Cripple Creek are generally less than 1.0 m thick, while coal outcrops on the West Ram block, farther to the west, appear to be less than 0.6 m thick. Conversely, to the east, along the Fall Creek trend, zones up to 4.5 m have been observed in outcrop and drillcore. Parallel to the Rocky Mountains, the development of coal zones tends to thicken from south to north. This may be related to the progradation of nonmarine sediments into the retreating Moosebar sea to the north, during Early Cretaceous time.

STRUCTURE

The Luscar project lies within the structurally deformed belt of the inner Foothills of west central Alberta. Strata of Early to Late Cretaceous age have been highly folded and faulted as a result of the Laramide orogenic uplift. The axes of the main structural features trend northwest, parallel to the Rocky Mountains to the west. Tectonic deformation appears to increase from east to west. In the east, anticlinal and synclinal structures form open folds with gentle dips. The number of reverse faults associated with the folding is decreased. To the west, folding is more intense and many of the anticlinal and synclinal structures contain vertical to overturned limbs. Reverse faults associated with these tight folds are more common with numerous splays and frequent repetition of stratigraphic sequences. The high degree of tectonic folding and faulting has also led to considerable small-scale deformation associated with the major structures. Along the South Ram River, west of the Forestry Trunk Road (Highway 40), folding in Luscar and Nikanassin formations strata is very intense, and the deformation appears to be almost ptygmatic in nature, (Plate 1).

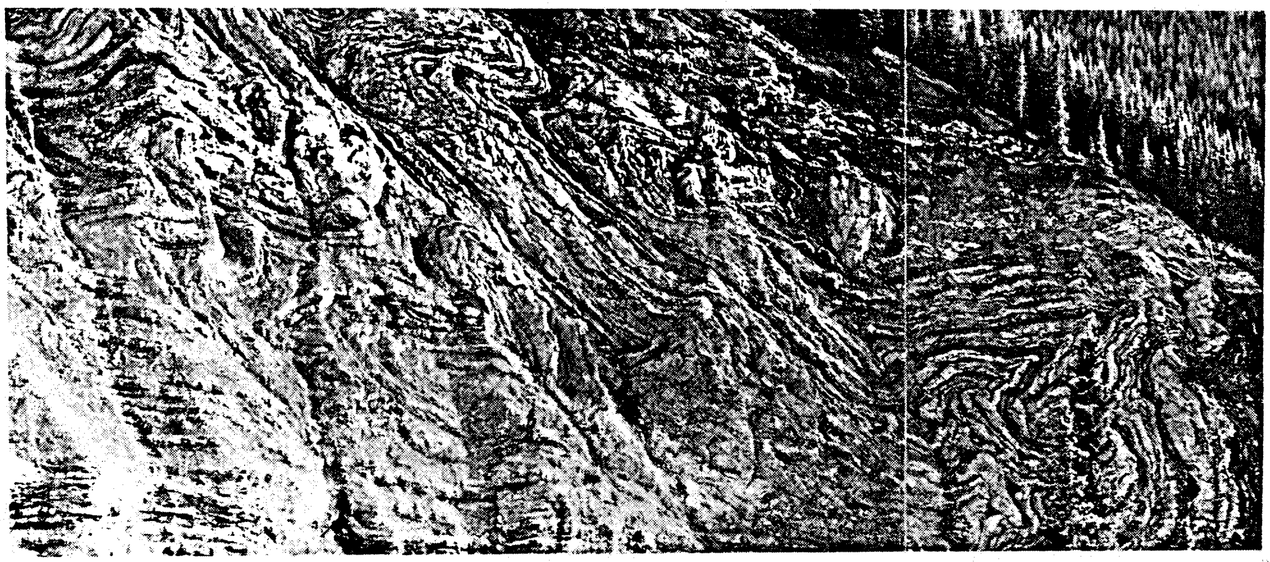

Plate 1. Ptygmatic folding of Nikanassin strata, Ram River.

The structural complexity of the strata within the project area has resulted in the coal bearing sequence being restricted to linear strike trends along the flanks of major folds or faults. There are relatively few areas where the strata is flat lying. Smaller-scale structural features, such as bedding plane fault splays and drag folds, have further complicated these trends. The intense deformation associated with the major structures has resulted in the coal, in most cases, being highly sheared. Along Cripple Creek, some structural thickening of the coal zones has been observed. It is possible that localized, structurally thickened pods of coal may exist within the project region.

RESOURCE POTENTIAL

Potential coal resources within the Luscar project area appear to be contained almost totally by the coal zones of the Grande Cache Member of the Gates Formation. Of the six coal zones recognized, only zones 1 and 3 appear to attain sufficient thickness to be considered mineable. Ranging in thickness from 0.5 m to greater than 4.0 m, these two main coal zones appear to be widespread in distribution. Preliminary results indicate that the coals thin toward the west, and may be too thin to be considered mineable along the furthest west strike trend of Gates Formation strata. Coal exposures in the eastern region of the project area suggest that the main coal zones are up to 4.5 m thick and favourable mining situations may exist.

Tight folding and bedding plane reverse faults are common throughout the project area, increasing in frequency toward the west. Individual coal zones have the potential to be structurally thickened, producing localized overthickened pods of coal that may improve the resource potential. The influence of Laramide tectonism has commonly resulted in intense shearing of the coal, resulting in a high percentage of fine coal in any potential mining deposit. The coal is medium to low volatile bituminous in rank, suitable for metallurgical purposes.

The exploitation of the coal resources of the eastern slopes region of the province of Alberta are still controlled by the regulatory categories established by the provincial coal policy of 1976. This policy is currently being revamped, and a new, updated version should be presented within the next few years. Recently, the Department of Forestry of the Alberta Government has produced a series of Integrated Resource Plans for the Alberta Foothills. The Nordegg-Red Deer River Sub-Regional Integrated Resource Plan (1986) covers the Luscar project area. This Integrated Resource Plan categorizes the lands within the study area by land usage. The 1:50 000 scale map sheets produced for the Luscar project illustrate the coal policy and land usage categories for the area, and compare these with the distribution of the coal bearing strata, thus allowing potential coal exploration targets to be delineated.

FUTURE WORK

Preliminary results of the Luscar project indicate that the compilation and analysis of existing geological data for the region can be synthesized into a series of map sheets, upon which resource assessments and coal characterization can be made. These 1:50 000 scale map sheets and accompanying report will provide valuable geological information pertaining to the coal potential within an area which, to date, has been poorly understood. As well, the map sheets will provide a useful data base for the coal industry with respect to future exploration efforts which may be conducted in the region. The comparison of the coal bearing regions and the Integrated Resource Plan of the Alberta Government allows the trends of near surface coal bearing strata to be categorized by land use sensitivity, thus delineating potential exploration targets for the project area.

Upon completion of this initial project, the regions from the Bow River to the Clearwater River to the south and from the North Saskatchewan River to the Blackstone River to the north will undergo similar analysis , and be integrated into a regional study of the resource potential of the Luscar Group in the Alberta Foothills.

ACKNOWLEDGMENTS

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STRATIGRAPHY OF THE MIST MOUNTAIN FORMATION (JURASSIC-CRETACEOUS KOOTENAY GROUP) IN THE ELK VALLEY COALFIELD, SOUTHEASTERN BRITISH COLUMBIA

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ABSTRACT

This study is based on 15 measured sections and 10 logged drillcores in the Mist Mountain Formation from the Elk valley coalfield. The sections contain 8.7% of their total thickness in coal, while the logged cores contain 10.4%. Individual seams in the sections range up to 13 meters in thickness. Seams between 1 and 2 metres thick are the most significant from both numerical and relative volume standpoints, followed by 2-to-3-metre thick seams on a numerical basis and 5-to-6-metre thick seams on a relative volume basis. In general, vitrinite contents of coal seams increase upsection, while semifusinite contents decrease. Liptinite content in seams averages 4.0% in a partial section containing coals of high-volatile A rank, but is practically nonexistent in seams within a section of low and medium volatile bituminous rank. The basal coal zone of the formation differs in its general stratigraphy throughout the study area, but always contains at least two seams. Two other coal horizons in the south part of the coalfield have been correlated, one of them, named the Imperial seam, for a distance of over 17 kilometres.

Results of Markov chain analysis of transitions within drillcore from the Mist Mountain Formation suggest a fining-upward sequence, typical of deposition within point bar and floodplain environments. The lower and upper parts of the formation are not markedly different in terms of their transition frequencies, and hence probably were deposited by nearly identical processes.

INTRODUCTION AND GEOLOGICAL SETTING

Economic coal seams of southeastern British Columbia's East Kootenay coalfields belong to the Mist Mountain Formation of the Jurassic-Cretaceous Kootenay Group. The Mist Mountain Formation overlies the Morrissey Formation and is overlain by the Elk Formation (Gibson, 1985). It ranges in thickness in southeastern British Columbia from less than 200 to greater than 600 metres, and averages about 500 metres. The Mist Mountain Formation in the Elk valley

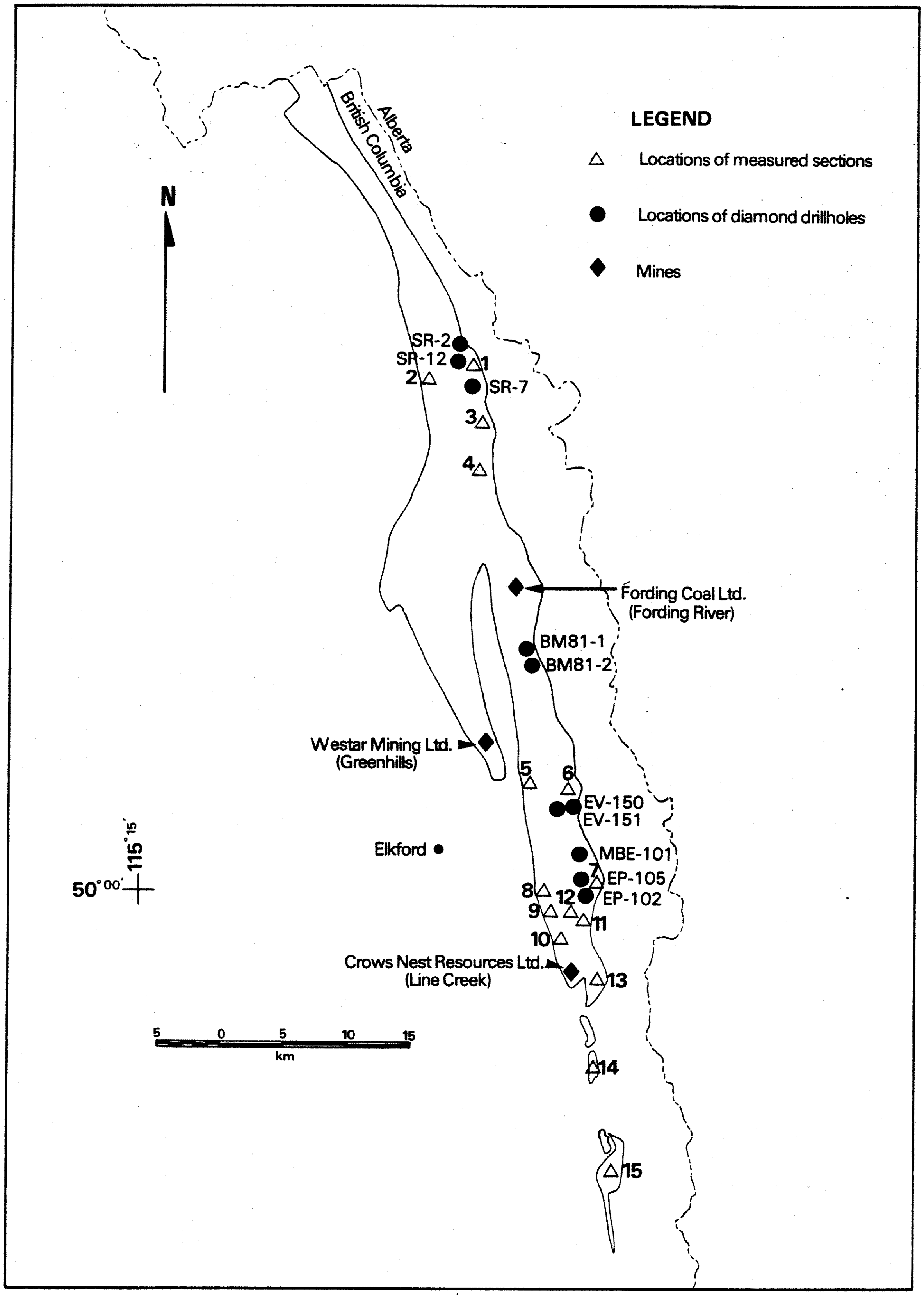

Figure 1. Outline of the Elk valley coal-field, with locations of measured sections and drillholes used in this study.

coalfield, as in most other areas of its occurrence, consists of an interbedded sequence of sandstone, siltstone, mudstone, shale, and coal, with rare conglomerate. The reader is referred to Gibson (1985) for a comprehensive treatment of the Mist Mountain's regional stratigraphy.

Of the formation's total thickness, approximately 10 per cent is composed of coal in southeastern British Columbia (Grieve, 1985). Individual coal seams range up to and occasionally exceed 15 metres in thickness. As a rule coal seams in the lower part of the formation tend to be thicker and more laterally continuous than those in the upper part, but there are many exceptions to this (Grieve, 1985).

The depositional environment of the lower Mist Mountain Formation is believed to have been an extensive deltaic-interdeltaic coastal plain, which was deposited conformably and abruptly on the subaerial beach ridge-eolian dune lithofacies of the Moose Mountain Member of the Morrissey Formation (Gibson, 1985). The upper Mist Mountain Formation is believed to represent a fluvial-alluvial plain.

The Elk valley coalfield is one of three structurally separate coalfields recognized in southeastern British Columbia. They occur in the Front Ranges of the Rocky Mountains, a region characterized by folds and thrust faults.

Geological mapping of the Elk valley coalfield has been carried out over the past several years by the Geological Survey Branch of the British Columbia Ministry of Energy, Mines and Petroleum Resources (Grieve and Pearson, 1983; Grieve and Fraser, 1985; Morris and Grieve, in prep.). As part of this mapping effort, considerable stratigraphic information has been collected. This includes measured stratigraphic sections from fifteen locations, along with detailed logs of ten diamond drillcores (Figure 1). In addition, suites of channel coal samples across the formation have been collected for maceral analysis at selected locations. This paper summarizes this stratigraphic information both qualitatively and quantitatively. Specifically, characteristics of the sections and cores will be described and compared. Variations in maceral composition of coal seams will be outlined. Correlations of coal seams will be proposed within a portion of the study area. Results of numerical modelling of rock type sequences in cores will be described. Final conclusions concerning stratigraphy and sedimentology of the Elk valley coalfield will be contained in a Geological Survey Branch bulletin.

COAL SEAM STRATIGRAPHY

SEAM THICKNESS AND DISTRIBUTION

Figure 2 shows an example of a generalized Mist Mountain Formation section (from Imperial Ridge) in the south part of the study area. As is typical throughout the study area, and in fact all of the southeastern British Columbia coalfields, coal seams occur throughout the entire Imperial Ridge section. Consistent with general trends for the region, the thickest seams are contained in the lower half of the formation.

TABLE 1
SUMMARY OF MEASURED SECTIONS OF MIST MOUNTAIN FORMATION

SECTION NO.	LOCATION	RELATIVE STRATIGRAPHIC POSITIONS		THICKNESS of section (m)	THICKNESS of coal (m)	%COAL
		Base of Section	Top of Section			
1	Weary Ridge	Base of MM	Upper MM	>513	64.0	12.5
2	Coal Creek	Lower MM	Upper MM	>307	29.4	9.6
3	Mt. Veits	Base of MM	Lower MM	127.7	7.6	6.0
4	Mt. Tuxford	Base of MM	Top of MM	550.5	37.5	6.8
5	Burnt Ridge Extension	Base of MM	Upper MM	453.0	40.3	8.9
6	Imperial Ridge	Base of MM	Top of MM	508.2	36.9	7.3
7	Ewin Pass	Base of MM	Top of MM	486.8	43.0	8.8
8	Burnt Ridge	Base of MM	Top of MM	576.4	65.3	11.3
9	Burnt Ridge South	Base of MM	Top of MM	587.0	47.0	8.0
10	Noname Ridge	Base of MM	Top of MM	527.1	44.7	8.5
11	Mt. Michael Lower	Base of MM	Top of MM	422.7	51.6	12.2
12	Mt. Michael Upper	Lower MM	Top of MM	455.1	42.0	9.2
13	Horseshoe Ridge	Base of MM	Middle/Upper MM	311.0	25.2	8.1
14	TeePee Mtn.	Base of MM	Lower MM	22.4	1.2	5.3
15	Crown Mtn.	Base of MM	Lower MM	72.4	5.8	8.0

MM = MIST MOUNTAIN FORMATION

Tables 1 and 2 indicate the percentages of coal and thicknesses of individual coal seams, respectively, contained within the measured sections, while Table 3 provides the percentages of coal contained within the drillcores, corrected to true thicknesses. Coal seams thinner than 1.0 metre are not considered in these summaries.

TABLE 2
SUMMARIES OF DRILLCORE LOGS OF THE MIST MOUNTAIN FORMATION

DRILLHOLE NUMBER	LOCATION	RELATIVE STRATIGRAPHIC POSITIONS		TRUE THICKNESS (m)	THICKNESS of coal (m)	%COAL
		Collar	T.D.			
SR-7	Weary Ridge	Basal Elk	Upper MM	227.7	20.2	8.9
SR-12	Weary Ridge	Middle MM	Lower MM	173.2	22.1	12.8
SR-2	Weary Ridge	Lower MM	Base of MM	140.9	23.1	16.4
BM81-1	Bare Mtn.	Upper MM	Base of MM	496.9	57.7	11.6
BM81-2	Bare Mtn.	Middle/UpperMM	Base of MM	291.4	34.0	11.7
EV-150	Ewin Creek	Lower MM	Base of MM	257.0	25.8	10.0
EV-151	Ewin Creek	Middle/UpperMM	Base of MM	353.6	39.7	11.2
MBE-101	Mt. Banner	Middle MM	Base of MM	290.2	28.7	9.9
EP-105	Ewin Pass	Upper MM	Middle MM	193.8	21.6	11.1
EP-102	Ewin Pass	Middle MM	Lower MM	256.6	40.5	15.8

MM = Mist Mountain Formation

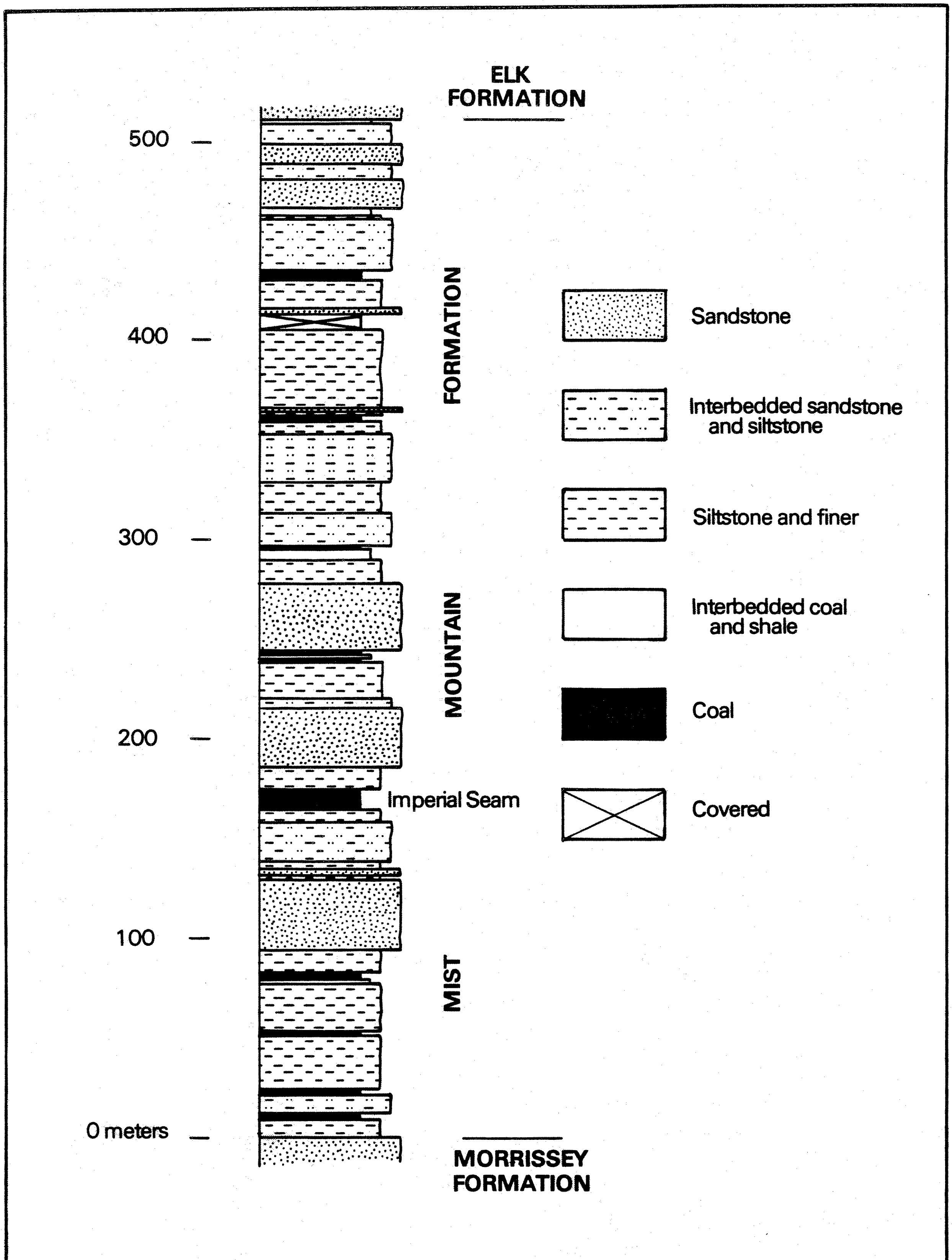

Figure 2. Generalized measured section of the Mist Mountain Formation from Imperial Ridge (section 6).

The measured sections contain an average of 8.7% of their total stratigraphic thickness in coal seams greater than 1.0 metre thick (Table 1), while the drillcores contain an average of 10.4% (Table 3). Part of this difference is likely due to covered intervals in the measured sections. It is apparent from Table 2 that coal seams between 1 and 2 metres in thickness are by far the most prevalent on a numerical basis. In order to gain an understanding of the relative volumes of each thickness category, each percentage value in Table 2 has been multiplied by the mid-point of each thickness range (see last column). Based on this calculation, the seams between 1 and 2 metres thick are still the most important, with the next most important category being those between 5 and 6 metres thick. On a local or site basis, of course, the very thickest seams potentially constitute the greatest volume.

TABLE 3
FREQUENCY OF OCCURRENCE OF COAL SEAMS OF VARIOUS THICKNESSES IN MEASURED SECTIONS OF THE MIST MOUNTAIN FORMATION
(SEE TEXT FOR EXPLANATIONS)

Thickness Intervals (M)	SECTION NUMBERS															TOTALS		CONTRIBUTION TO COMPLETE SECTIONS	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	All Sections	Complete Sections	Percent	Relative Volume
1-2	6	6	3	10	4	1	4	6	7	8	5	8	4	1	2	75	41	42.7	64.1
2-3	2	3	1	4	3	3	1		2		4	6				29	14	14.6	36.5
3-4	4	1			3	4	2	1	2	1		1	1		1	21	10	10.4	36.4
4-5	3	1		1	2		2	1	1	2	2		1			16	9	9.4	42.3
5-6		2		2		1	1	1	1	1	2		1			12	9	9.4	51.7
6-7	1							1			1		1			4	2	2.1	13.7
7-8	2				1			1	1	1		2				8	3	3.1	23.3
8-9								1	1	1						3	3	3.1	26.4
9-10											1					1	1	1	9.5
10-11						1		1								2	2	2.1	22.1
11-12								1								1	1	1	11.5
12-13																			
13-14							1									1	1	1	13.5

SEAM COMPOSITION TRENDS

Maceral analysis of channel samples collected during the course of field mapping is not yet complete. Results for sampled seams from throughout only two measured sections, Weary Ridge (1) and Coal Creek (2), will be discussed here. Their vitrinite contents are displayed in Figure 3.

Vitrinite is the most abundant maceral in all samples analysed. It ranges from 60.0 to 93.3% (average 81.2%) of the total of the Weary Ridge seams, and from 67.0 to 85.3% (average 77.0%) of the Coal Creek seams (Figure 3). Liptinite is essentially nonexistent in the Weary Ridge seams, but ranges from 1.0 to 6.7% (average 4.0%) of the Coal Creek seams. The relatively high liptinite content of the Coal Creek seams is almost certainly due to the relatively low rank of coals in the Coal Creek area (high volatile A bituminous) compared with the Weary Ridge area (low and medium volatile bituminous; Grieve, 1987). Semifusinite is the most common of the inertinite macerals in all samples, ranging from 3.7 to 29.3% (average 13.9%) of the Weary Ridge seams, and from 8.3 to 19.0% (average 13.7%) of the Coal Creek seams (Figure 3). It shows a strong inverse relationship with vitrinite contents. Fusinite and macrinite contents are low, with combined averages of 0.75 and 0.35%, respectively. Other inerts, chiefly inertodetrinite, comprise a combined average of 3.9% of all seams.

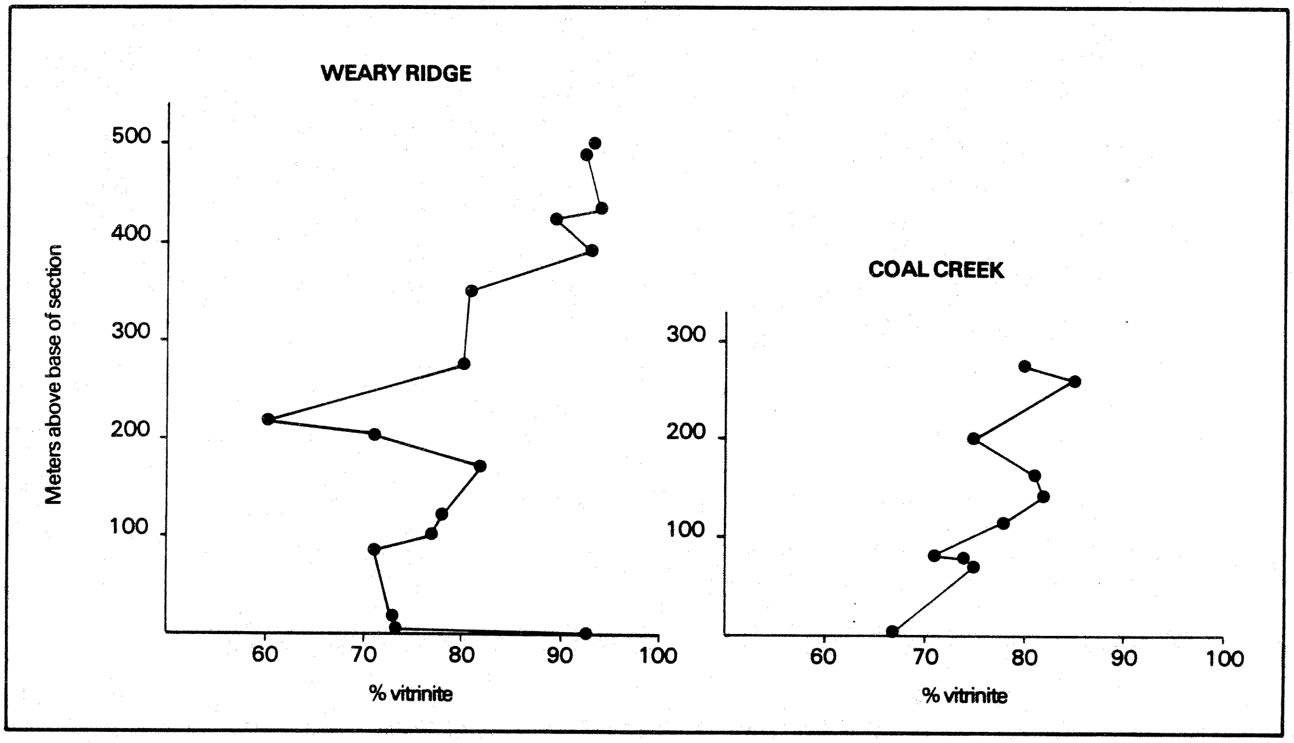

Figure 3. Variations in vitrinite composition with stratigraphic position in channel samples from Weary Ridge (section 1) and Coal Creek (section 2).

Stratigraphic trends in maceral composition of Mist Mountain Formation coals have been pointed out previously by Cameron (1972) and Pearson and Grieve (1985). In particular, a general trend of increasing vitrinite content, with corresponding decrease in inertinite content, is known to occur upward in the stratigraphic section. Vitrinite contents for the Weary Ridge and Coal Creek sections (Fig. 3) confirm this general trend. The very high vitrinite content of the seam which occurs at the extreme base of the formation at Weary Ridge appears somewhat anomalous, but confirms previous evidence that the lowest seam is not usually the most depleted in vitrinite (Cameron, 1972).

SEAM CORRELATION

With the exception of the carbonaceous zone which occurs at the base of the Mist Mountain Formation in most

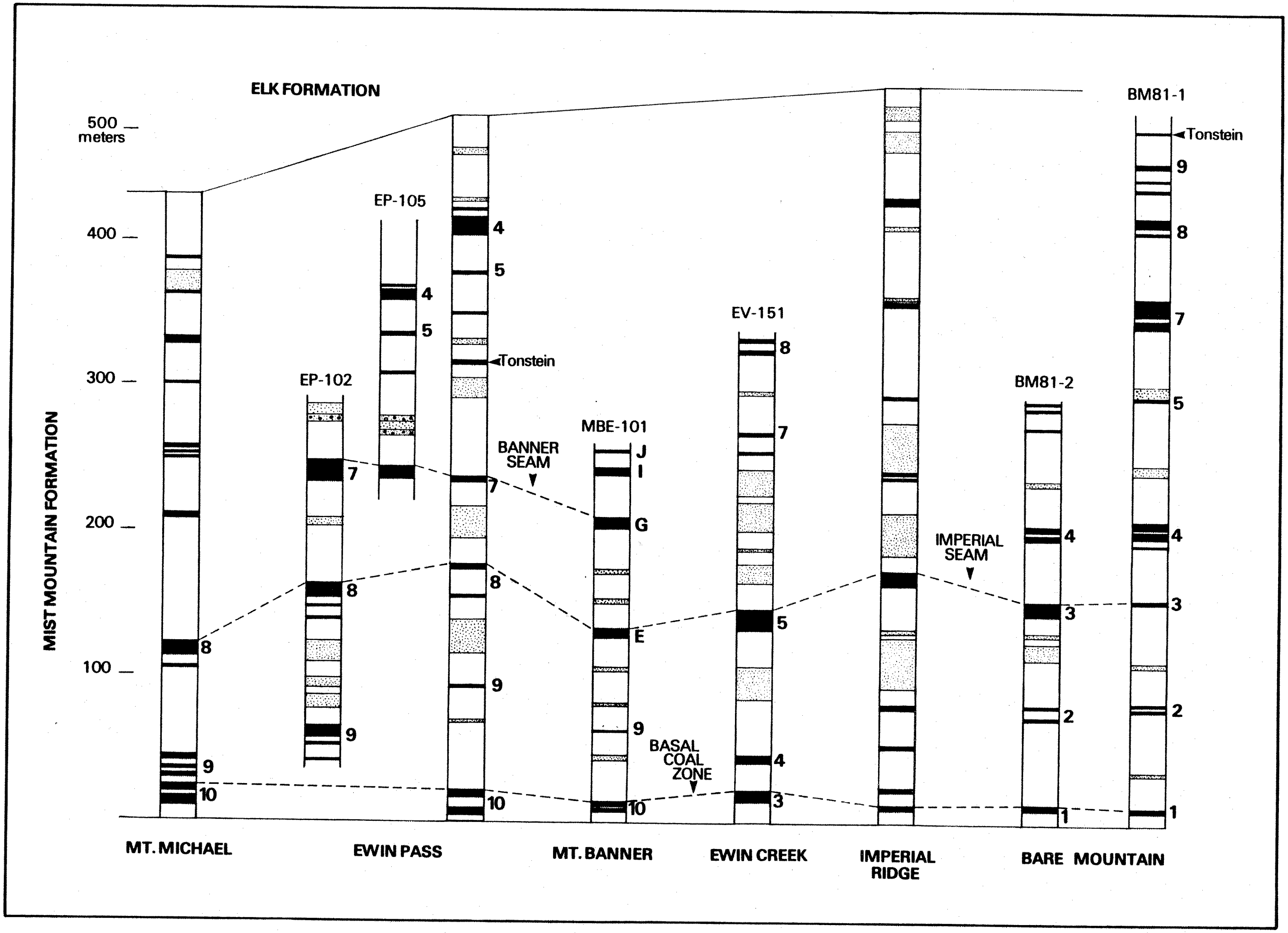

Figure 4. Idealized drillcore logs and measured sections from the Mist Mountain Formation in the south half of the Elk valley coalfield, with proposed seam correlations indicated.

areas (Gibson, 1985), regional correlation of coal seams and other strata of the Mist Mountain Formation is difficult. This is related to pronounced facies variations, and the lack of known regionally extensive markers. This problem is compounded by structural complications. On a local scale, seam correlation is carried out using any of a variety of methods, including geological mapping, seam tracing, visual recognition of coal seams based on physical characteristics, characterization of seams based on analytical parameters, and geophysical log interpretation. Grieve (1984) reported the occurrences of two instances where tonsteins were used to correlate coal seams a distance of 1.4 kilometres (see below).

An attempt at more regional correlation is described here. Figure 4 shows simplified versions of six of the core logs and three measured sections, along with one definite and two proposed seam correlations. These are discussed briefly below. These correlations are based on relative stratigraphic postions, relative seam thicknesses, nature of roof and floor rocks, and geophysical log signatures.

Basal coal zone

The only firmly established correlation shown in Figure 4 is that of the basal carbonaceous zone of the formation. It has been informally referred to as the "basal coal zone" (Grieve and Elkins, 1986). It rests directly on the Morrissey Formation, but its upper contact can not be rigidly defined. Although correlation of this zone is self-evident, it is worth discussing for two reasons. First, this zone contains important reserves of coal in southeastern British Columbia. Second, there are considerable differences in its appearance, even in closely-spaced holes.

The lowest approximately 20 metres of the Mist Mountain Formation section of each drillcore which contains the base of the formation is plotted in detail in Figure 5. Each example contains at least two separate coal seams. In most cases a coal seam rests directly on the Morrissey Formation. The thicknesses and positions of individual coal seams vary widely between different holes, even in the cases of the closely-spaced pairs EV-150 and EV-151, and BM81-1 and BM81-2. The interbedded strata within the basal coal zone are mainly shales and shale-dominant intermixed shale and sandstone units. They are massive to well laminated, and may be rooted, burrowed, and/or distorted. Coal banding and coal spar are also very common features, especially in proximity to coal seams. The strata immediately overlying the basal

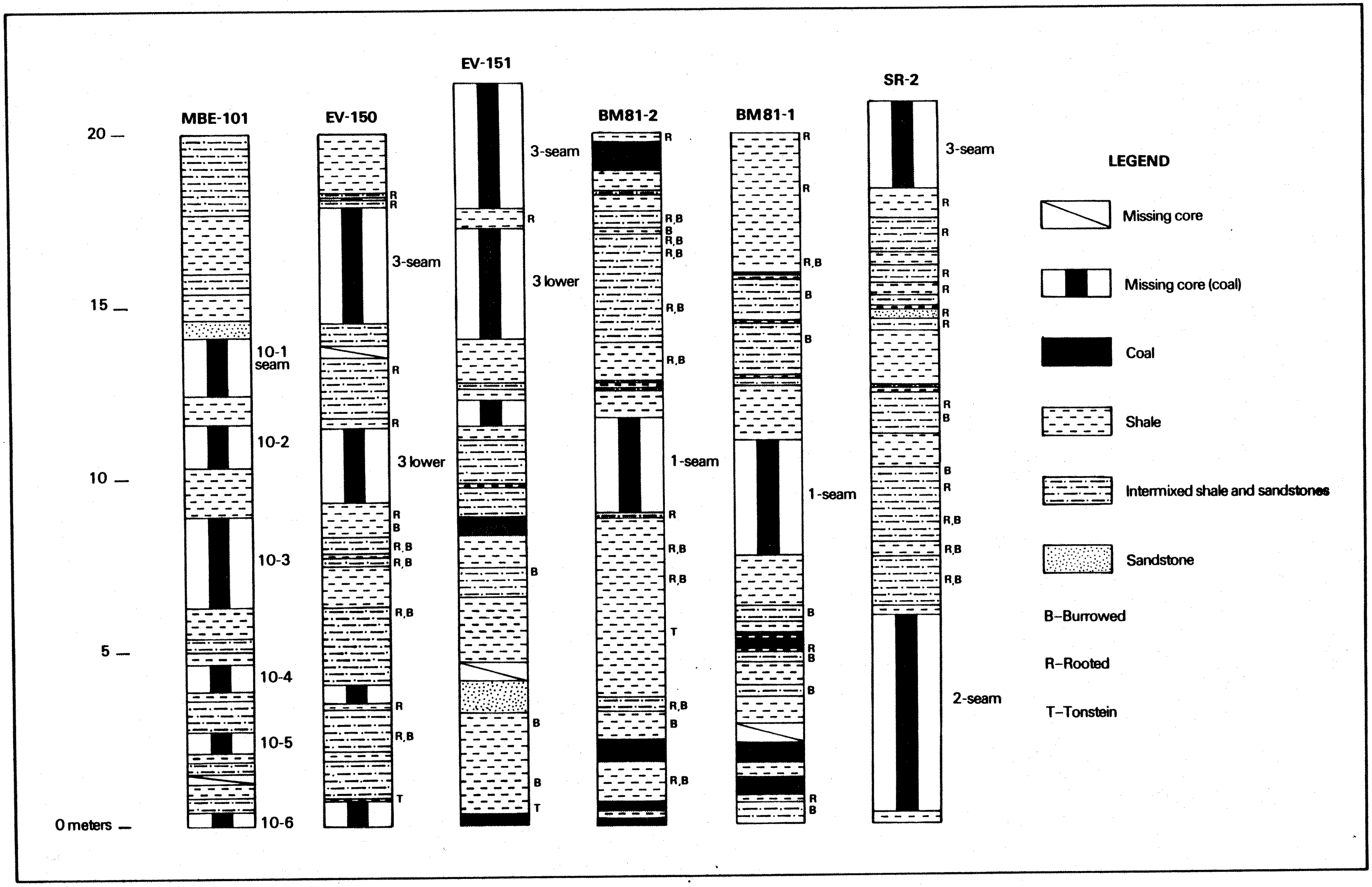

Figure 5. Comparison of drillcore logs from the basal coal zone of the Mist Mountain Formation.

coal zone are also fine grained and are not distinguishable from clastic rocks within the zone.

Imperial coal seam

The name Imperial seam was applied to the thickest seam in the Imperial Ridge measured section (Figure 2), north of Ewin Creek (Grieve and Fraser, 1985). The same seam is known to occur in drillholes EV-150 and EV-151 on Ewin Creek, where it is referred to as 5-seam (Figure 4). Moving to the south, the Imperial Seam is tentatively correlated with E-seam in core MBE-101 from Mt. Banner, and with 8-seam in core EP-102 and in the Ewin Pass measured section (Grieve and Elkins, 1986). Based on mapping and seam tracing, the Imperial seam can also be identified in the Mt. Michael lower sheet measured section (Figure 4). North of Imperial Ridge, the Imperial seam is believed to correlate with 3-seam in drillholes BM81-1 and BM81-2 on Bare Mountain. The overall strike length of this correlation is approximately 17 kilometres.

In all cases, the seam is thick and is mainly devoid of shale partings. It has similar roof rocks throughout (mainly a carbonaceous shale) and a similar geophysical response (Grieve and Elkins, 1986).

Banner seam

The term Banner seam is introduced here to represent 7-seam in drillholes EP-102 and EP-105 and the Ewin Pass measured section, and G-seam in drillhole MBE-101 on Mt. Banner (Figure 4). This seam is believed to have been washed out by the stream which deposited the thick sandstone units between 5-seam and 7-seam in drillhole EV-151 on Ewin Creek. It may correlate with 4-seam in drillholes BM81-1 and BM81-2 on Bare Mountain, but this is highly speculative.

Tonsteins

Tonsteins have been recognized in Mist Mountain Formation strata for some time (Mériaux, 1972; Grieve, 1984; Grieve and Elkins, 1986; Gibson, 1985; Goodarzi et al., in prep.). To date they have not proved to be useful regional correlation tools. As mentioned above, two instances of tonsteins extending over 1.4 kilometres were noted by Grieve (1984). One example was a distinctive band found in a thin coal seam between 7-seam and 5-seam on the Ewin Pass property (Figure 4). The other was a group of distinctively coloured bands in the roof of 10B-seam from the basal coal zone from Line Creek Ridge, which hosts Line Creek Mine. In both cases, microscopic and macroscopic features were used in conjunction with mineralogy and geochemistry to confirm correlations made on stratigraphic evidence. During core logging involved in this study, a few tonstein bands were found (see Figures 4 and 5), but regional correlation using tonsteins was not achieved. In part, this failure may have been due to the fact that most coal core had been removed from core boxes for analysis. A summary of information known about tonsteins in the Mist Mountain Formation in southeastern British Columbia can be found in Goodarzi et al.(in prep.).

NUMERICAL SEQUENCE MODELLING

Statistical analysis of lithological sequences in drillcores of the Elk valley coalfield was carried out. An embedded, first-order Markov chain analysis was used. This method is based on a test of the assumption that the occurrence of a particular unit at any given position within the stratigraphic column is dependent on the nature of the immediately underlying unit. The list of eight rock-type codes used in the analysis is given in Table 4.

TABLE 4
ROCK-TYPE CODES USED FOR MARKOV ANALYSIS OF DRILLCORE LOGS
(DERIVED FROM RUBY ET AL., 1981)

Code	Explanation
CGL	Conglomerate. Generally chert pebble composition.
SAND	Sandstone. Generally medium to very coarse grained. May be massive, flat bedded, or cross bedded.
SS>SH	Intermixed shale and sandstone, with sandstone in greater abundance than shale. Includes flaser-bedded sandstone, and wavy-bedded sandstone with interbedded shale. Sandstones generally fine grained.
SS=SH	Intermixed shale and sandstone, with both in roughly equal amounts. Predominantly lenticular bedded sandstone with interbedded shale. Sandstone generally fine or very fine grained.
SH>SS	Intermixed shale and sandstone, with shale in greater abundance than sandstone. Includes shale with lenticular sandstone streaks, and sandy shales. Sandstone generally fine or very fine grained.
SHALE	"Shale series". Generally non-carbonaceous, grey siltstone, silty mudstone or mudstone. May be massive or laminated.
C-SHL	Carbonaceous shale. Generally dark grey to black mudstone or shale with coal streaks, bands or spar.
COAL	Coal series. Most often missing from core. Where observed it includes banded coal, dull massive coal, and coal with shale interbeds or streaked with shale.

METHODS OF STUDY

The core log database file was converted to an ASCII file consistent with the CAL DATA software used in the analysis. Certain modifications to this latter database file were made prior to statistical analysis. Most notably, all transitions from a specific rock type to the same rock type were eliminated. This was necessary because the type of Markov chain analysis employed (embedded) is based on changes in lithology, irrespective of unit thickness. Another modification was selection of only Mist Mountain Formation units.

The modified database, which contains 3707 legitimate transitions, was then subjected to statistical analysis. The statistical computer programs developed and described by Kilby (in Kilby and Oppelt, 1985) were used. The first step in the procedure is generation of a count transition matrix which displays the number of occurrences of each possible type of upward transition in the data. Next, an expected matrix is generated, which represents the number of upward transitions of each type which would occur in a totally random sedimentary sequence containing the same quantities of the various rock types. The difference matrix is then generated by subtracting the second matrix from the first. Unfortunately, space here does not permit display of the matrices. However, they may be found in Grieve (in press).

The difference matrix identifies which upward transitions occur more frequently than at random, i.e., those which are represented by positive values. Values in the difference matrix can be misleading, however, as the rock types which are most common in the database potentially have the largest difference values associated with them. To provide a more balanced analysis of the difference matrix, it is necessary to convert the positive frequency values in the difference matrix to probabilities (percentages in this case) based on the total number of transitions each unit is involved in.

The probability difference matrix was converted to graphic form for easier interpretation (Figure 6). All positive upward transitions in the matrix, except those below an arbitrary cut-off of 1%, are displayed as an arrow connecting the two lithologies. The positions of the various lithologies on the diagram were selected to simulate a general fining-upward sequence and to show the upward transitions in as simple a manner as possible.

The count transition matrix was tested for the Markov property by means of a chi-square test. In this application, rejection of the null hypothesis implies that the transitions observed are dependent to a significant degree (not random) and thus form a Markov chain.

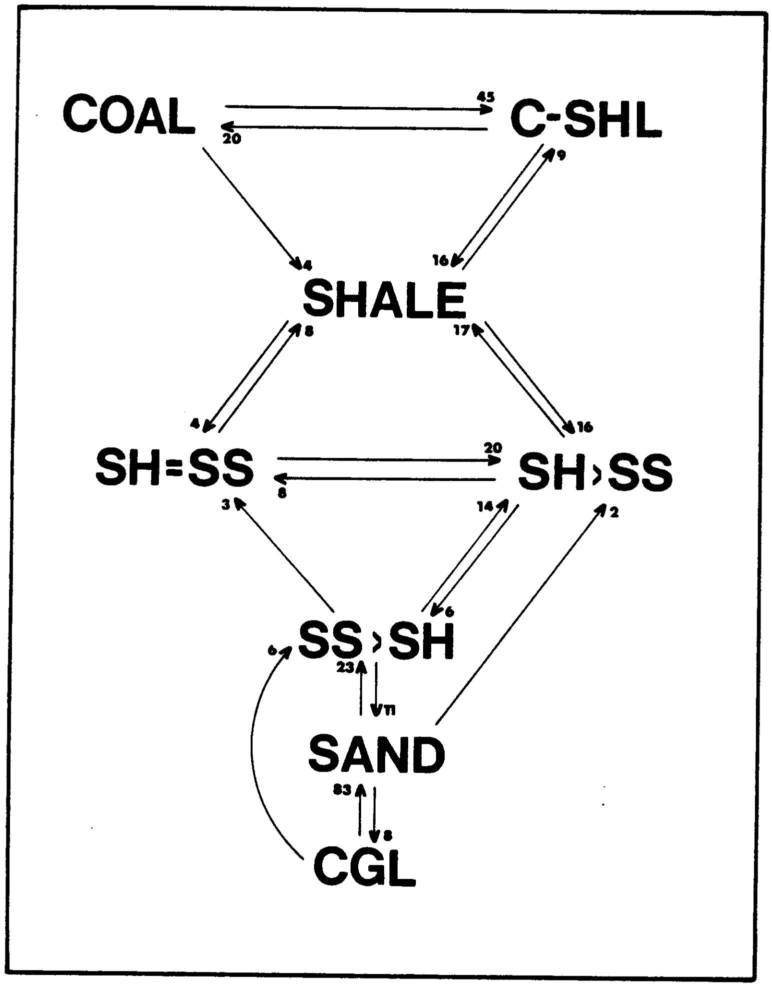

Figure 6. Transition diagram based on Markov analysis of Mist Mountain Formation sediments in drillcores. Numbers represent positive values in the difference matrix converted to percentage probabilities. Values less than 1% are not plotted. See text for explanation.

The process was repeated twice, once for each of two subsets of the database. The first represents all strata within 200 metres of the base of the Mist Mountain Formation, and the second represents strata more than 200 metres above the base. The first contains 2216 transitions and the second contains 1485 transitions. These were generated to see if there are any sedimentological differences between the lower and upper parts of the formation in the study area.

RESULTS

Starting at the base of the transition diagram (Figure 6), CGL, although a rare rock type, shows a very strong trend (83% probability) to be overlain by SAND. SAND is most likely to be overlain by SS>SH (23%). SS>SH is most often overlain by SH>SS (14%), but is nearly as likely to be overlain by SAND (11%). SS=SH tends to be overlain by finer units, either SH>SS (20%) or SHALE (8%). SH>SS is most likely to be overlain by SHALE (17%), but is also overlain by coarser rock types SS=SH (8%) and SS>SH (6%). SHALE shows a trend to be overlain by the coarser rock type SH>SS (16%), but also may be overlain by C-SHL (9%). C-SHL shows roughly equal likelihood of being overlain by SHALE (16%) or COAL (20%). COAL is most likely to be overlain by C-SHL (45%).

The chi-square test of the transition matrix for the Markov property yielded a value of 452,321. This represents a very strong rejection of the hypothesis that the observed rock-type transitions are produced by random events.

DISCUSSION

Fluvial sediments in general can be subdivided into those derived from point bar deposition and those deposited in the floodplain (Walker and Cant, 1984). In the Mist Mountain Formation the point bar environment is represented by prominent fining upward "channel" sandstone bodies, which consist predominantly of medium-grained or coarser sandstone, along with rare conglomerate, which forms as basal channel lag deposits, and fine and very fine-grained sandstone to siltstone in the upper parts.

The floodplain environment in the Mist Mountain Formation, which is the more common, includes levee, crevasse splay and flood basin deposits (Gibson, 1985). As pointed out by Dunlop and Bustin (1987), levee deposits are difficult to recognize in the Mist Mountain Formation, especially in vertical sections, and may be indistinguishable from crevasse splay deposits. All rock types finer than and including fine-grained sandstone are included in the floodplain environment, with the finest units deposited in the flood basin.

These results confirm a fining-upward depositional sequence with sandstone (or conglomerate) at the base and coal at the top, with numerous combinations of transitional events possible within the sequence. For example, CGL (channel lag) is nearly always overlain by SAND. SAND is overlain by an intermixed sandstone and shale unit, usually SS>SH. Interestingly, the direct fining upward transition from SAND to SHALE is not observed to a significant degree. If SAND is assumed to be the characteristic component of a point bar deposit, and SHALE is taken as the major component of the flood basin deposit, then it is apparently not possible to make the transition from the one environment to the other without the intermediate lithologies. This suggests that either the intermixed sandstone and shale rock-types are an integral part of the upper portions of point bar deposits, or that another floodplain environment must first be "passed through" before reaching the flood basin. The possibilities for the latter suggestion are levees and crevasse splays, which, as was pointed out earlier, are difficult to distinguish. The intermixed sandstone and shale rock-types are expected to be characteristic of both (Dunlop and Bustin, 1987).

Deposition of distal crevasse splay deposits on the floodplain is believed to have occurred in the instances where intermixed shale and sandstone units, either SS=SH or SH>SS, directly overlie SHALE. These results suggest that this is more likely to occur than the transition from SHALE to the carbonaceous units, C-SHL and COAL. Interestingly, COAL only occurs overlying C-SHL to a significant degree, suggesting a gradual transition to the coal-forming environment, and perhaps suggesting a relatively isolated environment for coal deposition. COAL is most often overlain by fine grained units, either C-SHL or SHALE, suggesting that coal deposition is terminated by invasion of flood basin sediments, perhaps related to increased rate of subsidence in the swamp.

The results for the lowest 200 metres of the Mist Mountain Formation and the overlying portion of the formation are not shown here. However, they are in general similar to those for the whole formation, and need not be described in detail. Moreover, the results for the two subsets of data are not markedly different from each other, suggesting that the same depositional processes apply to both.

ACKNOWLEDGEMENTS

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STRUCTURAL STYLE OF COAL MEASURES IN THE SOUTHEASTERN CANADIAN CORDILLERA

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ABSTRACT

The structural style of coal measures of the Kootenay Group in the southeastern Canadian Cordillera has a marked affect on the mineability and quality of the coal. Coal measures throughout the southeastern Cordillera are similarly characterized by pervasively sheared and comminuted coal. However, the overall style (geometry) of the coal measures displays considerable variation which reflects the amount of shortening by folding and faulting and the nature of the stratigraphic succession. In the Vicary Creek-Dutch Creek areas on the Coleman thrust plate the coal measures comprise near monoclinal panels repeated by high to low angle splays of the Coleman thrust fault. The coal seams and carbonaceous mudstones were the locus of intrastratal slip and are extensively sheared and comminuted and very markedly in thickness. At Tent Mountain the coal measures are characterized by broad to tight concentric-flexural-flow folds which have been cut but high angle thrust faults which for the most part post-date major folding. Coal Mountain is characterized by structurally stacked, rotated thrust faults, which were active early in the deformational history and flexural-flow folds that were flattened during buckling. The oldest thrust faults, at the top of the stack, are the most tightly folded whereas progressively younger faults, lower in the stack, are more open. Progression from old tightly folded thrust to less tightly folded thrusts suggests that thrust faults active early in the deformational history became locked during folding leading to propagation of younger and lower thrusts. At both Tent Mountain and Coal Mountain major thickening of coal occurs in the hinge areas of synclines and to a lesser extent, anticlines. The thickening of the coal has been accommodated by cataclastic flow of the coal from the limb areas to the hinge and, at least in some structures, there is evidence for transport of coal along the fold axis.

INTRODUCTION

In the western Canadian Cordillera the structural style of the coal measures has marked effect on the mineability and quality of coal. Because of the recessive nature of the coal measures and (commonly) complicated structure and stratigraphy, detailed structural mapping and stratigraphic analysis required for mine development requires extensive drilling and trenching. In order to develop structural models of the coal measures, three areas of contrasting structural styles in the southeastern Canadian Cordillera have been mapped in detail with particular emphasis on documenting the kinematic and dynamic evolution of the coal measures in different tectonic settings. This paper briefly outlines the structural style of the coal measures of the Kootenay Group and presents some general observations and conclusions concerning the mechanical behavior of the coal during deformation and its implication on overall style. This paper is a precis of a lengthier article in preparation from which the cross-sections presented here have been taken (Bustin, in preparation).

BACKGROUND AND METHODS

In the southeastern Canadian Cordillera major resources of high quality coking and thermal coal of bituminous rank occur in the Mist Mountain Formation of the Kootenay Group (Gibson, 1985). The Kootenay Group is a major easterly thinning clastic wedge of Late Jurassic-Early Cretaceous age in the southeastern Canadian Cordillera. The Mist Mountain Formation is the main coal-bearing unit in the Kootenay Group and locally includes more than 15 economically important coal seams which range up to 20 m in stratigraphic thickness (Gibson, 1985). The Mist Mountain Formation is an entirely nonmarine interval (Gibson, 1985) that conformably overlies the Morrissey Formation, and in the Crowsnest and Elk coalfields, is conformably overlain by the Elk Formation.

The age of the Mist Mountain Formation has not been precisely determined although it is considered to be Late Jurassic to Early Cretaceous (Gibson, 1985). The stratigraphy and sedimentology of the Kootenay Group has been the subject of many studies because of the economic potential of the coal and long history of mining (see summary by Gibson, 1985; Dunlop and Bustin, 1987). The Mist Mountain Formation for the most part is poorly exposed which, coupled with sparse subsurface information, has severely handicapped detailed geological studies. In and around coal mine sites however, road cut, pit faces and exploration drill holes provide excellent control for detailed mapping and for observation and measurement of mesoscopic fabric elements.

This paper is based on detailed mapping of three areas of contrasting structural style (Fig. 1): the Vicary Creek-Dutch Creek area north of Coleman, Alberta; Tent Mountain on the Alberta-British Columbia border north of Corbin; and Coal Mountain, near Corbin, British Columbia. The three areas were selected based on access to surface exposures, mine records and availability of drill hole logs. Many of the ideas presented in this paper have evolved from discussions with coal mine geologists and access to their interpretations and their experience is gratefully acknowledged.

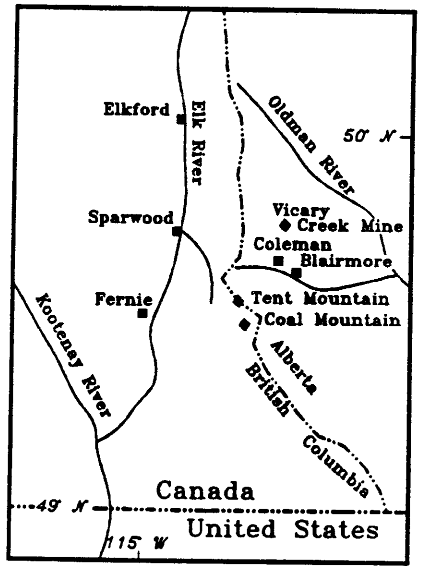

Figure 1. Index map to the study area showing the location of the Vicary Creek, Coal Mountain and Tent Mountain coal mine areas.

VICARY CREEK-DUTCH CREEK

In the area between Vicary Creek and Dutch Creek, north of Coleman Alberta, the Mist Mountain Formation occurs in the immediate hanging wall of the Coleman Fault, a major west dipping thrust with a stratigraphic separation of about 2200 metres and a lateral throw estimated to be 22 kilometers (Price, 1972). The Mist Mountain Formation is about 250 m thick and comprises a sequence of thick to thin bedded fine- to medium- grained quartz arenites, dark colored and variably carbonaceous mudstones and siltstones and two or three seams of medium volatile bituminous coal. The Belly River Formation occurs in the footwall of the Coleman Fault and locally, adjacent Vicary Creek and to the north of Dutch Creek, horses of Crowsnest Volcanics occur in the fault. The Mist Mountain Formation throughout the map area is predominantly planer and dips variably steeply to gently to the west and strikes northerly. Locally major to minor splays of the Coleman Fault repeats the Mist Mountain Formation and intrastratal peels occur in the footwall of these faults.

A coal seam, locally referred to as the Number 2 seam has been mined from Vicary Creek north to South Racehorse Creek. The mine operations have been underground room and pillar operations with the exception of the Racehorse Strip mine. The #2 seam throughout the mined area and in the mapped area further north pinches and swells, ranging in thickness from 0.5 to about 10 m and averages about 5 m in thickness. Although some of the variation in thickness may be depositional, the associated

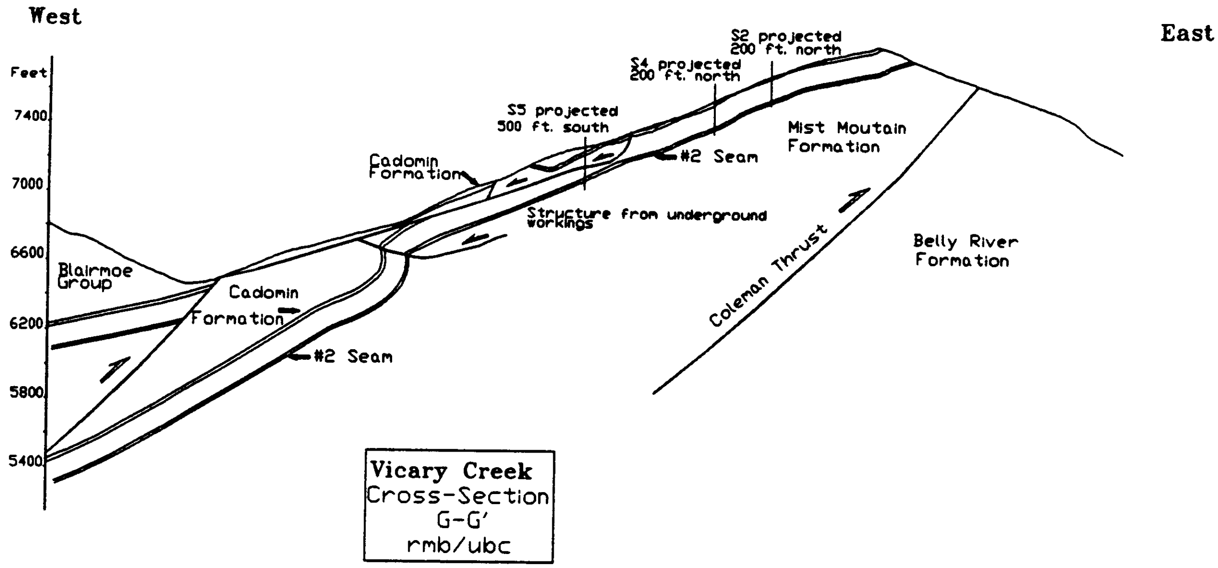

Figure 2. Vicary Creek-Dutch Creek Area. Cross-section from just north of the Vicary Creek mine portal. The coal seam geometry is based largely on underground workings.

structures and character of the coal indicate that it is mainly structural.

Structural Style:

The structural style of the coal measures in the Vicary Creek-Dutch Creek area is dictated by thick competent sandstone units and incompetent coal seams and carbonaceous partings. The general overall geometry of the formation is one of planer monoclinal panels, locally repeated by splays of the Coleman Fault with associated footwall intrastratal peels (Figs. 2,3). The minimum amount of shortening of the coal measures across the map area is approximately 10% based on detailed cross-sections. Within the monoclinal sequences there is considerable evidence for intrastral slip within the coal seams or along carbonaceous horizons. Slickenside striae are pervasive in the immediate roof and floor and within the coal seams and contraction and extension faults commonly offset the seams and small folds and flexures are common within the roof rock. Contraction faults lie in h0l (terminology of Sander, 1942), rise out of surfaces of intrastral slip along the hanging wall of coal seams or carbonaceous partings, cut up section at angles of 10 to 35^{o} and pass into other surfaces of intrastral slip. The extension faults lie in hkl, have offsets from several centimeter to several metres and cut bedding at preferred angles of 40 to 60^{o}.

The #2 seam is highly comminuted and has been the locus of intrastratal slip. Axis of rotation of slickenside striae on bedding surfaces and contraction faults define a mean

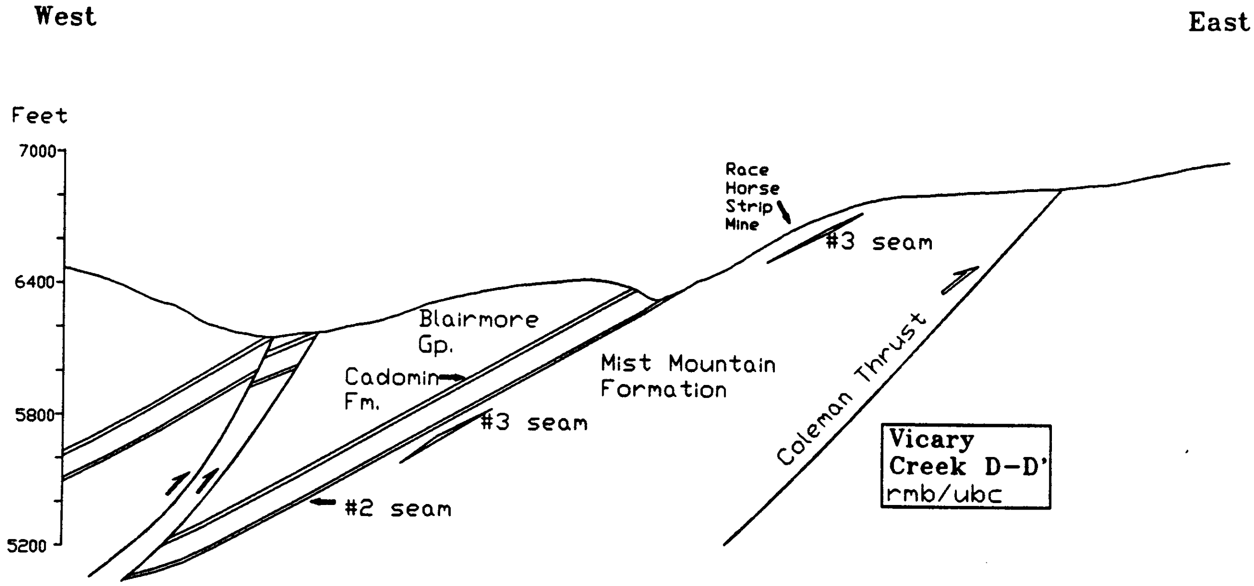

Figure 3. Vicary-Creek-Dutch Creek Area. Cross-section from south of south Race Horse Creek.

kinematic b axis during slip which is nearly horizontal and close to parallel to the b kinematic axis of the coal measures. The direction of motion during slip inferred from the slickenside striae, dip of contraction faults and drag and parasitic folds provide evidence for offset of successively higher strata to the east. Offset of older extension faults by intrastral slip and contraction faults is evident in outcrop and in underground workings (Norris, 1958; Bustin, 1982). The axis of rotation of these older extension faults cumulatively do not define a preferred axis of slip.

In the region directly north of Vicary Creek there is evidence for a late stage of westerly directed thrusting as a result of gravitational sliding (Fig. 2). A number of drill holes and the mine workings established the presence of a easterly dipping contraction fault which has resulted in drag folding of the #2 seam. The strata above the area of gravity sliding are extended and brecciated and large, currently active exposed fractures up to 10 m in length and 1 metre in width, provides evidence for ongoing deformation.

TENT MOUNTAIN

At Tent Mountain located on the British Columbia-Alberta border north of Corbin Alberta, the Mist Mountain Formation is on the order 650 m thick (Fig. 1). Tent Mountain occurs in the hanging wall of the Lewis Thrust sheet and on the eastern margin of the Fernie synclinorium. Here the Mist Mountain Formation comprises thin to thick bedded sandstones, dark, locally carbonaceous siltstones and shales, rare conglomerates and nine major seams of bituminous coal. Also of structural importance at Tent Mountain is the presence of thick (about 60 m) massive sandstones of the Morrissey Formation directly underlying the Mist Mountain coal measures.

Structural Style:

The structural style of the coal measures at Tent Mountain is dominated by broad upright to tight and overturned concentric folds cut by two moderate to high angle west dipping reverse faults with stratigraphic separations ranging from 100 to 600 m and several minor reverse faults. The major thrust faults climb progressively up-section to the north and, although locally ramps and flats exist, steepen to the east. The folds for the most part appear to be younger then major thrust faults that cut them. The folds are flattened possible as a result of thrust faulting or alternatively thrusting may have been initiated as a result of room problems resulting from flattening late in the buckling history of the folds. The marked contrast in competency between the thick sandstone units within the coal measures and the Morrissey Formation at the base of the Mist Mountain Formation and the coal seams and carbonaceous shales imparts a distinctive structural style to their mesoscopic structures. Coal is for the most part comminuted (sheared) and slickensided and in many localities there is evidence for cataclastic flow of the coal towards synclinal or anticlinal hinges giving rise to structurally thickened hinges and thinned limbs. Coal locally has been injected into fault zones. The folds are geometrically defined as type 1C and have amplitude to wavelength ratios on the order of 0.1. The minimum amount of shortening across Tent Mountain, although variable, averages about 55%. Small scale extension and contraction faults with displacements on the order of centimeters to a few metres pervade the coal measures and sandstones are fractured. Drag folds with amplitudes of a few metres are commonly developed in the coal seams adjacent major thrusts.

The kinematics of deformation of the coal measures was studied in detail in three separate open pit exposures (Bustin 1979, Bustin in preparation). The most demonstrative exposure is the 4-pit structure (Fig. 4 and 5). Here a major south plunging syncline is cut by a moderate to high angle west dipping thrust fault with a stratigraphic separation of about 600 m at the level of outcrop (pit face) and a displacement on the order of several kilometres. The fault cuts abruptly down section to the south (Fig. 6) where only the eastern limb of the syncline is preserved. The 4-pit syncline has been in part faulted out by the over-riding thrust and has been flattened. The mesoscopic structures of the syncline are varied and reflect flexural-slip

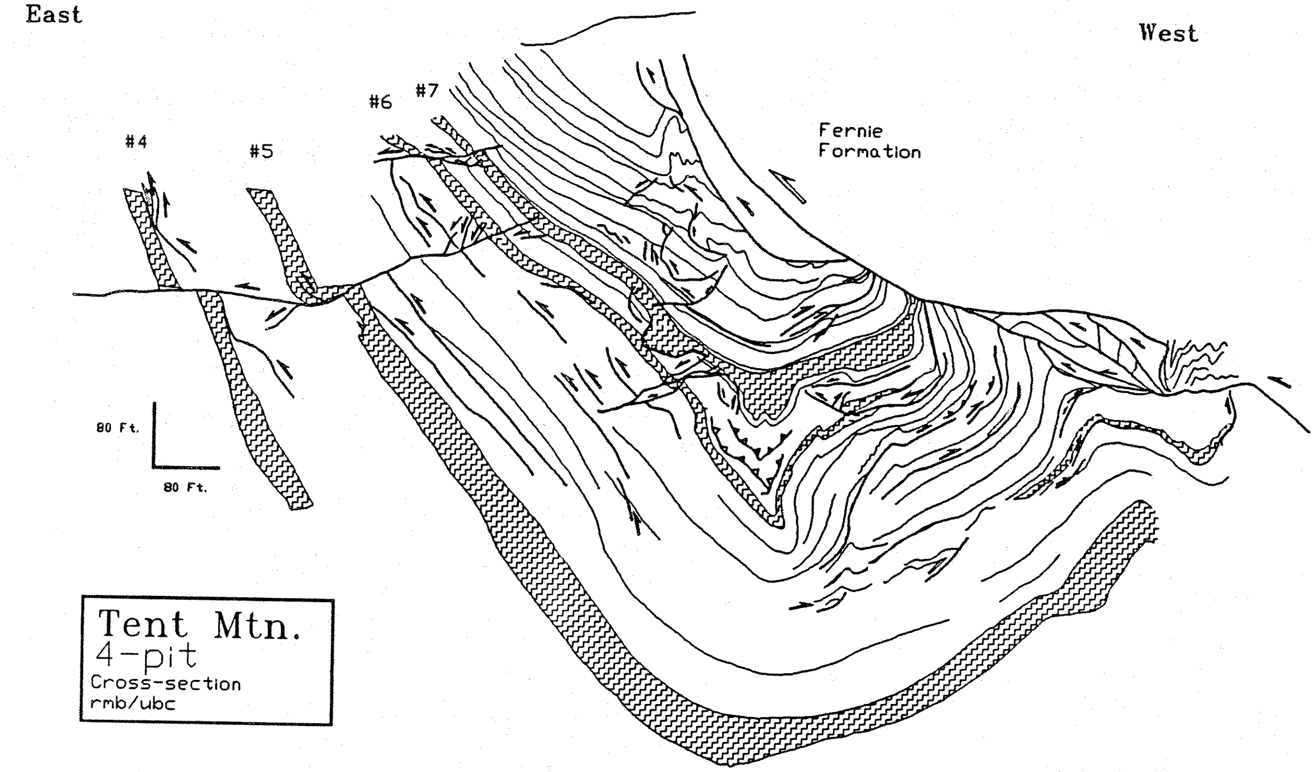

Figure 4. Plane table map (cross-section) of the 4-pit structure. The hatched areas are the major coal seams. The mesoscopic fabric elements from the structure are detailed in Bustin (in preparation).

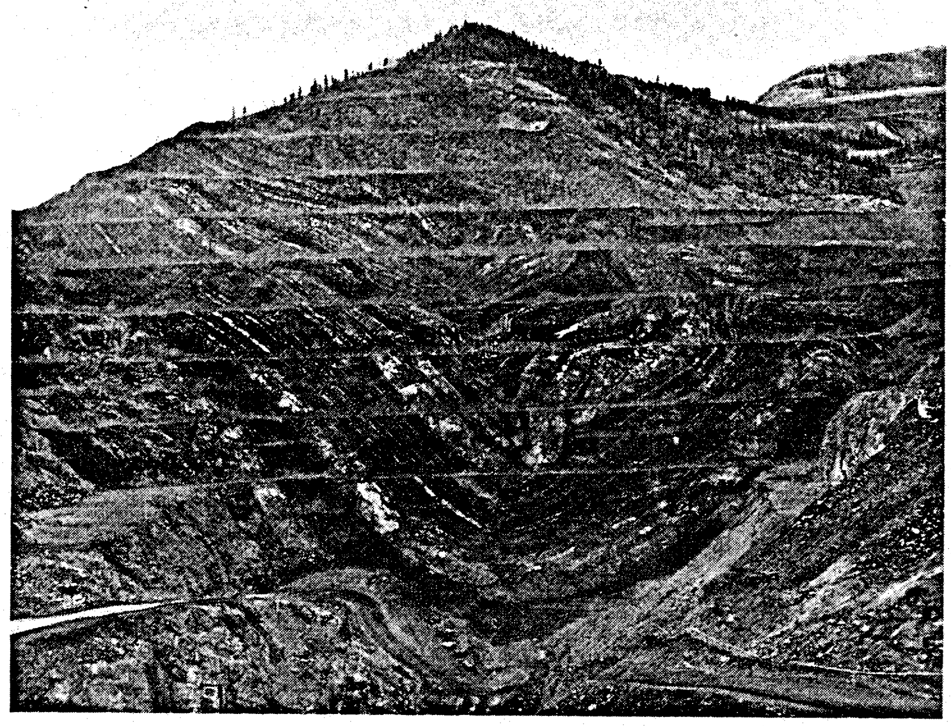

Figure 5. Photography (looking south of 4 pit Tent Mountain shortly after mining was completed and prior to reclamation and flooding.

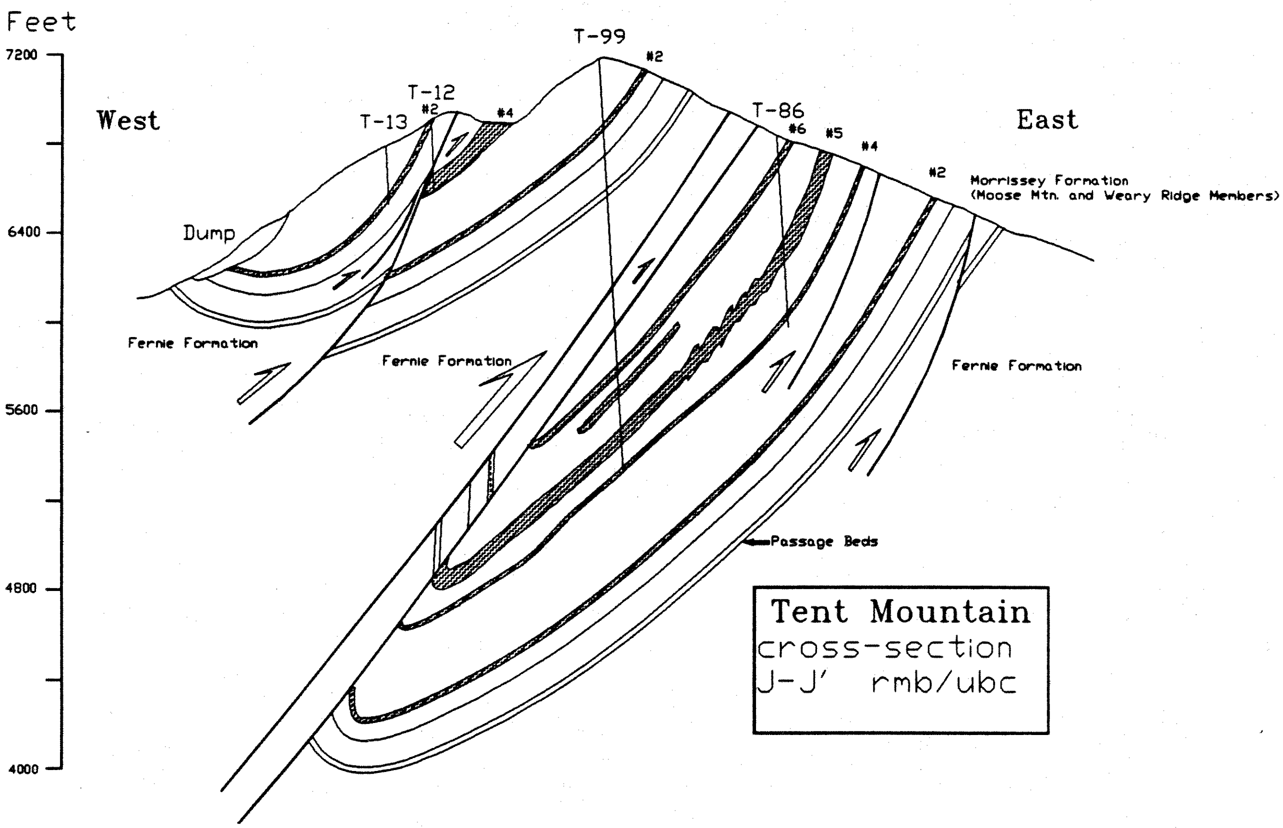

Figure 6. Cross-section from southern Tent Mountain. Here the west limb of the 4-pit syncline is faulted out.

folding between competent layers and flexural flow folding of incompetent strata. Contraction and extension faults are common on both limbs of the syncline. The faults commonly rise out of surfaces of intrastratal (flexural) slip, cut across several beds, either up (contraction) or down (extension) section and then pass into other surfaces of intrastratal slip. North-trending, east-dipping extension faults with displacements of 0.5 to 5 m cut obliquely across the syncline. An additional set of faults strike obliquely to perpendicularly across the fold axis and are arranged more or less symmetrically about the axial surface. These faults give rise to extension or contraction in the plane of bedding. Coal seams in the syncline are pervasively comminuted (sheared) and are structurally thickened and thinned with all the major seams being thicker in the hinge area and thinner in the limbs of the syncline.

The axis of rotation of slickenside striae on bedding surfaces show a strong preferred orientation which is near horizontal and parallel the syncline axis. Many of the contraction faults are cozonal with and rise out of surfaces of intrastratal slip. The direction of preferred motion inferred from the slickenside striae and dip direction of contraction faults indicate movement of the hangingwall strata out of the hinge zone of the syncline, consistent with flexural slip folding. In addition to the well defined kinematic-b axis of slip (consistent with flexural slip), there is a large scatter of slip axes that have no readily apparent geometric significance.

In this latter group are a large number of fault orientated obliquely and perpendicularly to the fold axis which have offsets indicative of movement of the hanging wall to the north. These faults collectively offset and are in turn offset by intrastratal slip surfaces which indicates that slip about the fold axis was coeval with slip oblique to the fold axis.

COAL MOUNTAIN

Coal Mountain is located in the hanging wall of the Lewis thrust sheet near Corbin, British Columbia (Fig. 1). The Mist Mountain Formation at Coal Mountain is at least 200 m thick and comprises thick to thinly bedded sandstones, siltstones, mudstones and at least two major coal seams. The lowest coal seam occurs at the immediate base of the Mist Mountain Formation and conformably overlies the Morrissey Formation. The basal seam, locally referred to as the Mammoth seam has a normal stratigraphic thickness ranging from 5 to 20 m thick and locally has been structurally thickened up to 200 m. The second coal seam occurs in the middle of the Mist Mountain Formation and is on the order of 1 to 2 m thick although it is absent is some areas and considerably thicker in others. The Morrissey Formation, similar to Tent Mountain to the north, is comprised of massive, resistant, and intensely fractures sandstone about 60 m thick.

Structural style:

Coal Mountain is composed of a complex stack of moderately to tightly folded east and west dipping thrust faults and broad to tight folds (Figs. 7, 8 and 9). The main structural elements on Coal Mountain are three major north trending synclines which include the main coal resources which have been extensively mined. The folds have an amplitude to wavelength ratio ranging from about .15 to .2 and are geometrically classified as type 1C (Ramsay and Huber, 1987). The synclines have variable plunge and are cut at low to high angles to bedding by thrusts which themselves are moderately to tightly folded. Six major thrust faults and innumerable minor thrusts and tears occur. Four of the major thrust faults are west dipping and two are east dipping. The most striking features of the faults is that the higher, older faults in the stack are substantially more tightly folded (smaller radius of curvature) and that the thrusts cut, at least locally, indiscriminately across competent sandstones of the Morrissey Formation and incompetent coal units. The characteristic ramping of faults across competent strata as seen in most deformed area is absent from Coal Mountain. In the central part of Coal Mountain two easterly trending near vertical dextral tear faults cut the succession. Estimated minimum amount of shortening across Coal Mountain is variable but averages 65%, based on detailed, serial cross-sections.

Major folds range from upright to overturned to the east and are broad to tight with narrow hinge areas. In the hinge areas of the folds, the thick bedded and competent sandstones of Morrissey Formation and thicker sandstone units of the Morrissey Formation are fractured and locally brecciated. The sandstone have consequently dilated up to 5-10% based on estimate of fracture spacing and width. The incompetent strata, and particularly the Mammoth coal seam, have dramatically thickened up to ten fold in the hinge areas of the major synclines. Thickening of the coal in the hinge area has been accommodate by cataclastic flow.

The main mesoscopic structural elements on Coal Mountain are small scale thrust and normal faults, slickensided bedded surfaces and small scale folds. For the most part mesoscopic fabric elements appear to have been overprinted by successive waves of deformation and their utility as kinematic indexes is consequently limited.

The kinematic history of deformation at Coal Mountain can be interpreted from the structural geometry. The pattern of thrusting and faulting clearly indicates that flexural flow folding and thrust faulting were concurrent and that flattening has promoted dilation and cataclastic flow of coal into the hinge areas. The oldest thrusts which are highest in the succession are the most tightly folded suggesting these faults

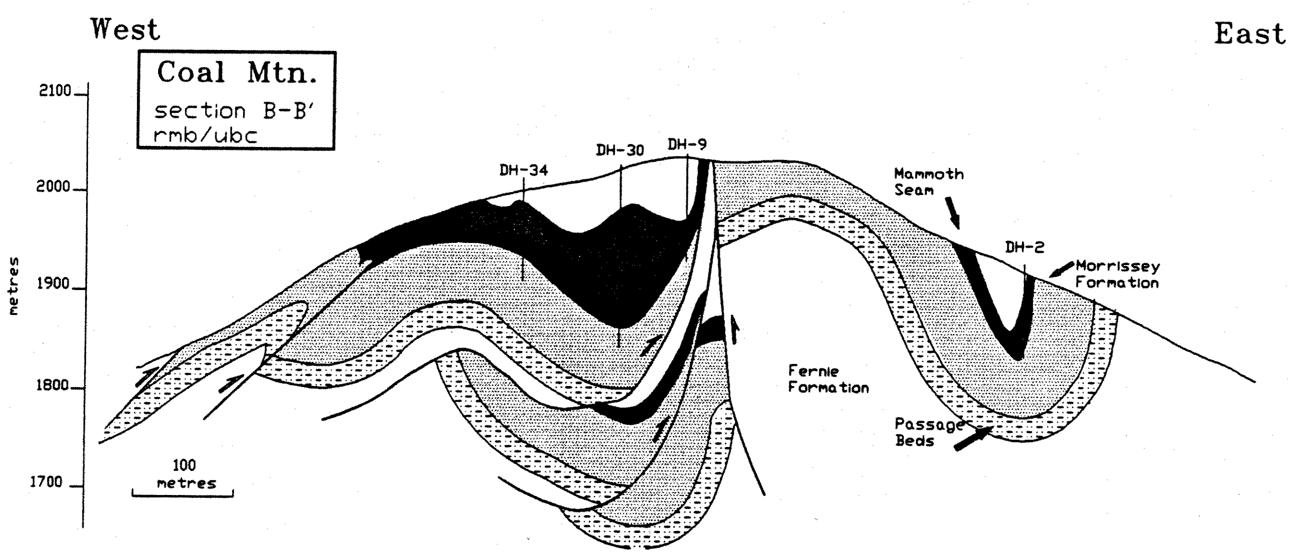

Figure 7. Cross-section of southern Coal Mountain.

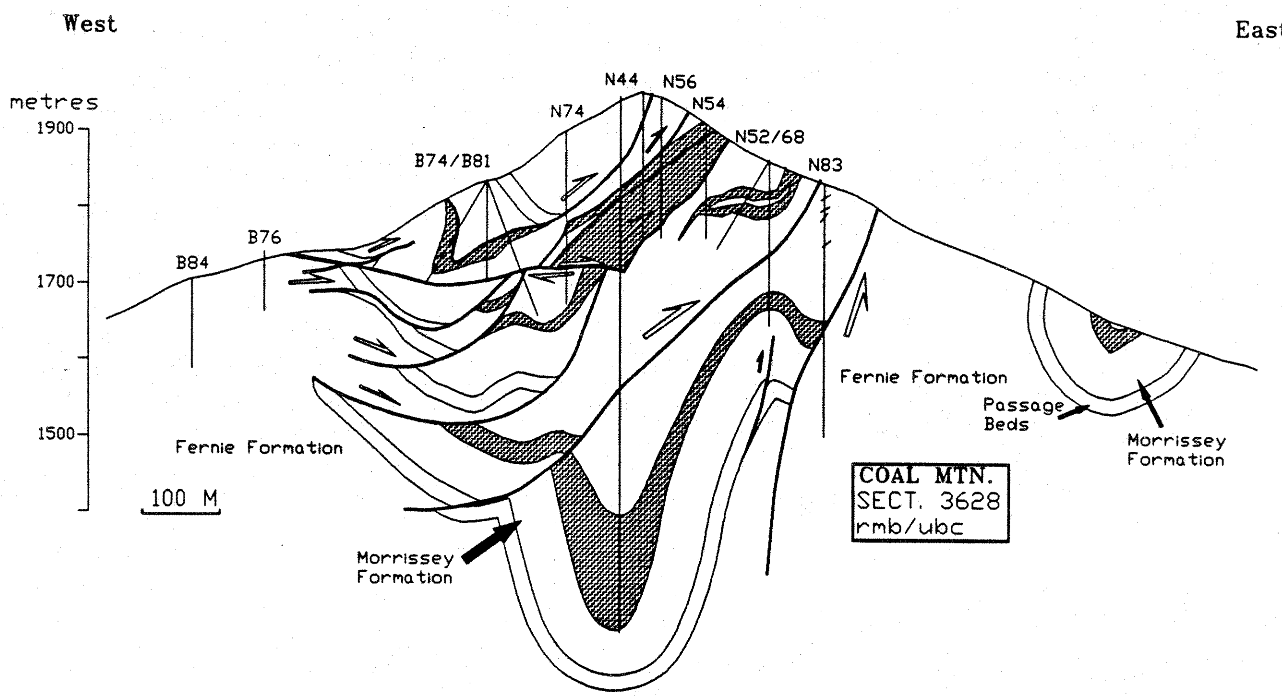

Figure 8. Cross-section of central Coal Mountain about 1000 m north of Figure 7.

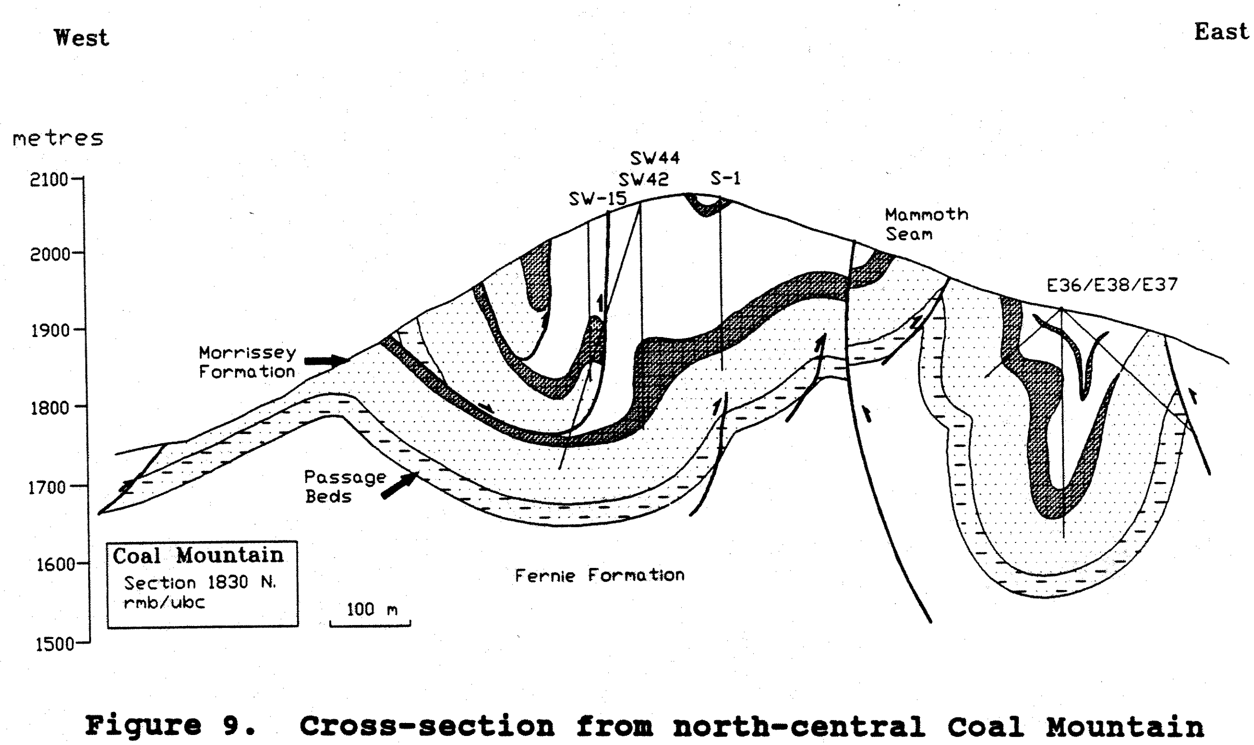

Figure 9. Cross-section from north-central Coal Mountain about 1800 m north of Figure 7. Note the near horizontal fault trace on the section which is a dextral tear fault and strata above the fault are plunging to the north.

were rotated during faulting and eventual locked, leading to propagation of younger underlying thrusts which in turn locked as deformation proceeded. The east dipping thrusts on eastern Coal Mountain are also folded and in part overturned to the east indicating these faults propagated simultaneously with folding. Tear faults cut all but the youngest (lowest) west dipping thrusts on the Mountain indicating they formed or continued to propagate until late in the deformational history.

DISCUSSION AND CONCLUSIONS

The Vicary Creek, Tent Mountain and Coal Mountain map areas have relatively distinctive structural styles progressing from thrust faulted near monoclinal panels at Vicary Creek to broad concentric folds of mainly type 1c and for the most part younger faults at Tent Mountain to tighter and more flattened folds and folded thrusts of several generations at Coal Mountain. The variation in structural style from Vicary Creek to Tent Mountain and Coal Mountain appears to be a product of both the amount of shortening and local variation in stratigraphy. The monoclinal faulted panels at Vicary Creek are characterized by massive conglomerate of the Cadomin Formation and thick bedded sandstone units of the Mist Mountain Formation which have experienced little flexure. The majority of the deformation (intrastratal slip) has been localized within the coal seams and the #2 seam varies significantly in thickness as a result of intrastratal slip, contraction and extension faulting and associated cataclastic flow (Bustin, 1979). At Tent Mountain and Coal Mountain, on the other hand, the coal measures are much thicker and have been shortened a greater amount. The coal measures at both Tent and Coal Mountains contain major intervals of incompetent interbedded siltstone, mudstone and coal which together with relatively thin competent sandstone units have given rise to high amplitude and relatively short wavelength folds of type 1C. At both Tent Mountain and Coal Mountain cataclastic flow of coal into the hinge areas from the fold limbs resulted from flattening during buckling.

The contrast in shorting and intensity of deformation and thus structural style between Tent Mountain and Coal Mountain and coal measures in the Vicary Creek-Dutch Creek area or the Fernie synclinorium to the west, reflects their structural setting. The Fernie synclinorium is characterized in general by broad open folds and thrust faults whereas both Tent Mountain and Coal Mountain are more intensively deformed. Tent and Coal Mountain overlie a major ramp on the Lewis thrust and thus may have experienced a substantially greater amount of shortening as a result of rotation and accompanying shear on the inner arc of the Lewis thrust plate as it ramped up to the east. The variation in structural style from Tent Mountain to Coal Mountain may reflect the different stratigraphic successions. In particular massive channel sandstone occur throughout the succession at Tent Mountain but are noticeable absent near the base of the Mist Mountain Formation at Coal Mountain which may account for the generally shorter wavelength of the folds (Ramsay and Huber,

1987) and greater degree of flattening associated with buckling at Coal Mountain.

ACKNOWLEDGMENTS

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DEPOSITIONAL MODELS FOR COAL EXPLORATION IN THE BOWSER BASIN

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ABSTRACT

The Bowser Basin is a sedimentary basin located in the north central part of British Columbia. The basin is known to be underlain by sediments of both marine and non-marine origin of Jurassic to Lower Tertiary age. Significant resources of coal have been delineated in the northeast part of the area in the Groundhog Coalfield including Mount Klappan and in the Telkwa deposit just south of Smithers. Additional coal deposits are known to occur throughout the Bowser Basin although the majority of the area within the present day basinal remnant is relatively poorly understood from the perspective of delineation of new coal occurrences.

From 1983 to 1985 Esso Resources Canada Limited-Coal Division undertook a series of reconnaissance mapping programs in the Bowser Basin to search for new and potentially economic coal deposits. The methodology used in approaching the programs was to reconstruct the depositional history of the various known coal deposits and extrapolate the facies relationships of marine, coastal plain and alluvial-fluvial sequences to best determine where coal may have been deposited in the progradational continental environment.

These methods proved successful in locating several new occurrences of coal in both paralic and limnic settings throughout the basin from the Jurassic through to the Cretaceous.

INTRODUCTION

The Bowser Basin is located in the north central part of British Columbia and covers an area of approximately 30 thousand square kilometers (Figure 1). The existing basinal remnant is underlain by a series of marine and continental sediments that were deposited in a stratigraphically and structurally complex successor basin during the Jurassic and Cretaceous periods.

Numerous coal occurrences east of the Nass River were reported by Dowling(1915) which led to exploration activity that subsequently delineated the Groundhog Coalfield. Sporadic

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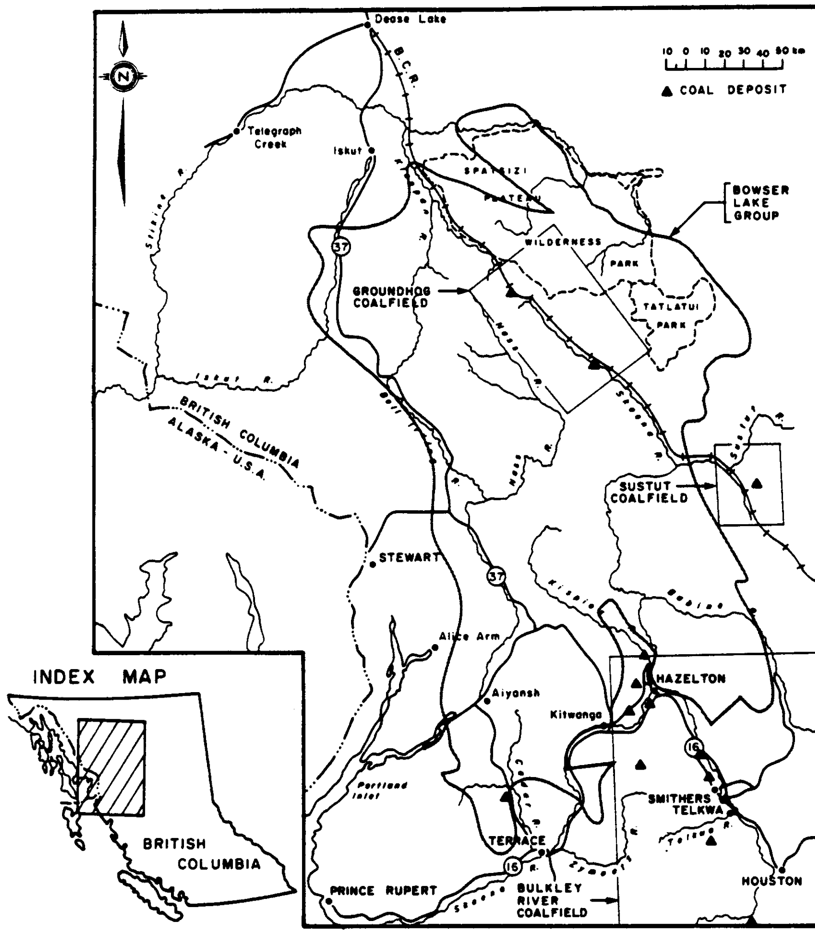


FIGURE 1. BOWSER BASIN LOCATION MAP with Bowser Lake Gp. and Coal Locations.(modified from Schroeter et al,1986).

exploration since that time has identified coal-bearing sediments throughout other portions of the basin. These areas include additional coals in the Jurassic-Cretaceous Groundhog Coalfield including Mount Klappan, the Cretaceous Bulkley River Coalfield, the Cretaceous Sustut Coalfield and other smaller occurrences along the perimeter of the basin. The majority of the remainder of the Bowser Basin was thought to be underlain mainly by sediments of marine origin and has not been well studied from the perspective of locating new coal deposits.

In the period from 1983 to 1985 Esso Resources Canada Limited-Coal Division completed a series of reconnaissance exploration programs for coal throughout the Bowser Basin using depositional models derived from existing basinal genesis theories and extrapolating knowledge from the known coal occurrences in this progradational continental environment (Berg,1984: Berg et al,1983 & 1984). Coals previously found occur in two depositional environments (Eisbacher 1973):

1) a prograding pro-delta to delta sequence (Duti-Slamgeesh)
2) an alluvial fan-coal swamp assemblage (Groundhog-Gunanoot).

Bustin and Moffat (1983) further defined a regional reconnaissance stratigraphy for the Groundhog Coalfield which elaborated upon the sedimentary sequences in the northeastern part of the basin.

For these exploration programs, coal was postulated to occur in two depositional environments:

1) the transition zone from marine to continental where coastal bogs and swamps existed in paralic deposits and
2) the back swamp and lacustrine areas of alluvial plains where raised bogs and forest moors existed as limnic deposits (Berg,1984: Berg et al,1983 & 1984).

It was felt that through the history of the basin these relationships existed not only in the Jurassic but also into the Cretaceous as the marine environment withdrew resulting in a stacked sequence of potentially coal bearing units throughout the stratigraphic section. While the effects of tectonic activity in the basin have resulted in complex structural geology, these sedimentary relationships are still able to be delineated.

The depositional facies boundaries of the marine, transitional and continental facies were mapped on a regional basis with previously undiscovered coals being found to exist in both of the later assemblages in the lesser explored areas of the Bowser Basin. The focus of this paper deals with the derivation of these models for coal deposition and their successful application as a reconnaissance tool.

REGIONAL GEOLOGY

BASINAL GENESIS

The Bowser Basin is an orogenic successor basin of Jurassic and Cretaceous age. During the Lower and a portion of the Middle Jurassic, subareal and subaqueous volcanics and associated sediments of westerly provenance were deposited as the Hazelton Group in an elongate eugeosynclinal trough between North America and Stikinia with sediment also being supplied southward into the trough by the young Stikine Arch. However this basinal configuration changed during the Middle and Upper Jurassic due to the rising of the Skeena Arch splitting the Hazelton Trough into the northern Bowser and southern Nechako Basins (Tipper, 1976). The arch contributed sediments northward for the Bowser Group while the rising Columbian Orogeny to the east supplied it westward and the Stikine Arch southward. Thus, the coastal configuration at this time consisted of continental exposures to the north, south and east with an onlapping marine environment to the west in which an island arc system, representing the easterly advance of the Coast Plutonic Complex, was situated. It is the sediments from these exposures which formed the marine, deltaic and fluvial deposits known as the Bowser Lake Group (Figure 2a & 2b).

By the Early Cretaceous the Skeena Arch was no longer a positive topographic feature and the Bowser Basin Group was succeeded by the Skeena and Sustut Basins and their associated sediments (Figure 2c). The present day configuration is the result of Laramide orogenic activity in the Cretaceous and early Tertiary and subsequent erosion (Figure 2d).

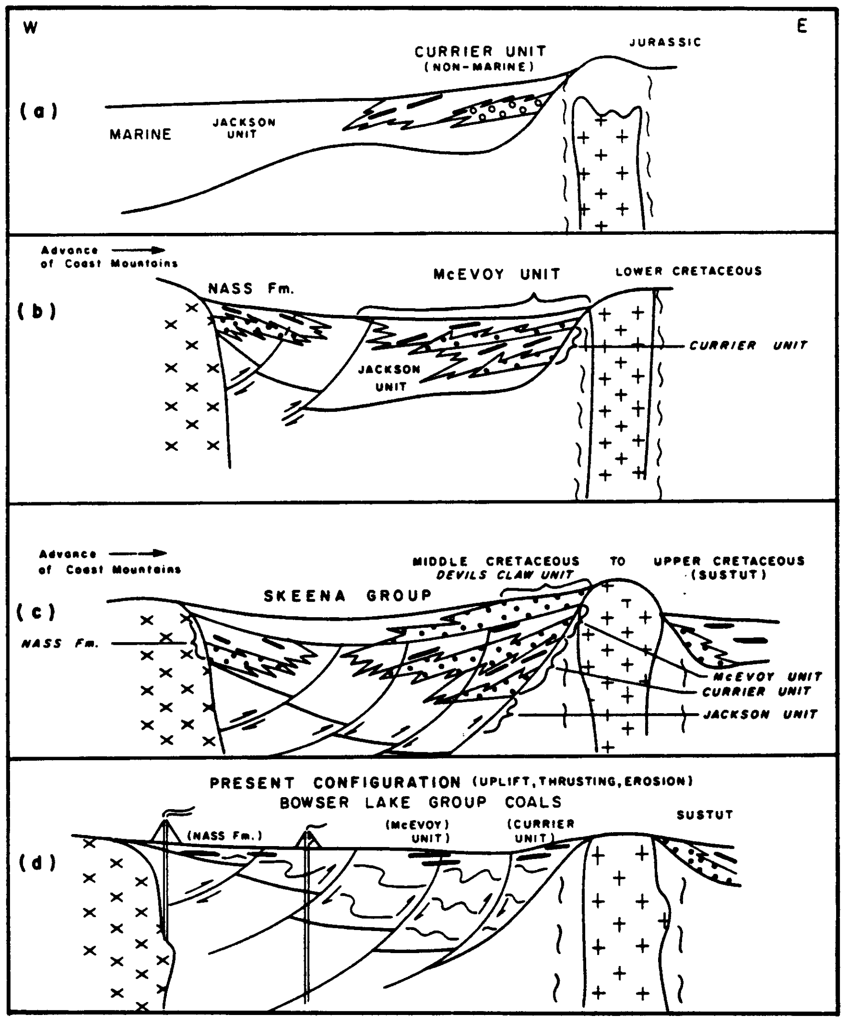


FIGURE 2. BASINAL GENESIS: 2(a) Jurassic, 2(b) Lower Cretaceous 2(c) Middle - Upper Cretaceous & 2(d) Present.

BASINAL STRATIGRAPHY

The Bowser Basin is distinct and recognizable from its surrounding geological setting as it contains a unmetamorphosed series of marine and continental sediments. This package is known as the Bowser Lake Group and covers an area of approximately 30 thousand square kilometers and is up to 3,000 meters thick.

Figure 3 compares stratigraphic units and ages throughout the basin from the work of various researchers.

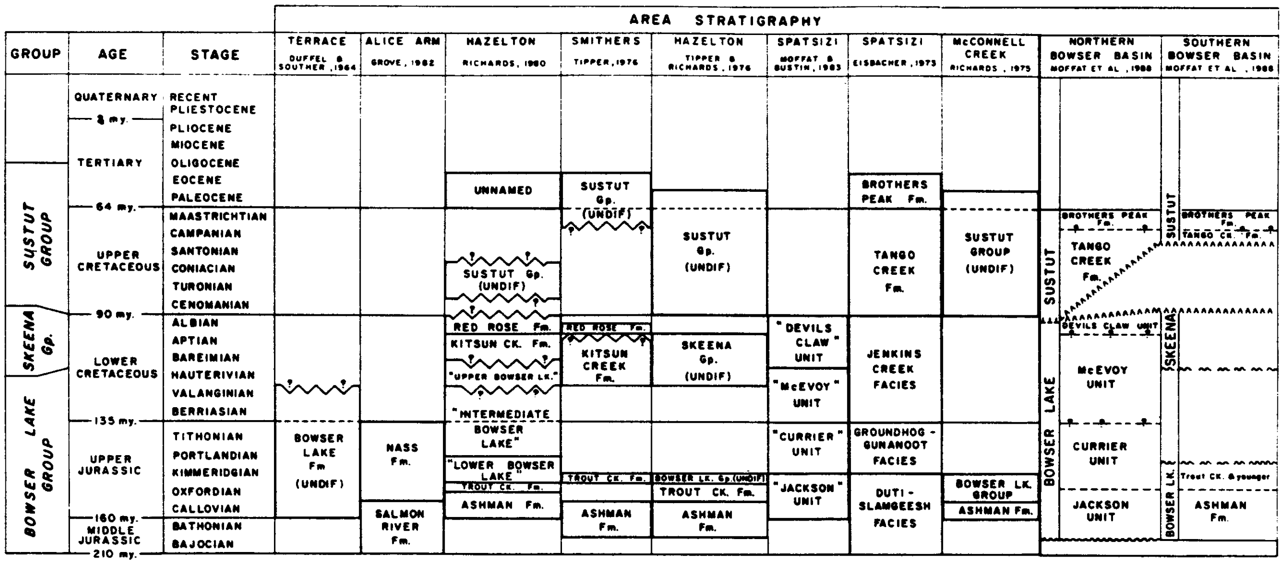


FIGURE 3. BOWSER BASIN STRATIGRAPHICAL CORRELATION CHART.

The base of the Bowser Lake Group is dated anywhere from early Bajocian in the Nass River and Spatsizi map areas, to early Callovian in the Terrace, Hazelton and McConnell Creek areas. Locally, the nomenclature also differs; it is the Ashman Formation in the Hazelton area (Richards, 1980) and in the McConnell Creek area (Richards,1975), either the Jackson Unit (Bustin & Moffat, 1983) or the Duti-Slamgeesh Facies (Eisbacher, 1973) in the Spatsizi, the Salmon River Formation (Grove, 1982) on the Nass River map and the Bowser Lake Formation in the Terrace area (Duffel & Souther, 1964). The lithological description of this basal series, finely laminated marine mudstones and siltstones grading upwards into fine grained sandstones and fossiliferous nearshore deposits, is consistent throughout the basin. Minor coals of Callovian age have been located in the Ashman along the east perimeter of the basin although areal extent is uncertain (G.Cave, pers.comm. 1988). The contact to the underlying Hazelton Group is unconformable in the Terrace and northernmost areas (Duffel and Souther, 1964) but grades southerly to a conformable interface with the Smithers Formation of the Hazelton Group (Tipper and Richards, 1976).

The Trout Creek Formation conformably overlies the Ashman in the Smithers and Hazelton areas and is a transitional facies containing sandstone, conglomerate and thin coals (Tipper and Richards, 1976). It was considered to be stratigraphically equivalent to the upper portion of the Jackson Unit and the Duti-Slamgeesh Facies in the northeastern area of the basin which are dominantly marine but become continental in nature up-section. More recent correlations have determined that the Trout Creek Formation is equivalent to the Lower Currier Unit (Moffat et al, 1988).

The Jackson and Duti-Slamgeesh sections are in turn comformably overlain by the Currier Unit (Bustin & Moffat, 1983) and the Groundhog-Gunanoot Facies (Eisbacher, 1973) respectively. Both are described as containing marginal marine, deltaic and fluvial sediments with the continental facies dominant in the northeast and marine to the southwest. In the Terrace area the Nass Formation is equivalent to the upper Jackson and Currier Units (Duffel & Souther, 1964). In the southern area the "Lower Bowser Lake" subdivision (Richards,1980) which is equivalent to the lowermost Currier Unit and Groundhog-Gunanoot facies, rests conformably above the transitional Trout Creek Formation. The section consists of fine grained deltaic front, plain and slope deposits grading upwards to fluvial and alluvial deposits. This passes into the "Intermediate Bowser Lake" subdivision (Richards, 1980) which contains the same environmental assemblages as the "Lower" but shows greater development of the floodplain facies. The lower sections are coeval with the alluvial fan and coal swamps of the upper Groundhog-Gunanoot Facies and the upper fluvial sequences of the Currier Unit. The upper portion though is equivalent to the marine and lacustrine deposits of the lower McEvoy Units (Bustin & Moffat, 1983) and the alluvial plain deposits of the Jenkins Creek Facies (Eisbacher, 1973).

Stratigraphically above the "Intermediate Bowser Lake" lies the "Upper Bowser Lake" subdivision's lower floodplain deposits (Richards, 1980). There is a marked difference between the outcrop distribution and induration of the "Intermediate" and "Upper" subdivisions which would suggest a hiatus in deposition between the two formations likely accompanied by a change in basinal configuration (Berg, 1984). It is possible, therefore, that the "Upper" subdivision is equivalent to the basal Skeena Group, a younger sedimentary formation, which is the equivalent of the northern Devils Claw Unit, a thick succession of alluvial conglomerates (Berg et al, 1985).

In a recent study (Moffat et al, 1988) palynological data indicates that the Jackson Unit is Middle to Upper Jurassic, the Currier Unit is Upper Jurassic, the McEvoy Unit is Upper Jurassic to Lower Cretaceous and the Devils Claw Unit is late Lower Cretaceous.

In summary, the first sediments of the Bowser Lake Group were marine followed by transitional marine and continental sediments resulting in an overall basinward progradation. The coastal plain and fluvial-alluvial deposits are best recognized in the northern portion of the basin.

METHODOLOGY

Geological knowledge of existing coalfields in the Bowser Basin indicate that peat swamps and bogs developed in both paralic and limnic environments in the overall progradational history of the basin. On this basis the exploration programs focussed upon tracing the transitional zone from marine to continental with the purpose of locating coals in coastal plain and alluvial-fluvial facies. Upon establishing this transitional boundary, work was concentrated in the non-marine portion of the basin.

Initially both helicopter and ground traverses were completed on mountain ridges and creeks to characterize sediments of each facies, with follow-up surface mapping in sufficient detail to reconstruct the regional geological picture. Detailed mapping was completed on areas of discovered coal occurrences.

PROJECT RESULTS

DEPOSITIONAL FACIES

Within the Bowser Basin four distinct sedimentary facies were recognized: marine, shallow marine, coastal plain and fluvial. It is considered that all facies were persistent throughout the Upper Jurassic to Lower Cretaceous with the spatial distribution controlled by marine regression to the south and west.

Marine Facies

Lithologies of the marine facies consist of dark grey to black fine-grained lithic sandstones, siltstones and mudstones. Thin chert beds, nodular limestones, ironstone concretions and minor calcareous mudstones were also observed. Repetitive fining upward cycles were noted and concluded to be turbidite sequences. Bedding features included small scale crossbedding, load casts and soft sediment deformation. The lithologies and sedimentary features are indicative of moderately quiescent deposition likely on a continental slope with periodic turbidite influx.

Shallow Marine Facies

Lithologies of the shallow marine facies include medium grey, medium grained lithic sandstone, dark grey siltstone and dark grey to black mudstone. The sandstones occasionally grade into a matrix supported lithic conglomerate containing chert pebbles and mudstone rip-up clasts. Sedimentary features include discordant, asymmetrical ripples in parallel bedded sandstone and small scale cross-bedding in the finer lithologies. Bioturbation and shellfish fossils including belemnites were observed, however, distribution was sparse. These observations indicate a shallow marine environment with probable tidal flat and upper shoreface facies of a progradational deltaic system with deposition being relatively rapid in this shallow, moderately high energy environment (Figure 4a).

Coastal Plain Facies

The coastal plain facies can be divided into littoral and paralic subfacies with the littoral deposits developed in the marine environment from the shoreline to upper shoreface, a zone of moderate energy levels. The paralic deposits developed in the non-marine region of a shoreline and are generally considered to have lower energy levels.

Littoral: Lithologies of the littoral subfacies are characterized by brown-grey, lithic to quartzose, fine to medium grained sandstone, and medium to dark grey siltstones. Several calcareous siltstones containing mollusc fossils were interbedded with the dominant lithologies. Bedding features included large bedding planes with small ripples with most lithologies being thinly bedded. These sediments and sedimentary structures suggest moderate to low energy fluctuations which may be indicative of bars and tidal flats shoreward of the shallow marine facies.

Paralic: Lithologies of the paralic subfacies include chert pebble conglomerate interbedded with light grey medium grained quartzose sandstone, dark grey siltstone containing abundant plant fossils, orange to brown, calcareous siltstone with bivalve fossils, thinly bedded mudstone, interbedded fine-grained sandstone and siltstone, carbonaceous shale, minor pinkish grey medium-grained feldspathic sandstone with medium scale festoon crossbedding, petrified logs and abundant coal seams. Iron staining and concretions were common in the fine-grained sandstones, siltstones and mudstones (Figure 4b).

Depositionally, the dark siltstone with the abundant plant fossils is a coastal marsh facies; the orange/brown calcareous siltstone with bivalves is a lagoonal facies; the thinly bedded mudstone, interbedded conglomerate and sandstone, siltstone, and carbonaceous shale are overbank, channel and back swamp deposits in a deltaic environment; the pinkish-grey, well sorted, feldspathic sandstone with festoon crossbedding is a coastal eolian sand dune; and the coal is a coastal bog or a near coastal raised bog.

Alluvial-Fluvial Facies

Lithologies of the alluvial-fluvial facies consist of chert pebble conglomerate, buff coloured medium to coarse grained lithic to arkosic sandstone, dark grey siltstone, carbonaceous shale, mudstone and coal. Petrified and coalified wood fragments, stem and fern imprints were also observed.
Sedimentary structures included massive to graded bedding in the conglomerate, trough crossbedding and flaggy bedding in the sandstones and thin parallel laminations in the finer sediments. The coarser grained lithologies were found in rather irregular cycles typical of an active fluvial system. The coal sequences are

limnic and were associated with carbonaceous shales and mudstone typical of back swamp deposits in the low energy portion of the environment (Figure 4c).

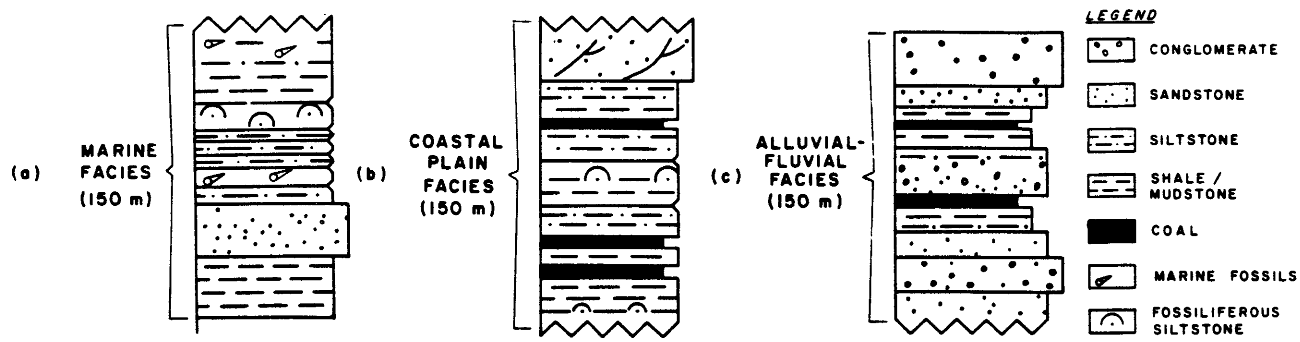


FIGURE 4. TYPICAL FACIES SECTIONS: 4(a) Marine, 4(b) Coastal Plain & 4(c) Alluvial - Fluvial. Note:Bed thickness not to scale.

COAL GEOLOGY

Coal seams were discovered in both the coastal plain facies and the alluvial-fluvial facies in the northern portion of the basin west of the Nass River (Peach et al, 1989 in preparation). Coals were also discovered in similar environments in the southern area of the basin.

Coastal plain facies coals are termed paralic coal sequences and alluvial-fluvial facies coals are termed limnic coal sequences.

PARALIC COAL SEQUENCES

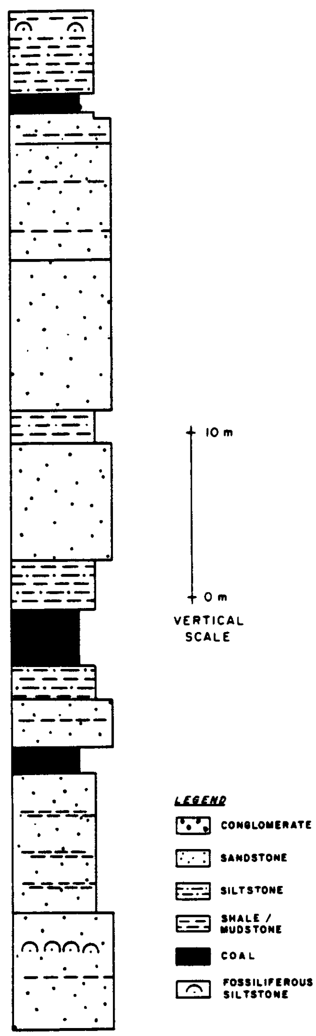
In the northern part of the basin paralic coals were found in an interbedded series of fine to medium grained sandstone, siltstone, mudstone and calcareous fossiliferous siltstone. In one area the total thickness for this series exceeded 500 meters and contained eight (8) coal seams. The lowermost six (6) seams were laterally continuous and ranged in thickness from 0.70 to 3.4 meters. One 60 meter interval (Figure 5) contained three coal seams with thicknesses of 1.5, 3.4 and 1.07 meters.

In the southern part of the basin several thin(< 1 meter) and discontinuous coals were found in association with marine fossils and thin beds of fossiliferous siltstone.

LIMNIC COAL SEQUENCES

Limnic coals were found in the northern part of the basin in association with repetitive cycles of chert pebble conglomerate, fine to medium grained sandstone, carbonaceous and non-carbonaceous siltstone, mudstone and carbonaceous shale. A typical sequence is shown in Figure 6. In all, eight (8) coal seams with thicknesses ranging from 0.20 to 2.2 meters with some minor partings of siltstone and mudstone were located along with many occurrences of shaley coal and carbonaceous shale. Most seams were poddy and discontinuous while four of the seams could be traced over greater distances.

In the southern portion of the basin limnic coals were found in sixteen (16) different localities in association with fine to medium grained sandstone, siltstone, mudstone and carbonaceous shale. Abundant plant fossils and log fragments were also found. Coal zones ranged in thickness from 0.10 to 3.0 meters with minor shale partings.



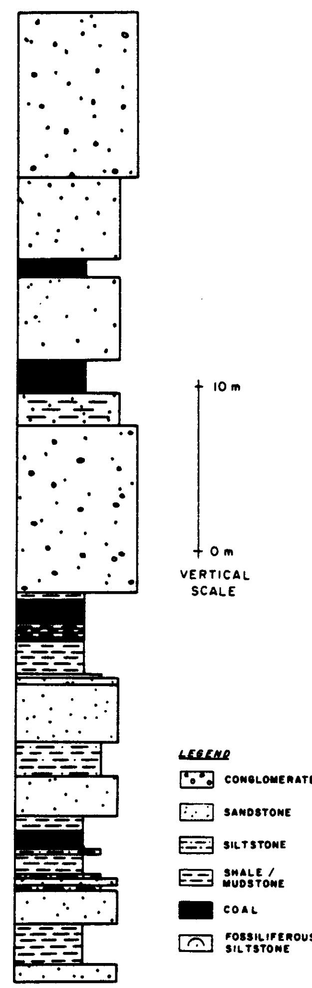


FIG. 5. PARALIC COAL SEQUENCE. **FIG. 6.** LIMNIC COAL SEQUENCE.

COAL STRATIGRAPHY AND AGE CORRELATION

The lithological descriptions of the coastal plain facies containing the paralic coal sequences are similar in character to those of the Currier Unit as described by Bustin and Moffat (1983) and could have been deposited in the same stratigraphic interval. The lithological descriptions of the alluvial-fluvial facies with limnic coal sequences are also similar to Bustin and Moffat's description of the McEvoy Unit. However because of the progradational nature of the continental environment it is probable that these sediments were deposited in similar facies of successively younger strata.

In the southern portion of the basin, coals were found in sequences of similar lithological description to the Bowser Lake Formation (Duffel and Souther, 1964) and the Nass Formation (Grove, 1982).

REFLECTANCE CORRELATIONS

In a study of reflectance data of the Currier and McEvoy Units by Bustin (1984) it was indicated that coals of the Currier Unit had reflectance values of 3.0 to 5.8 RoMax. Coal from the McEvoy Unit ranged from 1.7 to 3.5 RoMax. It was noted that reflectance values decreased up-section. Another trend noted that reflectance values decreased to the west and was explained by the relative decrease in the age of the sediments due to the westerly movement of the shoreline during the marine regression.

Coals from the coal sequences discovered in this program showed reflectance values of 2.1 to 3.8 RoMax with one showing a value of 4.3 (J. Allan, 1984). In plotting the range of reflectance against the Currier and McEvoy Units it can be seen that the range nearly matches the McEvoy and is correlative with the McEvoy Unit (Figure 7).

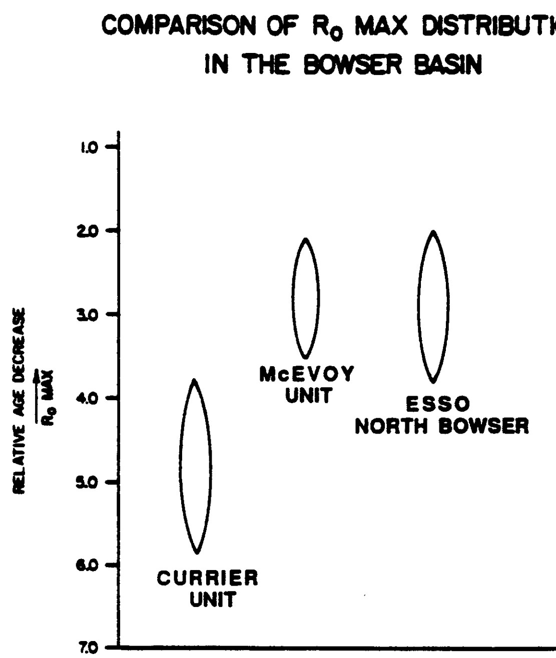


FIGURE 7. REFLECTANCE & STRATIGRAPHIC COMPARISONS IN THE NORTHERN BOWSER BASIN.

Reflectance data on the coals from the southern area of the basin show RoMax of 3.43 for coals of the Upper Bowser Lake Group to 6.57 for coals in proximity to intrusions.

COAL RANK

According to Bustin (1984) most of the coals occurring in the Currier Unit are anthracite or meta-anthracite, with the McEvoy coals being mainly semi-anthracite. Paralic and limnic coals from the northern portion of the basin as described in this paper are primarily semi-anthracite based on reflectance and proximate analysis data (Berg et al, 1985). Some coals are classified as anthracite although, for the most part, they are not as high in rank as the anthracites and meta-anthracites of the Currier Unit. This would indicate that these coals are younger than the Currier and correlative with the McEvoy Unit.

Coals from the southern portion of the basin are classified as anthracite and meta-anthracite based on both reflectance and proximate analysis data (Berg, 1984) and are considered to be equivalent to the Currier Unit.

PALYNOLOGY

Palynology studies on sediments of such high rank were not well developed in the early to mid 1980's. Recent techniques developed by G.E.Rouse have been used to obtain spore assemblages on three coals; two paralic coals and one limnic coal from the northern area. The results reported indicate the coals from the paralic sequence are of Oxfordian to Kimmeridgian age and are correlative with the lower Currier Unit. The coal from the limnic sequence was younger than the paralic coal and was of Kimmeridgian age and correlative with the upper Currier Unit (G.E.Rouse, pers.comm. 1989). These results would appear to conflict with the correlations made using the reflectance data in which the coals were correlated with the McEvoy Unit. A more detailed evaluation of the stratigraphic correlations, sedimentary and structural geology of these coals is underway (Peach et al, 1989 in preparation).

CONCLUSIONS

The methodology of reconstructing the depositional environment in the Bowser Basin has been proven successful in locating new coal occurrences. These coals were found in both coastal plain and alluvial-fluvial facies of a progradational continental environment similar to or the same as the depositional environments that exist in the Groundhog Coalfield to the east and also in similar sequences along the perimeter of the basin in the south.

The coals that were discovered in the northern part of the basin have been correlated with the Currier Unit of the Groundhog

Coalfield on the basis of palynological information. Using reflectance as a regional correlation tool these same coals are correlated with the McEvoy Unit. Further work is needed to address the discrepancy between the two interpretations. The coals discovered in the southern part of the basin are considered to be in the Nass Formation and equivalent to the Lower to Intermediate Bowser Lake group in the south and the Currier Unit in the north.

Successful location of new coal deposits during this program indicate that additional coal deposits may yet be discovered in relatively unexplored areas of the Bowser Basin using models of coal-bearing depositional environments in a regional framework.

ACKNOWLEDGEMENTS

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GEOLOGY AND COAL POTENTIAL OF TERTIARY SEDIMENTARY BASINS, INTERIOR B.C.

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ABSTRACT

This paper provides general information on the geology and coal occurrences of Tertiary sedimentary basins in the interior of British Columbia, and discusses regional, stratigraphic and age relationships of various basin groupings.

Strata consist of nonmarine sandstone, conglomerate, siltstone, mudstone and coal in varying proportions, deposited in narrow structural troughs on an uplifted pedimented surface. Deposition occurred within fluvial (braided to meandering streams), alluvial fan, lacustrine and swamp environments. Contemporaneous tectonism and volcanism affected local depositional patterns.

Coal occurs in the finer, mudstone dominated units, generally in the middle to upper portions of the stratigraphic successions. They are characteristically interbedded with thin mudstone-siltstone layers, and can contain high levels of ash material. In places individual coal zones are reported over 100 m thick. Coal rank generally ranges from lignitic to high volatile B bituminous, with variations probably controlled mainly by variable geothermal conditions.

Climate was apparently a major factor that controlled original coal seam development. A generally humid, warm-temperate climate prevailed throughout British Columbia in the early Tertiary. After the middle Oligocene a less favourable coal-forming climate prevailed. Contemporaneous with climatic deterioration was the continued uplift of the Coast Range to the west and the subsequent higher flow regimes in the ensuing drainage basins.

Present information indicates that Tertiary basins with the greatest coal potential are located south of 51 degrees latitude and are Eocene in age. These are: Hat Creek, Princeton, Tulameen, and Merritt. Other sizeable deposits are documented further north but these have not been well delineated.

INTRODUCTION

During late Mesozoic to early Cenozoic time the interior of British Columbia underwent episodic tectonism and volcanism caused by the collision and oblique subduction of oceanic crust along the western edge of the continental North American Plate. As a result, much of the interior was uplifted and faulted, causing the establishment of numerous narrow intermontane basins. These basins acted as catchment points for fresh water clastic deposition from early Cenozoic to the present. Between 10 and 50 million years ago several periods of explosive volcanic activity occurred causing the infilling of low lying areas which were previous centers of sediment deposition. This complex interaction of geologic forces created numerous unique sedimentary-volcanogenic deposits, some of which contain coal-bearing strata.

These basins have been examined periodically since the late 1800's but, because of poor bedrock exposure and lack of readily accessible markets, there has been only limited coal exploration. More recently some deposits have attracted attention due to renewed interest in thermal power generation.

This study was originally supported by the Geological Survey of Canada (GSC) in order to compile and update available geological information on these basins. This paper summarizes some previously unpublished information resulting from the author's field studies in 1977 and from his participation in the GSC-funded small core drilling program in the Quesnel area in 1978. It draws on published and unpublished reports by others in order to present a more complete overview of coal possibilities in Tertiary intermontane basins.

Figure 1 shows the location of each major coal basin. Each major basin will be described briefly for its individual characteristics and its relationships to adjacent basins. Coal potential is summarized. Additional information specific to each basin is available from company reports on file at the B.C. Ministry of Energy, Mines and Petroleum Resources office in Victoria.

COAL BASINS

PRINCETON BASIN

Background

The Princeton basin is a northerly elongated sedimentary basin located in the Similkameen district (figs. 1 and 2). It is approximately 4 to 7 km wide and 24 km long for a total area of about 170 sq. km.

Between 1909 and 1961 a number of small underground mining operations produced a total of 2 megatonnes for local consumption and the railways. Difficult mining conditions and low coal prices eventually caused the suspension of all operations. From 1971 to 1975 Bethlehem Copper Ltd. completed 15 diamond drill holes and conducted a gravity survey in the southern half of the basin. Cominco Ltd. drilled 11 additional holes in 1981 and 1982 in the northern part of the basin. Both firms dropped their interests, leaving the area presently unlicensed.

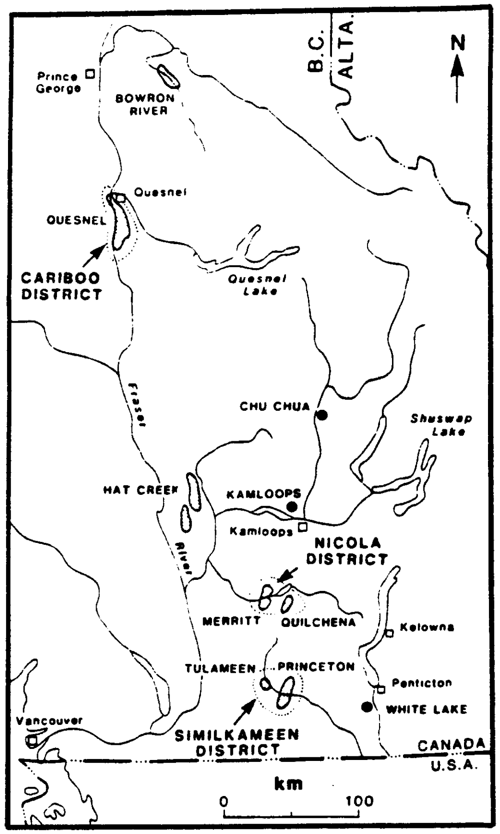

Figure 1. Major Tertiary coal basins, Interior B.C. after Smith (1989)

Geology

Coal-bearing strata in the Princeton basin were named the Allenby Formation by Shaw (1952a) based on exposures along the Similkameen River (figs. 2 and 3). Strata consist of a 1 900 m thick sequence of moderately lithified sandstone, siltstone, mudstone, coal and local volcanic deposits. This sequence unconformably overlies Eocene volcanics and Triassic Nicola Group argillites. The Allenby Formation has been dated as middle Eocene, based on a K-Ar date on the Princeton Ash located 30 m below the lowest major coal seam.

Strata of the Allenby Formation have been folded into an ellipsoid basin with dips generally toward its center. Secondary folding oblique to the main axis has brought underlying Nicola Group to the surface 3 km north of Princeton, and this effectively divides the Princeton basin into northern and southern sub-basins. Dips are generally greatest on the east side of the basin but decrease to between 15 and 25 degrees on the west side. Normal faults locally truncated the coal-bearing strata.

Coal Potential

In the southern sub-basin Shaw (1952a) identified four main coal zones in a 500 m stratigraphic interval (Table 1). Historically, the lowest zone or Princeton Black was the main producing zone because of superior thickness and quality. All zones, however, display high lateral variability in thickness and continuity and contain numerous partings of mudstone, siltstone and occasional bentonites. In the past these partings and adjacent strata have caused significant roof and floor problems, with soft sediment squeezing during underground operations.

Table 1. Princeton Coal Zones

Zone name	Net thickness (m)	Gross thickness (m)
Golden Glow	1.5	7.3
Bromley Vale	4.6	25.9
Pleasant Valley	1.8	30.5
Princeton Black	9.1	18.3

To date no significant coal has been reported in the northern sub-basin.

Bethlehem Copper (1975) has estimated that up to 10 megatonnes of in situ surface mineable coal remain. An additional large reserve of underground coal is also present if the roof and floor problems previously encountered can be solved.

The Princeton coal quality is summarized in Table 2. Generally the coal is subbituminous A to B. The seams exhibit a variable ash content and in some cases could require beneficiation to meet market requirements.

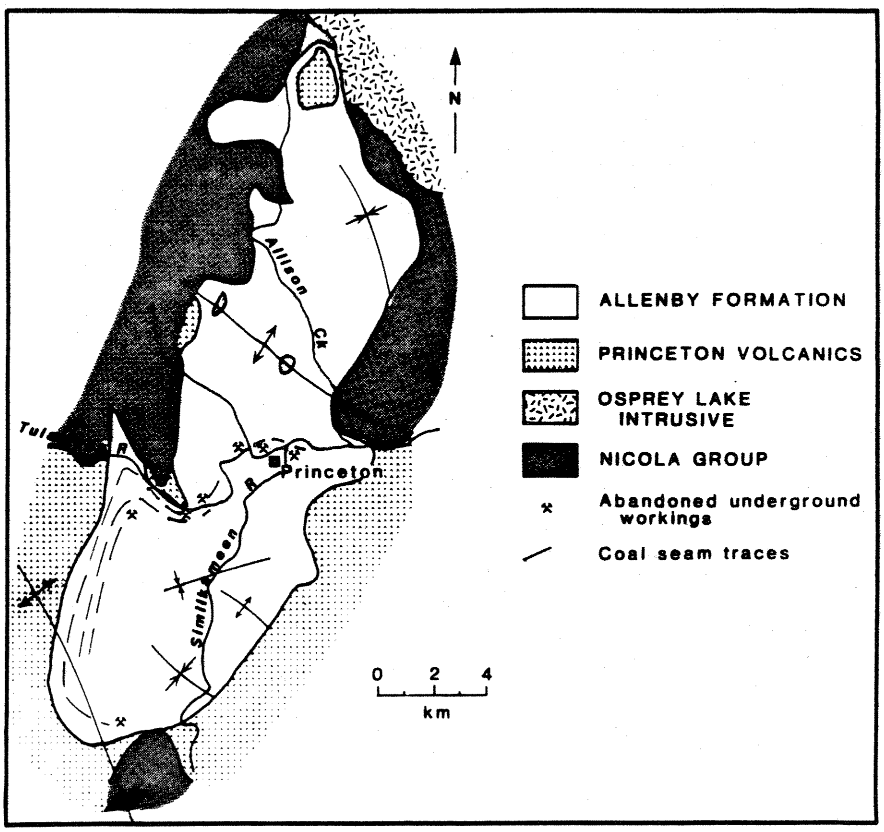

Figure 2. Princeton basin geology after McMechan (1975)

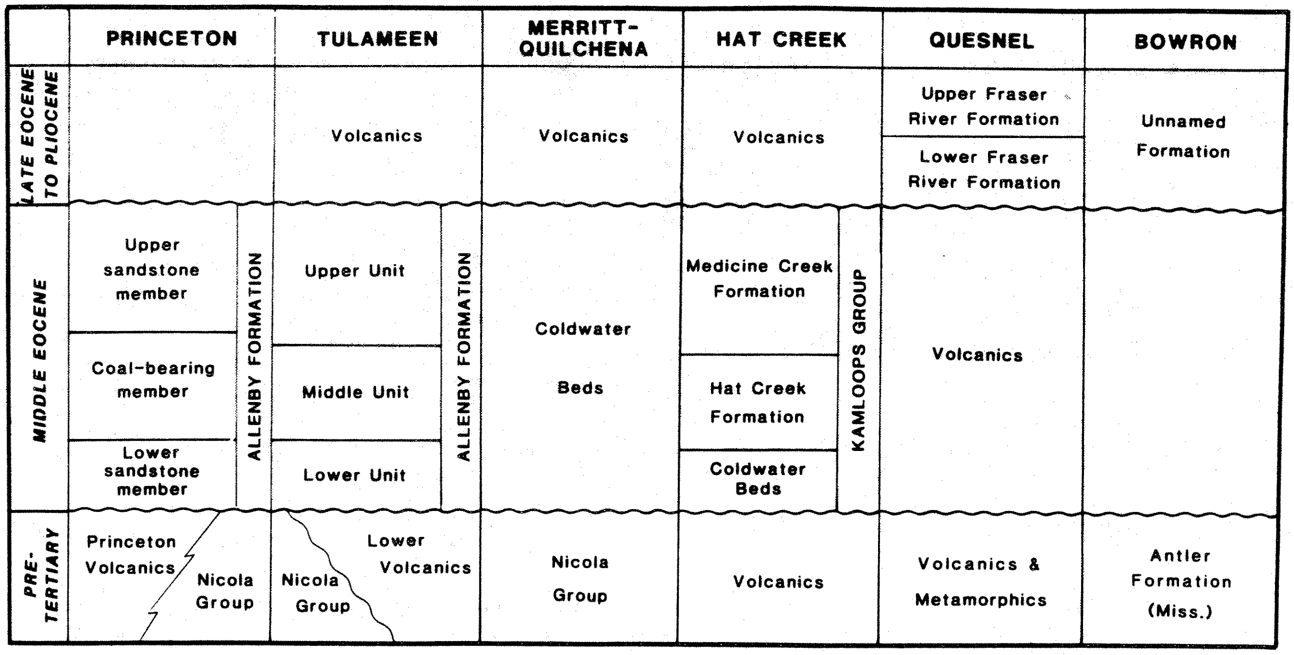

Figure 3. Stratigraphic succession summary, modified from Williams and Ross (1979)

Table 2. Generalized Coal Analyses - British Columbia Tertiary Basins

Area	Type	Moisture %	Ash %	Volatile Matter %	Fixed Carbon %	Heating Value MJ/kg	Sulphur %	Rank
Princeton	R	20.5	8.0	30.5	41.0	21.92	0.6	Sub A to B
	C	-	-	-	-	-	-	
Tulameen	R	12.0	40.9	-	-	14.19	0.6	High Vol. B to C
	C	12.0	14.5	30.2	43.3	23.26	0.6	
Merritt	R	8.0	18.0	31.9	42.1	24.42	0.5	High Vol. A to C
	C	8.0	10.0	34.9	47.1	27.45	0.5	
Hat Creek	R	22.5	32.5	23.8	21.2	11.56	0.4	Lignite A to Subbit. C
Quesnel	R	43.0	19.5	20.0	17.5	10.23	0.5	Lignite A
	C	-	-	-	-	-	-	
Bowron	R	-	-	-	-	-	-	High Vol. B to C
	C	8.0	11.7	32.8	47.5	25.12	1.0	

R = raw coal, C = clean coal

TULAMEEN BASIN

Background

Located 20 km northwest of Princeton is a smaller oval shaped sedimentary basin of approximately 15 sq. km in surface area. This basin, referred to as Tulameen or Coalmont, is located on a plateau 500 m above the Tulameen River (Fig. 4).

Underground mining was carried out successfully from 1919 to 1940. In 1954 the Mullins strip mine opened adjacent to the previous underground operations at Blakeburn. A total of 2.4 megatonnes have been produced, 90% from underground mining. Coal activities ceased until Imperial Metals Ltd.

acquired coal licences in the early 70's and carried out some limited surface mapping. Cyprus Anvil optioned the licences from Imperial in 1976. In 1977 and 1982 Cyprus Anvil completed 12 diamond drill holes, and 16 bulldozer trenches along the coal seam subcrop. Imperial Metals presently (1989) holds 14 coal licences covering the entire basin.

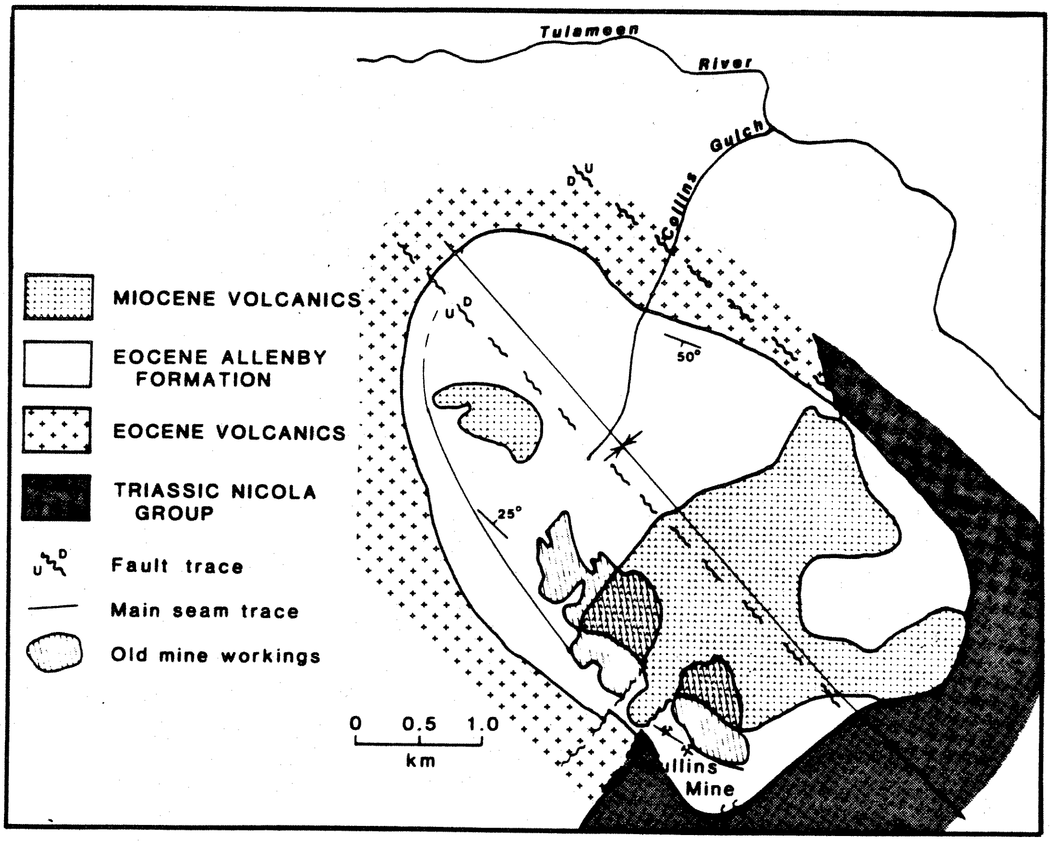

Figure 4. Tulameen basin geology, modified from Williams and Ross (1979)

Geology

The coal-bearing strata at Tulameen have been assigned to the Allenby Formation (Williams and Ross, 1979; Fig. 3). As in the Princeton basin, the Allenby Formation unconformably overlies Triassic Nicola Group and Eocene volcanic rocks. Shaw (1952b) reported a total thickness of between 800 and 1 000 m of interbedded sandstone, siltstone, mudstone, coal and local tuff layers.

The Allenby Formation is divided into three units. Coarse clastic material dominates the upper and lower units. The 140 m thick middle unit is finer grained and consists mainly of interbedded mudstone and coal. K-Ar dating of tuff layers gives an approximate age of 47 my or middle Eocene. At Tulameen the Allenby Formation is unconformably overlain by flat lying Miocene volcanic rocks ranging from zero to over 140 m thick.

Coal and associated strata were folded into a broad northwest trending, syncline (Fig. 4). Dips on the southwest limb range between 20 and 30 degrees, whereas on the northeast limb are reported between 40 and 65 degrees. A drill hole in the approximate center of the basin indicated a minimum depth to the coal zone of 500 m. Two sets of normal faults are present; the major set runs parallel and the minor set runs perpendicular to the axis. The minor set is most prominent along the southwest limb and faults appear to die out toward the synclinal trough. Underground mining encountered volcanic rock in some of the northeast trending fault zones. Displacement on faults are reported as generally small.

Coal Potential

Most previous mining was restricted to the "Main" zone along the southwestern edge of the basin (Shaw, 1952b; Fig. 4). This zone consists of a thick sequence of coal layers interbedded with numerous mudstone and bentonite partings. It is 15 to 27 m thick and contains between 40 and 80% coal. This variability is caused by an increase, in a northerly direction, of the number and thickness of seam partings. The "Lower" zone is 20 m below the Main zone and, where found, is 7 to 7.5 m gross thickness (Shaw, 1952b). The Lower zone also contains many thin inorganic layers. Little is known about the coal potential on the northwestern basinal edge.

Surface mining potential is restricted by previous workings to the south and by steep dips to the north. Cyprus Anvil (1978) estimated 11 megatonnes of recoverable coal at 3:1 strip ratio for a 1 500 m strike length northwest of the previous workings. The inferred coal resources, both surface and underground mineable, have been estimated to total 140 megatonnes (Dolmage Campbell & Associates Ltd., 1975).

The high volatile B to C bituminous coal in the Tulameen basin is higher rank than coal in the Princeton basin (subbituminous). Elevated ranks at several locations near the north end of the basin are probably the result of higher geotemperatures caused by nearby volcanism. Donaldson (1973), and Williams and Ross (1979) reported very high vitrinite content in coal samples, usually in excess of 90%. The seam's higher rank and high reactive content give it some weak coking properties (Donaldson, 1973). See Table 2 for a summary of some other selected quality characteristics.

MERRITT-QUILCHENA BASINS

Background

These two basins are combined here because of their geographic proximity in the Nicola district and their geologic similarity. The Merritt or Nicola basin is located at the junction of the Coldwater and Nicola rivers at Merritt. Tertiary sedimentary rock underlies an irregular shaped area of approximately 60 sq. km (Fig. 5). Quilchena is a northeast elongated basin of about 35 sq. km in surface area, located 20 km east of Merritt. Several other small Tertiary outliers occur in the vicinity but none of sufficient size to be of present commercial interest. Thick glacial drift and limited subsurface information hamper accurate delineation of basinal boundaries.

At Merritt several underground mines operated intermittently between 1906 and 1963. During this period about 2.7 megatonnes were produced mainly from the Coldwater Hill and Coal Gully areas (Fig. 5). In 1960 Imperial Metals Ltd. acquired coal licences and completed 16 rotary test holes. In 1968 and 1969 Sumicol Consultants Ltd. drilled 3 continuous core holes, and in 1980-81 Shell (Crowsnest Resources Ltd.) funded a surface seismic program and drilled 23 exploration holes. The Quilchena area was not mined previously, but some limited exploration was carried out by Shell in 1980-81 when four test holes were drilled and a test trench excavated. At present, Imperial Metals Ltd. holds licences over a portion of the Merritt basin. The Quilchena basin has no coal licences.

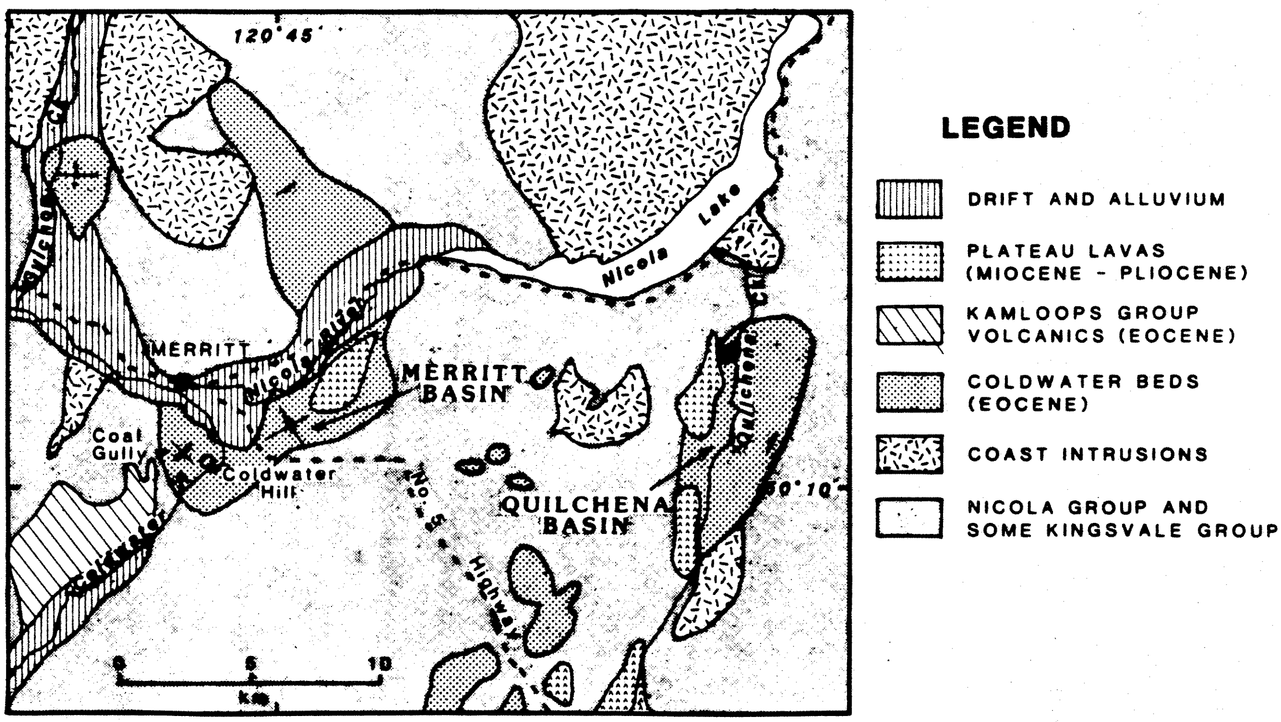

Figure 5. Merritt-Quilchena basins geology

Geology

The coal-bearing Coldwater beds unconformably overlie volcanic rock and argillites of the Triassic Nicola Group (Fig. 3). They are, in turn, locally overlain, with apparent angular unconformity, by younger volcanic rocks of the Kamloops Group or unnamed Miocene basalts. The Coldwater beds consist of moderately to well lithified sandstone, mudstone, conglomerate and seams of coal (Cockfield, 1948). The sequence is dominated by thick sandstone units which grade laterally into finer clastic sequences. Correlation of individual units has not been possible because of this rapid lateral facies variation. This indicates an unstable depositional setting in both basins. The base of the Coldwater is generally the coarsest with the finer coal-bearing units found higher in the stratigraphic section.

The stratigraphic complexity has hampered definition of structural relationships. Limited information from surface exposures and records of underground workings at Coal Gully and Coldwater Hill show at least two sets of fold axes perpendicular to each other, trending approximately northeast and northwest. Superimposed on these axes are local folds and small displacement normal faults. Dips at Merritt range from flat lying to near vertical. At Coal Gully and Coldwater Hill dips are more moderate, ranging between 25 and 30 degrees.

At Quilchena strata generally dip toward the center of the basin at angles less than 40 degrees.

Coal Potential

Only a few occurrences of thin coal seams have been reported in the Quilchena basin. At Merritt, coal seams are reported to be thicker, but seam lenticularity has made correlation between areas difficult. Shell (1981) reported that the thickest known coal zones occur at Coal Gully and Coldwater Hill adjacent to previously mined areas. The Coldwater Hill section has up to six zones from 25 cm to 2 m over 140 m interval (B.C. Report of the Minister of Mines, 1946). Six zones are also reported at Coal Gully over a 235 m thick stratigraphic interval. Here, individual zones are up to 8 m gross thickness. Zones at both sites commonly contain thin inorganic layers.

Shell (1981) reported that the area between Coal Gully and Coldwater Hill has the most promising surface mineable coal resource possibilities. This area is, however, covered with thick till. Shell estimated 5 megatonnes of remaining in situ coal within surface mining depths (8:1 strip ratio). Additional significant underground mineable reserves may be present in the same area.

The rank of coal in the Merritt basin ranges between high volatile A and C bituminous. Ash content over a mining zone varies according to the amount of enclosed parting material. When beneficiated this coal shows some weak coking characteristics. No rank or quality information is available for Quilchena coal. Its general characteristics may be similar to those of coal near Merritt, by virtue of geographic proximity and age similarity.

HAT CREEK

Background

The Hat Creek field consists of two poorly exposed coal deposits located 20 km west of Cache Creek. The northern or No. 1 deposit is 3.5 sq. km and the larger No. 2 deposit, 3 km further south, is approximately 25 sq. km (Fig. 6). Although never mined, the area has undergone extensive exploration since 1925. B.C. Hydro and Power Authority acquired the coal licences in 1957 and since then has drilled over 270 test holes, excavated several bulk samples and funded a gravity survey. Most of the previous exploration has been centered on the No. 1 deposit. B.C. Hydro's licences presently cover all near surface coal-bearing strata.

Geology

A 1 500 m thick sequence of Tertiary sedimentary strata unconformably overlies a pedimented Cretaceous or older volcanic-metamorphic terrain. This sequence, named the Kamloops Group (Cockfield, 1948), is divided into three units (Fig. 3). The lowest comprises the Coldwater beds consisting of 375 m of indurated sandstone and conglomerate with minor amounts of siltstone and mudstone. The overlying Hat Creek Coal Formation (Church, 1977) comprises 400 to 500 m of coal, mudstone, siltstone and minor sandstone-conglomerate layers (Fig. 6). On average, the formation is 65% coal by volume. Conformably overlying the Hat Creek Coal Formation is the

Medicine Creek Formation consisting of at least 600 m of monotonous mudstones and siltstones. Locally, the Kamloops Group is unconformably overlain by Miocene plateau basalts, lahars and sandstones. The Kamloops Group has been dated at middle Eocene, based on K-Ar dating of lahars in the Medicine Creek Formation.

The No. 1 and No. 2 deposits have undergone slightly different tectonic histories. The No. 1 deposit comprises two south plunging half synclines truncated on the southeast end by northeast trending gravity faults (Fig. 6). Dips on this deposit average approximately 25 degrees (Church, 1977). Folding apparently preceded faulting (Marchioni, 1985). The No. 2 deposit occurs within a graben bounded by north trending normal faults. Displacements on the western faults appear to have been greater than the eastern faults, causing a trap door type rotation of strata. Dips of beds in the No. 2 deposit average 25 degrees to the west.

Coal Potential

For both deposits the Hat Creek Coal Formation is divided into four main coal zones identified in descending order by the letters A to D (Fig. 6). Goodarzi and Gentzis (1987) attributed the extreme thickness of coal units to favorable subsidence rates at the time of peat accumulation. They interpreted the swamp/marsh depositional setting to be a within a fluvial-lacustrine environment. Because of strata dip, all seams subcrop in

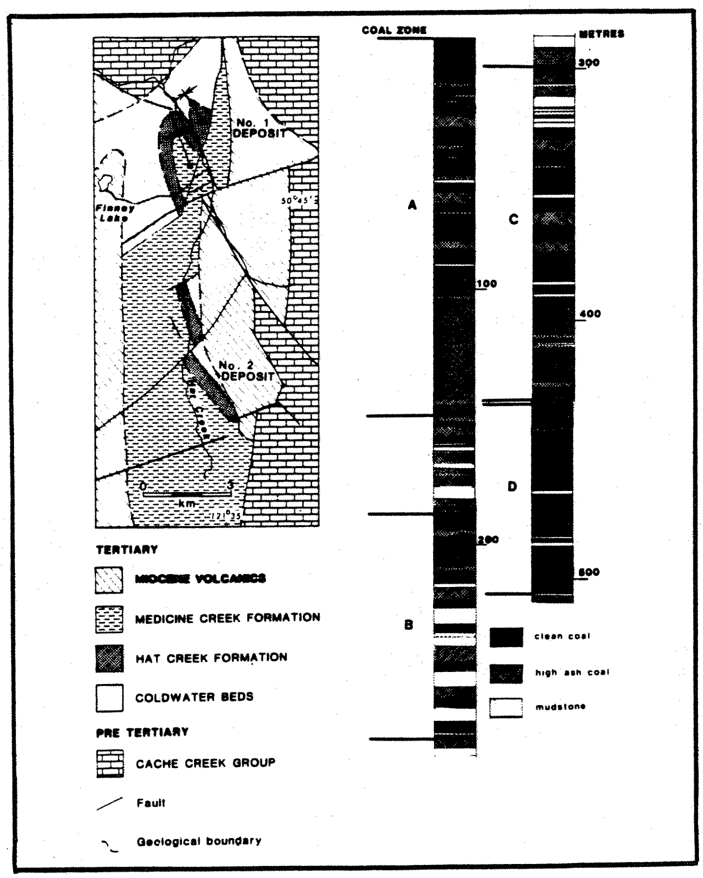

Figure 6. Hat Creek deposits and typical coal section; section after Goodarzi and Gentzis (1987)

each area. However, most near surface coal is covered by a mantle of glacial drift and red clinker caused by spontaneous combustion of the coal. Thicknesses of till and clinker are reported to be up to 75 m in the No. 1 deposit.

Papic et al. (1977) estimated recoverable coal to 180 m depths for No. 1 and No. 2 deposits at over 400 and 600 megatonnes, respectively. Recoverable coal quantities increase four fold by increasing the depth cutoff from 180 to 460 m. The overall strip ratio at the deeper limit is approximately 3:1.

Hat Creek coal ranges in rank from lignite A to subbituminous C (Ro max. 0.38 to 0.50%, Goodarzi, 1985). Results from petrographic examination indicate that the No. 1 deposit has a slightly higher rank than the No. 2 deposit. Goodarzi (1985) established that the Hat Creek coals contain a very high huminite (juvenile vitrinite) content, commonly exceeding 90%. Table 2 reports generalized quality characteristics for these coals. The ash content of the mining zones can vary significantly depending on the amount of parting material present. Selective mining will be required to minimize ash in the run-of-mine product.

QUESNEL BASIN

Background

Coal-bearing strata at Quesnel are contained in a narrow basin along the present Fraser River 130 km south of Prince George (figs. 1 and 7). The basin extends 40 km south from its northern limit at Quesnel. Its average width is 4 km. Outcrops are rare because weak lithification makes bedrock very susceptible to erosion. Additional possible erosional remnants of Tertiary strata occur further north along the Fraser River and its tributaries, but are relatively small and have no commercial significance at present.

Previous coal exploration in the main basin included 3 test holes completed by Cariboo Coal and Clay Co. in 1930, 21 rotary test holes by Master Exploration Ltd. in 1971-72, and 3 diamond drill holes by the GSC in 1978. Master Exploration Ltd. had acquired coal licences near the south end of the basin, but has subsequently drop their interests.

Geology

An estimated 560 m thick succession of poorly lithified Tertiary sediments, named the Fraser River Formation, overlies Eocene volcanics in a narrow fault controlled trough. These sediments are informally divided into two distinct members separated by an angular unconformity. The lower Fraser River Formation (Graham, 1978, Fig. 3) consists of 360 m thick, mudstone siltstone dominated sequence with minor sandstone, conglomerate and coal. The upper Fraser River Formation consists of at least 200 m of massive conglomerate and sandstone grading upwards to siltstone, mudstone, diatomaceous clay, and occasional thin coal seams. Palynological evidence (Piel, 1971) indicates that the lower member is early Oligocene in age, whereas the upper member is mid to late Miocene. Flat lying plateau basalts locally overlie the Fraser River Formation. Reoccupation of the ancestral

Fraser River subsequent to Miocene volcanism caused deep erosion through the upper and lower Fraser River sediments along the main axis of the basin (Fig. 7).

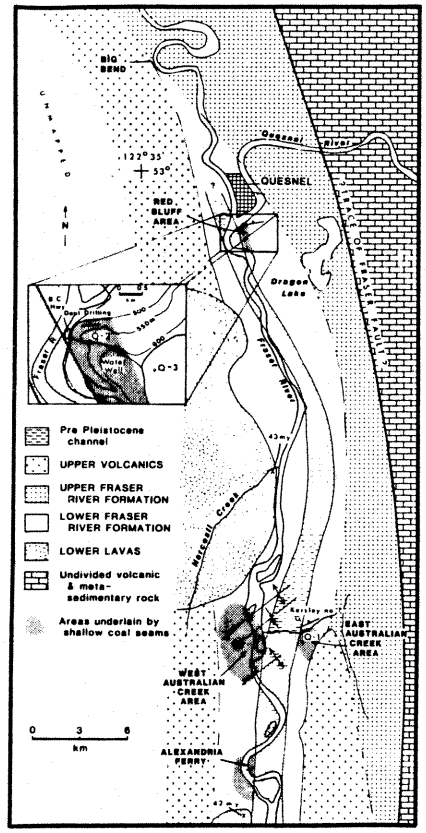

Figure 7. Quesnel basin geology

The coal-bearing lower Fraser River Formation underwent a minor tectonic event. Dips up to 55 degrees are reported but are commonly less than 20 degrees. Folds with no apparent preferred orientation dominate the tectonic setting. The upper Fraser River Formation is flat lying.

Coal Potential

The relative scarcity of bedrock exposure and subsurface information has hampered determination of coal potential. However, several areas have reported coal occurrences. At Red Bluff, immediately south of Quesnel townsite, the B.C. Department of Highways drilled a series of shallow cable tool holes which penetrated a possible 30 m coal zone averaging 60% coal by volume (Fig. 7). This zone appears to dip 5 degrees to the north. A water well drilled 800 m southeast of these holes penetrated an 18 m thick coal zone of similar material. In 1978 the GSC drilled a continuous core hole in the immediate vicinity (location Q 2, Fig.7) but only penetrated a 100 m thick sequence of mudstone, coaly mudstone and thin coal layers (Graham, 1979). Where penetrated, individual seams ranged up to 60 cm thick. Drilling also showed a very limited area for coal development.

Master Exploration Ltd. delineated a small coal area at West Australian Creek, 25 km south of Quesnel (Fig. 7). Drilling showed the presence of a major coal zone from 2.3 to 9.6 m net thickness. The zone contains several thin to thick inorganic layers and displays considerable lenticularity over short lateral distances. It has been folded into a gentle northeast trending syncline with dips on the limbs of less than 10 degrees. Up to 28 megatonnes in situ may be present at depths of less than 90 m. Lakes (1930) reported results of a continuous core hole located 3 km east of the coal area drilled by Master Exploration. This hole was reported to have penetrated two coal zones of 4.2 and 21.9 m thick. Records show that these coal zones contain numerous clay partings. GSC hole Q1, drilled near the hole reported by Lakes (Fig. 7), did not penetrate any thick coal zones. Coal-bearing strata have been truncated between east and west Australian Creek sites by a deeply incised pre-glacial sand-filled channel (Fig. 7).

At Alexandria Ferry, 7 km further south (Fig. 7), a 1.0 m thick exposed seam, dipping to the south at 15 degrees, was reported (B.C. Min. Mines, 1923, P. A126). Subsequent drilling by Master Exploration Ltd. failed to locate any seam extension.

There have been very few records of coal in the upper Fraser River Formation, and these report seams too thin and dirty to be of present commercial interest.

Coal at Quesnel is lignitic rank, with apparently high inherent ash content. The relatively poor quality of coal and absence of identified large surface mining possibilities render the coal deposits of little commercial significance.

BOWRON BASIN

Background

The Bowron basin is a northwest trending elongate area along the Bowron River valley, 50 km east of Prince George (figs. 1 and 8). Coal measures are poorly exposed because of thick drift cover over the area.

Since it was first discovered by Dawson (1878) the area has undergone sporadic coal exploration from 1946 to 1981. In 1974, Norco Resources Ltd. started acquiring coal rights in the field and presently holds 19 licences covering the whole known extent of coal measures. To date, Norco and its partners have drilled over 100 test holes, and have driven at least two exploration adits for bulk sampling.

Geology

Coal occurs in an unnamed sequence of sandstone conglomerate and mudstone estimated in excess of 700 m (Klein, 1978). These strata, of late Eocene age or younger (Smith, 1988), were deposited on Mississippian sedimentary rocks in a graben type basin. The sedimentary succession is characterized by a generally coarsening upward sequence. The coal zone is approximately 35 m thick and occurs directly above a conglomerate-breccia unit found at the base of the succession.

The coal measures have been tilted in a northwest trending monocline. Dips at surface average about 45 degrees to the northeast, but appear to flatten at depth to between 10 and 20 degrees. Holland (1949) described two sets of secondary small displacement normal faults, one set parallel and one oblique to the basin. Drag folding and shearing are associated with the fault zones.

The northwestern and southeastern limits of this monocline are masked by thick glacial drift.

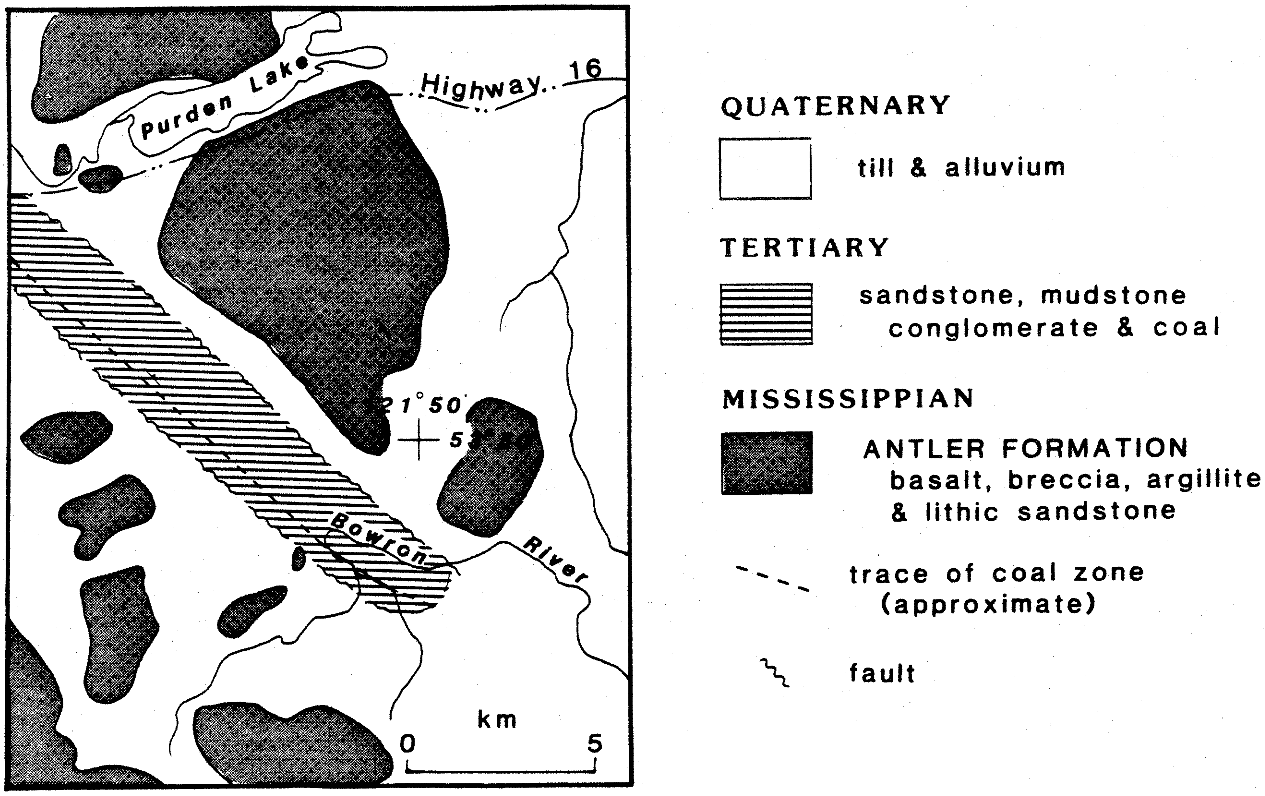

Figure 8. Bowron basin geology

Coal Potential

Drilling by Norco has delineated one to two zones near the base of the sedimentary sequence. The lower zone is thicker being up to 3.4 m thick in places. The upper zone is thinner and not considered to be of mineable thickness. Drill hole evidence demonstrates a high degree of zone variability caused by the discontinuous nature of the partings.

Till and gravel over the coal measures commonly range between 25 and 45 m thick, which eliminates any surface mining potential. Norco has estimated at least 50 megatonnes of in situ coal available by underground mining methods. Because of the seam variability described earlier, it is anticipated that difficulties would be encountered in recovering coal by underground methods.

Testing of coal indicates a high volatile B to C bituminous rank with high ash content. However, through beneficiation, an acceptable conventional market product could be prepared (Table 2). Two other important features of this coal are its higher sulfur content, generally exceeding 1% in the raw and clean coal state, and the coal's unusually high amber content which enhances its heating value and reactivity.

OTHER BASINS

Coal-bearing strata of Tertiary age are also reported at White Lake (Church, 1973), Kamloops (Graham & Long, 1979), Chu Chua (Uglow, 1922), Mt. Greer (Tipper, 1963 and Gulf Canada, 1981), Tuya River (Eisbacher, 1974 and Esso Resources, 1979), and the Sustut basin (Eisbacher, 1974). Other Tertiary sedimentary basins are reported in the literature but have very limited information on the presence of coal. None of these basins has any present exploration or licensing activities. Although these basins are of limited present interest, they do help in understanding the Tertiary geologic framework of the interior of B.C. Some of the important factors that affect coal distribution are summarized below.

GEOLOGIC FRAMEWORK OF TERTIARY BASINS

SEDIMENTOLOGY

The stratigraphic succession in all Eocene basins represent deposition in predominantly fluvial-lacustrine settings. The coarse, basal conglomerate-breccia unit found in most basins represents local infilling of valleys by debris flows, fans and braided streams. The thick, fining upward sequence above the basal unit represents a transition from high gradient braided streams to lower gradient meandering streams as valley bottoms become wider caused by the infilling of lower lying areas. Locally, small lakes and ponds developed along the river course. Coal is generally associated with the finer, mud dominated layers and represents swamp conditions in overbank areas. Tertiary coals are commonly split by thin mudstone-siltstone layers, suggesting that flooding in the overbank areas was common. Occasional thin to thick sandstone-conglomerate layers occur in the mudstone dominated units and probably represent channel facies. The notable exception to this model is the Hat Creek Coal Formation at Hat Creek. Intensive drilling of this deposit has failed to locate any channel facies. The cause of this is uncertain. One possibility is that the Hat Creek basin was a closed watershed, with no major trunk streams within the basin. If true, then a delicate balance between subsidence rate and vegetal buildup would seem necessary over long periods of time.

Paleocurrent information has been reported for only four basins south of latitude 51° North. The Princeton, Merritt and Quilchena basins show a southerly paleocurrent direction (Hills, 1965), whereas the White Lake basin shows a northerly paleocurrent direction (Church, 1973). Based on the fluvial nature of the strata and the apparent contemporaneous age of deposition, it is likely that some of the Eocene basins in the southern interior of the province were at one time interconnected by at least one trunk stream. The dominance of a southerly paleocurrent direction suggests that the main flow was to the south, but may have had local reversals, of occasional northerly flowing tributary streams.

EFFECTS OF VOLCANISM AND TECTONISM

Many parts of the Intermontane Belt underwent episodic Tertiary volcanic activity. Souther (1977) stated that the volcanics were related to block faulting and were preserved in grabens and half-grabens. As such, the areas of thick volcanic accumulation commonly coincided with areas of Eocene sediment deposition. In most of the Eocene basins, volcanism occurred contemporaneously or after sedimentary deposition except in the Princeton and Tulameen basins, where volcanism predated sediment deposition. Contemporaneous volcanism greatly affected depositional characteristics, causing large influxes of coarse detrital material, and diminishing the development of coal seams in overbank areas. Postdepositional volcanism has in some cases infilled the basins and has prevented erosion of some of the underlying strata.

Eisbacher (1977) and Monger and Price (1979) have suggested that major right lateral transcurrent movement has occurred along a series of fault zones running north through the interior of British Columbia and linking with the Tintina Fault in the Yukon Territory. The exact age of faulting is not known, but Monger and Price (1979) date it between late Cretaceous and Oligocene time. Evidence along the Fraser Fault in south-central British Columbia suggests that major right lateral movement may have commenced after emplacement of middle Eocene sedimentary and volcanic rocks and prior to deposition of Oligocene strata within the Fraser Fault zone. The amount of translation along these faults may be as much as 400-500 km (Eisbacher, 1977; Monger and Price, 1979). Regardless of the amount of translation, the original distance between Eocene basins in the south and older sedimentary basins to the north may have been much less, having been separated by major right lateral displacement after deposition.

CLIMATE

Little is known of Paleocene climatic conditions in British Columbia because of the limited distribution of strata of this age. The middle Eocene, however, is well represented throughout the province and generally contains a varied and well preserved microflora. Rouse and Mathews (1961), Hills (1965), Hopkins (1969) and others have described the assemblages as containing floral groups indicative of subtropical to cool-temperate affinities. The wide range of climatic conditions may have been caused by the general high relief within the region of the province (Hills, 1965). Late Eocene to Oligocene sedimentary rocks found in the Yukon (Hopkins and Norris, 1974; Hopkins et al., 1975) also contain microflora species of temperate to warm-temperate affinities indicating warm conditions prevailed over large areas of western North America during this time.

Microflora collections from Miocene strata indicate a cool-temperate climate with a relatively high annual precipitation rate in central British Columbia (Mathews and Rouse, 1963; Piel, 1977). Mathews and Rouse (1963) compared this climate to the present climate in southern Ontario, and to Kentucky and Tennessee in the eastern United States. Although peat swamps develop under these climatic conditions, large amounts of vegetal buildup are restricted by the seasonal temperature-precipitation variation and by the more limited varieties of plant life.

DISCUSSION

When considering future coal exploration and development possibilities of the region, various areas can be eliminated as being least promising based on age of strata and the depositional settings. Early Oligocene strata do contain thick coal beds, but they are of lesser interest because of poor quality, low rank, and generally limited areal extent. Eocene basins are known to contain coals of sufficient thickness, rank and tonnage to be considered of economic interest. In the southern interior, Eocene basins have been well defined except for a few locations where additional coal-bearing strata may underlie Kamloops Group or Miocene volcanic rocks. The undiscovered areas of greatest coal potential are to the south and east of the Hat Creek deposits in the Cache Creek area. In the northern interior, coal exploration activity has been limited. Unlike the southern basins, thick Quaternary cover and a more subdued terrain have made basin definition difficult over large areas of the northern interior. Between the Sifton and Sustut basins to the north and the Hat Creek basin to the south is a 600 km long area with scattered occurrences of Eocene sedimentary rocks. Based on the premise that these occurrences may have been linked in the Eocene by major trunk streams, it is possible that additional coal-bearing sedimentary basins of Eocene age occur north of Hat Creek but are covered by younger volcanics.

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FUTURE PROSPECTS FOR EXPANDED UTILIZATION OF STEAM COAL

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INTRODUCTION

From history lessons during our schooldays, we learned that the steam era began during the industrial revolution of the 19th century. The fires of that revolution were fuelled by coal, and coal industries sprang up in newly industrialized countries as a result of the demand for coal. The rapid rate of economic development and social progress made by the newly industrialized countries was due in large measure to the utilization of their own indigenous coal resources. Records show that from the late 19th century until the early 1950s, coal played a dominant role in world energy markets.

In the early 1950s, circumstances changed and almost all coal used for industrial energy, chemical feedstock, domestic heating, and transportation energy, was replaced by petroleum products and natural gas. The ready availability of cheap oil through the 1950s and 1960s led to a progressive reduction in the importance of coal as an energy source. Faced with competition from a world glut of cheap oil, coal was in serious danger of being phased out as a primary source of energy.

However, the oil crisis of 1973 gravely affected the balance between supply and demand in the international oil market as prices escalated sharply and supplies were disrupted by political actions in the Middle East. The economic structure of the industrialized world that had by that time become heavily dependent upon oil, proved too rigid to absorb the shock and awakened the world to the need for some structural adjustment in the energy economy. To meet this challenge, the world's industrial nations began efforts to reduce their dependency upon oil, and seek a more balanced distribution among energy resources. As a consequence, we now see the beginning of a new multi-energy era in which steam coal is re-emerging as a primary source of energy.

The discussion that follows is related to steam coal, the properties and utilization considerations of which are distinctly different to those of coking coal. In the absence of relevant records for historical market trends and other data required for interpretation purposes, the author has drawn from his own knowledge and experience gained since entering the coal industry in 1947.

CHANGING MARKET FORCES

To keep the energy scene in perspective, it should be remembered that the industrialized world has gone through several energy substitutions in some 140 years. For instance, between 1850 and 1910, wood was replaced by coal. In the late 1800s and early 1900s, work animals were partially replaced by railway locomotive coal; then between 1900 and 1950, both animals and coal were replaced by motor fuels and oil and gas. Direct wind and water sources were replaced by hydro between 1890 and 1940. Throughout this period there has been a steady rise in the proportion of fossil fuels converted to electricity prior to consumption. What we are now witnessing, is a trend back to coal as a substitute for oil in the largest of all energy markets; power generation.

It is worth noting that all through this history of almost continual substitution of fuels, coal has always been available at competitive prices. It has been the scarcity of alternative fuels as reflected by their high prices at a particular time, which has brought about a substitution in favour of coal. Historical experience has shown that coal production increased or decreased to meet demand as reflected by prevailing market forces in the energy sector.

This characteristic is strongly supported by the geological evidence which shows that the massive global reserves of recoverable coal, are many times greater than the equivalent oil reserves. Set against such evidence, the historically stable consumption pattern for coal, cannot be attributed to production constraints. However, since the late 1970s, an upward trend can be seen in the supply curve, as coal begins to replace oil in the generation of electricity. This trend reflects a major growth in the international trade in steam coal.

Coal use today is essentially confined to (a) steam raising, and (b) manufacture of metallurgical coke. Identified as steam coal and coking coal respectively, each must possess the necessary properties to match their utilization needs. With few exceptions, they are not interchangeable. In the case of steam coal, it is particularly important that the coal properties and the combustion system employed to burn the coal, are compatible.

COAL BY WIRE

"Coal by wire", is a phrase coined to identify the link between coal and electricity in order to publicize coal's role in electricity markets. As a marketing slogan it is appropriate, because electricity is the world's largest energy market, and energy is an essential element of economic development and social progress of all countries. Of the four major sectors of world energy use, only electricity can power many of the functions vital to a developed, technological world. This is reflected in electricity demand which has trebled over the last twenty years in the Western World, and continues to increase faster than both total energy use and overall economic growth. As can be seen from Figure 1, coal is the greatest source of electricity generation. It is no coincidence to find that today's largest market for coal, is that for power generation.

In comparison with competing fuels, coal has major advantages which are likely to ensure its expanded use in the power generation market. For instance, there are very few plans for major new oil or gas-fired power stations; most of the sites suitable for hydro power have already been used; renewable energy sources are as yet uneconomic; and plans for nuclear power have been drastically cut back and in many cases, abandoned. This leaves coal as the strongest candidate for meeting future demands, on the grounds its abundance and diversity safeguards both security of supply and price stability. Further, because of the constant upward trend in electricity demand, an expanding market for steam coal seems assured. Confidence in this forecast is reinforced by the growth in international steam coal trade, which is due almost entirely to the increased use of steam coal for power generation.

THE INTERNATIONAL COAL TRADE

Unlike the trade for coking coal, international trade in steam coal is a relatively recent development, only taking off after the 1973 oil crisis. Table 2 shows the main coal indicators for 1987 and Figure 2 shows the world coal movements in 1987. Respective coking and steam coal tonnages within the international coal trade between 1973 and 1988, are shown in Table 1. In the case of Canada, it is of interest to note that while exports of coking coals to Pacific Rim countries account for more than 40% of Canada's total coal production, Canada does not play any significant role in international steam coal markets.

The growth of international trade in steam coal coincided with the turn of events following the 1973 oil crisis when coal began replacing oil. Until that time, oil demand had grown enormously to dominate the world's energy markets. New discoveries of oil in the Middle East had kept supply ahead of demand, but in the early 1970s the domination of one region and a single cartel inevitably brought instability and price escalation. This led to a drive by the industrialized world to reduce their dependency upon imported oil, and gave rise to a worldwide trend back to coal. This in turn promoted an increase in world coal movements as oil was replaced by coal in existing power stations equipped with boilers that were coal tolerant. Construction programs for new coal-fired power stations were implemented, and forward energy plans based on coal, began to be put in place.

This confidence in coal is attributable to the comfort factor that coal reserves exist in every continent of the world, and by changing from oil to coal, power utilities can feel secure in the knowledge that it will neither run out in the foreseeable future, nor will supply become dominated by any one region or political grouping. The "BP Statistical Review of World Energy", shows accessible coal and lignite reserves at the end of 1986, to be in excess of one million million (10^{12}) tonnes; sufficient to last for 226 years at 1986 levels of production.

The infrastructure of international coal supply is now highly developed and flexible. Many mines are tailored specifically to the world market and producers have become skilled in responding quickly to market demand. More companies from an increasing number of countries are involved in the international steam coal trade, and world port capacity has expanded to such an extent that it would not be a constraint even if the entire export output from one supplying country ceased to be available.

PROSPECTS FOR INCREASED UTILIZATION OF STEAM COAL FOR POWER GENERATION

Based on the ever-increasing worldwide demand for electricity, a strong case can be made that power generation represents great potential for the expanded utilization of steam coal. Since electricity is already the biggest market for coal, it should remain so for the foreseeable future. Current trends support this conclusion, although it is recognized that almost any fuel can be used to generate electricity. While the choice of fuel will depend primarily on economic factors; strategic, environmental and safety considerations are equally significant issues which affect the eventual choice. It is worth comparing the most significant fuel options, in the setting of a large scale and rapidly expanding international electricity market.

Renewable sources which include solar, wind and geothermal power, provide less than 1% of the world's electricity; a small contribution reflecting their low cost effectiveness, especially for large scale use.

Gas prices have fluctuated almost as much as oil prices in the last fifteen years, and despite the expansion in international grids, only a very small percentage of natural gas enters world trade. Figure 3 shows world gas consumption in 1986 and as can be seen, internationally traded gas accounted for only 13% of the total. Because of the high demand for premium fuel in household heating and cooking, and for certain industrial processes which require very clean and controllable heat, except in special cases, gas is likely to remain prohibitively expensive for large scale power generation.

In the aftermath of the oil crises of the 1970s, almost all plans for major new oil-fired power stations in the Western World, were abandoned. Because of the risk associated with oil, both in terms of its supply security and price stability, very few plans exist today for new oil-fired installations. The oil price shocks of the 1970s can be identified from Figure 4 which shows crude oil prices since 1880. It is of interest to note that although oil demand grew enormously from 1880 through to the 1970s, the price of crude oil hardly changed, a situation which is unlikely to be maintained when serving an ever increasing worldwide demand for electricity.

The history of nuclear power has been marked by a succession of optimistic claims - and subsequent disenchantments. Disappointing costs and performance have been a recurrent theme, but perhaps the most disturbing feature of nuclear power, is that of its operational safety and its environmental impact. Decommissioning of nuclear stations when they reach the end of their operating life remains an unknown factor. Public concern over these issues, and debate among legislators are responsible for the decline across the world, in orders for nuclear plants. This downward trend is reflected in a lowering of projections of the future level of nuclear capacity.

To illustrate this; in 1974, the International Atomic Energy Agency (IAEA) in Vienna predicted that world nuclear capacity in the year 2000, would be 4,450 GW; more than 16 times the current nuclear capacity and more than double the size of the world's entire electricity system in 1987. By 1986 the world's nuclear capacity was only 260 GW and the IAEA had scaled their projection down to 505 GW; less than one-ninth of their 1974 forecast.

Hydro power is the world's second largest source of electricity generation. If the initial site costs are modest, hydro power is an attractive option, as running costs are low. But hydro production is only possible when topography is favorable and rainfall is high. Most of the sites suitable for hydro power have already been exploited and the sites that remain, have been left either because they are difficult and expensive to develop, or are prized for their amenity value.

On the grounds (1) that renewable sources of energy for power generation can be discounted as uneconomic; (2) that oil and gas are insecure and economically unstable; (3) site constraints prevent hydro power from being expanded to meet future demand, and (4) the operational safety and environmental safeguards for nuclear power cannot be guaranteed; coal is the only significant fuel with the potential for meeting the increasing worldwide demand for electricity in the foreseeable future. The abundance and diversity of the world's coal resources should ensure security of supply. The case is strengthened because coal-fired power stations are based on proven technology and have a good record of reliability that extends over a century.

Coal is rapidly replacing oil as the standard fossil fuel for new electric power generation, and its projected future demand in international markets is illustrated in Figure 5. The upward trend which reflects the increased use of coal for power generation, is unaffected by the current oil surplus.

COAL PROPERTIES WHICH INFLUENCE COMBUSTION

The successful utilization of steam coal is dependent on two closely inter-related factors; the physico-chemical properties of the coal, and the operational characteristics of the combustion system in which the coal is burned. These factors can be accommodated when a system is designed to burn coals of known quality; but when an existing system is required to burn substitute coals that are not well defined, extreme care must be taken to ensure that the coal properties and the system design are compatible. Matching a coal with its utilization needs is critical because of the wide range of combustion systems that comprise the steam coal market. Although coals can be characterized, each coal is unique and should be judged accordingly.

All forms of combustion produce carbon dioxide, which accounts for about half the total radiative gases entering the atmosphere that give rise to the so-called "greenhouse" hypothesis. While clean coal technology and advanced combustion technologies are likely to make an important contribution in ensuring future environmental protection, the first task is choosing the right coal for the job. This calls for recognition that no one property in a steam coal influences combustion on its own; there are many which have to be taken into consideration and these are summarized in Table 4, and briefly described below:

FUEL RATIO: Fuel ratio is a parameter defined by the ratio of Fixed Carbon to Volatile Matter. This is a key factor which experience has shown, strongly influences combustion efficiency. While an empirical correlation has not yet been developed, coals with a fuel ratio in excess of 1.8 can usually be ruled out for use as steam coal. High fuel ratios result in poor carbon burn-out.

MOISTURE: Moisture whether surface or inherent, in dry bulk coal used for suspension firing, impairs combustion performance by (a) reducing pulverizer capacity, (b) retarding ignition, (c) decreasing flame stability, (d) increasing flame length and furnace volume, (e) increasing induced draft fan requirements, and (f) causing corrosion in the colder regions of the boiler.

ASH: Increased ash contents, dilute the combustible coal constituents and adversely affect pulverizer capacity, flame stability, heat transfer patterns and the combustible carry-over in fly ash. It will be obvious that the higher the ash content, the more inert material there is to be collected in the system and conveyed to disposal. For example, if the ash content of a coal were to increase from say 10% to 15%, the boiler ash system would have to handle 50% more ash.

VOLATILE MATTER: Increased volatile matter produces improvements in ignition, flame stability and carbon burn-out as well as decreases in flame length and furnace size.

FIXED CARBON: Fixed carbon is the char that remains after evolution of volatile matter from coal. It should not be confused with the carbon content, as determined by ultimate analysis. The speed of burn-out or reactivity of this carbonaceous residue is a critical parameter in designing burners and furnaces.

MACERAL FORMS: The maceral constituents of a coal have a pronounced effect on combustion performance, and the relative proportions of the different macerals present, can be used to predict how easy a coal will burn. Although the maceral forms vary widely, depending on the source material of the plants and the geological history of the coal seam, three main groups are routinely identified by petrographic examination. These are vitrinite, exinite and inertinite.

Vitrinite, which is derived from large fragments of wood and bark, usually contains little mineral matter. It expands when heated, exposing a large surface area that burns readily.

Exinite consists mainly of coalified spores, pollens and algae. It is high in resin and burns freely.

Inertinite is made up of fusinite and semi-fusinite. It is characterized by a low volatile content and a graphitized form of carbon which burns slowly without swelling.

GRINDABILITY: Hardgrove Grindability Index (HGI) is used to provide an indication of a coal's hardness. An index of 100 denotes a friable and easily ground coal, whereas an index of 35 denotes a difficult coal to grind.

CALORIFIC VALUE: The calorific value of a coal is based on its heating value.

ASH FUSION TEMPERATURES: The fusion or melting characteristics of coal ash are universally used to predict the sintering (fouling) or melting (slagging) tendency of fly ash deposits. The higher the ash fusion temperature, the lower the degree of potential slagging.

ASH COMPOSITION: From a combustion point-of-view, ash quality is more critical than quantity. Eight major elemental oxides in coal ash (Al_2O_3, SiO_2, CaO, Fe_2O_3, MgO, Na_2O, K_2O and TiO_2) have been used to predict both fouling and slagging of fly ash. The degree of fouling has been found to be largely related to sodium.

MINERAL TRANSFORMATION: The original mineral matter in coal is transformed in the flame into radically different sizes and species, that may impact on boiler availability.

SULFUR: During combustion, the sulfur in coal is converted to SO_2, the emission of which must meet standards statutorily imposed in order to reduce air pollution.

CHLORINE: When levels of chlorine exceed 0.3%, corrosion of boiler tubes occur.

NITROGEN: A major precursor of acid rain, NO, is produced by the oxidation of coal nitrogen in flames.

NEW TECHNOLOGIES AND THEIR POTENTIAL FOR INCREASING COAL UTILIZATION

The replacement of oil by coal in steam generation is already well underway and despite the disadvantages inherent in handling coal in its dry bulk form, this major market will remain one for dry bulk coal. However, while power generation will continue to be coal's largest market, conversion of existing oil-fired industrial boilers also represents a large potential coal market. Historically, the principal factors that have adversely affected conversion from oil to coal, are:

- the high cost of plant conversion
- the more cumbersome and expensive handling/transportation
- the environmental constraints on burning.

Development of coal-liquid mixtures has overcome these disadvantages and now allows coal to be used as a direct replacement for oil to fire large utility and industrial boilers. Because these mixtures behave as a liquid, they have all the advantages and convenience enjoyed by oil.

The technology of feeding existing oil-fired power plants with a coal-oil mixture (COM) has been commercialized in Japan where a one million tonne per year COM production facility at Onahama currently serves as a source of fuel for generating electricity in local power stations.

However, of the alternative coal-based fuels projected to meet future energy needs, coal-water-mixtures (CWM) are the most promising. Like coal-oil mixtures, CWM has been developed for use as a direct replacement for oil to fire utility and industrial boilers. The largest boiler to be fired with CWM, is the No. 8 unit of 600 MW capacity at the Nakoso power station in Japan. This unit is currently fired by oil, coal, and CWM in a multi-fuel feed system in which 15% of the feed is CWM, 35% coal, and 50% oil. Prior to the current firing of No. 8 unit at Nakoso, 100% CWM had been used to fire the No. 4 unit of 75 MW capacity. It is encouraging to note that while some derating was anticipated with CWM when it was used to replace oil, none occurred.

As a result of the experience gained at Nakoso, and other successful pilot projects conducted on an industrial scale over the past five years in several other countries, it has been widely demonstrated that a stable coal-water fuel can be manufactured, transported, stored, handled and burned in utility and industrial boilers. At the meeting of signatory countries to the IEA Coal-Liquid Mixture Agreement held in Tokyo, November 7-11, 1988, member countries were agreed that CWM technology is now ready to be commercialized. It is expected that the technology will gain widespread acceptance as user confidence becomes established.

Japan is cited because that country is among those most earnestly striving to reduce their heavy dependency upon imported oil. Since it has very limited indigenous energy resources, Japan is in the vanguard of these new technologies, out of necessity. Already the world's largest coal importing country, their imports of steam coal are forecast to double within the next decade. Table 3 shows the world seaborne coal imports forecast 1990-2005.

Although the world's abundant coal reserves are diverse, a significant proportion of them comprise low-rank coals which all share one major impediment to widespread commercial use - high inherent moisture. Until now high moisture ranging from 25% to 65% has made transportation costs prohibitive and relegated these coals to local use or generation of electricity at the minesite. This situation has been changed by a unique non-evaporative drying technique in which the structure of such coal is fundamentally altered and made similar to that of higher rank bituminous coal.

Commonly known as hot-water-drying this new technology is a major breakthrough in coal processing. The process can be represented as the irreversible removal of inherent moisture by induced coalification. In essence, the technology induces coalification in a condensed time scale of minutes rather than geological eras, thus effecting a permanent reduction in inherent moisture. The significance of this feature, is that unlike coal dried by conventional thermal drying in which evaporative processes are employed, hot-water-dried coal does not re-absorb moisture when it is exposed to humid air or water. As a consequence, the high moisture levels and low heating values of these low-rank coals are no longer an economic barrier to their off-site use. From a utilization point of view, their positive features are an asset. They ignite easier, burn faster and are often lower in sulfur than many bituminous coals. Because they are highly reactive, good combustion efficiencies are achieved with maximum carbon burn-out. A major advantage resulting from beneficiating these low-rank coals, is that re-use of their inherent moisture as the vehicle solvent allows them to be manufactured into CWM with an energy density equal to or even greater than the parent coal.

The facility to beneficiate low-rank coals is particularly important to many of the world's developing countries as they constitute the majority, and in some cases, their only carbonaceous reserves in large enough quantities to be of economic significance. In such countries, exploitation of these reserves would promote more rapid social and economic development and contribute towards making them more energy self-sufficient.

THE ENVIRONMENTAL IMPACT OF COAL UTILIZATION

No discussion on coal utilization would be complete without addressing the environmental issues. Public attention is focussed firmly on the impact all industrial activity has on the environment, and currently the "Greenhouse Effect", is a major topic of worldwide interest. All forms of combustion produce carbon dioxide, which accounts for about half the total radiative gases entering the atmosphere that give rise to the so-called "Greenhouse" hypothesis. Whether the hypothetical consequences of using fossil fuel are exaggerated, or not, the use of coal has always been associated with environmental problems that have had to be overcome. In a historical context, the first step was improving stack emissions.

Coal combustion equipment was specially designed to minimize smoke, and tall chimney stacks improved the dispersion, and thus reduced local ground level concentrations of SO_2 from large industrial sites. These measures dramatically improved local air quality and industrial areas that are still active, are much more pleasant places to live in than they were thirty years ago. However, dispersion of combustion products (SO_2 and NO_x) produced during oil and coal combustion, is no longer enough. Expectations have increased and standards have rightly become more demanding. The spectrum of clean coal technology has been broadened to include long range as well as local effects on coal use.

In today's climate of more stringent environmental control, three basic approaches to burning coal more cleanly are being pursued. These are; advanced coal preparation techniques; advanced combustion technologies, and treatment of the flue gases.

Although they can do nothing about formation of undesirable combustion by-products, advanced coal preparation techniques can remove or reduce many of the impurities present in the as-mined coal.

Control during combustion minimizes the formation of free sulfur dioxide, and allows combustion adjustments to avoid, or at least reduce, the formation of oxides of nitrogen.

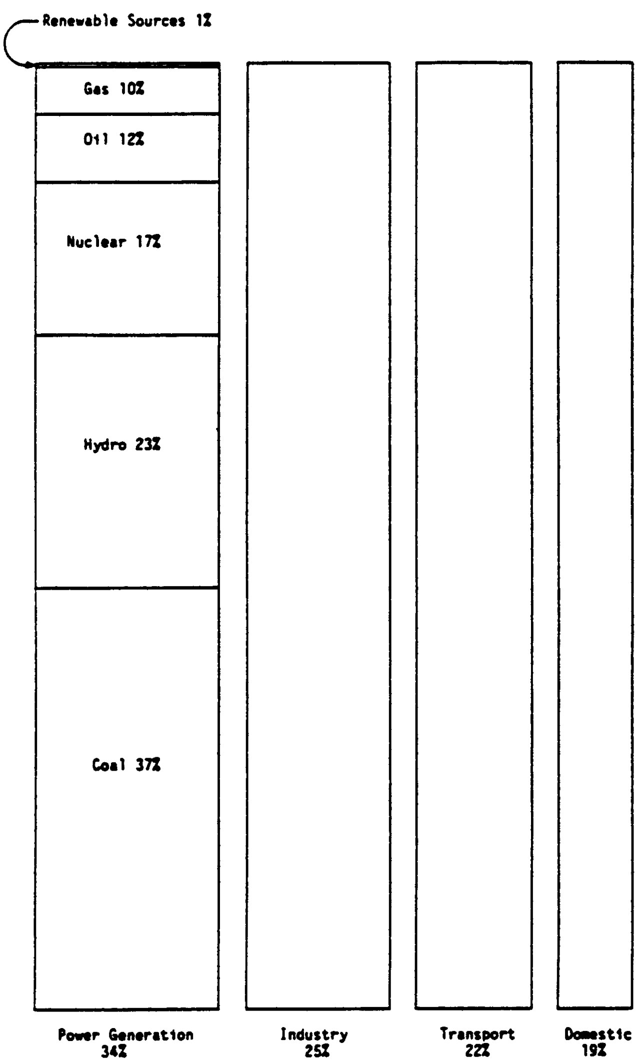
By treatment of the flue gases after combustion, virtually all dust and grit can be removed and this is also the major method for preventing a high proportion of sulfur reaching the atmosphere as SO_2.

Looking at the immediate future, current technological developments will allow coal-fired power plants to be cleaner and safer; thus changing the traditional dirty smoke-stack image which has characterized the industry to date. New coal utilization technologies combined with advanced, higher efficiency power generation cycles will significantly lower emissions. In such a strong market, steam coal producers will find considerable growth opportunities to compete and participate in a clean-stack power industry.

The success of coal producers will depend on their ability to match reserves with the most appropriate technology to produce a user-specific marketable product.

Figure 1

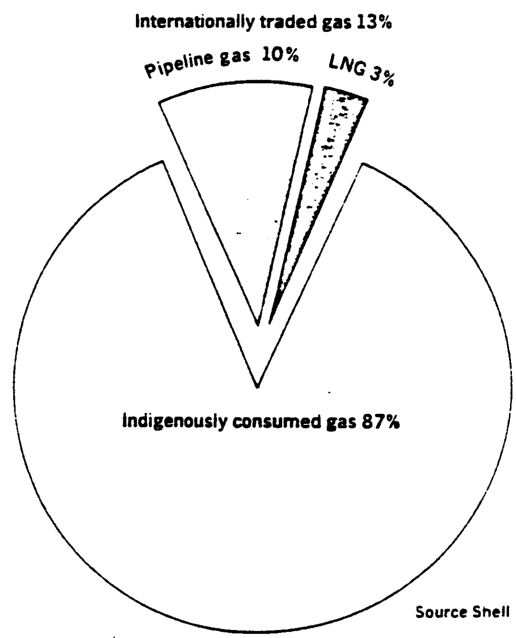
WORLD ENERGY SECTORS



Source: Shell

Figure 3

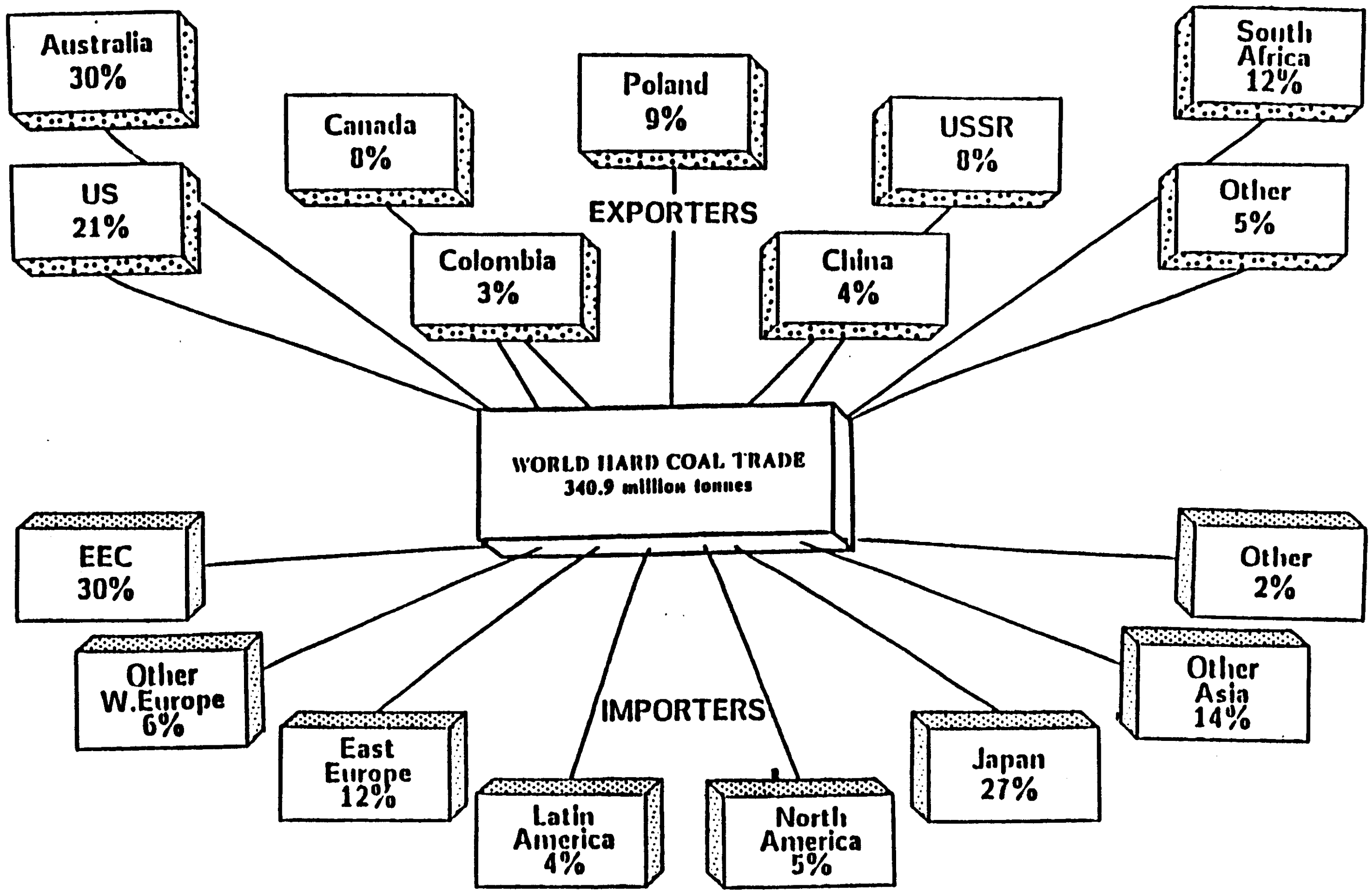
World gas consumption 1986
(1665 billion cubic metres)



Source Shell

Figure 2

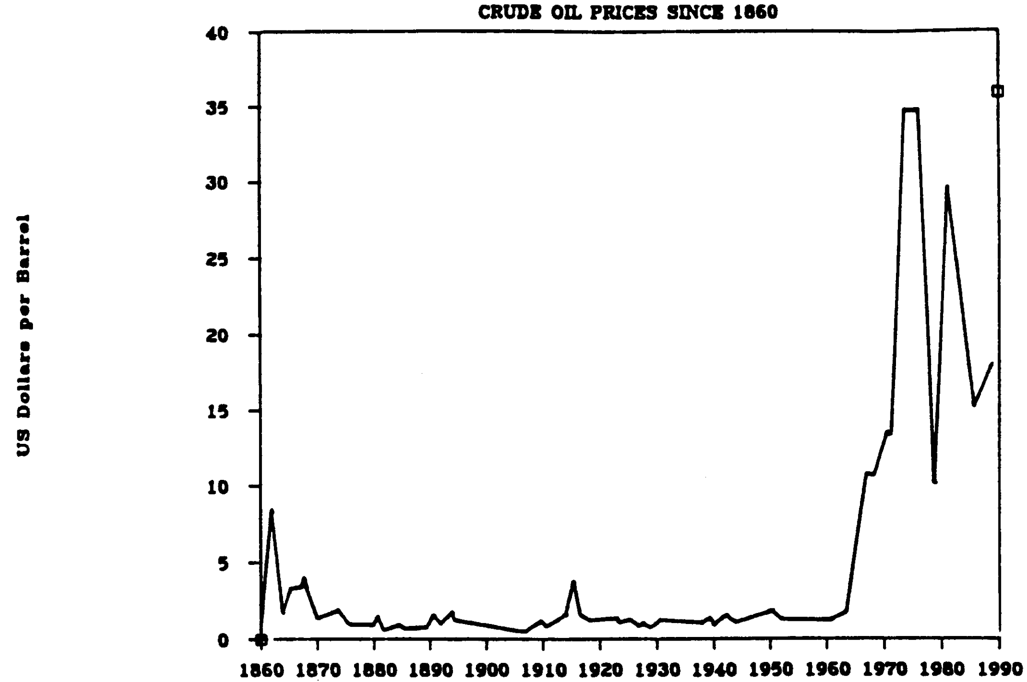
WORLD HARD COAL MOVEMENT IN 1987



Source: International Coal Report - Coal Year 1988

Figure 4

CRUDE OIL PRICES SINCE 1860



Source: BP

Figure 5

WORLD SEABORNE STEAM COAL IMPORTS

Source: Chase Manhattan Bank

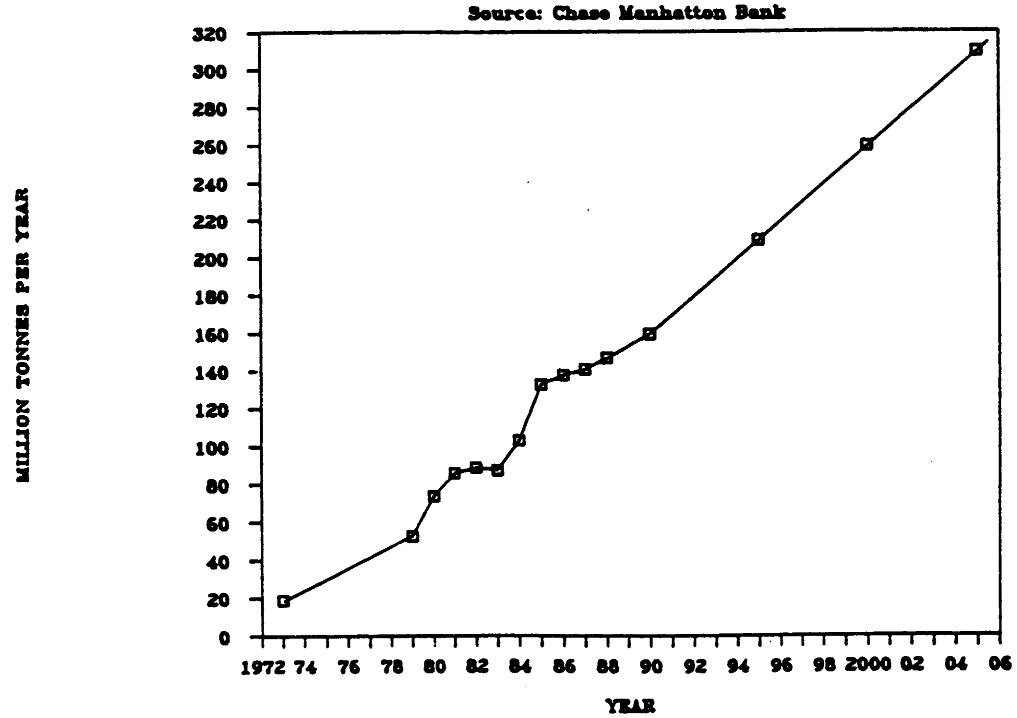


Table 1

WORLD COAL TRADE
1973 - 1988
(Million Tonnes)

Year	TOTAL WORLD COAL TRADE	COKING COAL		STEAM COAL	
		Total	Seaborne	Total	Seaborne
1973	177.1	117.7	87.0	59.4	19.0
-	—	—	—	—	—
1979	232.5	127.8	104.0	104.7	53.0
1980	256.2	138.7	114.0	117.5	74.0
1981	271.3	144.9	122.0	126.4	86.0
1982	269.2	139.6	120.0	129.6	89.0
1983	266.0	135.3	112.0	130.7	87.6
1984	304.7	155.8	131.6	148.9	103.6
1985	335.8	165.0	140.7	170.8	133.1
1986	336.1	161.0	137.3	175.1	138.2
1987	340.9	164.4	141.9	176.5	141.1
1988e	345.3	165.9	144.6	179.4	147.0

"Seaborne" trade excludes overland, barge and lake deliveries.

Source: Chase Manhattan Bank e = estimate

Table 2

1987 MAIN COAL INDICATORS
(Million Tonnes)

Production		Exports		Imports	
China	925.0	Australia	102.0	Japan	92.5
US	831.6	US	71.1	S. Korea	21.8
USSR	758.4	S. Africa	42.6	Italy	19.7
Poland	193.0	Poland	31.0	France	14.6
W. Germany	191.2	USSR	27.1	Canada	14.3
India	187.2	Canada	26.7	Taiwan	13.4
S. Africa	176.5	China	13.1	Netherlands	12.6
Australia	152.1	Columbia	9.6	Denmark	12.0
UK	104.4	W. Germany	6.4	Belg/Lux	9.8
Yugoslavia	72.3	UK	2.3	UK	9.8

Source: International Coal Report (1988)

Table 3

WORLD SEABORNE IMPORTS
1985 - 2005

(Million Tonnes)

	Actual		Forecast			
	1985	1986	1990	1995	2000	2005
STEAM COAL						
US	1.8	2.0	2.9	4.2	5.2	6.6
W. Europe	72.2	69.1	79.3	103.4	121.2	140.5
Asia:						
Japan	22.8	22.6	26.5	37.4	53.8	65.0
Other Asia	27.5	31.8	37.2	47.0	56.9	71.9
Total Asia	50.3	54.4	63.8	84.4	110.7	136.9
Latin America	0.7	0.7	1.5	2.4	3.5	4.8
Africa/ME	3.7	4.2	6.4	8.4	11.5	12.8
CPE Europe	3.5	3.4	4.4	5.5	6.4	7.0
CPE Asia	1.5	1.5	1.5	1.2	1.0	1.0
Total World	**133.7**	**135.3**	**159.6**	**209.5**	**259.7**	**309.6**
COKING COAL						
PCI	1.2	3.0	8.3	17.5	27.1	31.8
Coking	139.9	137.6	138.1	133.2	128.6	128.8
Total	**141.2**	**140.6**	**146.6**	**150.7**	**155.6**	**160.7**

Source: Coal Year 1988

Table 4

COAL PROPERTIES INFLUENCING COMBUSTION

Fuel Ratio	Calorific Value
Moisture	Ash Fusion Temperatures
Ash	Ash Composition
Volatile Matter	Mineral Transformations
Fixed Carbon	Sulfur
Maceral Forms	Chlorine
Grindability	Nitrogen

UPGRADING OF SASKATCHEWAN LIGNITES

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ABSTRACT

Saskatchewan has within its borders large quantities of low-grade coal. This coal is accessible by strip-mining which keeps the mining costs amongst the lowest in Canada. Currently, the majority of lignite output is utilized within the province for mine-mouth power generation. Approximately 20 percent of the coal is exported to Manitoba and Ontario, again for power generation.

Saskatchewan, independently and within the Action Committee on Low-Sulphur Western Coal to Ontario, is examining its lignite resource and means to improve the marketability of this resource. A number of studies have been undertaken with this in mind, examining upgrading and stabilization technologies that are technically feasible at the present time.

The marketability of upgraded lignite depends on both the cost and characteristics of the product coal. At present, the province is concentrating on the characteristics of the upgraded product which is dependent on the type and severity of the process used and the type of coal that forms the feedstock. Results indicate that feedstock is very important and that a considerable amount of work remains to be done in Saskatchewan before there is a complete understanding of the quality of the reserves.

INTRODUCTION

In order to provide some background to current activities in low-rank coal upgrading, it is necessary to examine some of initiatives that have been undertaken by the various governments and the rationale behind these initiatives. These will be examined primarily in the context of Saskatchewan and the lignites found in the southern portion of the province.

As with all resource industries, the coal producers of western Canada, along with the provinces as resource owners, would like to see increased utilization of their product. Increased use leads to more revenues for the producing companies, more jobs are important to the communities in the producing areas and, for the province, more royalty and tax benefits. The potential magnitude of social and economic benefits to Western Canada is detailed in the report of a Federal/Provincial Task Force entitled "Western Canadian Low-Sulphur Coal - Its Expanded Use in Ontario" released in June 1986. The benefits described in this report are substantive. By way of example, using data provided by the Coal Association of Canada, an additional one million tonnes of lignite exported to Ontario would require an additional 45 mine employees, which would result in 150 to 200 people employed in total. In most coal mining areas this would be a very significant boost to the economy.

The impact of the 1986 report, was to stimulate a great deal of interest in the western provinces, particularly by the provincial governments. The goal of increased coal production and its impacts were clearly laid out; but the question of how to attain this goal, in whole or in part, remained unanswered. It is obvious that the benefit of western coal lay chiefly in its low sulphur level and, compared to Appalachian coal, its low mining cost on an energy unit basis. Delivered cost of energy is another matter, here western coal is not competitive. It is the delivered cost of the coal that must be reduced to make western coal a viable alternative to the medium to high sulphur U.S. coal. The 1986 report indicated that at contract prices even the cost of installation and operation of scrubbers on southern Ontario thermal power plants was insufficient to counteract the competitive advantage of eastern U.S. coals. The spot market prices of 1987 with reduced coal and coal transport prices led to some optimism that western coal could be made more competitive.

The potential outlined in the 1986 report and the recognition that coal and coal transportation costs must be reduced to spur sales in central Canada led to the formation of the Action Committee on Western Canadian Low-Sulphur Coal to Ontario. This Committee, composed of the premiers of the three western provinces and Ontario together with the Deputy Prime Minister, created an Intergovernmental Secretariat whose mandate was:

a) to consult with all relevant private sector interests to determine their views as to what actions governments could take to improve the competitiveness of western Canadian coal in Ontario, and

b) to recommend how the governments could co-operate with each other and the private sector in pursuing those initiatives where collective action seemed desirable.

The Intergovernmental Secretariat met with many of the groups involved in the production and transportation of coal and requested their input and opinion on a strategy for the expanded use of western coal. Through this consultative process, the Secretariat outlined possible technological, regulatory and policy options which could impact on the delivered cost of western Canadian coal in Ontario. The various options were assessed in terms of potential impact, implementation, cost and timing. A total of fourteen research and development initiatives were selected in four broad categories:

A. Mine Production Improvements.
B. Coal Product Improvements.
C. Transportation Improvements.
D. Fiscal and Regulatory Improvements.

The fourteen initiatives are summarized in Table 1.

The Secretariat recommended government support for these initiatives because:

1. They offer reasonable potential to reduce the delivered cost of western Canadian coal to Ontario and the probability of success in the near term is relatively high.

2. There is evidence of the broad applicability of these initiatives within the coal and/or transportation industries.

3. They are supported by one or more elements of the private sector.

The Secretariat estimated that the overall costs of these initiatives over the expected 4 to 5 year life of the program would be in the order of $85 million. The cost of commercialization of these technologies, which is considered to be the prerogative and responsibility of the private sector, is not included in these calculations.

Although the private sector can and must take the lead role, the Secretariat concluded that these initiatives all require government support to accelerate their development. The Intergovernmental Secretariat and the project steering committees have begun their activities and are working towards the fulfillment of the goals set by the Action Committee. To date none of the projects have been completed and so it is too early to judge how successful it will be.

Project Title	Lead Government	Time Frame	Potential Impact
A. Mine Productivity Improvements			
In-Pit Crushing and Conveying in Western Surface Coal Mines	Alberta	2-4 years	up to $1.00/tonne
Underground Thick Seam Extraction Using Room and Pillar System of Mining	Alberta	3 years	up to $2.90/tonne
Process Automation	B.C.	2-3 years	up to $0.50/tonne
B. Coal Product Improvements			
Ash Reduction, Refuse Reprocessing and Fines Processing	Alberta	2-4 years	up to $0.50/tonne significantly improved environmental impact significantly increased resource base
Coal Blending to Meet User Specifications	B.C.	2-3 years	significantly increased potential demand
Low Rank Coal Upgrading	Sask.	3 years	commercial plant to produce product competitive in price and quality with higher rank U.S. coals
Coal-Oil Agglomeration	B.C.	2-3 years	significantly increased potential market and increased coal yield of 10%
C. Transportation Improvements			
Rail Efficiencies and Overhead Burdens	Canada	3 months	lower cost of moving coal
Thunder Bay Terminal Operations	Ontario	6 months	economies of scale
Laker Transportation	Ontario	6 months	economies of scale
Coal-Oil Mixture Slurry Transportation Concept	Alberta	3 years	$10 to $15/tonne
D. Fiscal and Regulatory Improvements			
Taxes and Regulatory Costs on Rail and Pipeline Traffic	Ontario	4 months	to be determined
Taxes and Regulatory Costs on Coal Producers	Coal Assoc. of Canada	4 months	to be determined

Table 1: Recommended Initiatives

SASKATCHEWAN PERSPECTIVE

Saskatchewan is involved in the initiatives developed under the Action Committee. The province has also undertaken some work outside the Action Committee in order to further develop lignite. It is important to put these lignite reserves in context prior to discussing their potential.

Saskatchewan has large reserves of lignite totalling approximately 7.5 billion tonnes of immediate interest (lignite in seams at least 1.5 m thick at depths less than 45 m) and 27 billion tonnes of future interest (lignite in seams at least 1 m thick and at depths less than 450 m) (Whitaker et al, 1978; Saskatchewan Power Corporation, 1984). The deposits of current interest are associated with the Ravenscrag Formation with surface-mineable seams covering some 3800 square kilometres. The province is currently engaged in updating this work to produce new, better substantiated figures. The deposits are found in four coal basins: the Estevan, the Willow Bunch, the Wood Mountain and the Cypress as shown in Figure 1. Currently, four mines are operating in the Estevan area and one in the Willow Bunch area.

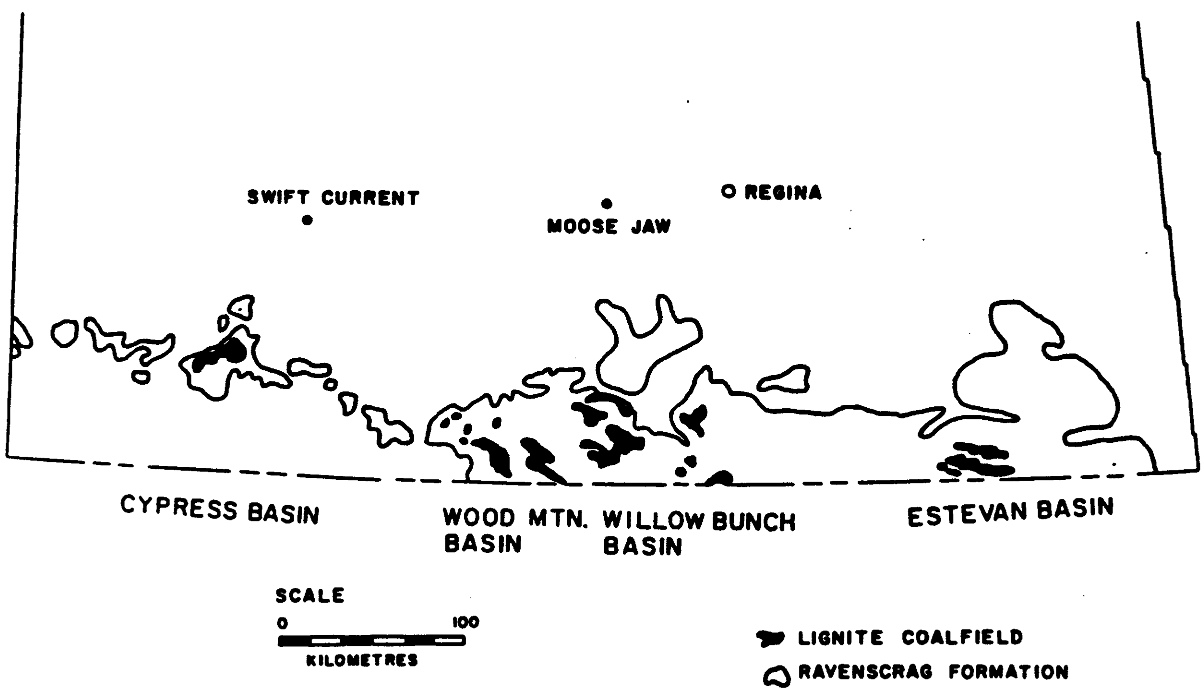

Figure 1: Coal basins of southern Saskatchewan. (From: Saskatchewan Power Corporation, 1984.)

The average quality of lignite declines from east to west across the four sasins. There is a progressive increase in moisture and ash content and a decrease in calorific value and carbon content to the west as shown in Table 2. While lignite is a low quality fuel, it does have the advantage of a relatively low sulphur content, varying from 0.3 to 0.5 percent. Lignite is also very reactive.

	ESTEVAN	WILLOW BUNCH*	CYPRESS
Moisture, %	37.5	39.5	40.9
Ash, %	9.1	13.7	17.5
Volatile Matter, %	24.6	23.7	21.5
Fixed Carbon, %	28.8	23.1	20.1
Calorific Value KJ/kg	15100	12235	10642
Sulphur, %	0.3	0.5	0.3

* similar for Wood Mountain

Table 2: Variation in lignite properties with coal basin. (From: Saskatchewan Power Corporation, 1984.)

Another major advantage of lignite is its relatively low extraction cost. Based on a price per unit of energy recovered, lignite is, relative to many other fuels, a very inexpensive energy source. While its high moisture and ash content have limited its economic transportation range, Saskatchewan lignite is located advantageously with respect to the eastern Canadian markets and the transportation routes to access those markets.

Saskatchewan coal mines currently produce 9 - 10 million tonnes annually. SaskPower is the largest customer, taking an average 80 - 85 percent of the mined coal. The other major customer is Ontario Hydro which consumes about 1 million tonnes per year in the Atikokan and Thunder Bay Generating Stations. The remainder, varying between 250,000 and 500,000 tonnes per year, is largely spot sales to Manitoba Hydro. Current production could be expanded to meet any foreseeable increase in demand.

Over the last three years, Saskatchewan Energy and Mines has been working towards defining a role for provincial support for, and participation in, lignite research and development. The department has met with lignite producers, lignite consumers and lignite researchers to gather their views of the needs and opportunities for lignite research and development. This process has been very informative.

Over the past two years, Saskatchewan has funded and participated in several research projects. Funding was provided through the Canada-Saskatchewan Heavy Oil/Fossil Fuels Research Program. Projects funded to date have focussed on three main areas:

- support for short-term research by producers and consumers including new mining technology and acid gas reduction technology,

- support for research to improve our lignite resource characterization data base, and

- support for technical and economic research on upgrading of lignite.

In 1987, the Coal Mining Research Company completed a technical-marketing study of Saskatchewan lignite for Saskatchewan Energy and Mines. The study examined lignite market expansion opportunities in Saskatchewan, Manitoba and western Ontario through the development of an upgraded lignite product. The study identified potential incremental industrial markets of up to 5 million tonnes per year, excluding the new Shand thermal power station. However, access to these markets will be dependent on the price of competing fuels - natural gas and oil - and the ability to develop and commercialize technologies that will provide acceptable, competitive and marketable lignite products.

To follow-up on the findings of this marketing study, a larger and more detailed study has recently been completed by Lobbe Technologies Ltd. (1989). The study examined the technical and economic feasibility of various lignite upgrading processes to produce an upgraded lignite product which possesses low sulphur, sodium, ash and moisture and which is easily transportable. The results of the study are very encouraging, identifying a number of different upgrading processes that are technically feasible and potentially economic. The study looked at solid upgraded products with the potential to compete in the utility and industrial market and an upgraded lignite water slurry (ULWS) with the potential to displace oil or natural gas in the industrial market. The market is sufficiently large and the economics sufficiently attractive that Saskatchewan considers upgrading to be worthy of more detailed study.

UPGRADING PROCESSES

As noted before, Saskatchewan is investigating the technical and economic feasibility and the resulting product quality of various upgrading processes. The processes under examination range from simple drying through hydrothermal treatment to partial pyrolysis. In many cases, gravity separation would be used at an early stage during processing to physically clean the coals to reduce the ash content. These results have been taken from the various studies funded through Saskatchewan Energy and Mines.

In the simplest case, lignite would be thermally treated in a fluid bed dryer to reduce the level of moisture in the ROM lignite from the 30 percent + range to something in the order of 12-15 percent, or even as low as 8 percent. To prevent moisture resorbtion, the dried coal would have to be coated with a hydrocarbon product or pelletized using a hydrocarbon binder. It is expected that this treatment would also prevent spontaneous combustion and reduce the dusting of the coal during transportation and handling.

In order to obtain a more stable product, a more severe treatment, in the form of hydrothermal or hot-water drying, is used. In this process, the moisture is removed from the coal as a liquid using hot water or saturated steam under pressure (Saskatchewan Power Corporation 1981, 1982). Saskatchewan has performed some tests of this technology at the University of North Dakota (UND) using a sample of lignite from the Poplar River Mine at Coronach.

In this hot-water drying process studied by UND (1989), the coal is finely ground prior to processing. This grinding stage would allow for a physical cleaning step to be added into the process to reduce the ash content. The ground coal is slurried and fed into a pressure tank where it is heated to 330°C at 140 bars pressure with a residence time of 5 minutes. For this particular test, there was no attempt to optimise the process for Saskatchewan lignite. The test conditions were based on numerous previous tests of North American lignites in both a batch autoclave and the continuous process development unit. In this particular test the upgraded coal was centrifuged, washed and slurried again to produce a coal-water-fuel for combustion testing.

Saskatchewan has also investigated, by means of bench scale tests, the Institute of Gas Technology process. This is a hydrothermal treatment process that produces a lump coal rather than a pulverized product. The processing is accomplished by heating the coal and water in a pressure vessel at a temperature of 288°C. Pressure is such that the water remains as a liquid. Residence time is in the order of 60 minutes. This process produces a wet-carbonised lignite. Table 3 shows the proximate and ultimate analyses for the ROM and hydrothermally treated lignite.

	ROM		HYDROTHERMALLY TREATED	
	As-Received	Dry	As-Received	Dry
PROXIMATE ANALYSIS, percent				
MOISTURE	32.6	—	28.3	—
ASH	6.2	9.2	6.3	8.8
FIXED CARBON	31.8	47.2	34.3	47.8
VOLATILE MATTER	29.4	43.6	31.1	43.4
ELEMENT, percent				
CARBON	67.9		72.9	
HYDROGEN	5.2		5.3	
NITROGEN	1.3		1.4	
OXYGEN	24.8		19.6	
SULPHUR	0.8		0.8	
EQUILIBRIUM MOISTURE	30.5		18.5	

Table 3: Lignite analysis. (From: Lobbe Technologies Ltd., 1988.)

The Dense-Phase process, while not tested, has also been short-listed as a process that has potential application in Saskatchewan. The objective of this process would be to produce a pulverized upgraded lignite product which could be used directly in industrial boilers and furnaces, without the necessity for lignite preparation at the user site. A similar concept with dry coal has been tested in West Germany by AJO-Stanhlau Gmbh. In this process the coal is again pulverized prior to treatment, which allows for the washing step to be included before the coal is thermally treated. The micronized coal is moved through the treatment vessel using compressed carbon dioxide to fluidize and transmit the coal. The coal is heated to between 350°C and 410°C within the pressure vessel. The product coal is then cooled and stored and the carbon dioxide recycled.

COAL PRODUCT QUALITY

The results outlined for the product coals are based on using Estevan lignite as feedstock. Estevan lignite has a run of mine heating value of 15 GJ/tonne.

With fluidised bed thermal treatment much of the moisture within the coal is driven off, resulting in a product with approximately 8% moisture. At these temperatures there are some physical and chemical changes within the coal, including the expulsion of some tars which plug pores and the breakdown of carboxyl groups. The result of this is a product with a heating value approaching 24 GJ/tonne and with an ash content in the order of 16 percent. The product is also lump coal, the produced fines (particularly from attrition in the fluid bed) can be utilized for process heat or pelletized using an asphalt binder.

The elevated temperatures of the Dense-Phase process produce a product that has a high calorific value; the product would be rated at 27 GJ/tonne with an ash content of approximately 11 percent and a moisture content of 4 percent. For purposes of transportation, the powder coal product could be pelletized or transported as a pulverized product for thermal use. Either way this is a very stable product because of the expulsion of tars from the coal which seals the pores. This is similar to the K-Fuel process currently undergoing commercialization in Wyoming, where a subituminous coal is upgraded using hydrothermal treatment and partial pyrolysis. Under these conditions there are significant structural changes in lignite with the product becoming more stable and less prone to spontaneous combustion. The evolved tar also acts as binder for the pelletizing of the coal for transportation. Wisconsin Power and Light have signed a contract for this upgraded coal which permits K-Fuel to begin construction of the first phase commercial plant. The sod has been turned for a 350,000 t/d output plant at the Fort Union Mine near Gillette, Wyoming.

The hot-water drying process is the process Saskatchewan investigated in greatest detail. The province has recently performed extensive tests using the University of North Dakota hot-water drying process for production of upgraded lignite water-slurry fuel, which will be referred to as the UND process for convenience. A bench scale test of the Institute for Gas Technology has also been performed with the results outlined above. No combustion tests have been performed on the product coal from this latter process.

The aim of the study at the University of North Dakota (Energy and Mineral Research Center, 1989) was to examine the quality of the hydrothermally treated lignite as a coal-water-fuel. While there is no immediate market for coal-water-fuels, particularly at current oil and gas prices, they do have potential if the slurry could be transported through a pipeline system. With a clean fuel it may well be possible to convert oil fired boilers to coal-water-fuel with relatively low retrofit costs. The UND produced fuel shows almost a 50 percent increase in the energy density from a lignite to a treated fuel; the change is from 2110 to 3130 Kcal per kilogram. This is based on a solids loading of approximately 58 percent.

The feedstock for the coal product from UND studies has been analyzed as shown in Table 4. This coal comes from the Poplar River Mine near Coronach, Saskatchewan. Some 6 tons of coal were sent from the mine to the UND for processing. This coal has a fairly high ash content as can be seen in Table 4 and it should be borne in mind that no ash removal step was incorporated in the process sequence.

The UND study was designed to produce a fuel with a viscosity of around 500 centipoise. Because no longer term storage tests were to be conducted, no chemical stabilisers were added. Likewise, no attempt was made to remove ash. Had these steps been performed, the solids loading would have been in excess of 60 percent and the energy density correspondingly greater. Rheology tests indicated that a blend of 80 percent combustion grind (30 micron average) and 20 percent micronized (less than 20 micron average) was optimal, producing an ideal particle size distribution. It was also found that a washing step following treatment removed the solubilised cations from the surface of the coal particles and substantially improved the rheology of the fuel. The results of this can be seen in Figure 2.

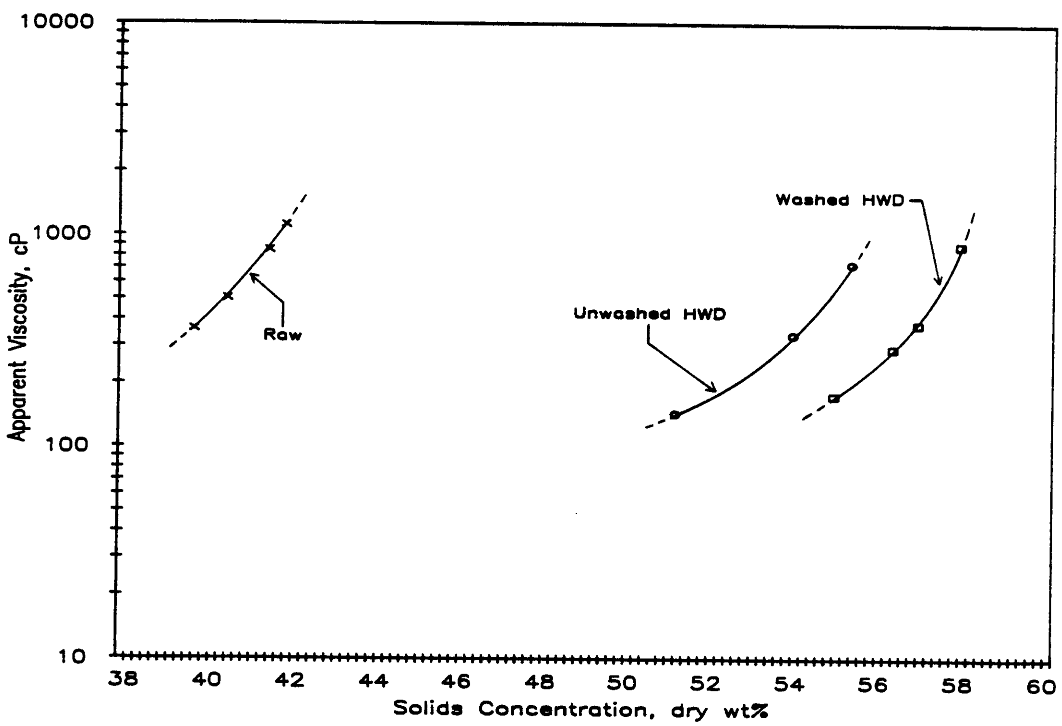

Figure 2: Rheological performance of hot water dried coal-water-fuels. (From: Energy and Mineral Research Center, University of North Dakota, 1989.)

	Raw		Product			
			Unwashed		Washed	
	As Recd	MF	As Recd	MF	As Recd	MF
Prox. Analysis (wt%)						
Moisture	30.1	NA	37.6	NA	37.7	NA
Vol. Matter	25.1	35.9	20.9	33.5	21.6	34.6
Fixed Carbon	30.4	43.5	27.2	43.6	28.3	45.4
Ash	14.4	20.7	14.3	22.9	12.5	20.0
Ult. Analysis (MF basis wt%)						
Hydrogen	5.9	3.7	6.4	3.5	6.5	3.7
Carbon	38.9	55.7	34.6	55.5	36.6	58.8
Nitrogen	0.5	0.7	0.5	0.8	0.5	0.8
Sulfur	0.5	0.8	0.4	0.6	0.6	0.9
Oxygen	39.8	18.4	43.8	16.7	43.3	15.8
Heating Value						
(Btu/lb)	6490	9290	5740	9200	6040	9680
(MJ/kg)	15.1	21.6	13.4	21.5	14.1	22.6
Ash Analysis (wt%)	% Elem.	% Ash	% Elem.	% Ash	% Elem.	% Ash
Silica	18.9	42.4	21.1	46.8	20.3	51.0
Alum. Oxide	11.8	23.3	9.7	19.1	8.6	23.5
Ferric Oxide	2.8	4.1	3.1	4.6	3.6	5.9
Titan. Oxide	0.6	1.1	0.7	1.1	0.7	4.0
Phos. Pentoxide	0.2	0.5	0.2	0.5	0.3	0.7
Calcium Oxide	8.3	12.2	9.4	13.7	7.6	10.2
Magnes. Oxide	2.8	4.9	2.0	3.5	1.9	2.0
Sodium Oxide	0.8	1.1	0.0	0.0	0.0	0.0
Potas. Oxide	1.8	2.3	2.0	2.5	0.5	2.1
Sulfur Trioxide	3.1	8.2	3.2	8.3	4.5	11.4

Table 4: Raw and product analyses for coals used in coal-water-fuel preparation. (From: Energy and Mineral Research Center, University of North Dakota, 1989.)

Table 4 shows relatively few changes in the proximate and ultimate analyses for the product versus the feedstock coals. Likewise, the ash composition does not change greatly with the exception of the elimination of sodium. The sodium has been solubilised and removed during the hydrothermal treating. Calcium has been affected in the same manner but not to the same extent. It should, however, be borne in mind that this was a test for coal-water-fuels not for solid fuels.

In terms of rheological performance, as shown in Figure 3, lignite does not perform quite as well as subbituminous coals. This figure does not show western Canadian subbituminous coals but it can be assumed that they perform in a manner similar to those from Montana. The energy density chart, Figure 4, shows that the percentage improvement in lignites in substantially greater than higher rank coals. With ash removal, the Saskatchewan lignite would have performed even better.

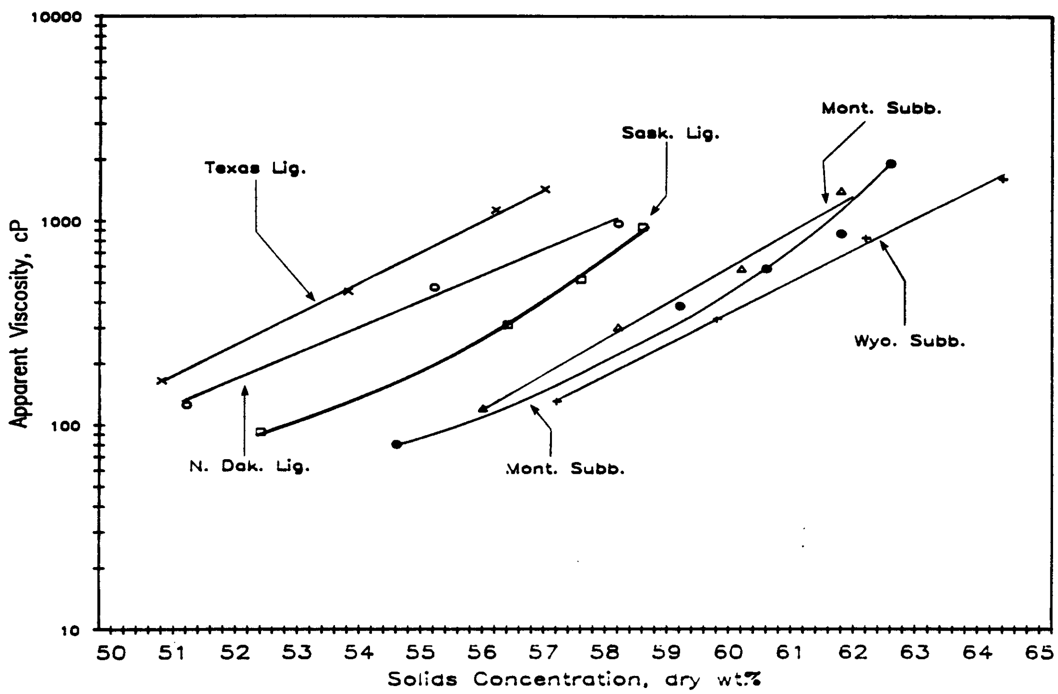

Figure 3: Rheological performance of coal-water-fuels prepared from various low-rank coals. (From: Energy and Mineral Research Center, University of North Dakota, 1989.)

Based on information available in the literature, the Lobbe Technology report (1989) compared several different processes for converting lignite into coal-water-fuels. Hydrothermal treatments all produced a fuel with much the same properties as those described above for the UND process. With a more severe thermal treatment (350°C using a Dense-Phase transport system), the energy density is likely to be improved by approximately 25 to 30 percent indicating a further potential for upgraded lignite water-slurry fuels.

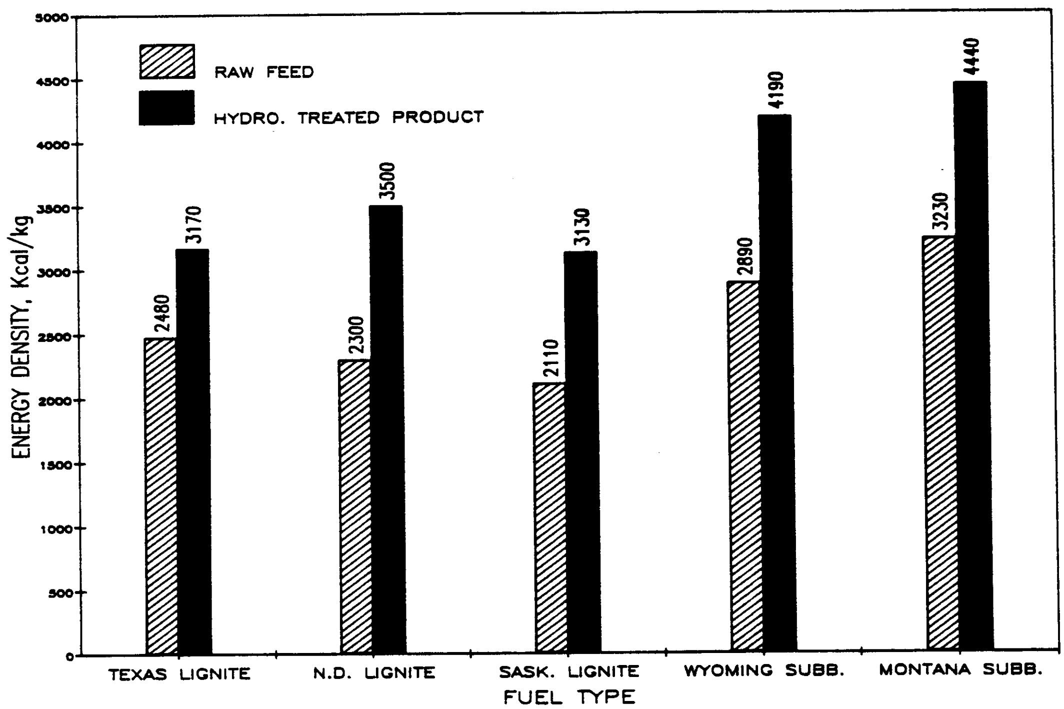

Figure 4: Energy density performance of various low-rank coal-water-fuels. (From: Energy and Mineral Research Center, University of North Dakota, 1989.)

To date, Saskatchewan has combustion tested only the coal-water-fuel as a part of its program. At both UND and CANMET the fuel was burned in test combustors designed to simulate an industrial boiler. In spite of the relatively low energy density, the test fuel burned extremely well as a result of its high reactivity. Carbon burnout was 99.8 percent. The high ash content of the original lignite resulted in some problems in the test combustor because of its quantity rather than its characteristics. An ash removal step during processing would substantially reduce the problem of ash fouling.

The combustion tests performed at CANMET (Banks et al, 1988) compares the lignite fuel to a reference bituminous coal-water fuel. Table 5 shows the comparative figures. Except for the ash, other emissions tend to be lower for lignite than bituminous coals, on an energy unit basis, particularly emissions of SO_x and NO_x. The combustion efficiency is also higher as indicated by the level of combustible material in the fly ash.

	ULWS	CWS	CWS
Fuel rate, kg/h	148.9	87.3	87.8
Thermal input, MJ/h	1612	2035	2047
Atomizing air			
Temperature, °C	34	25	21
Flow rate, kg/h	29	30	23
Combustion air			
Temperature, °C	200	235	201
Flow rate, kg/h	454	784	629
Furnace exit temperature, °C	770	903	879
Flue gas analysis, volume			
O_2 %	2.6	5.0	2.0
CO_2 %	17.2	14.2	16.0
CO ppm	34	31	47
NO ppm	358	656	728
SO_2 ppm	642	1296	1269
Combustible in fly ash, wt %	4.4	10.2	28.5
Bottom ash, approximate depth, cm	>10	<0.5	<1
Distribution of ash, wt %			
Furnace bottom	81.5	24.7	10.5
Furnace wall	3.8	11.8	15.8
Superheater tubes	0.2	1.2	1.1
Flue pipes and heat exchangers	14.5	62.3	72.6
Total ash collected, kg	51.9	8.5	9.5

Table 5: Comparison of combustion performance of upgraded lignite water slurry (ULWS) and coal water slurries produced from bituminous coal. (From: Banks et al, 1988.)

With reference to the economics of the various processes two tables summarise the information detailed in the Lobbe Report. Table 6 gives the results for solid upgraded products, showing the process, product quality and plant output. The costs per GJ f.o.b. plant are estimates based on information gained from the literature and manufacturers, they are not detailed engineering estimates. Figures in the order of $2.00 to $2.50 suggest that these processes may be economic if capital and operating costs can be reduced and, therefore, these processes should be examined in more detail. These prices are not yet competitive with US bituminous coals but are worthy of further investigation. Table 7 shows the figures for Upgraded Lignite Water Slurries based on the same criteria as Table 6.

PROCESS	DESCRIPTION	PRODUCT	PRICE[1] For $10/t Lignite $/GJ	PRICE[1] For $14/t Lignite $/GJ
IGT	A hydrothermal treatment process including lignite crushing, desliming, hydrothermal treatment at 270°C and partial pyrolysis of the lump size product.	Lump size 25.2 GJ/t 18.2% ash	2.84	3.10
SPC Solid	A hydrothermal treatment process including lignite crushing, washing, hydrothermal treatment at 270°C, and drying.	Lump size 19.1 GJ/t 13.4% ash	2.34	2.61
Dense-Phase Solid	A thermal treatment process including lignite crushing, washing, pulverization thermal treatment at 410°C in dense-phase system.	Powder 27.4 GJ/t 11.4% ash	2.04	2.32
Fluid Bed Drying	A thermal drying process including lignite crushing, desliming, drying in fluidized bed at 310°C, cooling and pelletizing of fines.	Lump size 24.2 GJ/t 16.64% ash	2.42	2.68

[1] f.o.b. plant at 15% DCF ROR

Table 6: Summary of evaluated upgraded lignite solid fuels. (From: Lobbe Technologies, 1989.)

PROCESS	DESCRIPTION	PRODUCT	PRICE[1] For $10/t Lignite $/GJ	PRICE[1] For $14/t Lignite $/GJ
Dense-Phase ULWS	A thermal treatment process including lignite crushing, washing, micronizing in Ergon Mills, thermal treatment at 350°C using dense-phase transport system, and ULWS preparation.	14.0 GJ/t 6.5% ash	2.64	3.02
UND - ULWS	A hydrothermal process including lignite crushing, washing, pulverization, and hydrothermal treatment at 270°C, micronizing and ULWS preparation.	11.4 GJ/t 4.6% ash	2.65	2.92
SPC - ULWS	A hydrothermal process including lignite crushing, washing, hydrothermal treatment at 270°C, micronizing and ULWS preparation.	11.4 GJ/t 4.6% ash	2.66	2.94
Ergon - ULWS	A hydrothermal process including lignite crushing, washing, micronizing in Ergon Mills using steam and ULWS preparation.	11.9 GJ/t 4.8% ash	2.10	2.43

[1] f.o.b. plant at 15% DCF ROR

Table 7: Summary of evaluated upgraded lignite water slurry fuels. (From: Lobbe Technologies, 1989.)

RELATION OF FEED TO PRODUCT COAL

The preceding discussion has focused on the upgrading processes and the characteristics of the finished product. It is evident that feed quality plays an important role in determining the quality of the product lignite and the cost of producing a quality product. Parameters such as lignite composition and feed size determine the calorific values and physical properties of the upgraded lignite.

The mineral matter composition determines how much sodium would be leached from the lignite during the hydrothermal dewatering process. The amount of sodium removed from the lignites increased significantly with temperature. Washing with warm (60°C) water decreased the sodium content by about 5 - 20 percent depending on the lignite. Thermal dewatering at temperatures below 275°C reduced the sodium content by 20 - 35 percent while dewatering at 300°C and above decreased the sodium content by 35 - 80 percent. There does not appear to be any additional increase in sodium removal when longer residence times are used.

This large decrease in sodium content could significantly affect the combustion properties of the lignites with respect to slagging and fouling. As sodium is removed, the basic properties of the combustion ash are changed with an increase of "Dolomite Ratio", which is an inverse measure of the extent of slagging and fouling to be expected during combustion.

The composition of mineral matter determines which trace elements will be removed during the upgrading process. Examples of a selective removal during the hydrothermal treatment are depicted in Table 8. For example, there is a significant reduction of barium for the Souris Valley Mine sample, but not for a Boundary Dam sample. Similar differences would be expected for other lignite samples, depending on the mineral matter composition.

LIGNITE	TRACE ELEMENT ANALYSES												
	Ag	Al	B	Ba	Be	Ca	Cd	Cr	Pb	Ti	V	Mn	P
BM (original sample)	3.0	10,000	130	460	<0.1	17,000	<0.1	2.0	9.0	310	6.0	15	530
BM (300°C)	2.0	9,200	75	560	<0.1	18,300	0.4	2.0	<1.0	350	7.0	15	590
SV (original sample)	1.6	10,200	120	670	<0.1	11,800	0.4	5.0	<1.0	200	18	9.9	110
SV (300°C)	4.0	10,400		270	<0.1	13,800	0.2	6.0	<1.0	210	16	12	82

BM - Boundary Dam Mine

SV - Souris Valley Mine

Table 8: Effect of hydrothermal treatment on selected major and trace elements concentration (ppm, daf). (From: Saskatchewan Power Corporation, 1981.)

The composition of mineral matter, and specifically the content of pyrite and quartz, determines erosive behavior of lignite during pulverized lignite transport (either pneumatic or hydraulic). High content of both minerals results in increased abrasiveness of the lignite, which often necessitates installation of ceramic lining in transport lines. For upgraded lignite water slurry fuel, abrasiveness of lignite would cause problems with erosion of burner assembly and fuel transport lines.

The maceral composition of the feed has a significant effect on equilibrium moisture of products of hydrothermal treatment. The presence of exinitic macerals, which are hydrocarbon rich and have high elemental hydrogen content, enhances the reduction of equilibrium moisture in the products (Figure 5). The reverse can be expected for the inertinite macerals, which do not generate oily or tar like materials during treatment at 250°C to 350°C.

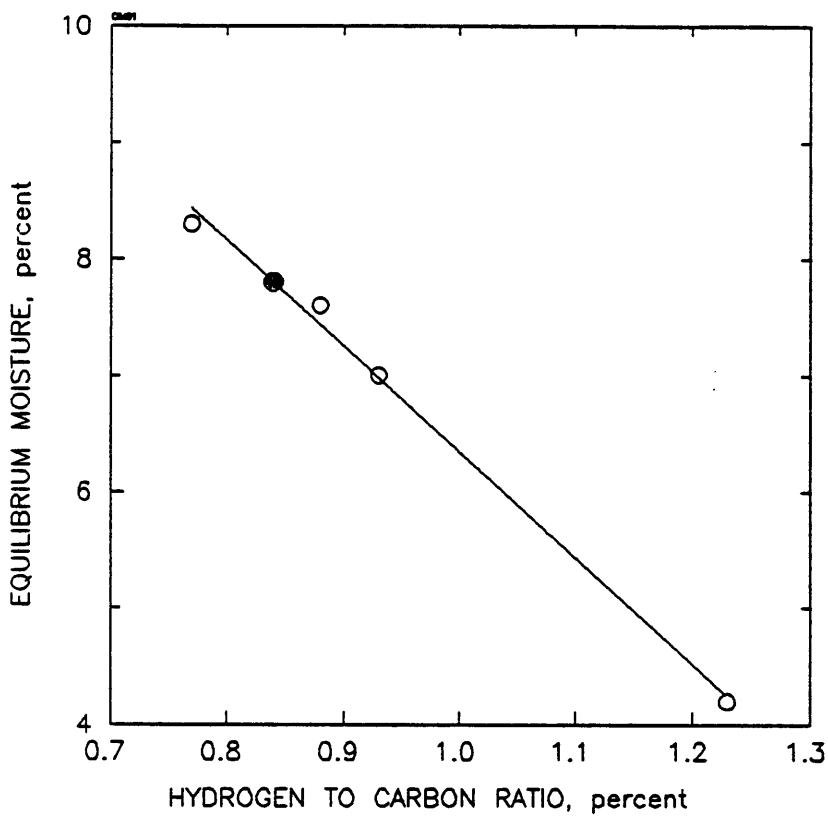

Figure 5: Effect of H/C ratio in coal on equilibrium moisture during hydrothermal treatment at 330°C.

The degree of oxidation of the lignite seam or ROM Samples can significantly affect the quality of lignite upgrading products. Highly oxidized samples have a higher yield of gas, larger quantities of water soluble materials and higher equilibrium moisture products.

The yield of soluble materials generated during hydrothermal treatment determines the extent of the energy recovery and capital requirement for the plant. The amount of soluble material also determines the equilibrium moisture of the product. During the thermal or hydrothermal treatment, the light oily materials present in macerals diffuse to the lignite surface which makes the lignite surface less hydrophilic. At high oxidation, the oily materials are more water soluble and, hence, are removed with the waste water. The energy loss due to water soluble materials may be as high as 8 to 12 percent.

Oxidation of lignite also results in higher gas yield during their thermal upgrading processes (mainly carbon dioxide) and lower energy recovery in the product.

Because of the strong effect that lignite properties have on the properties of the upgraded products, examination of the quality of lignite resources in the province has taken a high priority. The province has funded work to characterize the coal from Estevan and Willow Bunch areas of the province using conventional coal petrographic techniques. This report (McDougall and Potter, 1988) provides information on the depositional history of the coal as well as providing information on the reactivity of the coals.

Chemical analysis of the coal forms a significant portion of the provinces's coal investigation budget. New infrared techniques allow for a more detailed analysis of individual coal macerals in the feedstock and of the solid products of coal conversion processes (Energy Research Unit, 1989).

The province is also cooperating with the Geological Survey of Canada to update the 1978 report on the coal resources of Saskatchewan (Whitaker et al, 1978). This new work will provide the province with a computerized data base of sufficient flexibility to allow for the determination of coal reserves in terms of both quantity and quality using virtually any criteria for value determinations. This is a system that has been developed by the Geological Survey of Canada. It is hoped that this will provide a tool for effective resource management.

CONCLUSIONS

Through activities supported by the province, the aim is to develop the extensive lignite reserves in the southern part of the province. The province is, therefore, supporting studies that will determine the quantity and quality of those reserves, as well as examining technologies for upgrading these coals to higher quality products to reduce transportation and user costs.

ACKNOWLEDGMENTS

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LOW RANK COAL PROPERTIES AND THERMAL UPGRADING POTENTIAL

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ABSTRACT

Several processes have been or are being developed to obtain stable, high heating value solid fuel with good handling characteristics from low rank coals. However, the quality of the product depends both on process treatment conditions and feed coal type. It is therefore essential to develop a fundamental understanding of the chemical and physical changes which occur during low rank coal upgrading. This paper reports some results from an on-going study aimed at characterizing western Canadian low rank coals and their behaviour in an evaporative drying low rank coal upgrading process. Properties of the product coal are related to feed coal rank and have been compared to similar naturally occuring higher rank coals.

INTRODUCTION

Low rank western Canadian coals (lignites and subbituminous) are generally utilized at mine mouth power generating stations. At present, over 90% of Alberta's electrical power comes from coal fired generating stations. The coals in use are typically high in moisture and ash but very low in sulphur content. No processing, aside from crushing is done before burning.

In eastern Canada, higher rank coals are used in coal fired generating stations. These coals are typically higher in thermal value, relatively low in ash and high in sulphur content. The present concern with acid rain and the need to expand western Canada's coal markets has provided the impetus to market western Canadian coals in eastern Canada.

One of the problems in accessing the thermal coal market in eastern Canada is the high cost of transporting western Canadian coal. The most straightforward way to reduce transportation costs per thermal unit is to reduce the moisture content of these low rank coals. Ideally, this moisture reduction would be irreversible and not lead to any increase in handling or storage problems. Many moisture removal processes have been developed and they can be roughly divided into two categories; evaporative and non-evaporative drying processes. In evaporative processes, the moisture is removed as a gas; in non-evaporative processes, the temperature and pressures are such that the moisture is removed as a liquid. The non-evaporative processes have the advantage that soluble ions and mineral components are also removed. This can be important in low rank coal which has significant sodium content. This discussion will not consider non-evaporative drying processes or other upgrading techniques such as solvent extraction, gasification, or partial pyrolysis since, in general, they produce a product which, although "upgraded" is often not a coal in the conventional sense. The less severe evaporative processes produce a coal product which is more closely associated, both chemically and physically, with a similar coal of higher rank. The temperatures at which this drying is irreversible (i.e. accompanied by some change in the physical and chemical structure) often results in de-carboxylation and an increase in aromaticity.

This paper discusses the results of a study which attempts to relate the properties of upgraded low rank coals to the chemical and physical properties of naturally occurring higher rank coals.

VARIATION OF COAL PROPERTIES WITH RANK

Because of its heterogeneous nature, there are numerous classification systems used to characterize coal. These include geological age, petrography (maceral composition and type), solvent extraction characteristics, oxidizability, friability and grindability, and rank. The ASTM system is commonly used to differentiate coals by rank. Vitrinite reflectance is also used, although in the lower rank coals the reflectance of eu-ulminite, a precursor of vitrinite is used when determining rank petrographically (Castano et al (1974), Bustin et al (1977) and Marchioni (1985)).

Table 1: Variation of selected coal properties with rank.

Property	Lignite	Subbituminous	Bituminous
Volatile matter (daf) %	52 - 64	44 - 53	14 - 46
Bed moisture %	35 - 75	25 - 35	8 - 10
Heating value (mmmf) MJ/Kg	14.6 - 19.3	19.3 - 26.8	24.4 - 36.1
Carbon (daf) %	60 - 68	68 - 77	77 - 89
Reflectance % (*)	<0.27 - 0.38	0.38 - 0.67	0.47 - 2.05
Oxygen (daf) %			
- COOH	3.0 - 3.55	2.4 - 3.0	1.0 - 1.3
- OH	2.75 - 3.3	2.5 - 3.3	2.0 - 2.4

daf = dry ash free
mmmf = moist mineral matter free basis
(*) From Davis (1978) and Stach et al (1982)

The ASTM method of defining coal rank uses heating value to differentiate low rank coals and volatile matter to classify higher rank coals. In an upgraded low rank coal, the moisture is significantly reduced and this makes rank determination by the ASTM method inadequate.

Oxygen content decreases as rank increases and although the total amount is important, more important is the form of the oxygen present. Low rank coals are known to have abundant oxygen in the form of carboxyl groups and at the temperatures used during many evaporative drying processes, these carboxyl groups can be driven off.

Reflectance is a widely ranging rank determinator (being valid from lignite to anthracite). Figure 1 shows the relationship between vitrinite reflectance and aromaticity (as determined by carbon 13 nmr) for several western Canadian coals. Rank increases steadily with increasing reflectance, while aromaticity, especially for the low rank coals, varies widely.

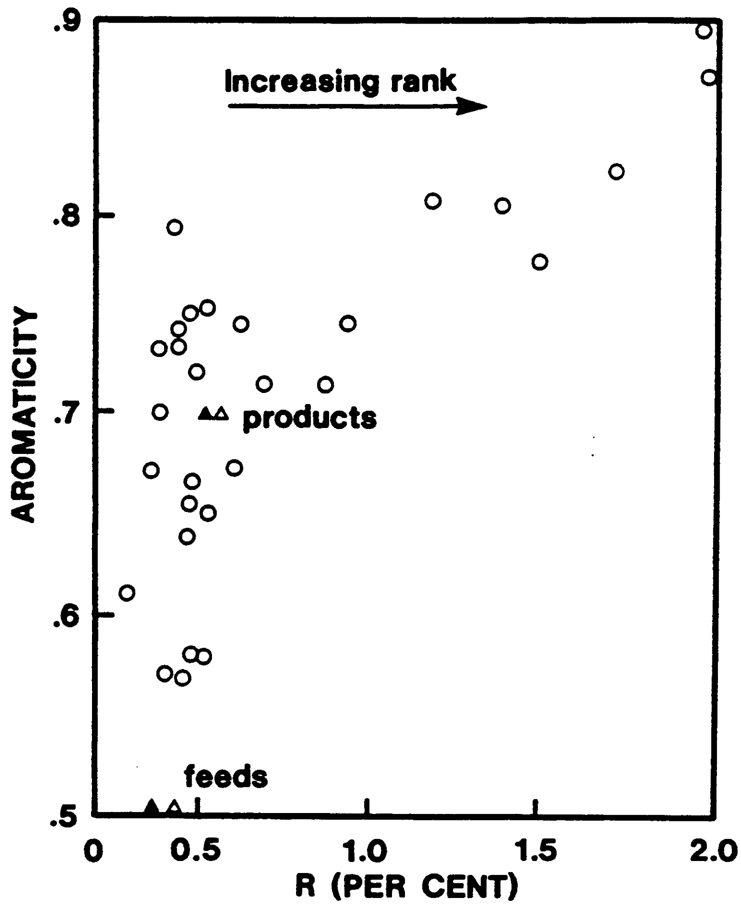

Figure 1: Aromaticity vs. Reflectance for several western Canadian coals. The triangles represent the feeds and products of an evaporative drying process. (Adapted from Axelson (1987) and Furimsky and Ripmeester (1983)).

The aromaticity determination by nmr is on a dry ash free basis because the nmr technique is only sensitive to the organic components in the coal. Figure 2 illustrates a carbon 13 nmr spectra of a thermally treated (350°C in a steam atmosphere) coal and the corresponding feed coal. The dotted lines illustrate the peak positions for oxygen containing functional groups. The large peak at about 25 ppm is due to aliphatic carbons and the large peak at about 125 ppm is due to aromatic carbons. The aromatic fraction is obtained by simply determining the areas of these peaks relative to the total signal. It is quite clear from Figure 2 that along with a loss of oxygen containing functional groups, a significant portion of the aliphatic carbons have been lost, thereby increasing the aromaticity of the product coal. This indicates that coals with a higher aliphatic fraction will undergo a more significant change under an evaporative drying process at these treatment temperatures (350°C).

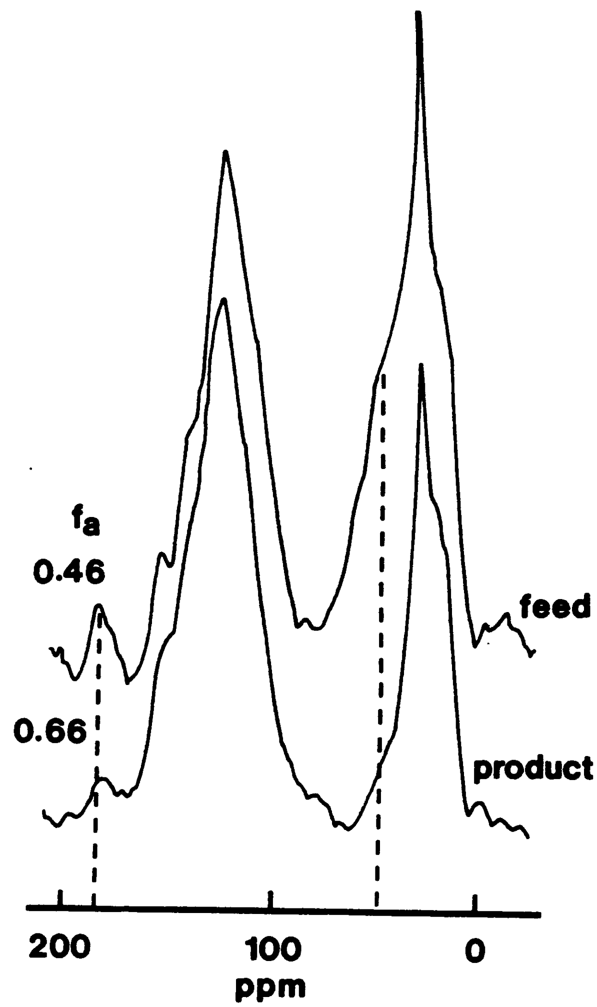

Figure 2: Carbon 13 nmr spectra of feed and product coals.

THERMAL UPGRADING POTENTIAL

In order to determine the extent to which the nominal rank of raw coal can be increased by thermal upgrading, several properties must be considered aside from the moisture content and subsequent increase in heating value. At temperatures above about 150 to 200°C, de-carboxylation reactions can occur (Speight (1983)). These de-carboxylation, devolatilization reactions are responsible for the observed rank increase via evaporative upgrading processes. Some coals are more amenable to upgrading and their behaviour can be traced directly to the inherent properties of the coal.

The chemical and physical changes which occur during natural coalification over geological time periods are different for bituminous and higher rank coals compared to subbituminous and lower ranks. It is thought that coalification in the early stages involves loss of moisture, oxygen functional groups (essentially carboxylic), and aliphatic carbons, whereas coalification at higher ranks involves dehydrogenation and condensation of aromatic groups. This is illustrated in the "dog leg" in Figure 1 which shows that for higher reflectance, or higher rank, the aromaticity trends up with rank. At lower reflectances, or lower rank, other chemical components are more important in determining the reflectance or rank and there is little correlation with aromaticity as determined by nmr.

Properties of upgraded western Canadian low rank coals were compared with the properties of naturally occurring higher rank coal using several chemical properties which correlate with coal rank. Two of the coals tested (Coals A and B), were thermally upgraded at about 350°C in a steam atmosphere. Heating value, moisture content, volatile matter, fixed carbon, aromaticity and reflectance of the raw coals and their products were determined.

Table 2 summarizes the significant results. It is evident that the two coals have been upgraded. The most significant effect from a practical viewpoint is the decrease in moisture content. The shipping costs per thermal unit of the upgraded coal will be significantly lower than for the untreated coal.

Table 2: Selected Properties of Feed and Product Coals.

	Coal A		Coal B	
Property	Feed	Product	Feed	Product
Moisture (ar)	32.52	3.31	27.16	3.00
Fixed Carbon (daf) %	52.85	59.31	54.50	59.90
Volatile Matter (daf) %	47.15	40.70	45.47	40.13
Heating Value (daf) MJ/kg	28.5	29.3	28.6	29.5
Heating Value (ar) MJ/kg	16.8	25.6	18.7	26.6
Oxygen (daf) %	19.0	17.4	19.4	17.0
Aromaticity (nmr) %	50	71	50	72
Reflectance %	0.38	0.53	0.45	0.56

daf = dry ash free
ar = as received
The heating values of the products expressed on as received basis refer to the product as it comes out from the reactor.

From a chemical point of view, there is an accompanying change in the parameters which are generally used as indicators of coal rank. The increase in aromaticity and reflectance indicate a change in coal chemistry that generally accompanies an increase in coalification or increase in coal rank. The nmr spectra in Figure 2 clearly show this chemical change. It is apparent in the case of these two coals that the lower the aromaticity (corresponding to a low fixed carbon content (Van Krevelen and Schuyer (1957))), the greater is the upgrading effect under these evaporative drying conditions. The reflectance values also increase to a limiting value, indicating that the lower the reflectance, the higher is the upgrading potential.

The nmr aromaticity does not corroborate this observation in this particular case because of the difficulties in determining aromaticity by this technique (Axelson (1987)). However, other evidence suggests that in general the nmr determined aromaticities do correlate well with reflectance and that coals with higher aromaticity will not change as much under evaporative drying conditions as will otherwise similar coals with high relative aliphatic carbon contents. The nmr spectra in Figure 2 show that the aromatic groups are relatively unchanged after processing while the aliphatic and oxygen containing carbons are significantly reduced.

A reduction in the concentration of exinites and an alteration of their morphology in the product coal was also observed. This is due to the highly reactive, relatively aliphatic nature of these macerals and indicates that their presence and proportion is important in determining the ultimate upgrading potential of a given coal. Higher rank coals (subbituminous A and high volatile bituminous) treated in a similar manner resulted in little or no upgrading as determined by both reflectance measurements and heating value changes. The chemical nature of the low rank coal, as measured by the aromaticity or by the maceral composition (in particular, the exinites), is important in determining the ultimate upgrading potential. The closer that the coal is to the dog leg in Figure 1, i.e. the point at which the aromaticity begins to trend upward with coal reflectance (rank), the less amenable it will be to upgrading via similar evaporative drying technologies. On the other hand, coals with nominally the same rank but with lower aromaticities, should be very good candidates for this type of process. Significant increases in thermal values can be achieved, along with the production of a coal product which is in many ways indistinguishable from its naturally occurring counterpart.

The fluorescing properties of the exinites are an excellent tool for the discrimination of these macerals from other coal components. This is illustrated in Figures 3 and 4 where the feed coal is shown under white light (Figure 3) and under blue violet light (Figure 4). The fluorescing exinite (sporinite, labelled s) can now easily be distinguished from the other macerals. This fluorescence behaviour also allows us to monitor the heat tranfer process in the large particles. The wavelength of maximum intensity or λ max should shift to longer wavelengths with increasing process temperature and the intensity of the fluorescence should decrease or disappear at about 350 °C for the sporinites (Ting and Lo (1975)).

Figures 5 and 6 illustrate the degradation which occurs in the exinite maceral at these temperatures. Figure 5 shows the maceral under white light. The fluorescence behaviour under blue violet light (Figure 6) clearly shows the degraded nature of this particular exinite component. The absence of a red shift of λ max (bathochromic shift, Goodarzi (1986)) in the treated coal would indicate that the interior of some of the largest

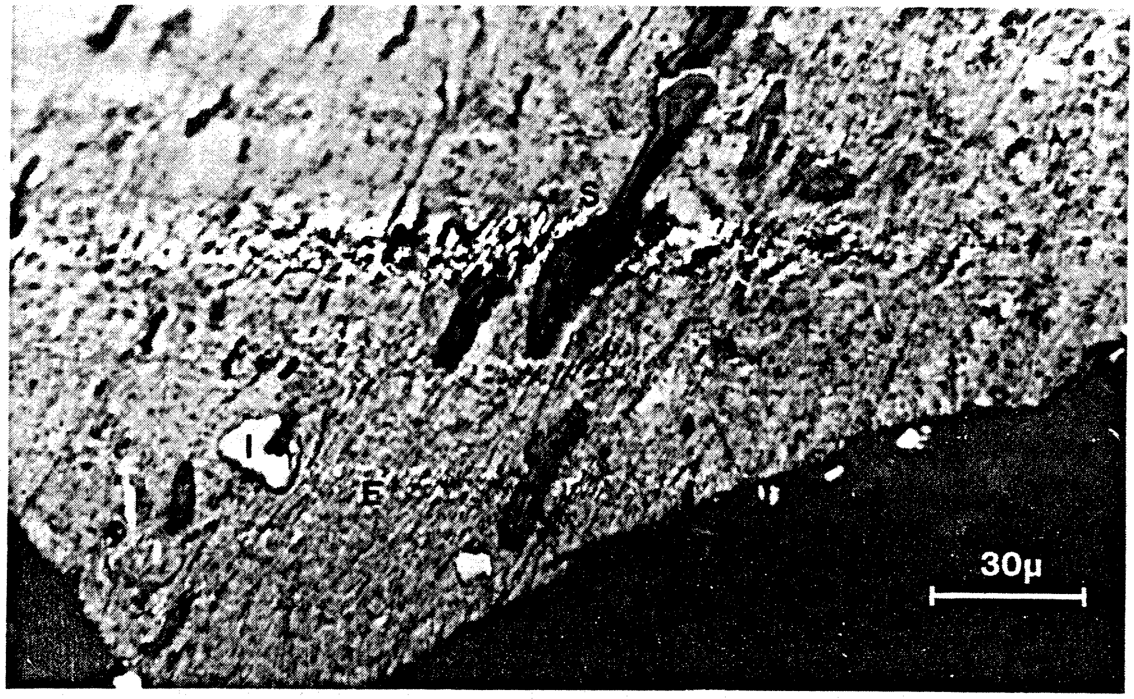

Figure 3: Feed coal showing eu-ulminite (e), inertinite (i) and exinite/sporinite (s) under white light.

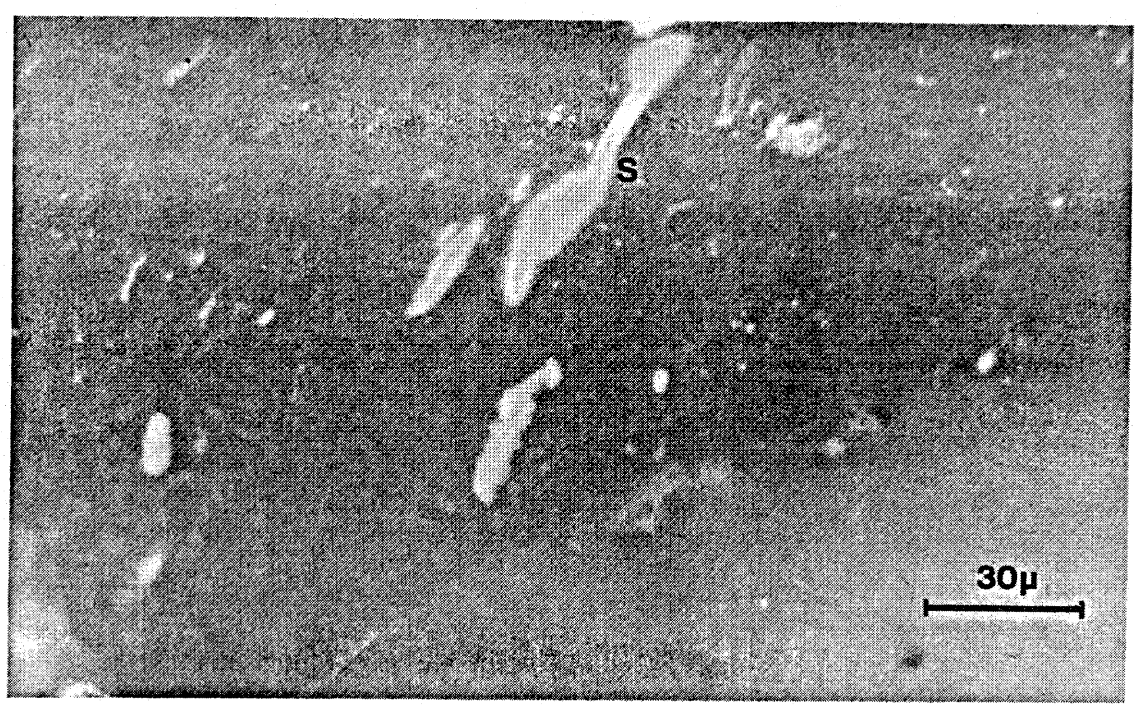

Figure 4: The same field of view as Figure 3. The fluorescence behaviour of the exinite is apparent.

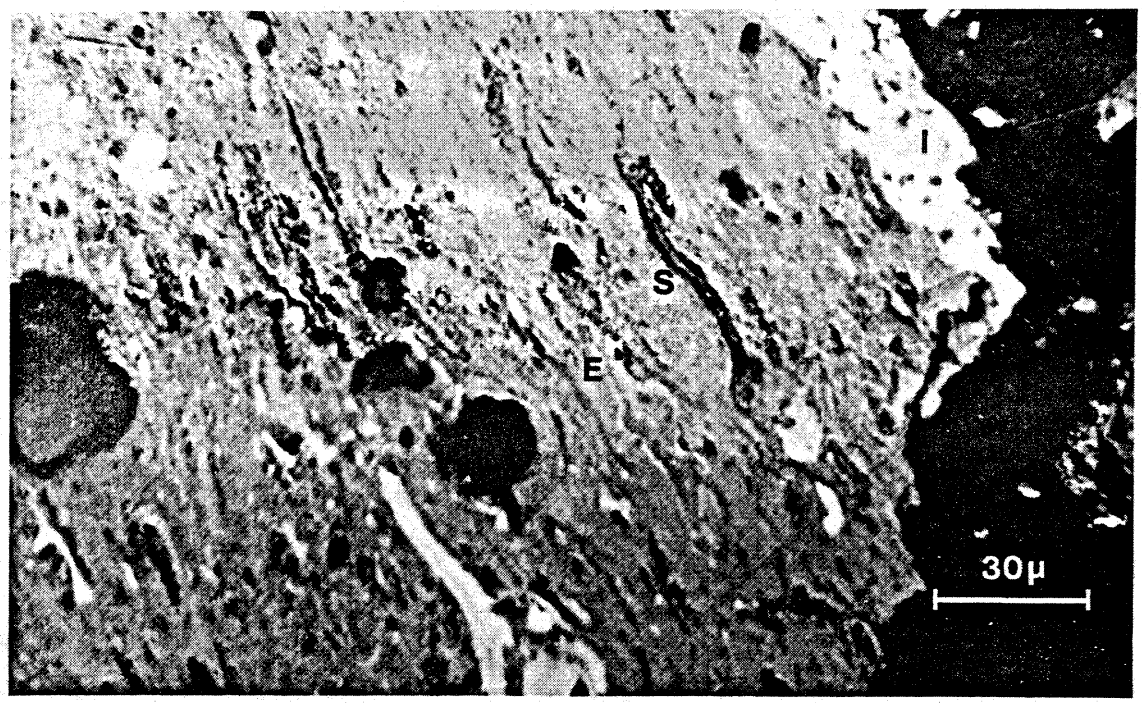

Figure 5: Product coal under white light showing eu-ulminite (e), inertinite (i) and exinite/sporinite (s).

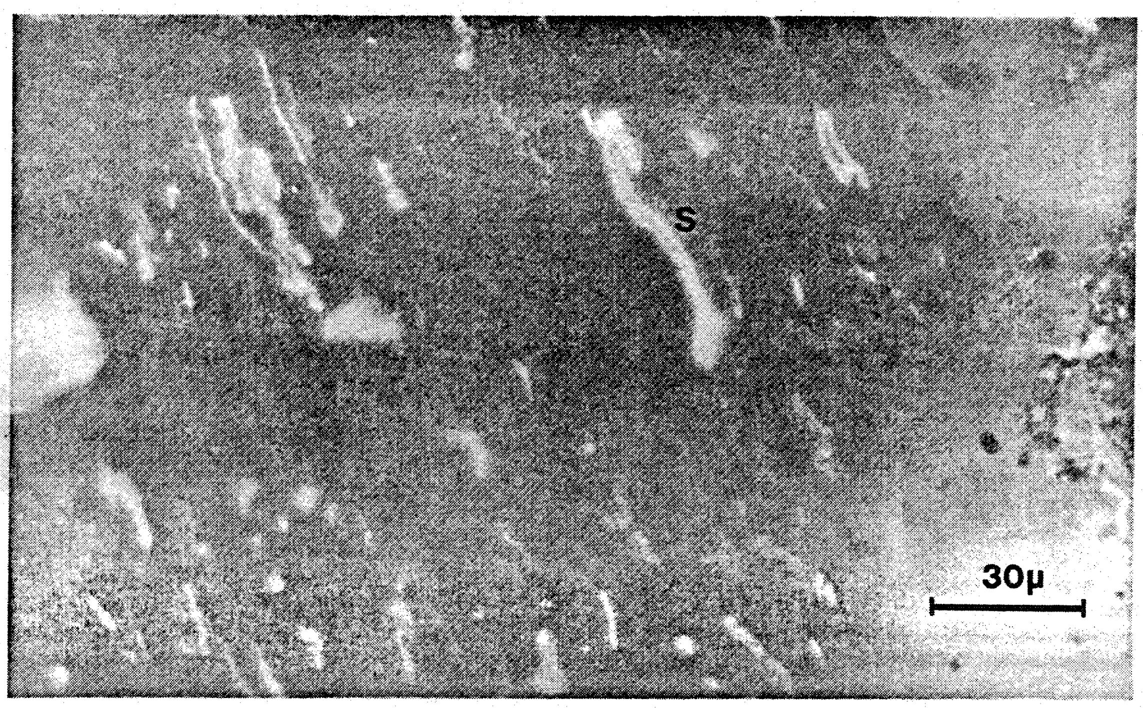

Figure 6: Degraded exinite maceral in the product coal (fluorescing under blue violet light).

coal particles did not attain the process temperature, due to a combination of large particle size and/or short residence time. The reflectance of the exinites and the huminites/vitrinites should increase with increasing aromaticity. This correlates with the nmr data in Table 2. The changes in fluorescence characteristics and reflectance values in processed coals simulate the variation of these parameters associated with increasing rank (Teichmuller and Wolf (1977) and Stach et al (1982)). Figure 1 shows that upgrading by evaporative drying produces a coal that stays in the range of aromaticity and reflectance for naturally occurring western Canadian coals. This behaviour is also observed for other coal properties and in fact the product coal can not be easily distinguished from naturally occurring higher rank coals. With feed coals of subbituminous A and up, the evaporative drying process at high temperatures tends to push them out of the range observed for most higher rank coals.

CONCLUSIONS

Upgrading of low rank coals by thermal treatment has many similarities to the natural coalification process. A decrease in oxygen content is observed along with an increase in reflectance and daf heating value. It has been observed that lignites and subbituminous coals undergo the most significant changes in thermal upgrading and that thermal treatments do not mimic natural coalification in the higher rank coals. In general this is probably due to the different mechanistic pathways. Lower rank coal upgrading involves loss of oxygen functional groups and aliphatic carbons, a relatively low energy process. Coalification at higher ranks involves dehydrogenation and condensation of aromatic groups which will not occur under the conditions of thermal evaporative drying processes.

Thermal upgrading potential is not directly rank dependent due to the definitions used to categorize the low rank coals. From the preliminary work reported here, aromaticity (as measured by reflectance) and/or maceral analysis were shown to be the best measures of upgrading potential. For coals of similar rank, the more aromatic the coal is, the less is its upgrading potential. Coals containing a higher percentage of (relatively reactive) aliphatic groups are more amenable to upgrading by the mild evaporative drying processes.

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EVALUATION OF THE PETROGRAPHIC CONTROLS ON COAL QUALITY AND THERMAL REACTIVITY

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ABSTRACT

Jurassic-Cretaceous coals of the foothills and mountains of Western Canada are often rich in inertinite macerals and lean in liptinites. The properties of these coals are therefore influenced by petrographic composition (type) and technological behavior is modified from that of rank - equivalent vitrinite - rich coals.

The thermal reactivity, both pyrolysis and combustion, of a series of 20 pulverized coals (sub-bituminous to low-volatile bituminous) has been investigated with a view to predicting thermal behaviour from knowledge of feed coal properties. It has been shown at laboratory scale that burnout under oxidizing conditions and devolatilisation under inert conditions can both be predicted using linear correlations between reflectance and thermal properties. The correlations are applied via coal reflectograms whereby both the rank and maceral composition of the test coals are described.

INTRODUCTION

Industrialized nations rely heavily on coal as a fuel for electricity generation and as a heat source for cement manufacture. Accordingly much research effort is directed at alleviating the environmental impact of coal combustion, in both human and natural terms. Thus, there is a vast literature available on the scientific and technological aspects of coal and coal-burning systems. Little, if any, of this is of direct value to the coal geologist for evaluating new coal deposits as thermal coal feedstocks for pulverised-fuel-fired utility boilers for example. Instead thermal coal quality is evaluated through ASTM tests to determine volatile matter, ash, calorific value, and so on. From these assay data, assumptions are made about thermal reactivity which, at some later stage and considerable cost, often have to be tested at large scale.

This paper describes some results from a geological research project which was designed to assess whether or not thermal reactivity (combustion and pyrolysis behavior) of coals is predictable from detailed knowledge of feed coal quality. As the study was formulated from the beginning with the coal explorationist in mind, a self-imposed restraint was that any procedure to evaluate thermal reactivity had to be appropriate to drill core samples.

PROJECT CONCEPTS AND METHODS

Some general comments are given below to explain how the project was designed and carried out.

PETROGRAPHIC CHARACTERIZATION

The research project was designed to investigate the thermal behaviour of Foothills and Rocky Mountain coals from western Canada. These coals are Jurassic-Cretaceous in age and are, geologically speaking, somewhat unusual in the context of other Western Hemisphere coals (Gransden et al 1979, Given 1984, Pearson 1985). High inertinite coals are the norm, a situation usually associated with Permo-Jurassic coals of South Africa, India and Australia (Stach 1975, Given 1984). As petrographic composition influences carbonization, gasification and liquefaction behavior of coals (Gransden et al 1979, Pearson 1980, Kalkreuth 1982, Riepe and Steller 1987), there is no a priori reason to expect that combustion is independent of coal maceral composition. The literature is relatively scant on this point, but some work has been done (Nandi et al 1977, Sanyal 1983, Jones et al 1985) which supports this contention.

Coal rank is a particularly influential factor in coal combustion, and it is a given that lower rank coals are easier to burn than higher rank coals. Arguably, reflectance of vitrinite is one of the best methods for coal rank determination, and some work is available which demonstrates consistent relationships between combustion performance (in fluidized beds) and feed coal rank measured by vitrinite reflectance (Vleeskens 1985).

Reflectance also discriminates between the various maceral groups in any individual coal. Hence this particular physical property is unique in that if the reflectance of an entire coal sample is measured, the resultant reflectogram contains information on both the rank and physical composition of the sample. Reflectance measurement is a standard coal petrographic technique, and it has the advantage over conventional descriptive maceral analyses of being objective, repeatable and reproducible. For these reasons, the principal tool used in this study to characterize feed coal quality was coal reflectograms. The instrument used for this was a conventional incident-light petrographic microscope equipped with a video camera and coupled to an image-processing unit.

IMAGE ANALYSIS SYSTEM

The original plan was to develop a system similar to that developed at Penn State University (Davis and Vastola 1977, Davis et al 1983). This system involved using a computer-controlled analog-to-digital (A/D) converter to acquire millivolt signals from the microscope photomultiplier tube. The computer controls acquisition, processing and storage of the data as well as controlling the stepping stage of the microscope. To this end an Apple II Plus computer was used for the preliminary work on the automated reflectance system.

This first system was tested and worked successfully in terms of acquisition, processing and display of data from polished surfaces of particulate coal/-epoxy mixtures. There were a number of technical limitations with the system, such as the speed of data acquisition and required measuring aperture size. The aperture size was such that a large number of mixed readings (epoxy/-maceral, maceral/maceral) were acquired thus skewing the data to lower reflectance values than anticipated. It was decided that the measuring aperture size needed to be effectively reduced to minimize the relative number of mixed readings acquired. Initially it was thought that the problem of epoxy/maceral readings could be solved by increasing the coal to epoxy ratio, but it was found that the ideal ratio of >80% coal was not practically obtainable. Although encouraging results were obtained from this system, it was decided to pursue image analysis techniques in place of conventional photometry as a possible means of overcoming the technical limitations encountered.

A survey of possible image analysis systems (at that time) revealed that there were no commercial systems available that could meet the requirements for the reflectance analysis of coal. A number of suppliers of components for image processing were approached, and it was decided to evaluate hardware from Imaging Technology. The necessary image analysis system was determined to be the following:

1. 4 frame buffers (512 x 512 x 8) which gave the capability of using a sub-micron measuring spot size with a resolution 256 grey levels;

2. an arithmetic logic unit (ALU) for processing acquired images;

3. a frame grabber for acquisition and display of video images;

4. a DEC PDP 11/73 mini computer with the ULTRIX II operating system (UNIX);

5. a high resolution black and white video camera, and

6. a high resolution monitor for viewing acquired images.

A multitasking operating system was chosen to allow for the simultaneous development and use of the image analysis software. This allowed for a current version of the software to be in use with a second version of the software for debugging or adding extra functionality. C was chosen as the programming language for its speed, ease of use, connections to the hardware in the system and its richness in character and bit manipulations (essential to image analysis). UNIX was chosen as the operating system for its wealth of program development tools and for its ease of learning and use.

Footnote - UNIX is a trademark of AT&T.

As can be seen from the accompanying functional block diagram (Figure 1) the video camera first acquires the image of the sample viewed through a conventional incident-light petrographic microscope. This image is transmitted to the frame grabber where a flash analog-to-digital converter digitizes and stores the image into an array of 512X480 elements each with a resolution of 1 part in 256 (8 bits of information). This digitization takes place in 1/30 of a second (the time it takes for the video camera to scan 1 complete frame). With this speed of digitization the frame is acquired, digitized and stored in essentially "real-time". With the image acquired and stored into a frame buffer, a flash digital-to-analog converter takes the image and converts it into a signal that can be used by the video monitor. Again this takes 1/30 of a second and the image appears on the monitor in "real-time". With these speeds of data acquisition, the image on the video monitor tracks the image of the video camera and there is no appreciable lag or time difference between the 2 images. The ALU is a pipeline ALU in that any operations (including no operation) on the image are done in "real-time" as the image is being passed through to the frame buffer. Thus no component of the image acquisition hardware will give any delay between the real image and the viewed image.

The image analysis system was set up to allow for a series of reflectance standards to be used to determine a relationship between reflectance and grey level. As well only the central area of the video camera image was used for reflectance data acquisition (due to the phenomena of vignetting inherent in all optical systems). Also since each pixel was small there were relatively fewer mixed readings (maceral/epoxy, maceral/maceral) than with a conventional photomultiplier tube.

Once the data was acquired from a number of frames (typically 100), a histogram of the data could be displayed (or printed). This histogram displayed the relative frequency of either reflectance or grey level values which in turn could be related to a number of properties of coal. The program could store either histogram or digital image data.

In general the image analysis system employed was one that provided functionality that could not be provided with any commercial system on the market at the time. It allowed complete flexibility for changes to the system and considering that all of the code was developed (and documented) in-house, it was easy to produce custom programs for not only the analysis of coal but for the analysis of any image from any source that could be scanned on a regular grid.

VITRINITE - INERTINITE HYPOTHESIS

The goals of the project required that some correlation be made between coal rank and composition, and some measures of thermal reactivity related to combustion. The approach taken hinged on the hypothesis that vitrinite - inertinite coals could be modelled as if they were blends of multi-vitrinite coals with the same range and frequency of reflectance values as the vitrinite

- inertinite mixture. The reasoning behind this hypothesis is that vitrinites and inertinites are derived from biochemically similar plant materials which are variably fossilised by sedimentologic facies controls (water levels, oxygen availability, pH, sedimentation rates, etc), into a continuum of materials which coal petrographers describe and categorize into the vitrinite and inertinite maceral groups. Petrographic observations of maceral morphologies and reflectances in inertinite-rich coals certainly support the continuum concept. Similar reasoning has since been used by Riepe and Steller (1987) to model coal hydrogenation behaviour.

TEST SAMPLE SUITE

The first step in the procedure involved determining the thermal behaviour (pyrolysis and combustion) of a series of concentrated vitrinites (purities >90%) to elucidate any rank relationships. The use of a single maceral group eliminates variability due to multi-component differences. The second step was to apply the results to predict behaviours of an expanded suite of whole coals (i.e. presumed multi-vitrinite mixtures). The results are described later.

The vitrinite samples were concentrated from stage-ground pulverized coals (-200 to +325 mesh) by a sequential process of froth flotation (for mineral matter suppression) followed by heavy liquid density separation (S.G. 1.30 $\pm$ 0.05). The feed samples represented a suite of 12 individual seam coals collected from various Western Canadian mines, selected to cover the following property ranges: volatile matter 44-19% (daf), carbon content 79.7 - 90.2% (daf) atomic H/C ratio 0.77 - 0.63, and vitrinite reflectance 0.52 - 1.49% (mean, random reflectance; oil immersion). The rank range covered in this suite is sub-bituminous A to low-volatile bituminous. A low-volatile bituminous U.S. Paleozoic sample was added to the Western Canadian suite, to fill a gap in the rank distribution of the Canadian samples.

For the second stage of the work, a series of 20 coals were combusted which consisted of the 13 coals from which the vitrinites were isolated and an additional 7 Western Canadian coals which also fell within the same rank range. The basic properties of the coals and the vitrinite concentrates are given in Table 1.

TABLE 1. PROPERTIES OF TEST SAMPLES

Spl #	Vitrinites: Volatile Matter % daf	Vitrinites: Carbon Content % daf	Vitrinites: Atomic H/C	Mean Random Reflectance %	Coals: Volatile Matter % daf	Coals: Carbon Content % daf	Coals: Atomic H/C
1	44.2	79.7	0.73	0.52	40.2	75.7	0.83
2				0.86	32.1	85.3	0.76
3	35.2	84.8	0.77	0.86	35.8	86.6	0.79
4	33.8	84.6	0.77	0.89	33.3	85.8	0.75
5	38.2	85.8	0.76	0.91	29.6	86.0	0.71
6				0.94	28.5	88.6	0.70
7	31.3	85.0	0.74	0.95	30.7	84.6	0.74
8				0.98	25.8	88.8	0.72
9	28.9	86.8	0.72	1.04	25.6	87.7	0.67
10				1.07	25.8	87.1	0.69
11	27.3	87.8	0.69	1.09	26.1	87.8	0.70
12	26.1	87.5	0.70	1.17	24.6	88.3	0.69
13	23.0	88.0	0.68	1.17	24.2	90.1	0.65
14				1.21	25.6	88.2	0.65
15				1.22	23.5	88.4	0.67
16				1.24	24.3	88.9	0.68
17	23.9	90.1	0.66	1.26	23.5	89.5	0.67
18	21.3	89.5	0.65	1.35	21.8	89.5	0.64
19	20.3	90.2	0.64	1.44	19.5	90.0	0.63
20	19.1	89.9	0.63	1.49	18.8	93.6	0.61

THERMAL REACTIVITY TESTS

All thermal reactivity testing was carried out under contract by Advanced Fuel Research (AFR).

An entrained flow reactor was used for pyrolysis and combustion tests. For pyrolysis, sized feed particles entrained in nitrogen are down-fed into the reactor with a furnace wall temperature of 1300°C. Complete devolatilization is easily achieved within the particle residence time of 0.7s., and a reaction mass balance is obtained by quantitative collection of all char, tar, soot and gas. The reactor is fully described in Solomon et al (1982).

Combustion test conditions were set by reducing wall temperatures to 900°C, under which conditions the most combustible samples just achieved near-complete burnout after 0.7s. residence in the reactor in 3:1 nitrogen: oxygen entrainment gas. Reaction mass balance is obtained once more through quantitative collection of all products.

IGNITION TESTS

Ignition tests were carried out on the coal sample suite at a late stage in the project. Advanced Fuel Research was again contracted to do the experimental work, using their transparent-wall reactor. In this facility, a stream of coal particles is injected into a stream of pre-heated air. Ignition and burning can be observed visually, and gas and particle temperatures before and after ignition are made using FTIR emission/transmission spectroscopy (Solomon, in Allan, in prep).

RESULTS AND DISCUSSION

COMBUSTION EXPERIMENTS

Combustion experiments with the vitrinite concentrates showed quite clearly that carbon burnout can be correlated with the rank of the feed coal. Figure 2 shows this relationship as the fraction of the sample reporting as unburnt char (daf basis) plotted against reflectance of the feed. (These tests were all performed under conditions which gave close to total combustion of vitrinite #3 in Table 1.) Linear regression analysis for this data set, under the specified AFR reactor conditions, gave the following relationship:

$$\text{Char (wt \%)} = 42.69 * R_o - 34.4 \quad (r = 0.85)$$

(Higher order regression equations of higher significance were also generated, but they included variables other than petrographic properties, i.e. carbon content, volatility, which are inappropriate to the following discussion). With this regression equation, one would then predict that complete burnout will occur when R_o is less than 0.81% and that zero burnout will occur when R_o is greater than 3.15% (assuming linear extrapolation of the trend beyond the upper limit of the experimental data set).

The results for all 20 test coal are shown in Figure 3 where actual and predicted values are cross-plotted and show a satisfying correspondence to the line of perfect correlation. The increasing divergence from the line of perfect correlation as unburnt char values exceed 25% occurs where the predicted values have significant components derived from reflectance values which lie beyond the experimental bounds of the predictive data set (R_o>1.5%) and probably illustrate the pitfalls of such extrapolations.

A subsequent experiment was performed whereby 20 whole coals were combusted under identical conditions to the vitrinite set. In reflectance terms all the coal ranks fell within the limits of the reference vitrinite set, and included those coals from which the vitrinites had been separated. The objective of the second experimental set was to determine whether the regression equation would accurately predict the burnout behaviour (measured by recovery of unburnt char) of the whole coals, despite the now-added variable of maceral heterogeneity (see discussion in previous section re: vitrinites and inertinites). To attain this objective, reflectograms were produced from each coal, and each reflectogram was simplified to a V-type

FIGURE 1 - Schematic diagram of the image analyzer

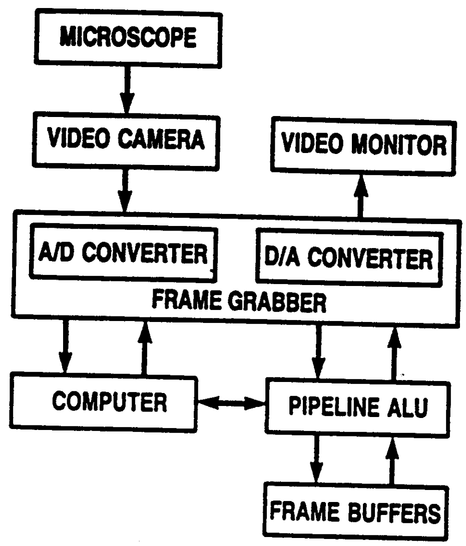
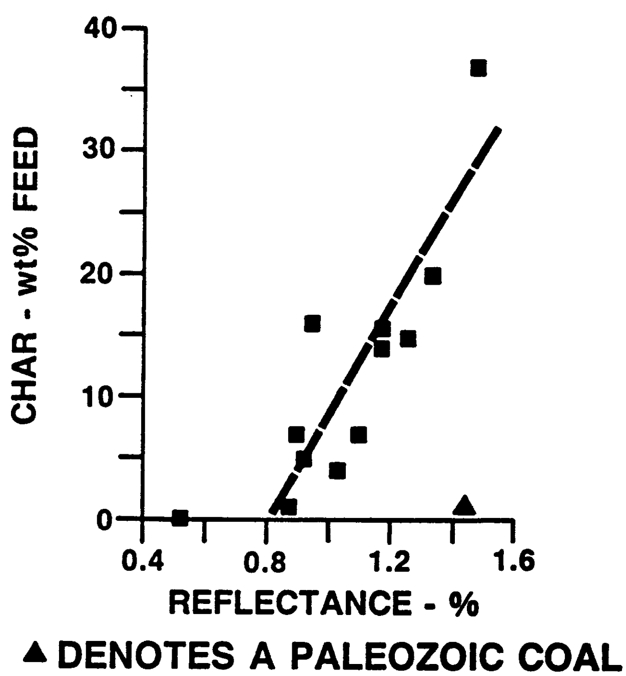


FIGURE 2 - Combustion char versus reflectance: vitrinites



distribution for ease of calculation. Using the regression equation, the contribution to total char of each V-type can be calculated and then each contribution is summed to derive a total predicted char value. The char factor for each V-type is calculated from the mid-point reflectance of each V-type. An example of this computation is given in Table 2 which shows the calculation of predicted char formation for coal #5 in Table 1, and 14.4 wt% of the feed coal (daf basis) is predicted to report as unburnt char. The subsequently measured value was 12.7%.

TABLE 2. WORKSHEET FOR PREDICTION OF CHAR FORMATION

V-Type	Char Factor A	Sample Composition By V-Type B	Produced Char (wt % daf) A X B
6	0.000	0.0	0.00
7	0.000	4.1	0.00
8	0.019	17.0	0.32
9	0.062	27.2	1.69
10	0.104	10.3	1.07
11	0.147	7.1	1.04
12	0.190	8.0	1.52
13	0.232	6.8	1.58
14	0.275	5.1	1.40
15	0.318	4.1	1.30
16	0.360	2.8	1.01
17	0.403	2.3	0.93
18	0.446	2.0	0.89
19	0.489	1.6	0.78
20	0.531	1.1	0.58
21	0.574	0.4	0.23
22	0.617	0.1	0.06
23	0.659	0.0	0.00
		100.0	14.40

Conventionally, volatile matter is used as a rank parameter for coals of these ranks. To estimate whether the petrographic method described above (i.e. including both rank and type data) is any more effective than conventional ranking for evaluating combustibility, a similar exercise was performed using a char-to-volatile matter correlation in place of the char-to-reflectance correlation. Figure 4 shows the differences (Δ) between actual and predicted chars plotted against %I, a petrographic factor derived from reflectograms which approximates the volume of inertinites in the samples. Use of volatile matter alone becomes less and less reliable as the feed inertinite increases, and this property is much less effective than the reflectogram predictor which compensates for both rank and type variability.

FIGURE 3 - Measured versus predicted combustion char yields

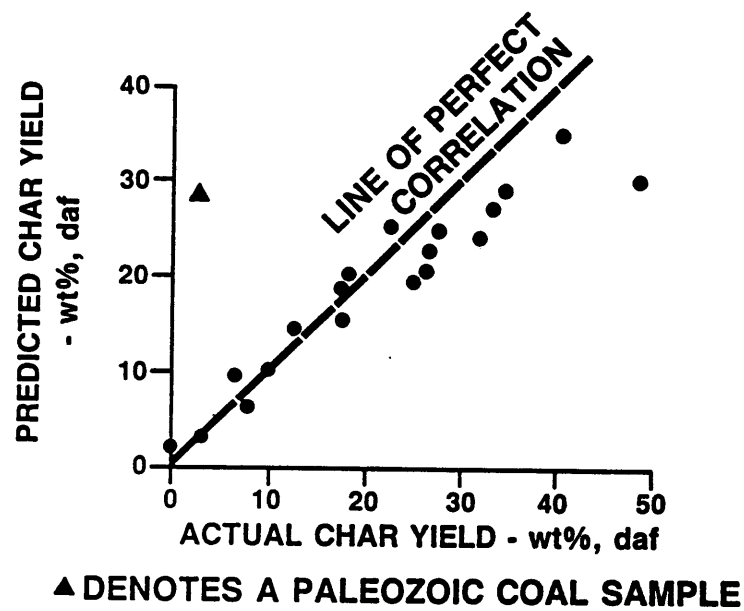
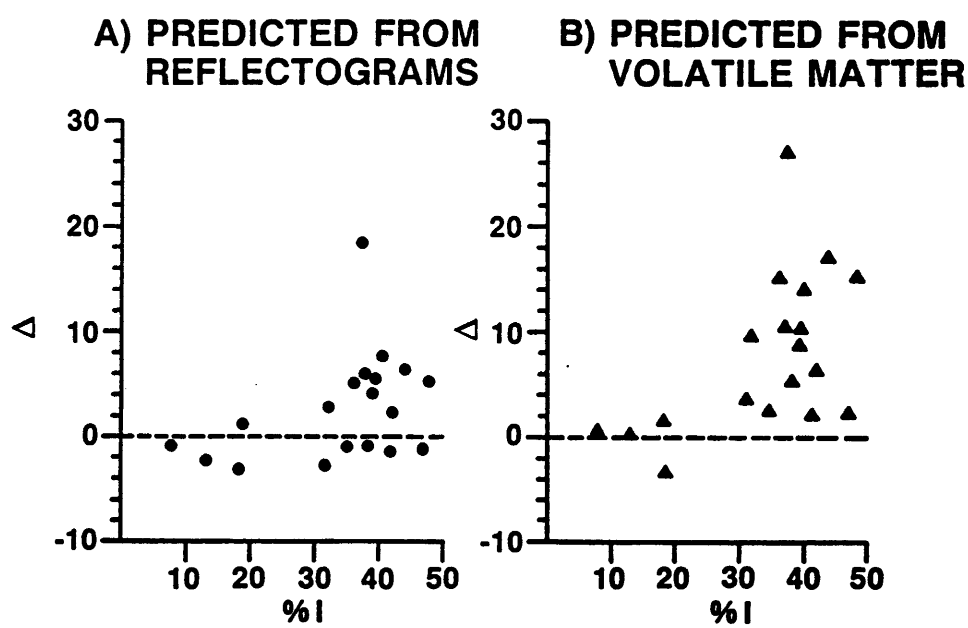


FIGURE 4 - Comparison of reflectograms and volatile matter as combustion char predictors



The combined influence of rank and type on combustibility is best displayed by Figure 5. Each data point is annotated with the measured residual char content from the combustion experiments. The ordinate is also annotated with theoretical values for the mid-point of each V-type along the axis, the values being calculated from the regression equation given above. The contoured field shows percent unburnt char (AFR reactor, 900°C) with the contours honoring 15 out of the 19 data points before considering error bars. Contours cannot be theoretically extended towards the abscissa, as inertinites always span wide reflectance ranges which shift with coal rank. The rational distribution of data in the field of Figure 5 is taken as strong evidence that coal combustion, at least at bench scale, can be modelled empirically by proper selection of those properties by which feed coal quality is evaluated.

VOLATILES AND CHAR

Volatility

Much discussion can be found in the literature concerning the question of whether combustion of pulverised coal is a homogeneous or heterogeneous reaction, and evidence supporting both possibilities can be found (Field et al 1967, Morrison 1986, and references in both). The problem was not addressed directly in this study but the related aspects of devolatilization and char reactivity were investigated experimentally.

Figure 6 shows the relationship between volatility of vitrinites (daf percent weight loss at 1300°C) and rank (reflectance) under the high heating rates (~ 10^5°C sec^{-1}) attained in the AFR reactor. With the exception of two data points, the data show an excellent linear correlation, and there are good experimental reasons for assuming large errors in the two exceptions (Allan, in prep). Following the same rationale for calculating volatility of whole coal from the vitrinite experimental set as was used in the combustion studies, pyrolysis results for four test coals were both predicted and measured in the AFR reactor (Table 3). As a matter of interest, proximate analysis volatile matter and other coal properties can also be calculated using this petrographic methodology (Allan and Gehring, unpublished results).

TABLE 3. COMPARISON OF 1300°C VOLATILITY BY MEASUREMENT (AFR) AND PREDICTION

Sample #	AFR Reactor Measurement (% daf)	Petrographic Prediction (% daf)
1	47.3	49.3
2	63.3	55.0
3	42.3	43.4
4	39.5	41.8

FIGURE 5 - Relationship between rank, type and char formation

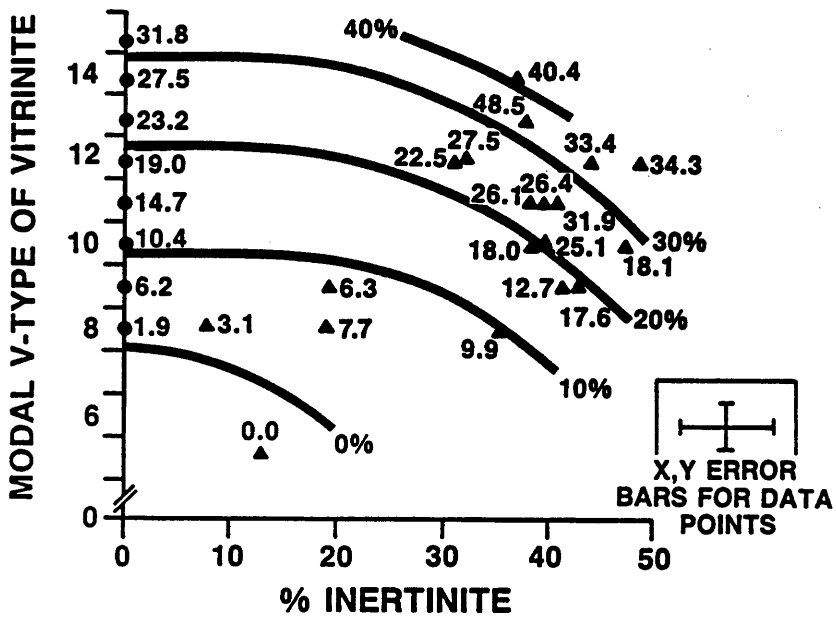
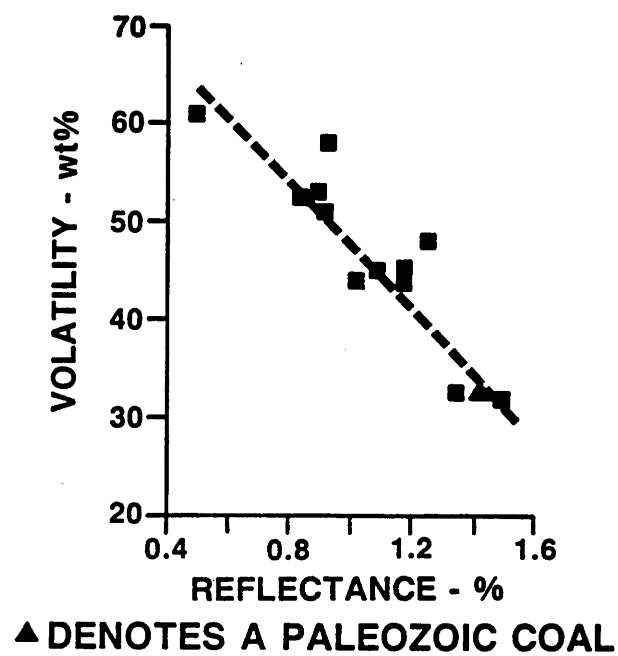


FIGURE 6 - Pyrolysis volatility versus reflectance: vitrinites



Based on this agreement of prediction versus measurement, one would hypothesize that a consistent relationship exists between volatility and coal rank and maceral composition (Jones et al 1985). In terms of combustion, the volatiles are presumed to be readily and completely burnt (excepting water) and so the mass loss due to these gases will account, in part, for the combustion behavior summarized in Figure 5.

Char Oxidation

Maximum char-forming potential is the complement of volatility (daf basis). As volatility is always less than 100%, partial to complete char oxidation must occur in the combustion tests to account for the observed data, and this is presumed to be the rate-limiting step in the overall gasification process. Thus, it is reasonable to assume that quantification of char reactivity might also contribute significantly to explaining the empirical combustion relationships shown in Figure 5.

A measure of char reactivity is the ratio of residual combustion char to pyrolysis char (P. Solomon (AFR), pers. comm). For the initial test vitrinites, the relationship between reactivity and rank is shown in Figure 7. This shows that complete gasification will occur, for these experimental conditions, when reflectance falls to 0.7%. Only one of the vitrinites fulfilled this condition, and it did show complete burnout. Char gasification then decreases continually with increasing rank, and, given the vitrinite - inertinite reflectance equivalence concept, any increase in inertinite contents at any rank ought to cause an increase in unburnt char (Nandi et al, 1977).

It is interesting to note that the models derived for the Western Canadian coal suite clearly do not apply universally as the almost total burnout of the high rank Paleozoic coal would not have been predicted. This result strongly emphasizes the need to work with geologically constrained sample sets (Neavel 1981; Jones et al 1984).

IGNITION TESTS

Ignition behaviour (ignition and combustion temperatures) was investigated for all 20 coals combusted as ignition behaviour might be another factor in explaining the observed combustion behaviour. Analysis of the results (Allan, in prep) failed however to show any obvious correlation between burnout during combustion and particle temperatures attained prior to, at, or following ignition which might contribute to the data shown in Figure 5. However it was found that the distance D_I between the injection point into the reactor and the point where visible ignition occurred did vary widely, and that this distance correlated well with coal rank (Figure 8). This correlation ($r = 0.82$ in linear regression analysis) was not improved by factoring in petrographic composition.

FIGURE 7 - Char reactivity versus reflectance: vitrinites

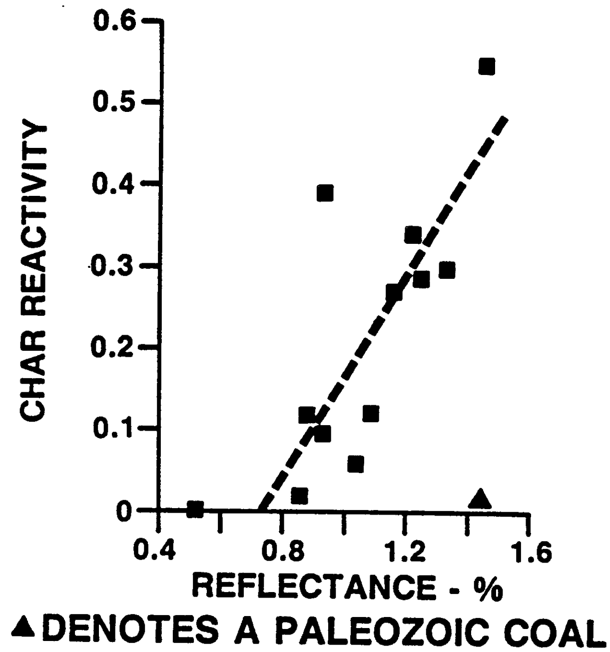
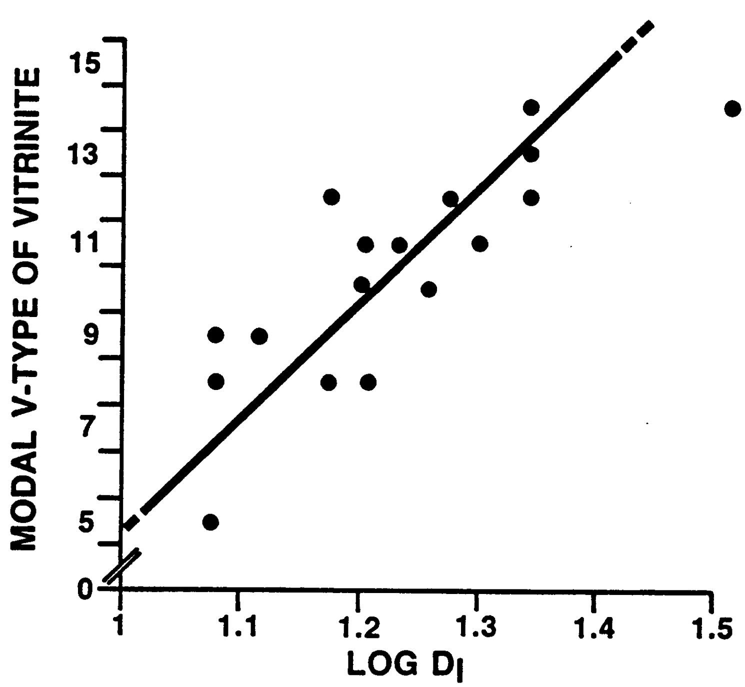


FIGURE 8 - Coal rank versus ignitability



This series of experiments show that the time available for char oxidation after ignition in the original combustion experiments was quite likely not equal for all the coal samples, and was not equal to the time taken to traverse the reactor path length. Figure 9 shows that, in fact, the amount of unburnt char expressed as a fraction of total potential char also correlates well with D_I. Although two different reactors are being compared here, D_I can be considered as a relative measure of the time required to reach ignition, and hence, in a fixed time-path reactor, a relative measure of the remaining reaction time available.

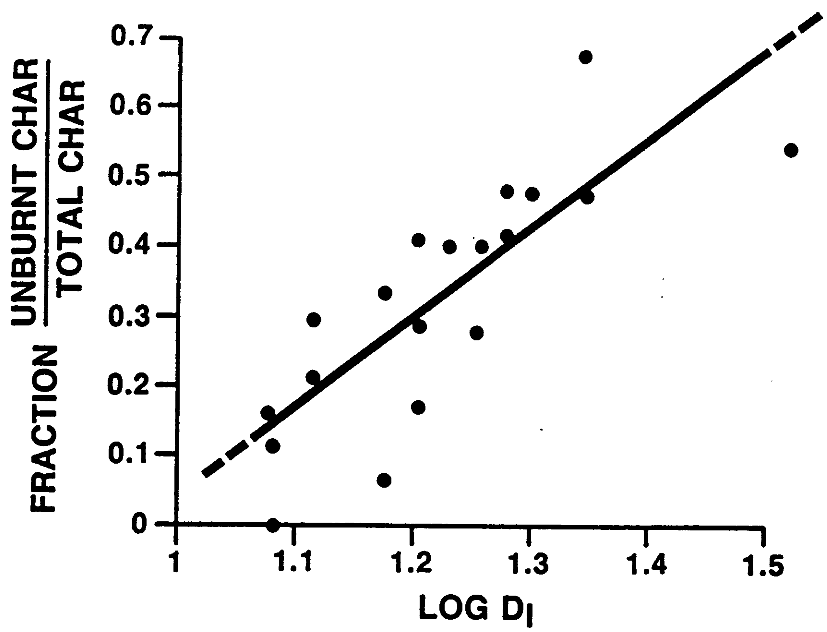


FIGURE 9 - Char reactivity versus ignitability

It can be reasonably assumed that a critical concentration of volatilized fuel gas is required in these experiments to initiate visible ignition (Eklund et al, 1987). If this critical concentration were to equal that achieved by total devolatilization, then the apparent relationships between ignition points and coal rank or fractional char consumption would be self-evident. This would be rather coincidental however, and hence is unlikely. Such a relationship would also have been reported in the literature if found by other investigators. More likely is the assumption that the time taken to reach a critical combustible concentration differs between coals and that the rate of volatiles evolution is therefore significant. (Composition of volatiles is another potential factor influencing flammability. This has not been investigated during this project, but data on the heating value of volatile matter (Morrison 1985) clearly suggest gas compositional differences).

That the rate of volatiles evolution might be rank-related can be rationalized in the following manner. The fundamental process of organic coalification is one of carbon enrichment at the expense of all other elements. Lower rank coals are enriched in oxygen relative to high rank coals. Rupture of C-O bonds requires less energy than C-C bond cleavage. Fuel gas build-up through devolatilization ought therefore to occur more rapidly in lower rank coals, and a rank-dependence would be expected. In addition, it was noted above that time taken to reach ignition appeared to be independent of maceral composition. Ignition point was determined visually and would obviously coincide with the ignition of the most flammable macerals. In vitrinite-inertinite mixtures this would be the true vitrinite, which is also the most oxygen-rich component of vitrinite-inertinite series.

CONCLUSIONS

The work described in this paper has shown that laboratory scale pyrolysis and combustion performance of coals can be predicted via a novel petrographic methodology. The methodology was developed specifically to evaluate Jurassic-Cretaceous age coals of western Canada, which are frequently high in inertinites. When total inertinites exceed about 25 volume percent of the maceral content, their influence must be accounted for directly in rationalizing whole coal quality and thermal behaviour.

The vitrinite and inertinite macerals in high inertinite coals can be treated as a series of materials with a continuum of properties. Thus, for a given coal, inertinite properties can be modelled as if they were a series of vitrinites whose reflectances exceed those of the true vitrinite end-member of the coal.

The importance of good geological control on any test coal series is emphasized. Somewhat fortuitously, a single coal sample of Paleozoic age from the eastern U.S. was included. In some instances (e.g. pyrolysis behaviour) its thermal reactivity fitted well with the model developed for Western Canadian samples. In other experiments (e.g. combustion performance), this coal showed widely divergent behaviour (see Figures 2 & 7). This variability, while not a new result by any means, emphasizes the provincialism in coal properties highlighted recently by Jones et al (1984).

The petrographic methodology used is not unique in its capabilities to predict pyrolysis and combustion behaviour of coals. A different procedure was used by Jones et al (1985) to investigate pyrolysis behaviour of coals, but the importance of the underlying principles of coal rank and type were recognized by those investigators. As has been found in other areas of coal utilization and in coal science in general (Neavel, 1981), these two independent variables are crucial to understanding coal.

ACKNOWLEDGEMENTS

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CONVERSION CHARACTERISTICS OF SELECTED CANADIAN COALS BASED ON HYDROGENATION AND PYROLYSIS EXPERIMENTS*

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ABSTRACT

Hydrogenation. The conversion rates were found to range from 8-78%. The highest conversions were obtained from reactive rich subbituminous and high volatile bituminous coals. For each rank level the coal containing the highest amount of reactive macerals has also the highest conversion. Results from this study suggest that some of the higher rank Western Canadian coals can be hydrogenated successfully despite their high contents of inertinite macerals.

Vacuum pyrolysis. The conversion rates were found to reflect closely rank and petrographic composition of the parent coals. The highest conversion rates were obtained from the liptinite-rich lignites and subbituminous coals (30-70%), whereas the conversion rates of the higher rank coals were found to be significantly lower (32-14%). The preliminary results suggest that vacuum pyrolysis might be an effective process in which valuable tar by-products could be generated from lower rank (thermal) coals prior to burning the coal.

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INTRODUCTION

Technological properties of coals are to a large extent a function of rank and petrographic composition of the parent coal. In hydrogenation, for example, the optimum rank to produce the highest liquid yields appears to be at the level of high volatile bituminous coals, while at lower and higher rank levels the degree of conversion decreases markedly (Whitehurst et al., 1980). In coals having the same rank levels the petrographic composition determines the susceptibility to conversion (Given et al., 1975) i.e. the ratio of reactive to inert macerals. Macerals are commonly identified by methods of incident light microscopy in which morphological characteristics and reflectance levels are used to define three major maceral groups, namely the vitrinite, liptinite and inertinite groups.

In technological terms the group of reactive components comprises the macerals of the vitrinite and liptinite groups and a portion of the maceral semifusinite. The latter consists of material which in its properties is thought to be at an intermediate stage between vitrinite and inertinite. The inert group comprises the macerals of the inertinite group plus mineral matter. In general the greater the amount of reactive macerals contained in a coal the better conversion can be expected (Fisher et al., 1942).

In the present study coals characterized by varying amounts of reactive and inert materials ranging in rank from lignite to low volatile bituminous were tested for their susceptibility to hydrogenation and vacuum pyrolysis.

The feedcoals were characterized petrographically using incident light microscopy techniques applying TAS (Texture Analysis System) and conventional petrographic methods. Vitrinite reflectance measurement was used to determine the rank, and maceral and microlithotype analyses to determine the petrographic composition. Chemical analyses involved the determination of elemental composition, ash contents and volatile matter contents.

The results presented here form part of a joint research project on conversion characteristics of coals between the Geological Survey of Canada, the Department of Chemical Engineering, Université Laval, Québec and Bergbau-Forschung, Essen, Germany. This paper focuses on petrographic and chemical characterization of the feedcoals and discusses their conversion rates. For further information in respect to yields (gaseous and liquid products) and the characterization of solid reaction products (solid residues), the reader is referred to Roy et al. (1985), Hébert (1986), Kalkreuth et al. (1986), Hébert et al. (1987) and Steller et al. (1987).

EXPERIMENTAL

PETROGRAPHIC ANALYSES

Coal. Rank and gross petrographic composition of the coals used in the hydrogenation experiments were established using an automated texture-analysis-system (TAS-Leitz). Details of the procedure have been described by Riepe and Steller (1984). In addition, conventional maceral analysis was used for detailed determination of macerals following the Stopes-Heerlen concept for maceral classification. Rank of the coals used in the vacuum pyrolysis experiments was determined by measuring vitrinite reflectances under standardized conditions (Bustin et al., 1985).

HYDROGENATION

In the hydrogenation experiments a bench-scale autoclave (2 l) was used. In each experiment 50 g of coal were mixed with 100 g of recycled oil from the Bergbau-Forschung coal hydrogenation plant and fed into the autoclave. The mixture was then reacted with hydrogen starting at 150 bar cold-pressure to approximately 350 bar at 450°C. The coal-oil mixture was kept at maximum temperature for one hour and then cooled down to room temperature. The solid residues were extracted with pyridine. Based on the amount of pyridine-insoluble residual material the degree of conversion for the coals was defined as follows:

$$\text{conversion (\%)} = \frac{\text{g coal (m.a.f) - g residue (m.a.f.)}}{\text{g coal (m.a.f.)}} \times 100$$

VACUUM PYROLYSIS

The operating conditions used for the pyrolytic reactions of the coal samples have been reported in detail elsewhere (Roy et al., 1985). The pyrolysis experiments were conducted in a bench scale retort using a final decomposition temperature of about 600°C at an average heating rate of 9°C min^{-1}. The absolute pressure was kept below 2 mm Hg.

CHEMICAL ANALYSES

Proximate and ultimate analyses on the feedcoals were performed using standard procedures at Bergbau-Forschung, Essen and Université Laval, Québec.

RESULTS AND DISCUSSION

HYDROGENATION EXPERIMENTS

Petrographic analyses of feedcoals

Rank

Table 1 lists the coals according to rank. The random vitrinite reflectances as determined by TAS were found to range between 0.40 to 1.47%. In terms of ASTM rank classes, three of the coals are subbituminous, eight are high volatile bituminous in rank, and one is low volatile bituminous in rank.

Composition

Gross petrographic composition was determined by TAS (Table 1). Figure 1 illustrates the reflectograms for the 12 coals analysed. Highest vitrinite contents occur in the handpicked vitrains (sample 1 and sample 4), which contain 89 and 85 Vol. %. Inertinite contents range from 10-55 Vol. %. In particular, some of the Western Canadian coals do have very high amounts of inertinite (Fig. 1, samples 3, 10, 12). The only other coal having a similar high inert content is the sample from South Africa (Table 1 and Fig. 1, sample 7). The liptinite contents are low to moderate. Only two coals have more than 10 Vol. % liptinite (Table 1 and Fig. 1, samples 8 and 9). In both reflectograms a distinct peak to the left of the major vitrinite peak indicates greater amounts of liptinite macerals (Fig. 1).

Table 1. Origin, A.S.T.M. rank classes, petrographic characteristics and conversion rates for feedcoals used in hydrogenation experiments.

Sample	Location	Seam	A.S.T.M. Rank	Vitrinite Reflectance Rrandom (%)[4]	Maceral Analyses Vol. % (m.m.f.)[4]			Conversion (%)
					Vitrinite	Liptinite	Inertinite	
1	Highvale Mine, Canada	No. 1	subbituminous	0.40	89[1]	1[1]	10[1]	78
2	Highvale Mine, Canada	No. 1	subbituminous	0.40	71[2]	1[2]	28[2]	49
3	Highvale Mine, Canada	No. 6	subbituminous	0.41	56[3]	1[3]	43[3]	8
4	Luscar Sterco, Canada	Mynheer	high vol. C bit.	0.49	85[1]	2[1]	13[1]	71
5	Luscar Sterco, Canada	Mynheer	high vol. C bit.	0.54	71[2]	8[2]	21[2]	29
6	Prince Mine, Canada	Hub	high vol. B bit.	0.67	83	5	12	10
7	South Africa	-	high vol. A bit.	0.82	41	8	51	59
8	West Germany	Gudrun	high vol. A bit.	0.87	65	15	20	61
9	West Germany	Zollverein	high vol. A bit.	1.03	64	13	23	78
10	Bullmoose Mine, Canada	B	high vol. A bit.	1.05	64	1	55	54
11	China	-	high vol. A bit.	1.06	66	4	30	34
12	Smoky River Coal, Canada	No. 10	low vol. bit.	1.47	48	2	50	65

[1] handpicked vitrain from [2]
[2] channel sample
[3] handpicked durain
[4] by TAS (Texture Analysis System)

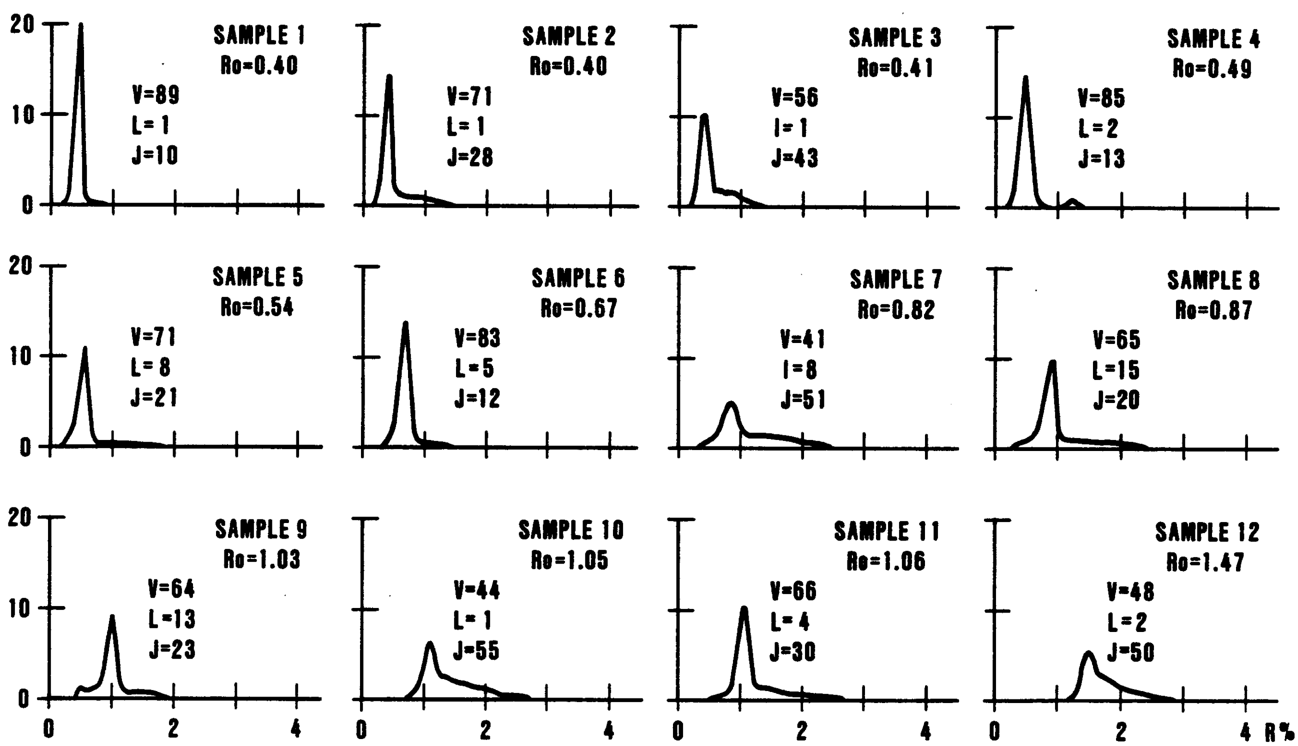

Figure 1. Diagram illustrating reflectograms as determined by TAS (Texture Analysis System), from which random vitrinite reflectances and maceral group distributions were calculated; from Steller et al. (1987).

At the present time TAS cannot differentiate between macerals that might have the same reflectances but different morphologies, as, for example, some of the inertinite macerals. Traditional manual maceral analyses showed that within the inertinite group there is considerable variation in the percentage of individual macerals. The macerals micrinite, macrinite and sclerotinite are rare or absent. The same is true for inertodetrinite, which was found to occur in larger amounts in sample 3 only (seam No. 6, Highvale Mine, Canada). Fusinite content is low to moderate, ranging from 1 Vol. % (sample 4, Luscar Sterco Mine, Canada) to 15 Vol. % in sample 2 (Highvale Mine, Canada, Seam No. 1). Semifusinite contents show the greatest variations of all inertinite macerals, ranging from 1 Vol. % (sample 1, Highvale Mine, Canada to 38 Vol. % in sample 10 (Bullmoose Mine, Canada). The determination of semifusinite is of particular interest, because this maceral is believed to react to some extent in much the same way as vitrinite. However, the degree of reactivity is not very well defined at the present time and may vary depending on rank and origin of coal samples.

Elemental analyses of feedcoals

The results of elemental analysis are shown in Table 2. With increasing rank (samples 1 to 12) the carbon content increases from 68.7% in sample 3 to 90.6% in sample 12, accompanied by a drastic decrease in oxygen, from 24.6% in sample 3 to 4.4%

Table 2. Elemental composition, ash content and H/C-O/C;-atomic ratios for feedcoals used in hydrogenation experiments.

Sample	Elemental Analysis (d.a.f.)					Ash (dry)	Atomic Ratios	
	C	H	N	S	O		H/C	O/C
1	75.0	5.26	0.79	0.29	20.2	6.8	0.84	0.20
2	74.5	5.04	1.00	0.34	19.7	15.4	0.81	0.20
3	68.7	5.28	1.04	0.14	24.6	57.5	1.01	0.27
4	79.1	5.76	1.39	0.26	13.4	9.1	0.87	0.13
5	78.7	5.14	1.08	0.24	15.6	24.6	0.78	0.15
6	80.2	5.32	1.34	3.73	10.0	10.3	0.80	0.09
7	85.0	5.15	2.32	1.34	7.3	12.1	0.73	0.06
8	83.7	4.91	1.65	1.87	10.4	8.4	0.70	0.09
9	88.7	5.27	2.04	0.68	5.6	4.8	0.71	0.05
10	88.5	4.87	0.92	0.22	6.1	12.2	0.66	0.05
11	79.8	5.09	1.08	4.75	6.5	35.8	0.77	0.06
12	90.6	4.61	0.99	0.27	4.4	14.6	0.61	0.04

in sample 12. The hydrogen content appears to remain fairly stable in this rank range. Two coals are characterized by high amounts of sulphur (samples 6 and 11), which occurs mainly in the form of pyrite. The H/C-O/C atomic ratios obtained from elemental analysis confirm the rank levels determined by vitrinite reflectance measurement. All coals fall within the van Krevelen "coalification band", indicating coal ranks from subbituminous to low volatile bituminous (Fig. 2). Variations of C/H-O/C ratios in samples 1, 2 and 3, which according to vitrinite reflectance have exactly the same rank (0.40 and 0.41% respectively), can be explained by differences in composition. Sample 3, for example, was found to contain larger amounts of inertinite macerals (43 Vol. %) and can thus be expected to have greater O/C ratios. Ash contents determined by proximate analyses were found to range from 4.8 - 57.5% (dry).

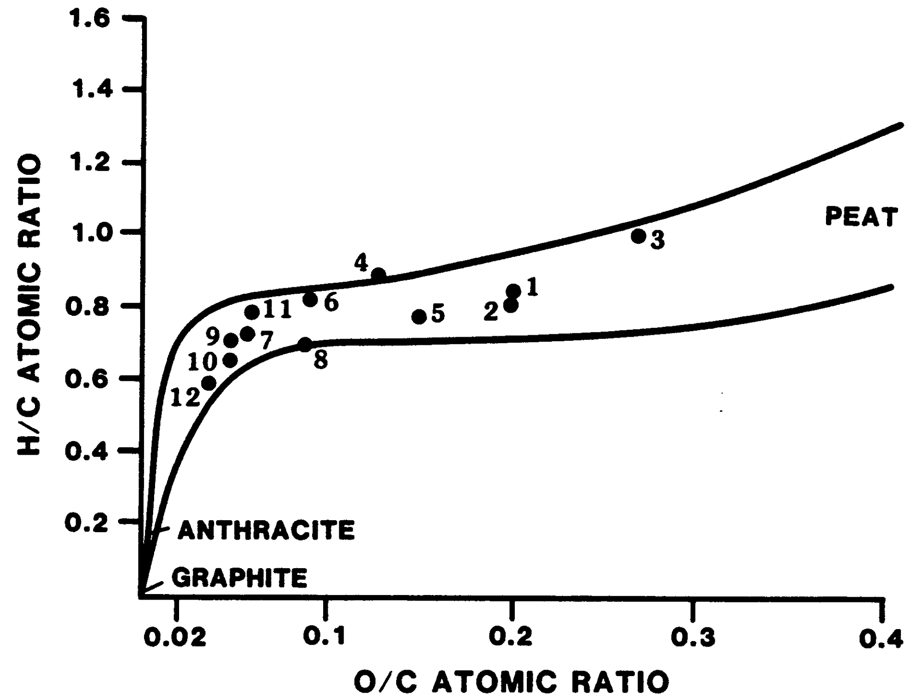

Figure 2. van Krevelen diagram illustrating H/C - O/C atomic ratios of feedcoals used in the hydrogenation experiments. Numbers refer to samples listed in Table 1; from Steller et al. (1987).

Petrographic characteristics and conversion rates

The degree of conversion for the coals analyzed in this study ranges from 8-78% (Table 1). The best conversion (>70%) was determined for the vitrinite-rich, low rank coals from Canada (sample 1, Highvale Mine; and sample 4, Luscar Sterco), and for sample 9 (seam Zollverein, W. Germany) which is high volatile A bituminous in rank. The relationships between rank, petrographic composition and conversion rates for all coals are illustrated in Figure 3. This figure shows clearly that within each ASTM rank class there is a strong relationship between the conversion rate and maceral composition, i.e. the amount of reactive macerals.

In the subbituminous coals from Canada the conversion increases from 8% for the inertinite-rich and ash-rich coal (sample 3) to 78% for the handpicked vitrain (sample 1), having 93 Vol. % reactive macerals. These values are the worst and best conversion rates recorded in the present study. They were obtained from the same coal zone and are clear evidence of the importance of maceral composition in the conversion of coals. In sample 3, the high ash content also may have had an influence upon the recorded low conversion rate.

A similar pattern of conversion dependency from petrographic composition can be illustrated for the high volatile bituminous coals. Samples 4 and 5 (high volatile C bituminous) were obtained from the same seam at Luscar Sterco, Canada. Sample 4 represents a handpicked vitrain lens (94 Vol. % reactive macerals) and sample 5 represents a channel sample from the same seam (81 Vol. % reactive macerals). The degree of conversion for sample 5 appears, however, to be somewhat low, possibly indicating an incomplete conversion. This is supported by the fact that in the residual materials from this hydrogenation run minor amounts of only slightly altered vitrinite components were observed, which is indicative of incomplete conversion.

The sole sample from high volatile B bituminous rank (Prince Mine, N.S., Canada) shows a conversion rate of only 10% although the amount of reactive macerals total 93 Vol. %. Analysis of the residual material from this coal revealed a maceral composition in the residue very similar to that of the feedcoal, and newly formed

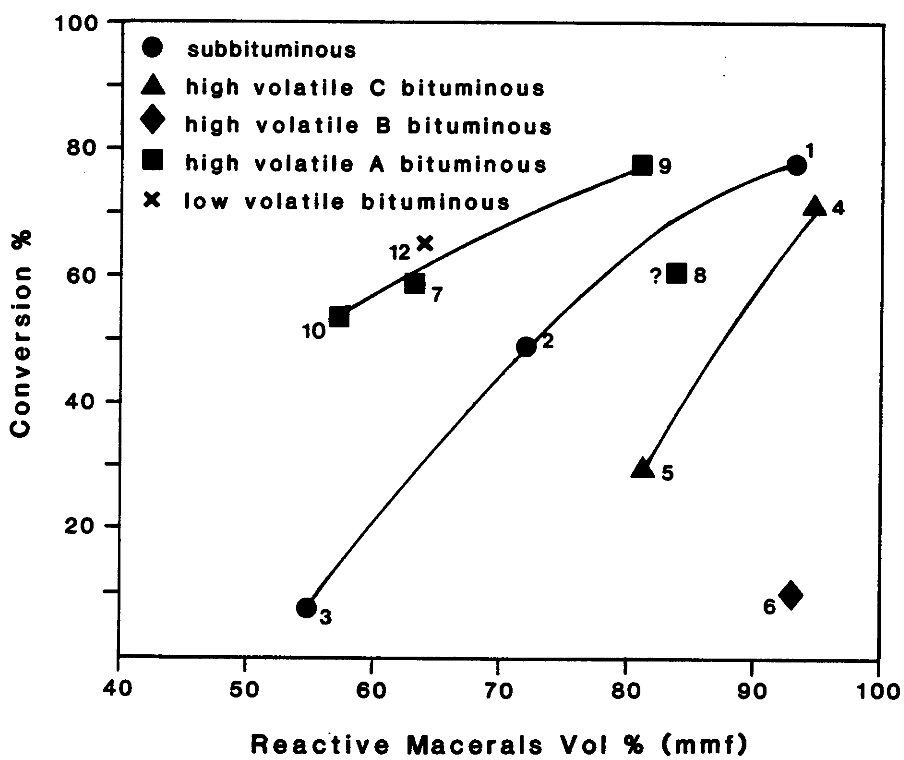

Figure 3. Diagram illustrating relationship between conversion rates, petrographic composition and coal rank (reactive maceral contents are based on averaged values from TAS and conventional maceral analyses). Numbers refer to samples listed in Table 1; from Steller et al. (1987).

materials such as semi-coke and coagulant were absent. These observations, together with the low conversion rate, suggest that the hydrogenation experiment failed, probably due to failures in the pressure or temperature controlling system.

In the high volatile A bituminous rank relatively high conversions were achieved even for coals containing large amounts of inertinite macerals. Sample 10 (Bullmoose Mine, Canada) has a conversion rate of 54% even though its reactive maceral content is only 57 Vol. %. The same is true for sample 7 (South Africa), which also has a considerable amount of inertinite macerals, in particular semifusinite. The highest conversion rate of 78% was determined for sample 9 (seam Zollverein, W. Germany), which has a reactive maceral content of 81 Vol. %. Deviations from the general trend are shown by sample 8 (seam Gudrun, W. Germany) and sample 11 (China) which, despite fairly high contents of reactive macerals, only have moderate conversion rates, of 61% and 34% respectively. In fact, sample 8 has not only a high content of reactive macerals but the highest amounts of liptinite macerals (15 Vol. % by TAS) within this group. At the present time, the discrepancies are not understood and further experimentation needs to be done on these two samples.

It is interesting to note that the sole sample representing low volatile bituminous rank (sample 12, Smoky River Coal, Canada) has a conversion rate above 60%, despite the fact that it also contains considerable amounts of inert macerals, and the content of reactive macerals is as low as 64 Vol. %, Figure 3.

From the conversion rates shown for subbituminous and high volatile A bituminous coals it is obvious that at higher rank levels the same conversion rate can be achieved with lower amounts of reactive macerals. In other words, low rank coals do need a much higher content of reactive macerals to obtain acceptable conversion yields. The higher rank coals from Western Canada, which are characterized by high amounts of inertinite macerals (sample 10, Bullmoose Mine, and sample 12, Smoky River Coal) do have acceptable conversion rates above 50%. These coals are currently mined and exported as coking coals. The results of the present study show that these coals also have potential for hydrogenation. Under the experimental conditions used, not only reactive-rich high volatile bituminous coals are converted easily but also the reactive-rich subbituminous coals. Good hydrogenation potential is also predicted for the low volatile bituminous coal.

VACUUM PYROLYSES EXPERIMENTS

Petrographic analyses of feedcoals

Rank

Table 3 lists the coals according to rank. The random huminite (eu-ulminite) reflectances for the lignites and subbituminous coals range from 0.37 to 0.49%. The maximum vitrinite reflectance for the bituminous coals range from 0.73 to 1.52%. The reflectances indicate a rank range from lignite to low volatile bituminous.

Composition

Table 3 lists the distribution in maceral groups (m.m.f.) for the coals used in the experiments. Macerals of the vitrinite group (huminite group in lignites and subbituminous coals) were found to range from 25 to 100 Vol. %. Liptinite macerals

Table 3. Origin, A.S.T.M. rank classes, petrographic characteristics and conversion rates for feedcoals used in vacuum pyrolysis experiments.

Sample	Location	A.S.T.M. Rank	Vitrinite Reflectance (%)	Maceral Analyses Vol. % (m.m.f.)			Conversion (%)
				Vitrinite	Liptinite	Inertinite	
1	Manalta, Sask.	lignite	0.37[1]	82	4	14	31.9
2	Hat Creek, B.C.	lign./subbit.	0.41[1]	74	26	-	49.6
3	Hat Creek, B.C.	lign./subbit.	0.41[1]	-	92	8	97.9
4	Marten Ridge, B.C.	lign./subbit.	0.42[1]	21	78	<1	70.2
5	Hat Creek, B.C.	lign./subbit.	0.44[1]	95	5	-	38.4
6	Vesta Mine, Alta.	subbituminous	0.44[1]	100[3]	-[3]	-[3]	30.7
7	Vesta Mine, Alta.	subbituminous	0.45[1]	86[4]	11[4]	3[4]	34.0
8	Highvale Mine, Alta.	subbituminous	0.45[1]	61	5	34	27.7
9	Forestburg, Alta.	subbituminous	0.49[1]	94	3	3	30.6
10	Peace River Coalfield, B.C.	high vol. B bit.	0.64[2]	53	2	45	27.0
11	Coal Valley, Alta.	high vol. B bit.	0.66[2]	66	11	23	30.4
12	Prince Mine, N.S.	high vol. A bit.	0.73[2]	85	7	8	32.4
13	Elk Valley, B.C.	high vol. A bit.	0.79[2]	99	<1	<1	25.7
14	Elk Valley, B.C.	high vol. A bit.	0.87[2]	86	5	9	32.4
15	Elk Valley, B.C.	high vol. A bit.	0.89[2]	88	4	8	28.7
16	Weary Ridge, B.C.	high vol. A bit.	1.08[2]	83	4	13	23.4
17	Peace River Coalfield, B.C.	med. vol. bit.	1.09[2]	28	1	71	22.5
18	Peace River Coalfield, B.C.	med. vol. bit.	1.15[2]	34	3	63	20.4
19	Cardinal River Mine, Alta.	med. vol. bit.	1.39[2]	73	1	26	15.6
20	Weary Ridge, B.C.	low vol. bit.	1.52[2]	71	-	29	14.6

[1] Mean random huminite (eu-ulminite) reflectance
[2] Mean maximum vitrinite reflectance
[3] handpicked vitrain from [4]
[4] channel sample

were found to range between nil and 11 Vol. %, except in three samples which had been selected for extraordinary high liptinite contents: sample 2 has a resinite content of 24 Vol. %, sample 3 represents enrichment of resinite (92 Vol. %), handpicked from Hat Creek lignite, and sample 4 was chosen for a very high alginite/resinite content of 66 Vol. %. Macerals of the inertinite group were found to range between nil and 70 Vol. %. One pair of samples (nos. 7 and 8, Vesta Mine, Table 3) was chosen to compare conversion characteristics for vitrinite-rich (vitrain) layers to whole seam characteristics.

Chemical analyses of feedcoals

Results of elemental analyses are shown in Table 4. Organic carbon contents increase regularly with increasing rank except in sample 3 (handpicked resinite) and sample 17 (petrographic analysis indicated high degree of oxidation). Oxygen contents decrease with increasing rank from 31.2% in the lignite to 2.5% in the low volatile bituminous coal. Virtually no oxygen content was determined in the handpicked resinite, whereas the oxidized sample (No. 17, Table 4) is characterized by a much higher oxygen content as would be expected for its rank range (see Table 4). The variations in carbon, oxygen and hydrogen contents for the feedcoals are shown in the van Krevelen diagram, Figure 4, in which the atomic ratios of H/C and O/C are plotted versus each other. The lower rank coals plot in an area characterized by relatively high O/C ratios and H/C ratios between 0.7 and 0.8. With increasing rank the H/C ratios remain fairly constant, whereas the O/C ratios decrease significantly as a result of decreasing oxygen contents. A few exceptions from the general trend can be explained by petrographic composition and effects of weathering. Samples 2 and 4 have relatively high H/C ratios which reflect the high amounts of liptinite macerals as observed microscopically (Table 3). Sample 17 (low H/C ratio and high O/C ratio) plots in an area far from the other samples of similar

Table 4. Elemental composition, ash content and H/C-O/C atomic ratios for feedcoals used in the vacuum pyrolysis experiments.

Sample	Elemental Analysis (d.a.f.)					Ash (dry)	Atomic Ratios	
	C	H	N	S	O		H/C	O/C
1	62.5	4.10	1.70	0.49	31.2	13.0	0.79	0.37
2	70.8	6.51	1.38	1.19	20.1	21.6	1.10	0.21
3	91.0	12.08	0.50	0.85	0.0	17.8	1.59	-
4	78.1	7.13	1.38	0.85	12.5	6.7	1.10	0.12
5	66.7	4.58	1.67	1.11	25.9	19.9	0.82	0.29
6	68.7	4.39	1.65	0.39	24.8	6.5	0.77	0.27
7	68.6	4.49	1.70	0.85	24.4	7.7	0.79	0.27
8	73.3	4.30	1.42	0.54	20.4	18.2	0.70	0.21
9	68.1	4.65	2.20	0.51	24.6	8.4	0.82	0.27
10	71.4	3.58	1.62	0.31	23.1	10.7	0.60	0.24
11	77.2	4.84	1.01	0.39	16.5	25.5	0.75	0.25
12	76.2	4.63	1.60	3.66	13.9	8.3	0.73	0.14
13	85.9	6.09	3.20	1.00	3.8	55.0	0.85	0.03
14	87.9	5.57	3.47	0.34	2.8	12.0	0.76	0.02
15	85.2	5.41	2.48	0.62	6.3	12.8	0.76	0.06
16	85.9	5.04	3.85	0.99	4.3	10.3	0.70	0.04
17	75.0	3.28	3.60	0.50	17.6	6.2	0.52	0.18
18	88.7	4.72	1.76	0.36	4.5	8.7	0.64	0.04
19	93.2	4.81	1.27	0.45	0.2	13.2	0.62	0.002
20	90.6	4.65	1.92	0.45	2.9	27.0	0.62	0.02

rank. Petrographic examination of this sample had shown a high degree of oxidation as a result of weathering of the coal seam. Sulphur contents were found to be very low in most of the samples except in the coal from Eastern Canada (sample 12, Prince Mine, sulphur = 3.66%). Ash contents determined by proximate analyses were found to range between 6.2 and 55 wt%, Table 4.

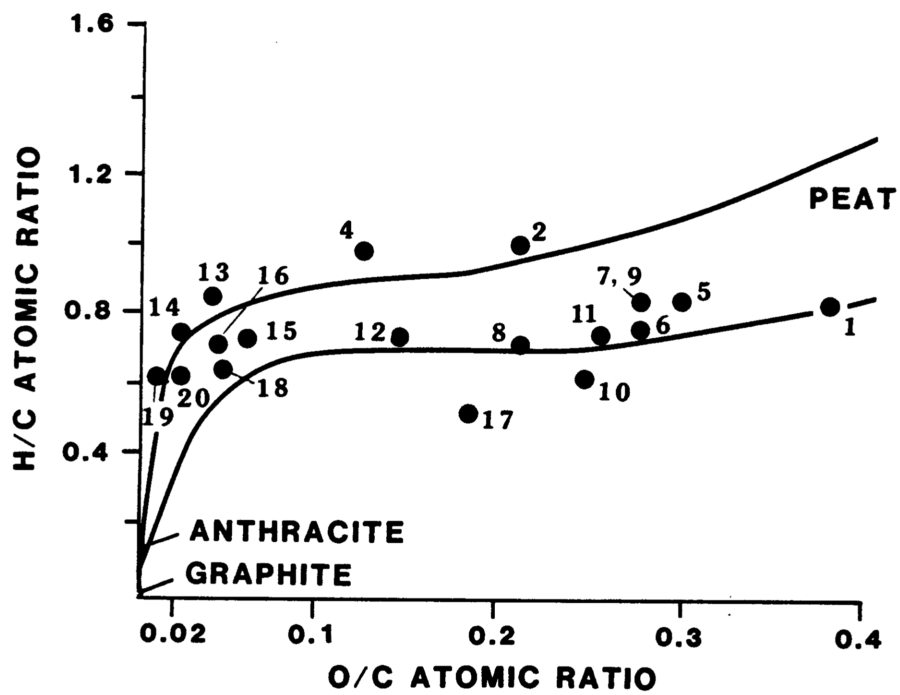

Figure 4. van Krevelen diagram illustrating H/C - O/C atomic ratios of feedcoals used in the vacuum pyrolyses experiments. Numbers refer to samples listed in Table 3.

Petrographic characteristics and conversion rates

Conversion rates were found to range between 14.6% in the low volatile bituminous coal (sample 20) and 70.2% in the liptinite-rich coal at the transition from lignite to subbituminous coal (sample 4). An extremely high conversion rate of 97.9% was determined for the handpicked resinite from Hat Creek (sample 3). The conversion rates decrease in general with increasing rank of the coal (Table 3). At the same rank level the conversion rates appear to be affected particularly by the liptinite contents (samples 2, 3 and 4) and samples 7 and 8.

Conversion rates obtained from the vacuum pyrolyses experiments were correlated with chemical and petrographic properties of the feedcoals (Hébert, 1986). A good correlation was observed with chemical parameters such as the H/C atomic ratios, volatile matter contents and calorific values. For the petrographic characteristics (reflectance and maceral contents) the best correlation to conversion rates was found by using a method originally developed by Mackowsky and Simonis (1969) for the prediction of coke strength. In this method Mackowsky and Simonis (1969) concentrated macerals of various ranks, determined the volatile matter contents and then calculated a correction factor based on the percentage of liptinite macerals present.

The final equation:

$$X_T = \text{Vol. \% Vitrinite} \times \text{Corr}_{Vi} + \text{Vol.\% Liptinite} \times \text{Corr}_{Li} + \text{Vol. \% Inertinite} \times \text{Corr}_{In} + \text{Del}$$

represents the calculated volatile matter of a coal based on maceral group contents corrected for rank level ($Corr_{Vi}$, $Corr_{Li}$, $Corr_{In}$) and liptinite contents (Del). The calculated volatile matter contents of the feedcoals using the above method matched very closely the values determined by proximate analyses (Hébert, 1986). The correlation of calculated volatile matter contents with conversion rates is shown in Figure 5. The curve has a high correlation coefficient of r = 0.997 and is valid for a reflectance range from 0.30 to 2.71% (lignite to semianthracite).

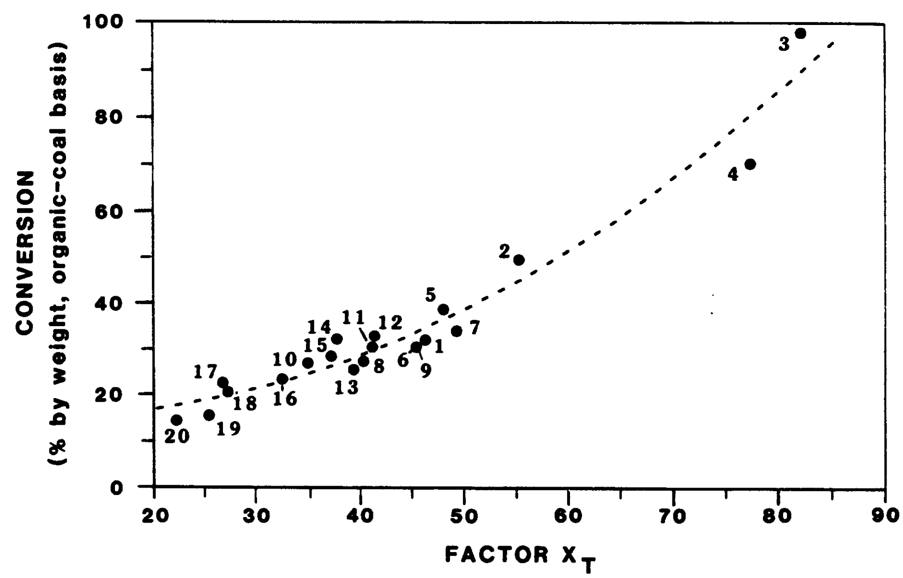

Figure 5. Correlation of conversion rates and calculated volatile matter (X_T) calculated from maceral group analyses and rank (Mackowsky and Simonis, 1969), modified from Hébert (1986). For definition of X_T see text.

CONCLUSIONS

1. *Hydrogenation*

Feedcoals. Petrographic and elemental analyses indicated a rank range from subbituminous to low volatile bituminous coals. Maceralanalyses showed wide variations in maceral contents at each rank level.

Conversion. The best conversion rates were determined for reactive-rich, subbituminous and high volatile bituminous coals. At each rank level there is a strong relationship between the rate of conversion and petrographic composition of the feedcoal with the highest conversion rates determined for the coals rich in reactive macerals. In hydrogenation, high volatile A bituminous coals appear to be superior to subbituminous coals, because they tend to achieve acceptable conversion rates requiring less amounts of reactive macerals. From the preliminary results it appears also that low volatile bituminous coals with substantial amounts of inertinite macerals can be hydrogenated successfully.

1. *Vacuum Pyrolyses*

Feedcoals. Petrographic and elemental analyses indicated a rank range from lignite to low volatile bituminous coal. Maceral analyses showed wide variations in maceral contents, particularly in the lower rank ranges. Three samples were characterized by anamolously high contents of liptinite macerals. One pair of samples represented a vitrain layer and a channel sample from the whole seam.

Conversion. Best conversion rates were determined for the liptinite-rich lignites and subbituminous coals. Conversion rates decrease in general with increase in rank. Conversion properties of the coals were found to correlate best wih petrographic characteristics, volatile matter contents and H/C-atomic ratios, in that order.

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PRESENT AND FUTURE TRENDS IN THE COKING COAL MARKET

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Introduction

The projection of trends and the use of instrumentation like a crystal ball is risky at the best of times. The 1980's and 1990's appear to be a threshold period for advancing technology in most industries including the iron and steel industry. I am going to go out on a limb today and suggest some of the trends that we can expect to see in iron making during the next decade and how these will affect the metallurgical coal market. This will be an interested observer's view and nontechnical as I do not have the background to talk in other than a general way.

Trends in Blast Furnace Technology to 1988

During the past ten to fifteen years, blast furnaces have become much larger than in the past. Typically furnaces built in the fifties and early sixties had hearth diameters of 28'-30' and working volumes of 40,000 - 50,000 cubic feet. Newer furnaces have been built at 40-45 foot hearth diameter and working volumes in excess of 100,000 cubic feet. The reasons for the size increase is economy of scale, to reduce the cost per ton of hot metal.

The increase in blast furnace size has led to a demand for higher quality cokes. The ironmaker cannot look just at mechanical strength of the coke any longer but must also look at strength maintenance during process. Coke serves three basic purposes within the blast furnace. Firstly, it provides energy through partial combustion. Secondly, the partial combustion gas is the reductant to reduce iron oxide to nacent iron. Thirdly, it provides permeability for gas flow and metal and slag flow. The blast furnace is a counter current reactor where the hot gases which create a reducing atmosphere move upward and the liquid iron and slag percolate downwards. If you were to visualize a blast furnace, you would see layer upon layer of material (the burden). These layers will alternate between iron ore, coke and sinter. As the layers move down through the furnace, heating and partial combustion of the coke take place to produce carbon monoxide which is the reductant gas. Porosity of the burden is of paramount importance as good gas percolation is required to achieve full reduction of the iron ore and maintain uniform heating across the furnace to avoid damaging furnace refractory. The ore and sinter are relatively fine averaging 0.5 inches. The coke is much coarser averaging 2.2 inches and provides the porosity for good gas flow. As the process proceeds, carbon is continually stripped from the coke and the weight of the burden continues to increase. The coke must maintain competency. If it weakens and breaks up, porosity is lost and furnace efficiency is reduced.

As the size of blast furnaces has increased, the demand for coke of high consistency and quality has also increased. The ironmakers today are asking not only about the mechanical strength of the cold coke but also the coke strength after reaction or CSR.

CSR has become a critical parameter in evaluating component coals in a coke blend. Coke occupies more than 55% of the blast furnace volume and about 75% of the blast furnace problems are related to coke. Many traditionally acceptable coking coals have reduced value when CSR is considered. There is a lot of research work at present to establish the factors which determine CSR. One common factor to effect the CSR, appears to be the acid/base ratio of the coal ash chemistry. Eastern Canadian and U.S. marine environment coals are generally higher in basic ash components than the western fresh water deposition coals. The eastern coals in general have lower CSR's than western coals. This has become a big plus for western Canadian and Queensland coals in the international metallurgical coal market.

Let us now look at coke production and the coke battery itself. Someone made the bold statement a few years back that the last coke battery had been built. Coke batteries are expensive to build and maintain, expensive to operate and have a lot of environment negatives attached with them, unless designed with good pollution control equipment. The capital cost of a million ton per year plant would be about U.S. $150 - 175 million. Most estimates put the cost of a coke plant at about 40% of the total ironwork's cost. Byproducts produced have to either be used in process somehow or be sold, usually at a loss, for secondary processing for neptheline, etc. In North America, we have been in a holding pattern for the past decade on new coke battery construction. However, the emerging economic powers in Asia and South America are still building coke plants as is Germany. The most recent and tallest (8 metre), was erected in Germany in 1987.

A Battelle Institute Report, Coke Making 1990, March, 1983 had the following table of average ages of plants worldwide.

COKE PLANT AGE	1981	1985	1990
Less Than 10 Years	42%	34%	26%
10 - 25 Years	40%	48%	54%
Over 25 Years	18%	18%	20%

We are rapidly approaching 1990 and the majority of the coke plants are reaching middle age. The table begs the question of what will we do for coke or to replace coke in the ironmaking process.

I believe that the answer will be partial replacement of coke within the blast furnace. The total replacement of coke is a technological challenge for the turn of the century. Initially we will be looking at supplements for coke shortage and more efficient coke usage. Between 1967 and 1980 the Japanese industry dropped its blast furnace coke ratio from 500 kilograms per tonne of hot metal to 450 kilograms per tonne. That was a ten percent reduction. Most of that was due to improved blast furnace efficiency. Since 1980, the coke consumption has increased, however they were able to use some inferior quality coals to maintain cost reductions. Japanese coke makers were able to use poor or non-coking coals because of improved knowledge and tight control over blend strategies.

During the late 1970's and into the 1980's, the Japanese and Europeans have been working with pulverized coal injection (PCI) to reduce coke consumption by direct carbon replacement. The process is not new. Experiments were conducted in the 19th century in Europe and in Russia and the United States in the fifties. The simplest fuels for injection are natural gas, tar or oil. However, due to thermal balancing in the blast furnace, there is a limit on how much can be injected in the tuyere area. In the case of coal, it can be injected at a higher rate on a carbon weight basis. Each hydrocarbon has a cooling effect when injected into the tuyere zone. Coal has a relatively lower cooling effect. Therefore, coals are better fuels for PCI. The best coals are anthracites followed by low volatile bituminous coals. However, even lignite could be used. The limitation on injection is the carbon/hydrogen ratio and thermal balance. Theoretically 30-40% of the coke could be replaced by PCI. In

Japan in 1980 there was little PCI in use. By 1987, PCI represented about 16% of total fuel consumption. PCI will continue to grow in importance.

If we think back to battery age trends, we can foresee a time when there will be a growing coke shortage. PCI can supplement the coke requirement and therefore can be considered as a stop gap measure to maintain ironmaking capacity during coke shortages.

I believe that the longer term effort will be the elimination of coke from ironmaking technology. By longer term, I am talking thirty to fifty years hence, so the metallurgical coal business will continue for quite a while yet. The new blast furnace technologies will still require coal for reductant but may use electricity or electricity and fossil fuel as the primary energy source. There are quite a number of processes and designs being investigated around the world at the present time. An excellent article on the research can be found in Ironmaking and Steelmaking, 1987, Volume 14; No. 2. The economic analysis therein points out the high cost of coke making facilities and why ironmakers are trying to move away from coke.

Whichever of these technologies comes to the fore, it is a good bet that it will start as a hybrid to the present blast furnace technology with coke playing a decreasing role.

Trends

So far I have talked generally about technological changes and blast furnace enhancements. We should now translate these into trends that would be expected in the metallurgical coal markets.

We would first look at the motivation of the ironmaker. His business has become increasingly competitive. Domestic producers in the industrialized world did not have to worry about imports twenty and thirty years ago. Today, newly industrialized countries are building facilities with capacity much in excess to domestic requirements. They are looking for export markets. In the United States, we have seen protective tariffs and quotas introduced to protect American production. We hear a lot about G.A.T.T. and know that eventually there has to be a system of freer trade worldwide for a healthy world economy. For a producer to survive in an open environment, he must produce a good quality product at a competitive price. That is the motivation of the ironmaker and will be the basis of trends in the metallurgical coal market.

1. <u>Quality Control</u>

I have talked about the trends to larger blast furnaces. They require consistent, strong coke. As coking coal producers, it is no longer enough to know the proximate analysis of our product and the F.S.I. We must also know and monitor the petrographic composition, thermal rheology, mineral ash analysis and carbonization characteristics. We have to become well versed in ironmaking technology in order that we can spot pending problems. Ironmakers do not like surprises. Statistical analysis of quality will become the order of the day. One customer has said to me he is not so much worried about the ash level he receives in the product but does worry about variance in ash from shipment to shipment. We will therefore, have to increase our knowledge of our products in terms of both characteristics and variation.

2. **Coking Coal Requirements**

In the past, only agglomerating coals were considered applicable for the metallurgical coal market. The Japanese and others are working on formed coke processes which will allow them to utilize non-agglomerating coals in the coking process. This has some very positive implications for steam coal producers. There will be a redefinition and reclassification of coal resources.

On the longer term, research will continue on coal based iron making. The high capital and operating costs of coke plants will be the prime motivation. This makes it of paramount importance for coal producers to maintain an active interest in the developments occurring within the iron making industry. Such interest may mean the difference between market opportunities or lack thereof.

3. **Alternative Coal Markets**

The price of steaming coal is also rising. I was talking to an Asian buyer who purchased about seven million tonnes in 1988. He expects that his companies' requirements in 1995 will be fifteen million tonnes and by the year 2000, they will require twenty-four million tonnes per year. His company is the main energy supplier for one of the emerging nations in Asia. His estimates probably preclude recessions or economic corrections, however there will be a massive demand for steaming coal in Asia. Improvement in prices will reflect that demand and represent excellent market opportunities.

Research is being conducted around the world on coal liquification and coal derived syncrudes. Energy prices have gone through a major value correction during the

1980's. We do know, however, that crude oil reserves are much lower than coal reserves so that at some period during the next couple of decades, the crude oil price will support synthetic crudes from coal.

4. **Environmental Considerations**

Environmental problems of air pollution and the potential of a greenhouse effect, hang over all fossil fuel utilization at present. In terms of sox and nox emissions, technology is in place now to reduce and eliminate those problems. Carbon dioxide emissions, however, are not solvable at this time. We should start by putting the problem in perspective. Gases produced from coal burning and steel production represent about five percent of the total man-made radiative gases which contribute to the greenhouse effect. That is to say that coal usage is a minor contributor to the problem. We in the coal industry, must spend more time educating the public on that point. In terms of acid rain, as mentioned, the technology is now available. It will be installed in new and existing plants. Both contributors; sox and nox can be reduced by about 90% now, so the acid rain problem can and will be eliminated over the next decades with no major impact on coal.

There is a conceptual electric melting process for iron being considered at the moment where coal and ore are heated in reduction unit. The off gases from the unit become fuel for an electric generation which supples current to run an electric melting unit, which melts the reduced iron to form hot metal. This simple concept would provide iron cleanly and efficiently. The combined cycle coal gasification process being investigated by electric utilities works on simple concepts as well to provide safe, clean energy. That is where I believe coal usage will be heading.

Conclusions

The metallurgical coal industry is beginning a period of change. The distinct differences between metallurgical and thermal coals will not prevail due to new technologies. There will be a significant overlap of the two and a redefinition of coal types, markets and resources.

The ironmakers are looking for ways to eliminate the high costs of coke plants. They are looking increasingly for quality and consistency standards. They are also looking for lower cost raw materials. For coal producers who do their homework and watch the market, there will be new opportunities. For those producers who do not, I will leave that to your imagination.

INFLUENCE OF GEOLOGY ON CSR (COKE STRENGTH AFTER REACTION WITH CO2)

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ABSTRACT

Although drum strength has historically been the coke quality parameter, more recently, coke reactivity and strength after reaction with CO_2 have become the principal criteria by which coals are selected to make blast furnace coke. Typical western Canadian medium volatile, Inertinite-rich coking coals produce cokes that are among the world's best in this test. Vitrinite reflectances of 1.0 to 1.6%, Inertinite contents of >30%, alkalinity indices of ≤1.0, high ash-fusion temperatures >2700°F, 1500°C, and low fluidity, all appear to be contributing agents. As yet however, there is no universally applicable prediction formula.

INTRODUCTION

CSR, or coke strength after reaction with CO_2, has become the more important means of evaluating the quality of coking coal and of controlling blast furnace performance within Pacific rim steel-producing countries, and is now a principal criterion by which coals are selected to make blast furnace coke. The purpose of this paper is to describe the various methods used to predict CSR and from them determine the geological factors which appear to influence CSR values.

In the late 1960's, Nippon Steel Corporation deliberately cooled and dissected three blast furnaces in an attempt to better understand the physical and chemical changes that take place in the thermal transformation of coke during its passage through the furnace. On this journey, coke undergoes a reduction in size caused by mechanical and thermal stresses, and gasification by CO_2 and H_2O. There is at the same time a decrease in drum strength, and an increase in reactivity. Cokes which have high reactivity to CO_2 have low CSR's, and vice versa. Cokes that have inherently higher drum strengths and lower reactivity to CO_2 are therefore desireable (Figure 1), and it has been demonstrated by NSC that to maintain trouble-free operation at large blast furnaces, CSR's should be maintained above 57 (Ishikawa, 1982).

A relationship between coal rank and the reactivity of coke to CO_2 (measured by weight loss), has been documented in studies using small numbers of samples (Schapiro & Gray, 1963; British Carbonization Research Assoc. 1978). These studies showed that

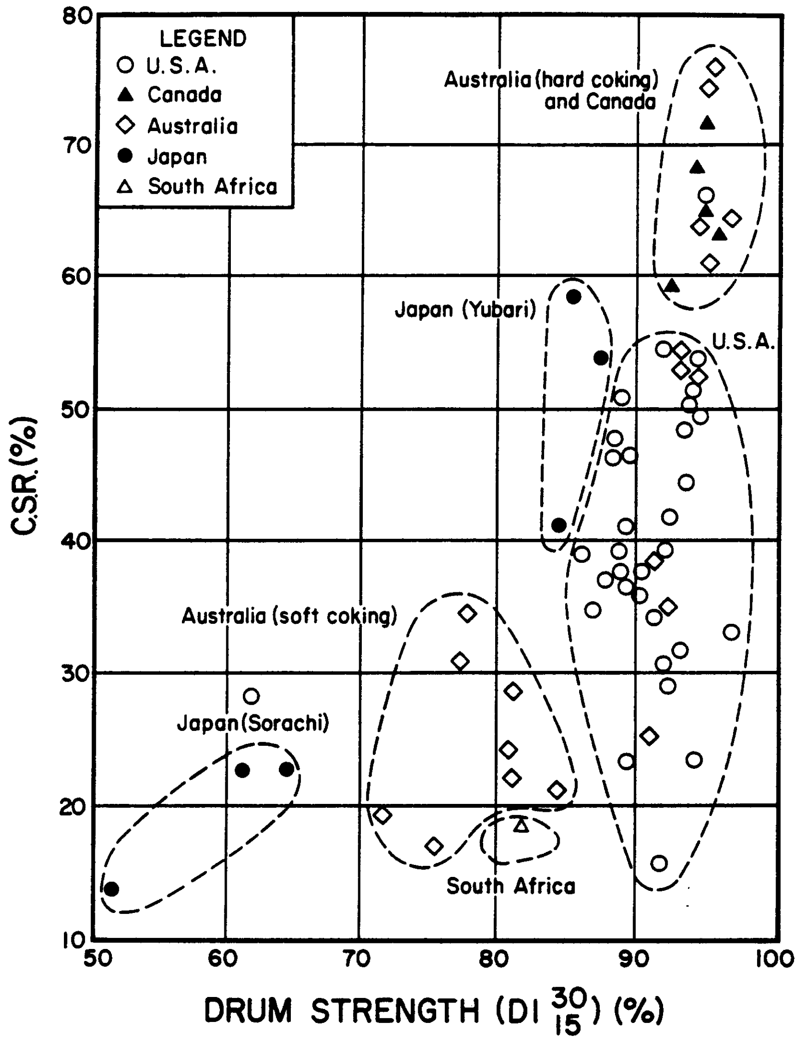

Figure 1. Relationship between CSR and Drum strength D30/15 (Ishikawa, 1982)

cokes from high volatile- and low volatile-coals suffered greatest weight loss, and that those from medium volatile coals were the least reactive. Subsequent coke microscopy studies have correlated the reactivity to the texture of the coke; fine mosaic carbons (from high volatile coals) and ribbon-like carbons (from low volatile coals) are more reactive than coarse-mosaic carbon forms (from medium volatile coal). Although a correlation between coke reactivity and coal rank had been established for a number of years prior to the advent of strength tests on reacted coke, a rigorous investigation of the geological factors which affect coke reactivity and strength from the perspective of the parent coals was not done until the 1980's.

COKE REACTIVITY & STRENGTH TEST

In the Nippon Steel Corporation (NSC) CSR test, 240 kg of wharf coke is reduced to 10 kg which is then crushed and screened

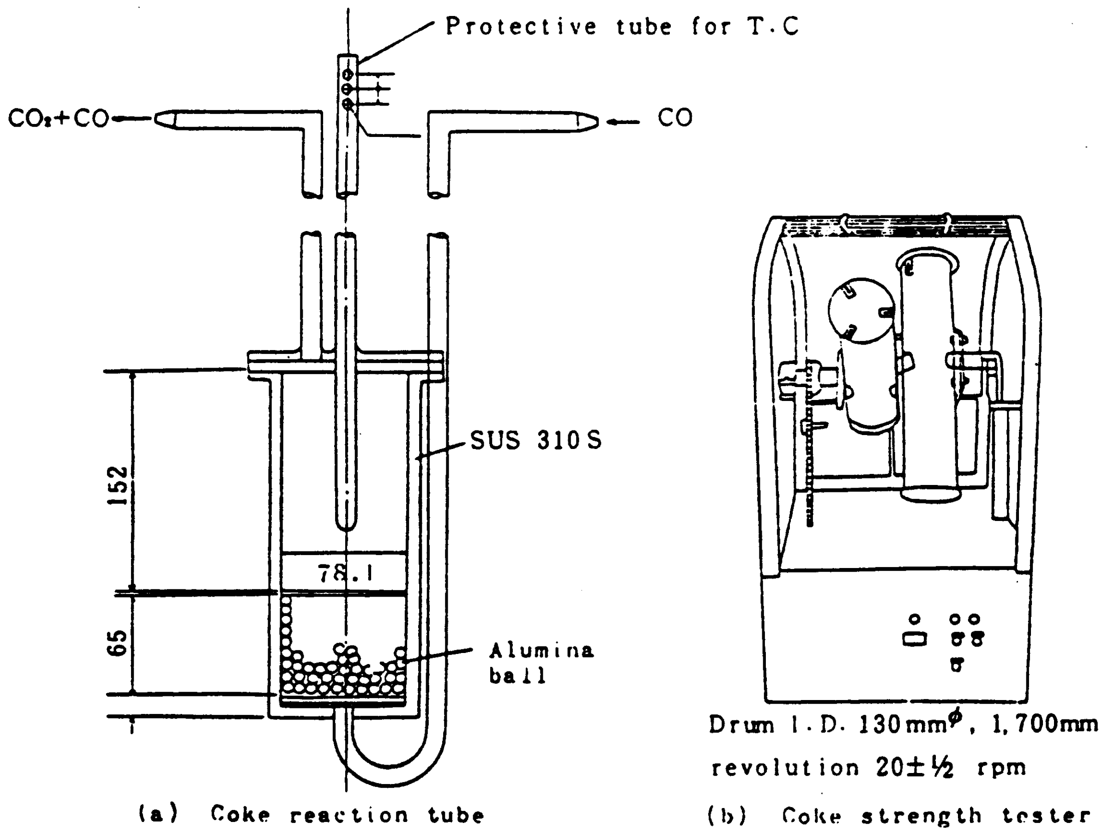

Figure 2. Schematic of CSR apparatus.

to 20±1 mm. A 200 g sample of this coke is placed in the reaction tube, and after heating to 1,100°C in N_2 gas flow, a switch-over to CO_2 is made. The reaction is sustained for two hours. After cooling and weighing the reacted coke to determine reactivity (CRI), a strength test is performed in an I-shaped drum. After 30 minutes at 20 rpm in the I-shaped drum, the coke is screened on a 9.52mm sieve and the weight of the material remaining on the sieve is measured for CSR. The apparatus is shown diagrammatically in Figure 2.

The following values are quoted:-

$$CSR = \frac{\text{Weight of residue on sieve after reaction}}{\text{Weight of material after reaction}} \times 100$$

$$CRI = \frac{\text{Amount of weight change}}{\text{Weight of material}} \times 100$$

The Kobe Steel method for determining coke reactivity is precisely the same as NSC's. However, for the strength test, Kobe Steel uses an I-shaped drum that is only 700mm in length (versus 1700mm), in which the reacted coke is tumbled for 20 minutes at 30 rpm and then screened on a 10mm sieve. As a result of the modified equipment, Kobe Steel's Reaction Strength Index (RSI) is slightly different from NSC's CSR value. To obtain the equivalent RSI, add 10 units to a CSR value (RSI = CSR+10).

CSR PREDICTION TECHNIQUES

Because determination of coke reactivity (CRI) and CSR (or RSI), is an expensive, time-consuming, two-stage procedure, in which the coal must first be carbonized, and the resulting coke tested, several prediction techniques have been developed using charaterstics of the parent coals. However, the usefulness of these prediction methods has been questioned (Valia 1989), and as yet, there is not a universally acceptable prediction technique.

NIPPON STEEL CORPORATION METHOD

In 1980, NSC published a model for predicting CSR (Hara et al.), based on vitrinite reflectance and Inertinite content (Figure 3). The NSC diagram shows that CSR increases with increasing reflectance up to a value of about 1.4%, and that for

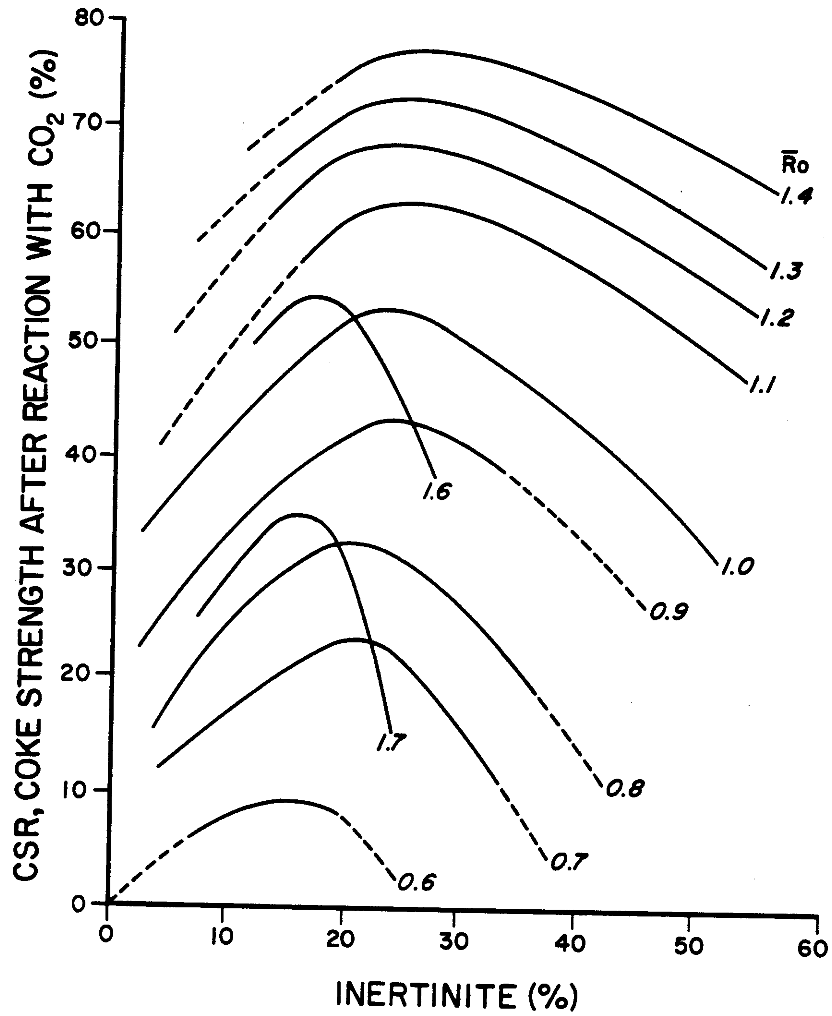

Figure 3. NSC's 1980, CRS-prediction model.

each reflectance level, the highest CSR's are obtained at an optimum inertinite content. It also shows that with increasing values of vitrinite reflectance, the resulting cokes will have lower CSR's.

Although this diagram suggests that western Canadian coking coals produce high-CSR cokes, it also implies that at any reflectance level the optimum CSR values would be produced by coals with inertinite contents of 15-25%, typical of Pennsylvanian-age coals.

Careful study of the diagram using a variety of coals of different rank and provenance confirms that it cannot correctly predict the CSR of cokes based only on petrographic data. For example, the Australian coal, Blackwater, from south Queensland, has a vitrinite reflectance of 1.04%, and an inertinite content of 39.0%. According to the NSC prediction such a coal should produce a coke with a CSR of about 50. The actual value of CSR for this coal is 32 (NSC, 1982).

Later studies by NSC have suggested that deviation from the predicted pattern of Figure 3, is caused by the catalytic nature (chemical composition) of the ash, and variation of coking properties, principally fluidity (Ishikawa, op cit., Sakawa 1982). In these studies, "refractory ash" enriched in acid oxides, Al_2O_3 and SiO_2, was less reactive than "catalytic ash" typically enhanced in basic oxides Fe_2O_3, CaO and MgO, or alkalis NaO & K_2O. The chemistry of coal ash is characterized by the "alkalinity index", where,

$$A.I. = \text{ash content (\%)} \times \frac{\text{mol (\%) of basic components in ash}}{\text{mol (\%) of acid components in ash}}$$

NSC subsequently indicated that calculation of CSR is by empirical equations from regression analysis, but they have not divulged the coefficient values.

KOBE STEEL METHOD

According to Kobe Steel's studies (Yoshida & Hoshino 1984), the factors which affect RSI are:-

1. Coke texture (a function of rank)
2. Chemistry of coal ash
3. Amount/size of coke pores (= maximum fluidity)

From regression analysis of parent coals Kobe Steel's prediction formula is:-

$$RSI = 70.9(\text{Romax}) + 7.8(\log \text{Max. fluidity}) - 89\left[\frac{Fe_2O_3 + K_2O + Na_2O + CaO}{SiO_2 + Al_2O_3}\right] - 32$$

BHP AUSTRALIA

Despite the Japanese studies, Australian researchers at BHP have produced another regression equation better suited to Queensland and New South Wales coals (Coin, Pers. Comm., 1985). The following equation of predicted-CSR versus measured-CSR on 52 coals and cokes has a correlation coefficient of 0.92.

$$CSR = 133.8 - 15.56*BI - 3.1*VM + 8.5*LMF + 0.22*INERTS$$

where, BI the Basicity Index, is $= \frac{Fe_2O_3 + K_2O + Na_2O + CaO}{SiO_2 + Al_2O_3}$

DISCUSSION

Data from the NSC prediction technique has been redrawn in Figure 4, with CSR as the independent variable, in a diagram that includes ASTM coke strength data. This figure shows that among coals that produce cokes of ASTM stability 50-60, typical U.S. coals (Inertinite contents of <25%) have CSR's of 50-63. In marked

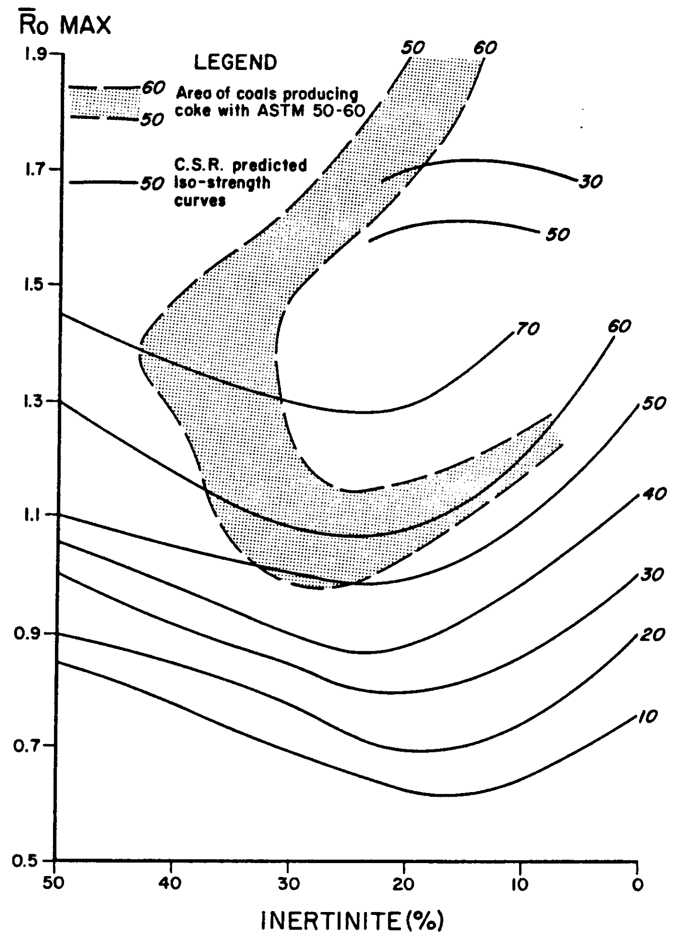

Figure 4. CSR prediction compared with coke strength data

contrast however, typical western Canadian coals (Inertinite contents of >30%) that produce the *same* strength cokes, have CSR's of 50-70+. In addition, coals strongly enriched in Inertinite (>45%), with vitrinite reflectances of 1.2% to 1.4%, and typically referred to as "weak coking" coals, have predicted CSR's equivalent to those from U.S. premium medium volatile coals. The figure also shows that the once-premium Pocahontas low volative coals have CSR's of 30-50, some 20 points lower than low-volatile Canadian equivalents.

Ishikawa's 1982 plot of CSR versus Drum Strength DI30/15 (Figure 1) confirms this interpretation. From his figure it can be seen that, U.S. coals with DI30/15's of >92 have CSR's of 15-55. In marked contrast, all western Canadian and some Australian coals with similar DI30/15's are shown to have CSR's of >59. The diagram confirms that for a blend of coking coals designed to produce a CSR in excess of 57, high-CSR Canadian and Australian coals will form the principal component, to which will be added small amounts of the lower-CSR coals. The so-called "weak coking coals" although individually very rich in Inertinite with low DI30/15's (<90), have good CSR's, and from the perspective of blending are superior to coals of higher DI30/15 but with low CSR's.

The Canadian coal industry can take some pleasure in reading that our coking coals are now seen to be superior to U.S. equivalents (Goscinski et al 1985), after decades of being subjugated by misunderstood "high semifusinite contents". But what are the underlying reasons for apparently similar cokes behaving so differently in reactivity tests? The principal differences between the U.S. coals and western Canadian coals are rank, maceral composition, and mineral matter type (Pearson 1980), which together explain most of the observed variations.

There is agreement between all researchers that reactivity correlates with coke texture, which in turn, is related to the rank of the parent coal. There is also agreement that elevated levels of base oxides act as catalysts in the reaction with CO_2. However, beyond this level of understanding, regression analyses dictate the inclusion of unlikely parameters in prediction formulae. For example, western Canadian coals are notorious for low fluidities, yet individually they produce cokes with some of the highest CSR's in the world. By contrast, the highly fluid U.S. medium volatile coals Pittston and Sewanee have CSR's of only 45 and 49 respectively. Does a low fluidity therefore correlate with a high CSR?

Higher fluidity, in general, correlates with lower carbon-bearing inertinite macerals, and more of the hydrogen-bearing reactive macerals, vitrinite and liptinite, together with a change of mineral matter from dominantly kaolinitic clays to calcite and pyrite. Inertinite-rich coals, with kaolinitic clay and quartz as dominant minerals, have refractory coal ash with basicity indices of ≤ 0.1. Inertinite-poor coals with pyrite (iron-bearing) and calcite (calcium-bearing) mineralogy, are enriched in the basic oxides, and have basicity indices of ≥ 0.35. Typically, Inertinite-rich coals have such an excess of refractory acidic oxides that high ash fusion temperatures are common (>2700°F, 1500°C). Among Inertinite-poor coals, there are sufficient basic oxides that ash fusion temperature are reduced (<2570°F, 1400°C). These observations show that fluidity, to some extent, correlates with an increase in the base/acid ratio (or basicity index).

Because NSC have shown that the amount of ash, as well as its chemistry, is significant, the alkalinity index is probably a better measure of the catalytic effect of coal ash than the basicity index. Figure 5, shows a contoured scattergram of twenty five Canadian and Australian coals plotted in terms of vitrinite reflectance and alkalinity index, where, A.I = Ash (%) x B.I., or,

$$A.I. = \text{ash content (\%)} \times \frac{\text{wt (\%) of basic components in ash}}{\text{wt (\%) of acid components in ash}}$$

Despite the limited data available, the diagram is an improvement over the original NSC diagram. It is reasonably accurate for inertinite-rich coals with alkalinity indices (AI's) of ≤1.0, but with only fair reliability for coals with AI's ≥1.0 and Ro's <1.3%.

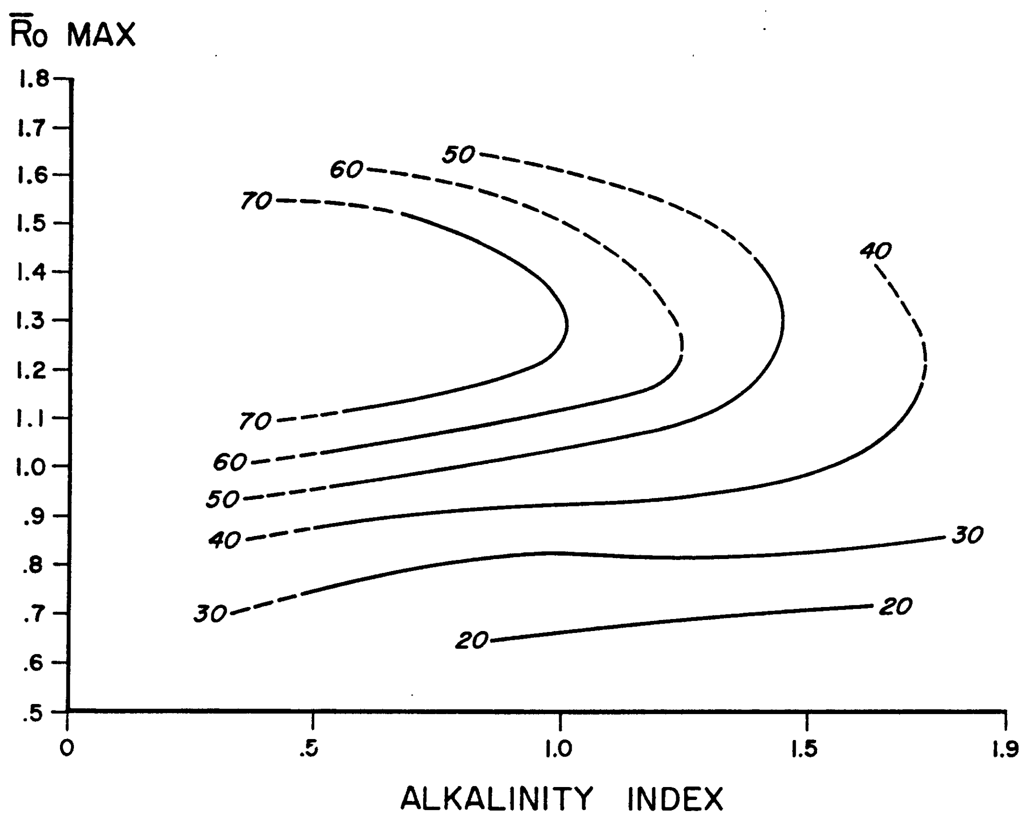

Figure 5. CSR prediction by RoMax, alkalinity index & ash.

Since the chemistry of the peatswamp environment, which ultimately controls the coalseam mineralogy and the hydrous nature of coals, is a function of pH, future research into CSR prediction may focus on a predictive technique using vitrinite reflectance, ash content, and a proxy for pH. The pH proxy could be, for example, the Hydrogen Index (or hydrocarbon generative capacity) of a coal, derived from RockEval analyses.

CONCLUSIONS

1. Correlations exist between coal rank and coke reactivity, and in a general way this can be used to predict CSR.

2. Coal mineralogy, and specifically the alkalinity index of ash provides information on the catalytic or refractory nature of chemical constituents in the ash, and can dramatically change a rank-only prediction of CSR.

3. A negative correlation may exist with Gieseler fluidity, such that reduced fluidity imparts higher CSR's. Why this should be so is not fully understood.

ACKNOWLEDGEMENTS

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IN-SEAM COAL QUALITY VARIATIONS IN FOOTHILLS/MOUNTAINS COALS OF ALBERTA

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ABSTRACT

Detailed in-seam coal quality profiles (ash and sulfur mainly) have been constructed for economic seams within the Foothills/Mountains coals of the Lower Cretaceous Luscar Group, lower Paleocene Coalspur Formation and the upper Paleocene Obed-Marsh coal zone. Vertical and lateral in-seam variations can be very wide, but in a mine setting, can be capitalized through selective mining and stockpiling. These same variations should be documented and carefully evaluated in deriving a depositional environmental model.

The Luscar Group coals were evaluated at the Smoky River mine, at Grande Cache, and for sulfur show only very slightly elevated values near the top and base of the No.4 and 10 seams (up to 0.6%, dry basis, db). Ash variations are related to water-lain clastic partings and inherent (plant derived) mineral matter content. Both seams show major water-lain clastic facies changes that support a proximal-coastal swamp interpretation. Inherent ash contents are generally low (<10%, db), except in intensely sheared zones, where values generally increase to twice the norm.

The Coalspur Formation coals have the lowest sulfur values encountered (0.1-0.3%); however, values can be elevated up to 0.5% at the seam top, base and below major partings. Ash in these coals is controlled by volcanic ash partings, water-lain clastics and inherent mineral matter, all of which can be related to the inferred alluvial plain environment of deposition. Water-lain clastics are generally thick enough to remove during mining and the inherent ash contents are moderate (10-20%,db). The presence of thin, non-removeable volcanic ash partings can raise the "as mined" ash content another 5-10%.

Sulfur contents within the alluvial plain derived Obed-Marsh No.1 seam is typically low in the mid-seam position and elevated at the top and basal positions. Sulfur values from a single location of the No.2 seam, were very high near the top of the seam. Inherent ash content for the No.1 seam is generally low (<15%, db) except near the seam top and base. The in-seam profiles can be related to a generalized depositional geochemical model.

INTRODUCTION

From an engineering or mining perspective, coal is sometimes viewed as a homogenous material in terms of its quality characteristics. It is often felt that a bulk sample or a large enough test pit will characterize the coal quality variations for a given deposit. This study shows that coal is a highly heterogeneous material in terms of its quality and great care must be taken in characterizing its quality. A correct and ongoing evaluation of using vertical profiling can provide better quality control, saving millions of dollars in mining costs. A thorough understanding of in-seam quality variations and controls, is also crucial in deducing an inferred depositional environment for the coal.

This paper describes preliminary studies to document and explain in-seam coal quality variations within the Luscar Group, Coalspur Formation and Obed-Marsh coal zones. Questions such as ... what are the in-seam coal quality variations, what factors are the coal quality variations seen related to and controlled by, are they systematic, and can we predict them? are addressed.

Some preliminary work on in-seam coal quality variations has been done in the Kootenay Group in southern Alberta (Macdonald, et al., 1987) and in the Gates Formation in the Cadomin-Luscar area (Langenberg et al. 1988). In the plains region, Demchuk and Strobl (this volume) have used vertical profiling to describe variations in the Ardley coal zone at the Highvale mine.

Coal quality variables can loosely be classified into two groups; those variables that were primarily controlled by the original depositional environment, and those variables that owe their variation to later burial history. This paper deals with the first group of variables, specifically ash and sulfur variations, as these are two of the most commonly monitored quality variables in coal mining.

Ash can be divided into three main groups; finely disseminated inherent mineral matter within the coal itself derived primarily from original plant material, discreet clastic partings transported and deposited in an aqueous medium (splay deposits, channels, etc.), and discreet clastic parting derived from air medium (volcanic ash). Sampling was generally undertaken so as to exclude visible partings, except for composite samples, so that the relative amounts of the three types of ash could be established.

LUSCAR GROUP COALS

INTRODUCTION

The Smoky River minesite at Grande Cache was chosen as an area to examine in-seam coal quality variations within the coal-bearing Gates Formation within the Luscar Group. Several pits were sampled to evaluate the No. 4 and 10 seams (appendix 1). Langenberg et al. (1988) has also examined coal quality variations within the Gates Formation coals in the Cadomin-Luscar coalfield.

ASH VARIATIONS

In-seam ash variations were examined within the No.4 and 10 seams at the Smoky River mine. The No.4 seam is thought to be approximately stratigraphically equivalent, though not necessarily time equivalent, to the Jewel seam in the Cadomin area by Macdonald et al. (1988). In-seam ash variations within the Jewel seam, at Cadomin, have been documented by Langenberg (1988) and show variations on a pit, and coalfield scale.

The No.4 seam at Grande Cache has very few partings north of the Smoky River and shows a marked argillaceous-facies change south of the river (figure 1, between Sections GC2 and GC6). Throughout most of the cross-section (figure 1) the base of the seam is characteristically very low in inherent ash (<6%, db). The central part of the seam consists of alternating very low (<10%) and low-ash (11-20%) correlative zones. The upper portion of the seam is consistently very low in ash, except for the uppermost 0.5 meters which becomes characteristically high in ash, due to interbedding with clastics.

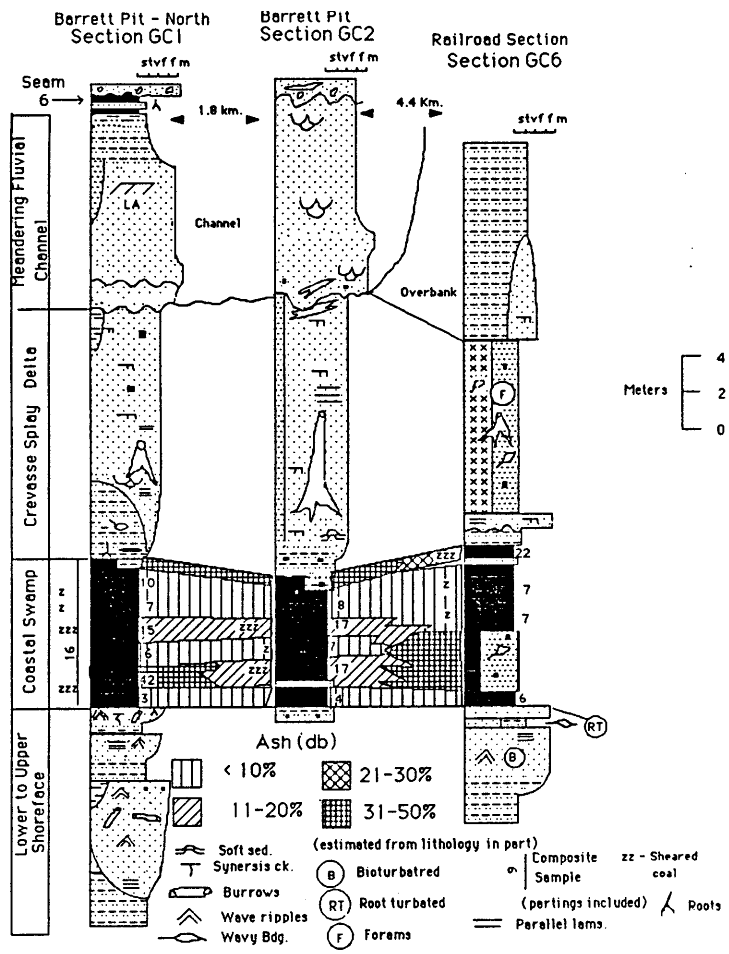

Figure 1. Stratigraphic cross section showing inseam ash variations within the No.4 seam and associated clastic depositional facies, Smoky River mine, Luscar Group coals.

The No.10 seam is much higher up stratigraphically in the Gates Formation and was sampled in two locations (figure 2). Figure 2 shows that this seam is characterized by a very low-ash basal zone, a central low-ash zone, an upper very low-ash zone and becoming interbedded with clastics in the upper half of the coal-bearing section (figure 2). The proportion of clastic material within the No.10 seam is seen to increase toward Section GC2.

Structural shearing and thrusting of coals into duplex and similar structures are believed to contribute to unpredictable ash contents, beyond what might be expected from the foregoing depositionally derived mineral matter. This structural influence has been documented in Kootenay Group coals by Bustin (1982) and Macdonald (1987) and for the Luscar Group coals in the Cadomin-Luscar coalfield by Langenberg (1988). This structural influence on ash content occurs through two mechanisms; 1) physical thrust repeating of partings into the coal, and 2) crushed and sheared coal being more susceptible to surface groundwater oxidation processes that reduce carbon content, leaving a relative enrichment in mineral matter. This process of ash augmentation is very apparent in the No.4 seam, in that most of the inherent ash is less than 10% (db), except those zones described as highly sheared (figure 1, multiple "zzz"'s).

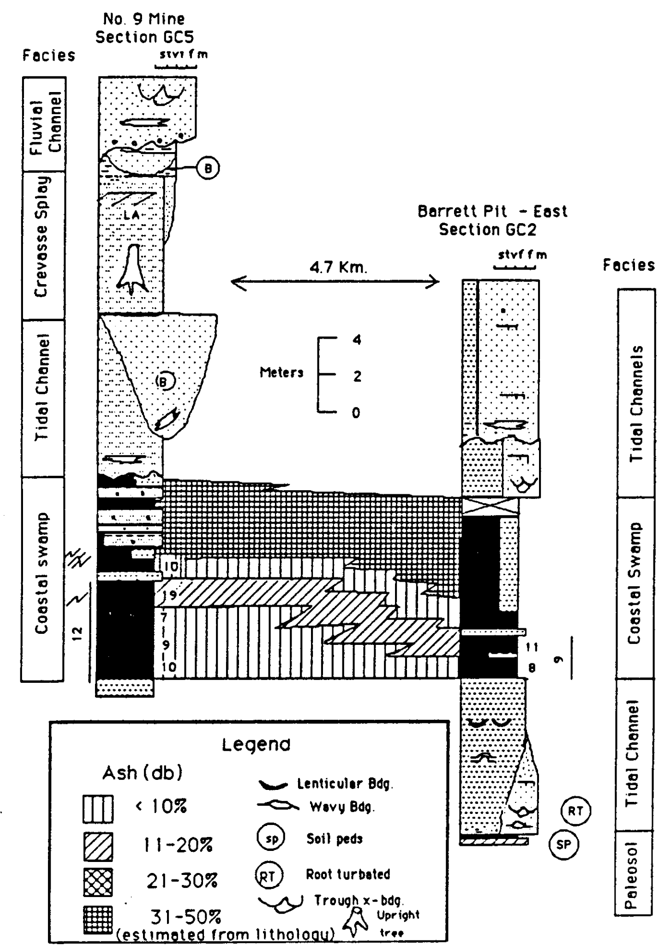

Figure 2. Stratigraphic cross section showing inseam ash variations within the No.10 seam and associated clastic depositional facies, Smoky River mine, Luscar Group coals.

From a mining perspective it is interesting to note that, for example the mineable portion of the No.4 seam at Section GC1 averages 16% ash (db, partings included), whereas the vertical in-seam inherent ash content varies from 3 to 42% (db). Similarly, the mineable portion of the No.10 seam at Section GC5 averages 12% ash (db), yet the vertical in-seam inherent ash varies from 7 to 19% (db). Being aware of these in-seam ash variations has helped mine operators to exploit these differences through selective mining or through blending at preparation plants.

SULFUR VARIATIONS

The in-seam sulfur content is relatively consistent, averaging 0.3% (db), throughout the central portion of the No.4 seam. Slightly higher values 0.4 to 0.6%, (db) are consistently found at the top and base of the seam. A channel sample at Section GC1 shows, however, that these slightly elevated basal and upper sulfur zones do tend to increase the overall "as mined" sulfur content to around 0.5% (db).

The sulfur values in the No.10 seam are also relatively consistent averaging 0.3% (db) in the central portion of the seam. Again, slightly elevated sulfur values (0.4%, db) are sometimes present near the top of the seam, though not at the base. In this seam the "as mined" channel sample shows a consistent sulfur value of 0.3% (db).

COAL-FORMING ENVIRONMENTS

Kalkreuth and Leckie (this paper) have suggested that Gates Formation coals formed behind active wave-dominated shorelines in areas undergoing subsidence related to shale compaction and dewatering. Macdonald et al. (1988), however, argues that in order for thick, relatively low-ash, low-sulfur seams to have accumulated, they must have done so several 10's to 100's of kilometers away from the active shoreline (or separated in time). Macdonald et al. (1988) further argues that the overall stratigraphic architecture of the Gates Formation suggests the thick coal-forming environments of the Cadomin area must have accumulated some distance landward. Langenberg et al. (in press) has suggested that the Jewel seam in the Cadomin area was deposited in an relatively dry, planar, low-lying forest swamp conditions, based on maceral and geochemical evidence.

The in-seam chemical profiles from this study suggest that the Grande Cache coals developed as planar, low-lying swamps in a more seaward proximal position, than the Cadomin coals. A more pronounced and abrupt facies change to water-lain clastics in both seams supports this. Coal-forming periods must have been relatively acidic, based on the low-sulfur, low-ash zones as suggested by the general geochemical model of Cecil et al. (1980). The presence of overlying brackish units, as described by Macdonald (1988), has probably resulted in the minor elevated sulfur values at the tops of the seams.

COALSPUR FORMATION COALS

INTRODUCTION

The Coalspur-Robb area was selected to study in-seam ash and sulfur variations within the Coalspur Formation coal zone. Several sections within the Luscar-Sterco Coal Valley mine and from roadcuts and abandoned pits in the Robb area were examined (appendix 1). Several coal seams occur within this area and informal names have been established along with regional stratigraphic correlations.

The sampling strategy employed was to attempt to provide at least one vertical in-seam profile showing ash and sulfur distributions for each of the main seams within the coal zone. In addition, several sections of the Val D'Or seam were sampled so as to not only provide vertical profiles, but also to provide in-seam lateral variations (figure 3). The sections sampled were generally undeformed, however, there are several areas in the Coal Valley region were the coals have been thrusted into complex duplex structures. Prediction of ash and sulfur in such areas, has not yet been studied.

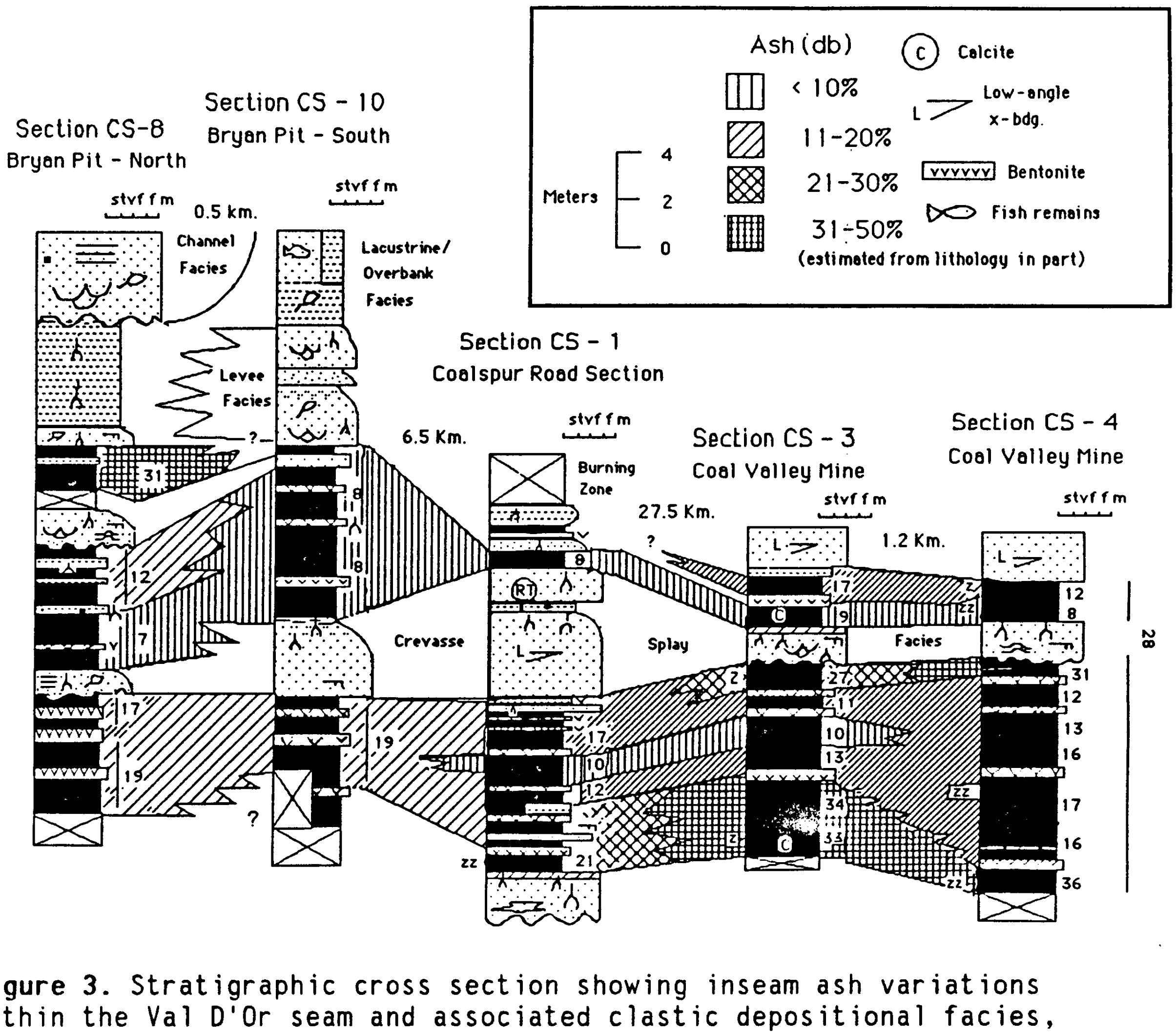

Figure 3. Stratigraphic cross section showing inseam ash variations within the Val D'Or seam and associated clastic depositional facies, Coalspur Formation coals.

ASH VARIATIONS

The majority of the discreet partings seen within the Val D'Or are bentonite, derived from volcanic ash beds (figure 3). The volcanic ash interpretation is supported by X-ray diffraction analysis performed on three of these beds which show them to be composed of montmorillonite, quartz and cristobalite. The clay size fraction of these samples is between 95-100% montmorillonite, and <5% illite and or kaolinite. These partings are generally thin (<10cm) and are generally not possible to separate during mining operations.

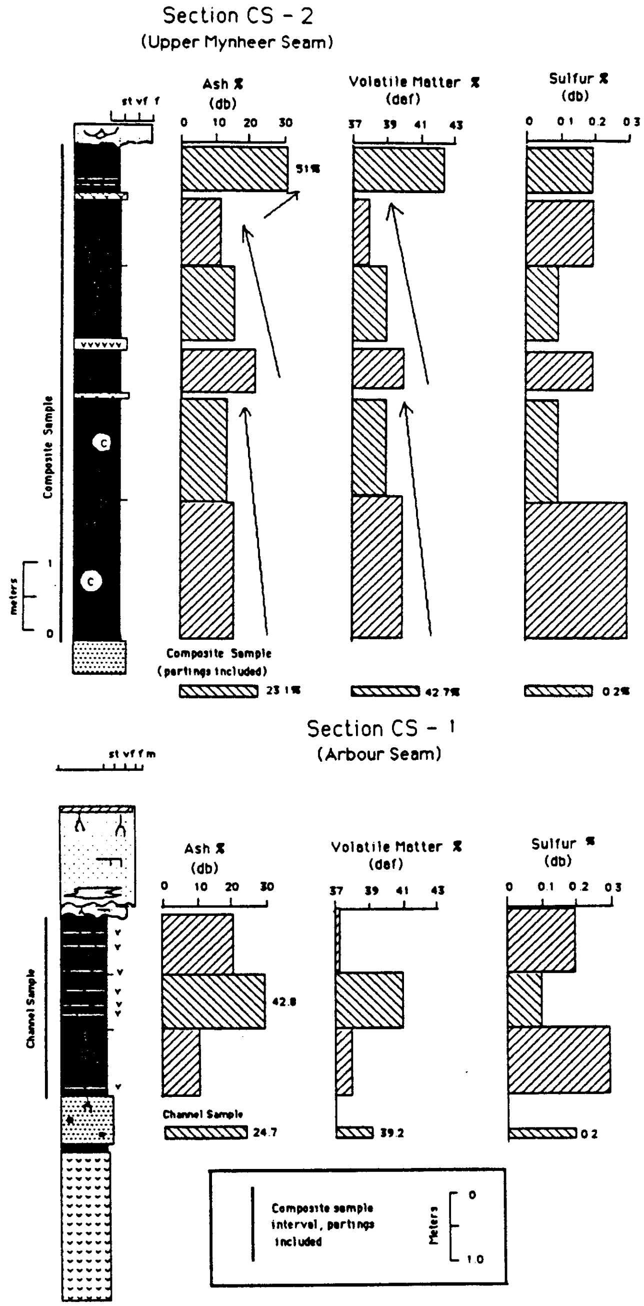

Figure 4. Vertical inseam ash and sulfur profiles for the Upper Mynheer and Arbour seams, Coalspur Formation coals.

The water deposited clastic partings are relatively few in numbers and, from a mining standpoint, are generally thick enough to selectively mine out. These partings are related to a crevasse splay facies associated with intermittent fluvial systems. The in-seam lateral ash variations shown on figure 3 are believed to be largely inherent plant derived mineral matter, as partings were generally excluded during sampling. It can be seen that this ash is generally moderate (11 to 34%, db) throughout much of the seam below the major crevasse splay deposit. Above this same splay unit, inherent ash contents are low to very low (<10%, db).

Again, from a mining perspective, channel samples that included the thin volcanic ash horizons, but excluded the thicker splay deposits show this "as mined" ash to be higher than the inherent ash. This is exemplified at Section CS-4 in which the inclusion of the six volcanic ash beds nearly doubles the inherent ash values to give a relatively high "as mined" ash content (figure 3, 28%, db).

Vertical in-seam ash distributions within the Upper Mynheer seam display two cycles of decreasing-upward inherent ash values (figure 4). The Upper Mynheer contains five volcanic ash partings, generally less than 10cm thick each. The Arbour seam, sampled along the Robb highway roadcut, contains up to seven thin volcanic ash horizons (generally less than 5cm). When all of these partings are taken together to form a composite "as mined" channel sample the Arbour seam has an ash content of 24.7% (db, figure 4). The vertical in-seam, inherent ash content varies considerably, with a very high-ash zone present near the middle of the seam and a moderately low ash zone near the base (figure 4).

The Silkstone or Wee seam shows a characteristic reduction in inherent ash upward toward the center of the seam, and an increase again near the top (figure 5). All of the inherent ash values are less than 20% (db), and even when the two volcanic ash partings are included to form an "as mined" channel sample the ash content is only 15.7% (db, figure 5). The McPherson seam was sampled at an abandoned pit above the town of Coalspur (Section CS-9, figure 5). This seam contains one major clastic crevasse splay partings, and six thin volcanic ash partings (each less than 5cm). The splay deposit divides the seam into an upper and lower units, both having generally low inherent ash values (<10%, db). The upper seam has a composite "as mined" ash content (partings included) of 13%, while the lower has a composite of 22% (db, figure 5). The higher composite values for the lower seam are related to the slightly more numerous and thicker volcanic and clastic partings.

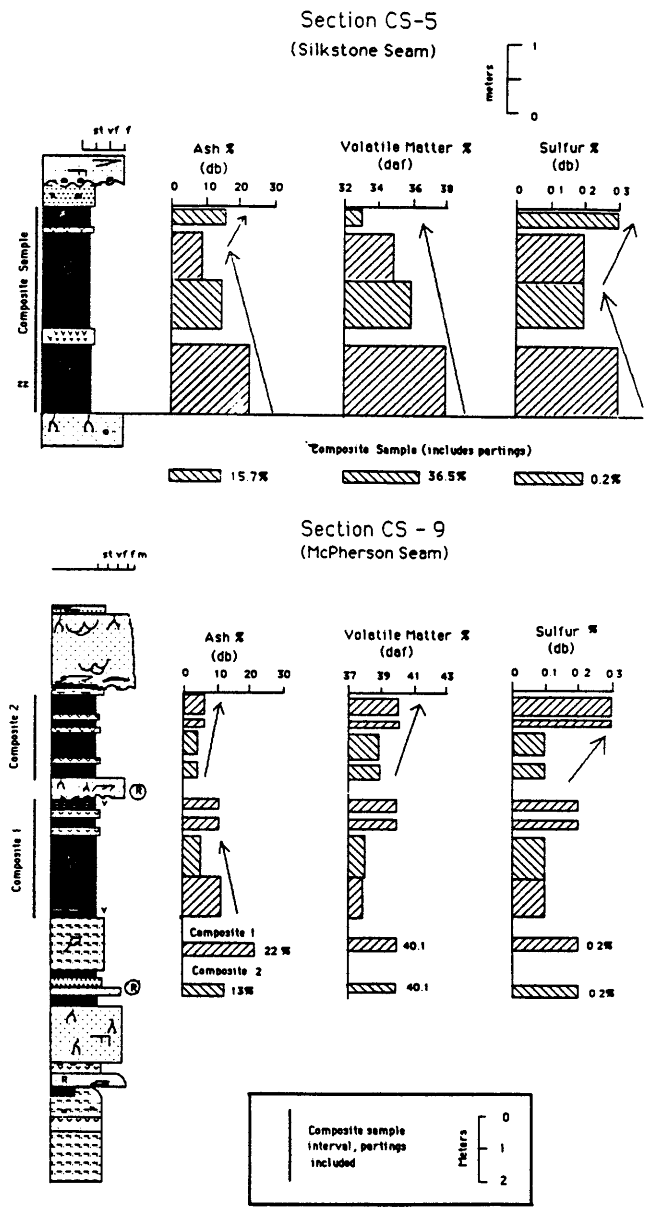

Figure 5. Vertical inseam ash and sulfur profiles for the Silkstone and McPherson seams, Coalspur Formation coals.

SULFUR VARIATIONS

Sulfur variations within the Val D'Or seam show a complex pattern of vertical and lateral in-seam variations (figure 6). Overall, the Val D'Or contains some of the lowest sulfur values encountered in this study, with most of the seam containing 0.1 to 0.2% (db) sulfur. Relatively "higher" values (i.e. > 0.3%, db) are commonly found at the top and base of the seam, and below the major crevasse splay parting.

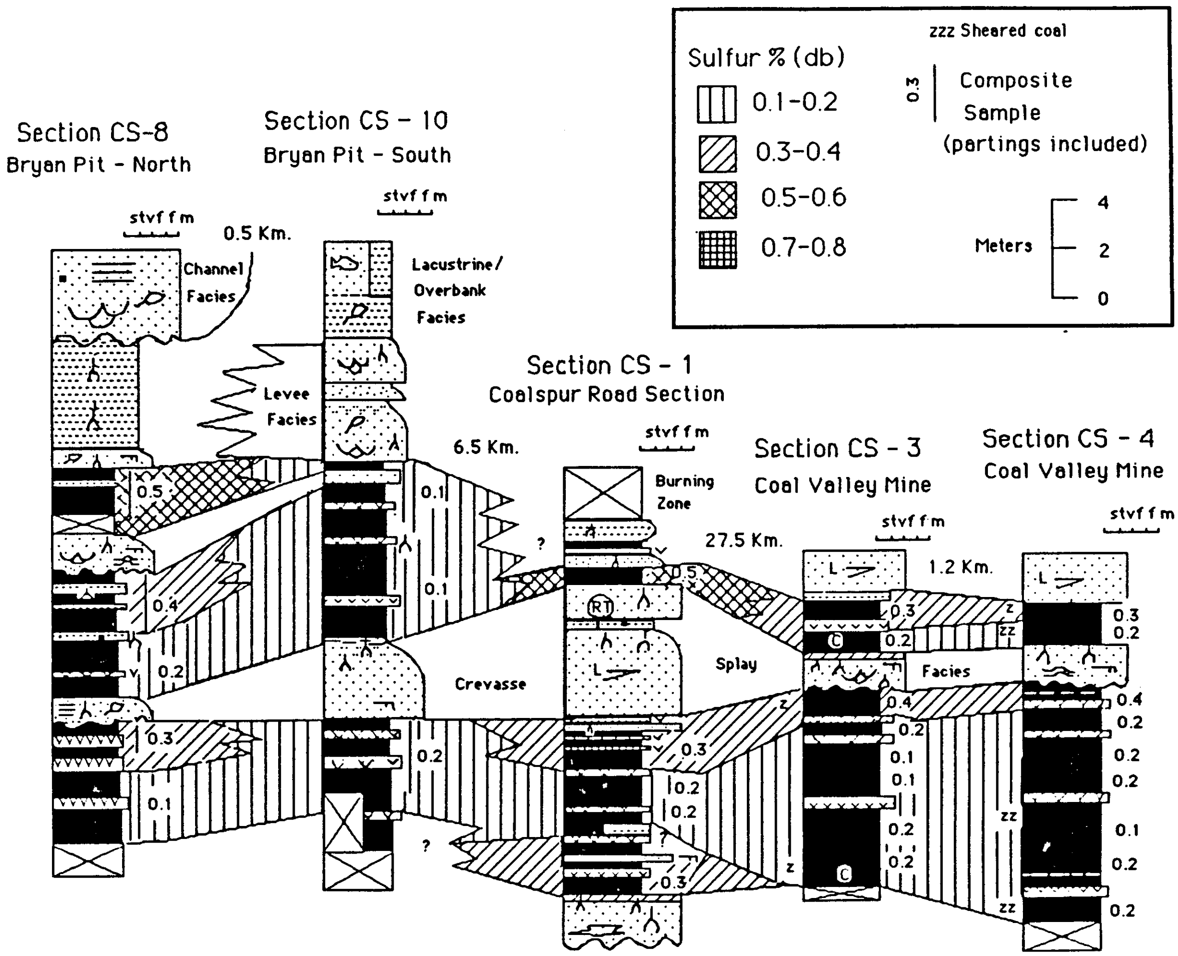

Figure 6. Stratigraphic cross section showing inseam sulfur variations within the Val D'Or seam and associated clastic depositional facies, Coalspur Formation coals.

In-seam sulfur within the Upper Mynheer seam is less variable than in the other seams with no values above 0.3% (db, figure 4). Sulfur values follow ash contents, to some degree, with increasing sulfur related to increasing ash. An "as mined" composite sample, that included partings, shows a sulfur value of 0.2% (db). The Arbour seam also shows little in-seam sulfur variations and displays an inverse relationship with ash (figure 4). The "as mined" composite sample has 0.2% (db) sulfur. The lowest sulfur values within the Silkstone seam are found in the middle of the seam, with slightly higher values present at the top and base (figure 5). "As mined" composite sulfur values are 0.2% (db) for the Silkstone seam. Bonnell and Janke (1986) report that most of the sulfur in the Silkstone is as the pyritic variety. The McPherson seam shows the same "as mined" sulfur value as for the Silkstone (0.2%, db, figure 5). Vertical in-seam sulfur variations are predictable within the lower and upper seam splits of the McPherson seam, being generally low at the base and increasing upward (figure 5). A relationship with ash is not apparent, except in a few cases.

DEPOSITIONAL ENVIRONMENTS

Richardson et al. (1987) recognized that the Ardley coal zone thickened to the west - up to 600m as did the total thickness of coal in the zone. The Ardley coal zone was said to have formed in a rapidly subsiding foreland basin during late Cretaceous to Paleocene time (Richardson et al, 1987). The same authors suggest that rapid subsidence near the basin axis (i.e. somewhere west of the present day Coalspur Formation outcrop) may have caused river systems to flow either north or south along the mountains. This would have left a relatively sheltered area to the east, where coal swamps could accumulate in a relatively quiet alluvial plain environment. Jerzykiewicz and McLean (1980) agree with the alluvial interpretation for coal formation in the Coalspur Formation and further suggest the following three sub-environments: 1) in abandoned channels; 2) in the overbank area of active channels and 3) on the floodplain, isolated from fluvial channels.

The in-seam chemical profiles suggest that for most of the Coalspur coals, coal-forming swamps were likely widespread, acidic (very low sulfur) and developed unhindered by frequent water-lain clastic influxes. Most of the partings were derived from airborne volcanic ash falls.

OBED-MARSH COAL ZONE

INTRODUCTION

The Obed-Marsh coal zone lies at the top of the Paleocene Paskapoo Formation and is best exposed northeast of Hinton, Alberta, at the boundary between the Alberta Plains and the Foothills. Of the five major coal seams in the Obed and Marsh Blocks, this paper will concentrate on the coal quality variations within the presently mineable No.1 and 2 seams. A vertical in-seam profile of seam 1, provided by Obed Mountain Coal Ltd.(figure 7), another section measured during this study (figure 8) and one profile from Seam 2 (figure 9) are discussed (appendix 1).

ASH VARIATIONS

The No.1 seam contains 4 to 6 clastic and volcanic partings, which when composited together to form an "as mined" sample, show 18.5% (db) ash (figure 8). The vertical in-seam inherent ash varies from approximately 12% to 40% (figures 7 and 8), with high values typically occurring at top and/or base of the seam. Maceral profiles reported by Gentzis et al. (this volume) suggest that these high ash zones are associated with high mineral matter contents and high inertinite portions of the seam.

The No.2 seam is not well exposed, at present in the minesite, and so only one section was available for study (figure 9). The seam contains only three visible partings. Inherent in-seam vertical ash contents are generally less than 12% (db), except for the uppermost portions of the seam, which rises to 38% (db). An overall upward increase in inherent ash is present throughout the seam. The accompanying maceral profile shows that the very high ash contents in the uppermost portion of the seam are due to both an increase in clastic partings and to plant derived mineral matter.

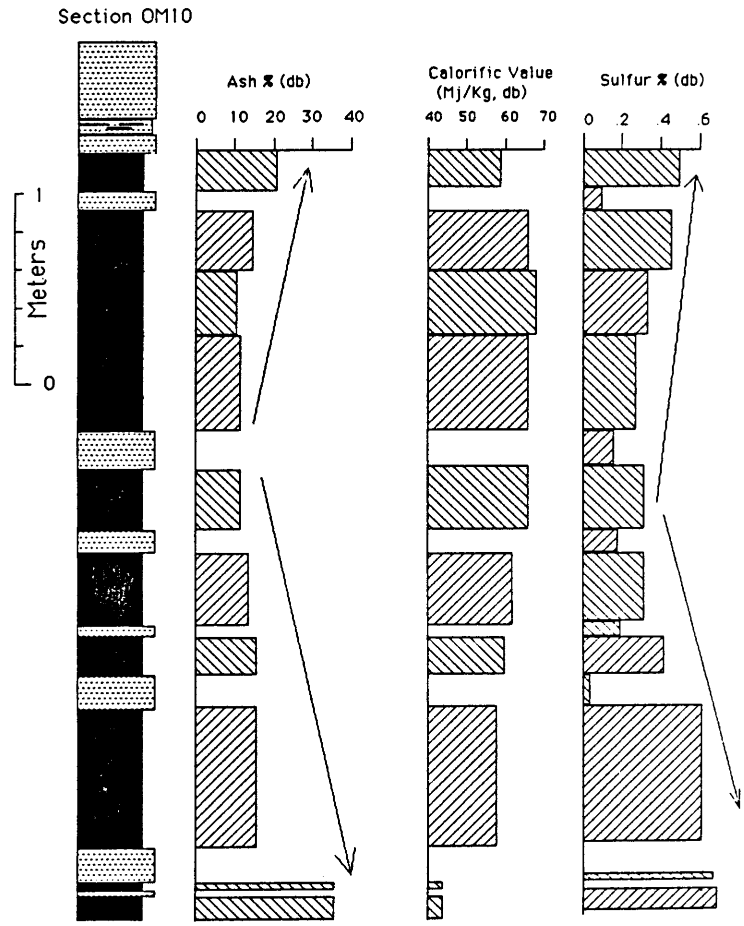

Figure 7. Vertical in-seam coal profile showing ash, calorific value and sulfur distributions within the No.1 seam, Stratigraphic section OM10, Obed-Marsh coal zone.

SULFUR VARIATIONS

Sulfur variations within the No.1 seam range from 0.2 to 0.6% (db), with the higher values almost always occurring at the top and/or the base of the seam (figures 7 and 8). The partings, where sampled, generally have very low sulfur values (<0.2%, db, figure 7). Bonnell and Janke (1986) report that organic and pyritic varieties of sulfur are in roughly equal proportions within the No.1 seam.

The No.2 seam was only sampled at one location and shows a fairly typical upward increase in sulfur from the base of the seam, which corresponds to and increase in ash in the same direction (figure 9). Section OM5 (figure 9) may not be representative of current mine production from this seam. Bonnell and Janke (1986) report approximately equal proportions of organic and pyritic sulfur for the No.2 seam, even when sulfur values become elevated. Field observations, however, show a large amount of visible pyrite on cleat faces within this seam.

DEPOSITIONAL ENVIRONMENTS

The clastics which immediately preceded the coal formation are the, largely noncoal-bearing, Paskapoo Formation. Several excellent roadcut exposures occur along the road to the Obed Mountain mine and are typically fine to medium grained sandstones showing several channel features, such as; lateral accretion bedding, large scale trough-cross stratification, scoured and pebble based channels, stacked channels, peat mats at the base of channels and fining-upward sequences (figure 8). Regionally, the Paskapoo Formation is recognized as being largely sandy in composition and having a very wide geographic extent. A braid-plain to slightly meandering fluvial river system would be consistent with this evidence. Jerzykiewicz (1985) envisaged an anastomosing fluvial system for the sequence in general and attributes the coal zone and interbedded clastics sediments to the fine-grained coaly termination of a major depositional cycle.

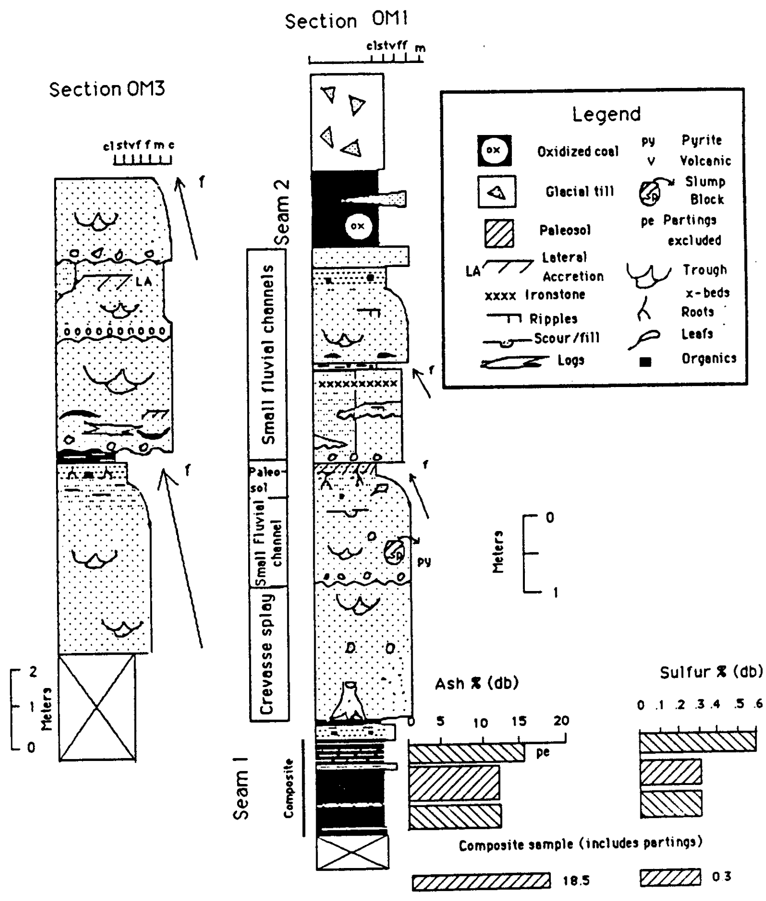

Figure 8. Stratigraphic sections OM3 and OM1 showing vertical in-seam ash and sulfur profiles through the No.1 seam and the sedimentology of the overlying and underlying strata within the Obed-Marsh coal zone.

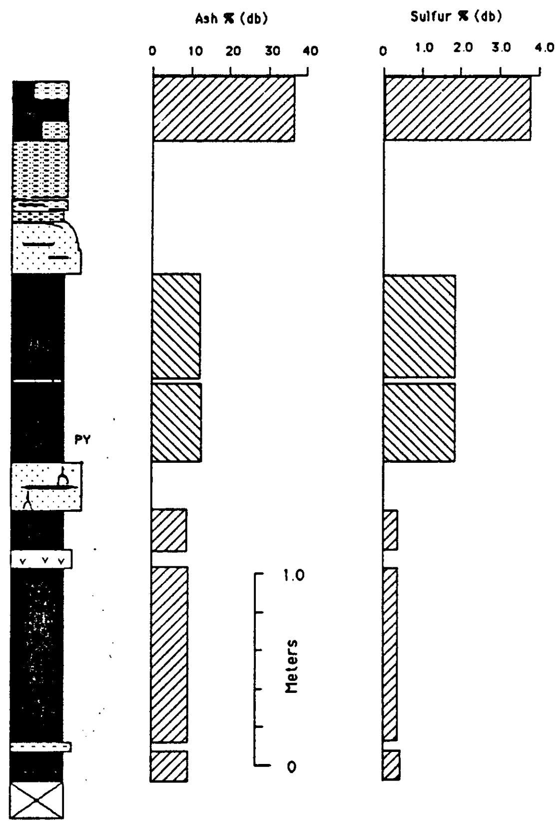

Figure 9. Vertical in-seam coal profile showing ash and sulfur distributions within the No.2 seam, Stratigraphic section OM5, Obed-Marsh coal zone.

The sedimentological interpretation for the clastics interbedded with the No.1 and 2 seams suggests (figure 8) an initial rise in the watertable, which drowned the peat-forming environment of seam No.1, followed by the introduction of a crevasse splay unit. Small meandering fluvial river systems, interrupted by low-water tables and the development of paleosols, characterize the remainder of the sequence.

The prerequisites for accumulation of thick peat deposits are: 1) an adequate supply of plant matter, 2) a balance between the groundwater level and peat surface, and 3) absence or limited presence of detrital clastic sediments (Teichmuller, 1982). Peat accumulation can occur adjacent to river systems with well-developed floodplains (Jerzykiewicz and McLean, 1980), however, as McCabe (1984) has pointed out it is highly unlikely that thick, low-ash peats will accumulate adjacent to such an environment - given the almost frequent flooding events, typical of such systems. This objection can be addressed, for coals found in an alluvial setting, by suggesting that the swamps were protected in time and/or space from such clastic flooding events. Raised swamps, with their upward domed shape, have recently been suggested by several authors to offer a spacial protection explanation.

The coal-forming depositional environment for the No.1 and 2 seams is envisaged to be a distal floodplain, generally isolated from active channels, except during deposition of the interburden. The chemical/geological evidence points to an evolution in the No.1 seam from; an initially restricted, alkaline swamp conditions at the base - yielding high-ash, low-sulfur coals; to the central portions of the seam which represented the maximum extent of the swamp - yielding low-ash, very low-sulfur coals; and finally to the upper part of the seam which again became alkaline due to the encroachment of the small fluvial and crevasse splay systems - yielding a high-ash, low-sulfur coal. The absence of very low inherent ash contents of this seam, coupled the presence of a few water-derived clastic partings argues against a raised swamp model and in favour of a low-lying planar type swamp for the No.1 seam (see Cecil et al., 1985 for criteria).

The No.2 seam also likely developed as a low-lying, planar swamp that was intermittently flooded with clastic material. Strongly oxidizing peat swamp conditions toward the end of the No.2 seam time, would lead to a high-inherent ash and high-sulfur peat as suggested in the general geochemical model of Donaldson et al. (1980).

ACKNOWLEDGMENTS

Funding for this work was supplied through The Office of Coal Research and Technology and through the Alberta Research Council. The present work is an outgrowth of a three-year study on coal quality variations carried out in a team effort at the Alberta Geological Survey. Permission to publish these results and access to mine properties were supplied by D. Fawcett (Smoky River Coal Ltd.), G. Johnston (Luscar-Sterco Ltd.) and C. Williams (Obed Mountain Coal Co. Ltd.). I also wish to thank my colleagues W. Langenberg, T. Gentzis, G. Mandryk and S. Treasure for their kind help and support. I am also very grateful to R. Strobl for his constructive review of this paper.

APPENDIX 1. Locations of Sections Examined.

Section	UTM Coordinates Easting	Northing	Section	UTM Coordinates Easting	Northing
GC1	358680	5989560	CS5	512350	5882300
GC2	360110	5989030	CS8	498575	5899675
GC5	355640	5989840	CS9	499700	5892350
GC6	363560	5985990	CS10	499025	5899375
CS1	499075	5892585	OM1	468700	5938050
CS2	518180	5878250	OM3	472300	5935850
CS3	520525	5874750	OM5	469650	5940200
CS4	520900	5874450	OM10	469950	5939150

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COAL FACIES AND IN-SEAM PROFILING, HIGHVALE NO. 2 SEAM, HIGHVALE ALBERTA

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ABSTRACT

In-seam profiling from two sites in the Wabamun/Highvale minesite, has illustrated that there are heterogeneities in the character of the Highvale No. 2 seam. Vertically and laterally, major differences are present in the petrographic, palynologic and chemical parameters of this coal seam.

Petrographically, there is a dulling-up appearance to the coal seam which is related to an increase in inertinite macerals. This may be due to increasing oxidizing conditions resulting from raising of the mire surface above the influence of groundwater. Palynologically, assemblages are dominated by _Taxodiaceaepollenites_ _hiatus_, which decreases in population slightly towards the top of the seam. This suggests that arborescent vegetation was predominant in mire development. Other components include _Laevigatosporites_ sp., _Stereisporites_ sp. and bisaccate pollen.

Ash and sulphur percentages are highest at the immediate base and top of the seam. An overall trend of increasing ash in the upper half of the seam may be due to airborne volcanic ash deposited on the mire surface. The increase in sulphur values at the top of the seam may be diagenetic in origin, introduced to the underlying peat by the flowthrough of fresh groundwaters replenished by an encroaching fluvial source.

INTRODUCTION

Coal beds are lithologically variable both vertically and laterally. It should therefore, be possible to divide a coal seam into facies as is done with other sedimentary rocks. Coal facies are a product of variations in vegetation type, water tables and clastic input to the mire at the time of organic (peat) deposition. Characteristics of these facies should be reflected in their maceral, mineral and floral content (McCabe, 1984).

Properties of a coal are thus a result of the depositional environment, and the diagenesis of the original peat. The documentation and integration of these coal facies with clastic facies studies can result in the development of a detailed depositional scenario for a coal seam (zone). These coal facies may identify trends in the variations of coal quality, thus aiding in mine planning and development, and regional exploration strategies.

Floral successions within modern peatlands have been documented in a number of studies (Anderson, 1983; Cecil _et_ _al_., 1985; and Moore, 1987).

Beginning with a low-lying mire, the accumulation and aggregation of peat result in the development of an ombrogenous bog under appropriate climatic, tectonic and depositional conditions. The resulting variations in vegetation type and hydrology corresponding to this succession should produce coals of varying character.

In-seam profiling comprises detailed sampling within a given coal seam such that successional aspects and the resulting coal facies may be identified. The purpose of this study is to document the vertical and lateral variations in coal quality within the Highvale No. 2 coal seam through in-seam profile analysis. This involves detailed megascopic and microscopic petrographic examination, palynology and coal geochemistry investigations. By documenting these coal facies, a depositional scenario can be constructed for this seam, and a better understanding of the relationship between organic sedimentology and coal quality can be attained.

STRATIGRAPHY OF THE WABAMUN/HIGHVALE AREA

The coals in the Wabamun/Highvale area make up part of the Ardley coal zone, in the Scollard Formation (Gibson, 1977). Six seams are present in the Highvale mine, and the coal zone is approximately 15 m thick (Figure 1 and 2). Most economic are the upper two seams (Highvale No. 1 and No. 2) with the remaining seams thinner and more argillaceous. In parts of the minesite, the No. 1 seam has been eroded by fluvial systems or sheared and removed due to glaciotectonism. The remaining seams (No. 2 through No. 6) are laterally continuous throughout most of the minesite.

The coal zone is lower Paleocene in age, corresponding to the palynological P1 and P2 zones (Demchuk, 1987), with the Cretaceous-Tertiary boundary situated immediately at the base of the Highvale No. 6 seam (A.R. Sweet, written comm., 1986) (Figure 1). A further discussion of the regional stratigraphy and sedimentology of the Ardley coal zone is presented in Richardson et al. (1988) and Baofang and Dawson (1988).

METHOD OF STUDY

Two sections of the Highvale No. 2 coal seam were described for this study. This seam was sampled from a mine outcrop location in Pit No. 4, and from a University of Alberta drill core located immediately south of Pit No. 3 (Figure 3).

Initially this seam was described on the basis of the presence of shale and bentonite partings. The coal itself was then differentiated on the basis of lithotypes following the terminology of Diessel (1965) (Figure 4). From these criteria, each resulting stratigraphic unit was sampled, and then representatively split for the various analyses conducted.

Coal petrographic and palynologic examinations, based on polished pellets and strew-mount slides, respectively, comprised a total of 100 counts for each sample. All coal chemical analyses were done to ASTM standards at the Alberta Research Council coal research facility in Devon, Alberta.

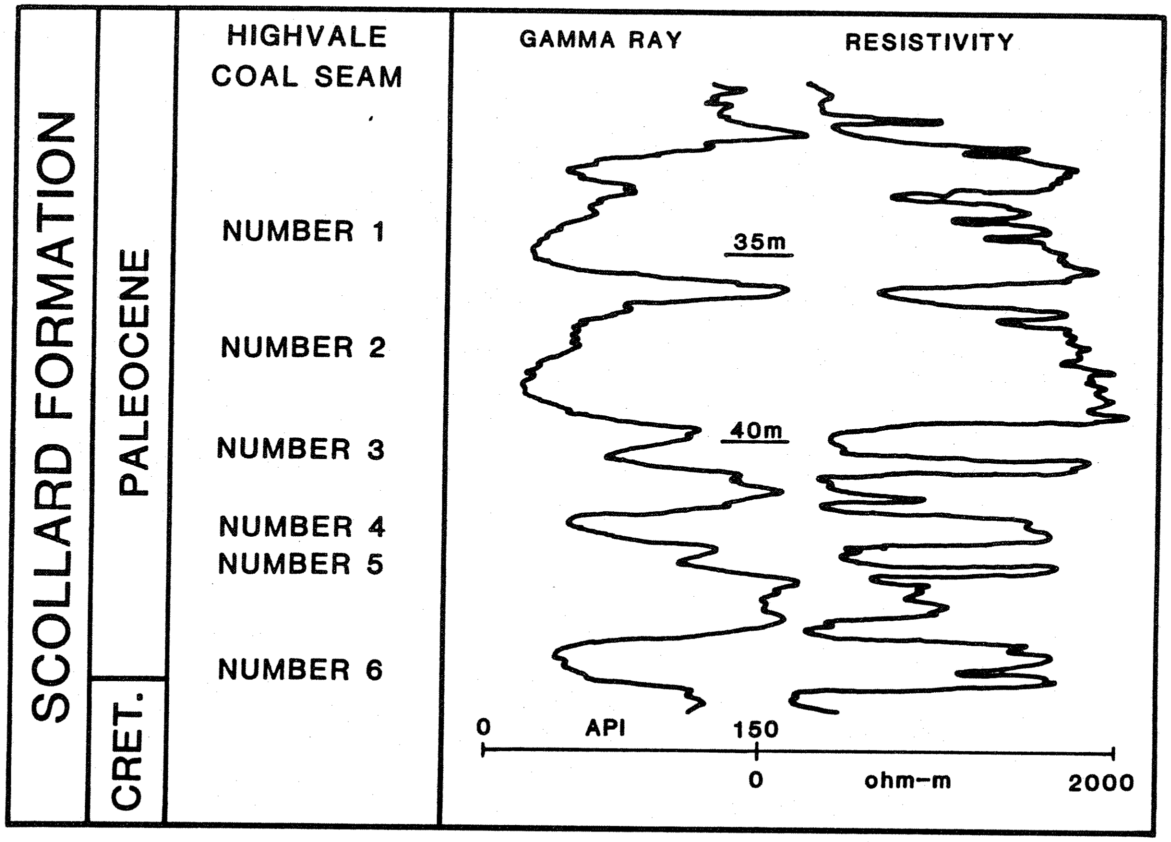

Figure 1. Stratigraphy and coal seam nomenclature at the Wabamun/Highvale minesite. Subsurface geophysical log is that from Pit No. 3 used for this study.

Figure 2. Photograph of mine wall at Wabamun/Highvale in which all six seams are exposed. Arrow points to the parting between the No. 1 and No. 2 seams. The No. 6 seam is exposed at the water level.

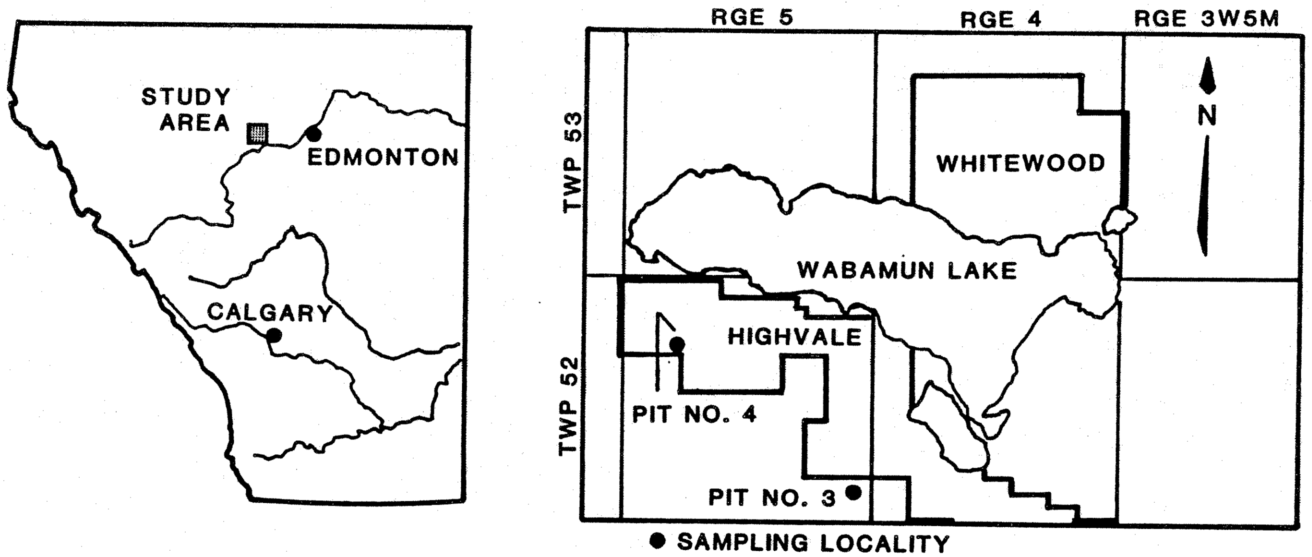

Figure 3. Map of study area illustrating outcrop locality in Pit No. 4, and corehole adjacent to Pit No. 3.

LITHOTYPES (STOPES)	LITHOTYPES (DIESSEL)	DESCRIPTION
VITRAIN	BRIGHT	SUBVITREOUS TO VITREOUS LUSTRE less than 10 per cent dull
CLARAIN	BANDED BRIGHT	BRIGHT COAL, THIN DULL BANDS 10-40 per cent dull
	BANDED	BRIGHT AND DULL COAL IN EQUAL PROPORTION 40-60 per cent dull
	BANDED DULL	DULL COAL, THIN BRIGHT BANDS 10-40 per cent bright
DURAIN	DULL	MATT LUSTRE less than 10 per cent bright
FUSAIN	FIBROUS	SATIN LUSTRE

Figure 4. Description of coal petrographic lithotypes of Diessel (used in this study) and comparison to lithotypes of Stopes (modified from Diessel, 1965, in Bustin et al., 1983.

RESULTS

PETROGRAPHY

Lithotype descriptions of the Highvale No. 2 seam illustrate that the base of the seam is comprised dominantly of bright coal components, with a distinct "dulling" of the coal towards the top. This trend is most evident from Pit No. 3 (Figure 5). In these profiles (Figures 5 and 6), bright and banded coal are concentrated at the base of the seam, giving way to dull coal and fusain bands in the upper half.

Previous studies have illustrated that brighter coal occurs predominantly at the base of seams and in the vicinity of partings, and that seams tend to display a dulling-up profile (Esterle and Ferm, 1986). One suggestion is that this dulling is due to nutrition depletion and stunting of the flora resulting from doming of the mire (ombrogenous bog). The fusain bands (charcoal deposits) present in Pit No. 3 may suggest that the accumulation of peat raised the mire surface above the water table, allowing for extensive oxidation of the peat. It is likely that the accumulation of peat also modified the hydrological regime within the mire, causing a relative rise in the mire surface with respect to the water table.

Microscopic petrographic profiles illustrate a distinct increase in inertinite macerals towards the top of the seam, corresponding to decreased huminite content. Liptinite percentages remain relatively consistent (Figures 5 and 6). This increase in inertinite and drop in huminite percentage, is further evidence of extensive oxidation of the peat towards the top of this seam. A similar trend is documented in other studies (Corvinus and Cohen, 1984; Esterle and Ferm, 1986). Diessel (1965) in correlating maceral associations to lithotypes, illustrated a direct relationship between the increasing dullness in coal appearance to an increase in inertinites. The increase of inertinite contributes to the dulling-up appearance in Seam No. 2 at Highvale.

PALYNOLOGY

All palynofloral assemblages are dominated by the Taxodiaceous pollen (Cypress) Taxodiaceaepollenites hiatus. This dominance ranges from 65 to 90 percent of the total assemblage. Other palynoflora which are common constituents of the assemblages are Laevigatosporites sp. (ferns), Stereisporites sp. (Sphagnum) and bisaccate pollen (conifers) (Figures 5 and 6).

From Pit No. 4 (Figure 6), there is an apparent trend in that Laevigatosporites sp. is relatively abundant in the lower half of the seam, which drops in abundance in the upper half corresponding to a Stereisporites sp. increase. In a study of the peats in the Fraser Delta of British Columbia, Styan and Bustin (1986), have illustrated that Stereisporites (Sphagnum) colonizes the mire after the mire surface is raised above the influence of fluvial activity and the mire surface has acidified. Although the percentages are relatively low, this shift to an increased presence of Stereisporites sp. documents a prominent stage in the evolutionary process of the peat accumulation which eventually became the Highvale No. 2 seam in this area (Figure 6).

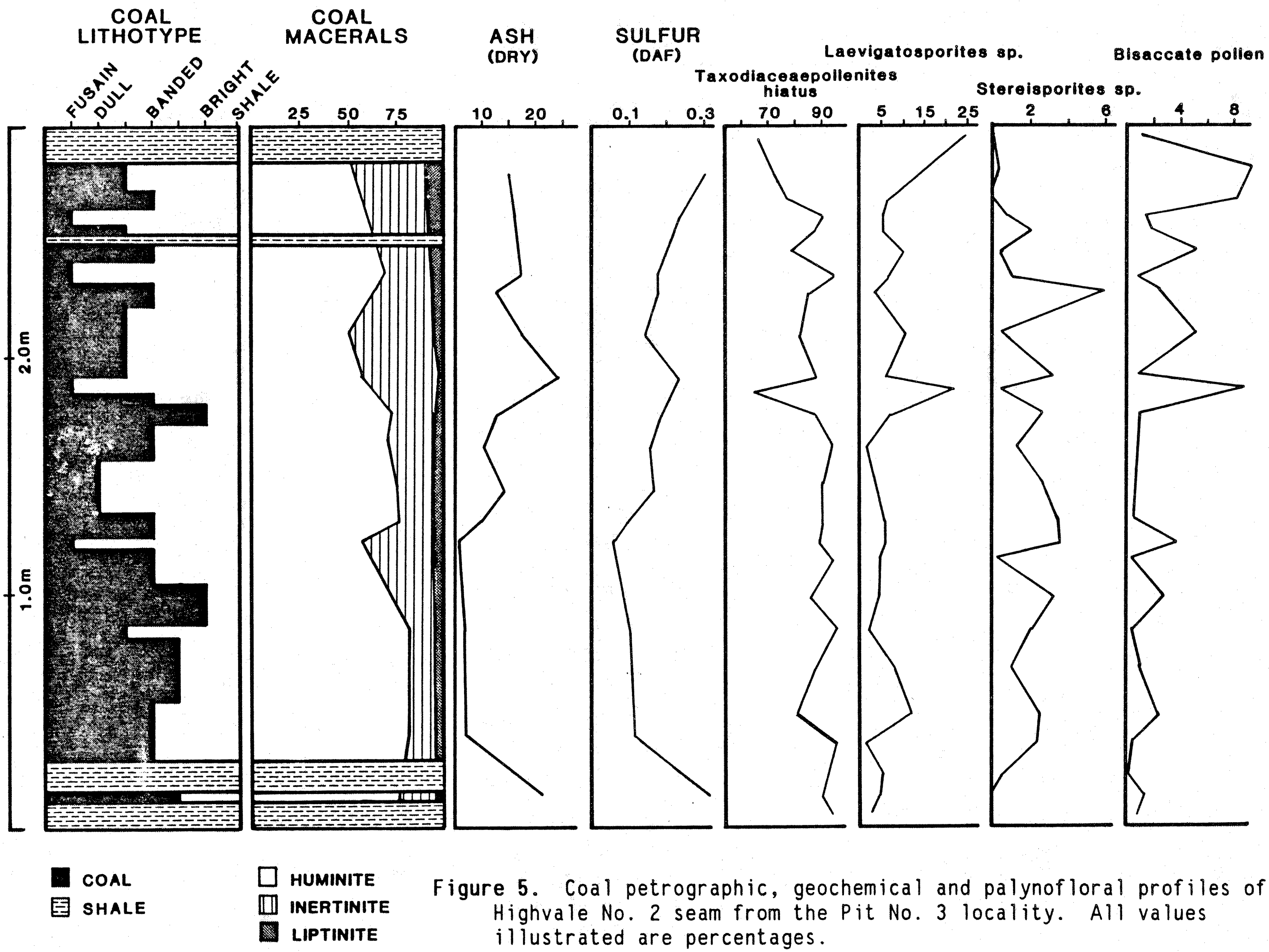

Figure 5. Coal petrographic, geochemical and palynofloral profiles of the Highvale No. 2 seam from the Pit No. 3 locality. All values illustrated are percentages.

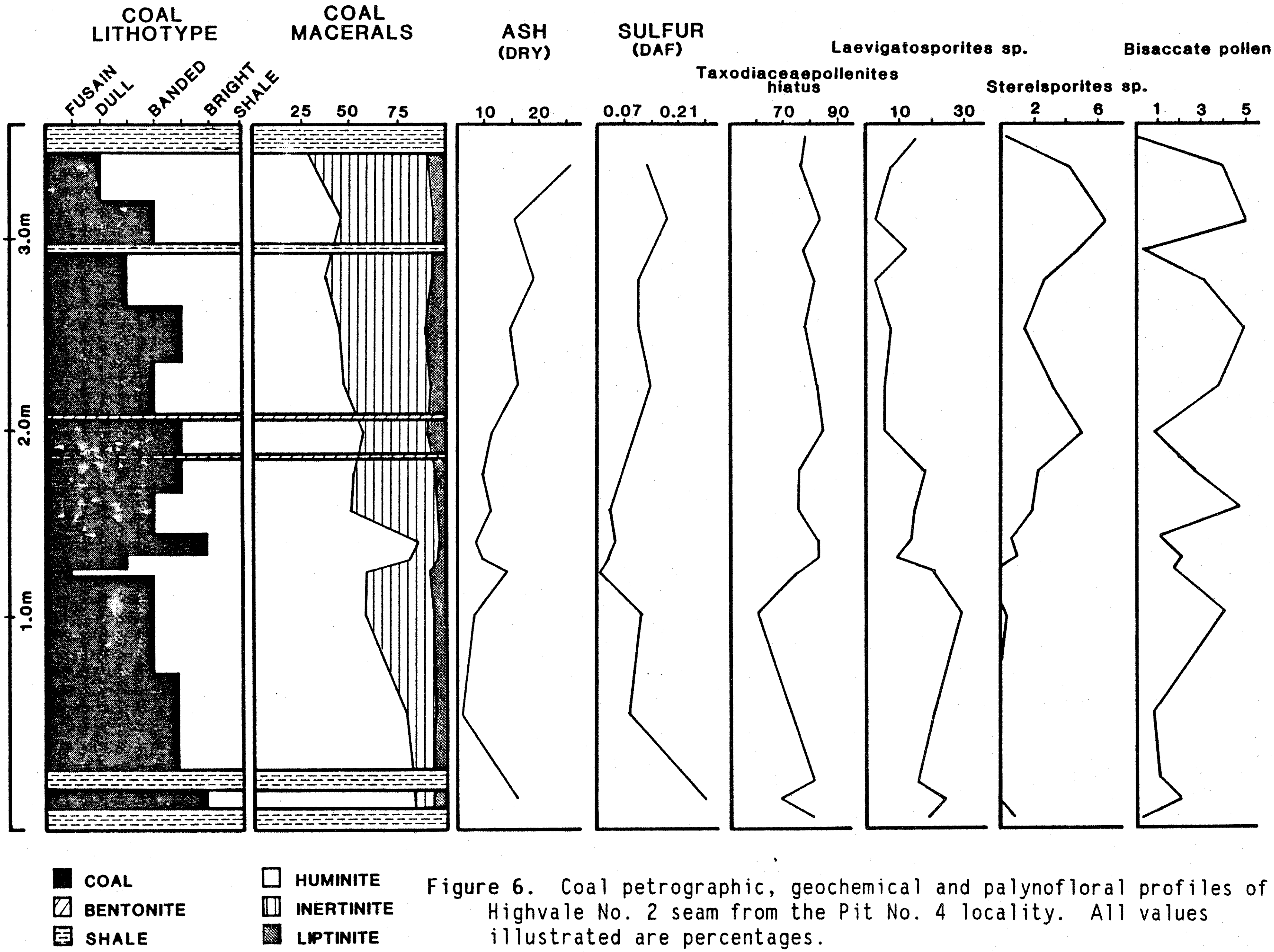

Figure 6. Coal petrographic, geochemical and palynofloral profiles of the Highvale No. 2 seam from the Pit No. 4 locality. All values illustrated are percentages.

Previous studies have illustrated that pollen from arborescent vegetation (Taxodiaceae and conifers of this study) is predominant at the base of coal seams and in the vicinity of shale partings (Smith, 1962; Esterle and Ferm, 1986). This observation is attributed to the presence of firm substrate and replenishment of freshwater. These relationships are supported in this study, and are evident in Pit No. 4 (Figure 6).

Palynofloral trends are less defined in the profile from Pit No. 3. Notice, however, the change from stable abundances in the lower part of the seam, to fluctuating percentages in the upper part, corresponding to a minor drop in Taxodiaceae percentages (Figure 5). This may be a result of changing hydrological regimes (water table) within the mire brought about by aggregation of peat and/or periods of local subsidence later in the life of the mire (the upper part). The persistent high percentages of Taxodiaceous pollen suggests that for long periods in the life of the mire, arborescent vegetation dominated and the water table was quite high relative to the mire surface.

The variation in palynofloral profiles, illustrate that laterally there are differences in the vegetational composition of the seam. These differences represent those parts of the mire in which the hydrological aspects differed, governing the type and succession of the flora.

GEOCHEMISTRY

From the coal utilization point of view, geochemical studies are important. The ash and sulphur components of the coal exhibit distinct and predictable trends. Ash values are highest at the base and top of the seam, and in the vicinity of partings (Figures 5 and 6). At the base of the seam, relatively high ash percentages are likely due to the uptake of inorganic material by colonizing vegetation (Clymo, 1983). In the vicinity of shale partings and at the top of the seam, the relatively high ash values may be due to fluvial flooding into the mire. In the case of the Highvale coals, a percentage of the mineral matter may be due to airborne volcanic ash. A number of bentonite partings are present in these seams, and are common in lower Paleocene coals throughout Alberta (Figure 6).

In the middle of the coal seam, ash values are relatively low (Figures 5 and 6). This may be attributed to the raising of the mire surface above the influence of fluvial activity or sustained periods in which the mire was sheltered from clastic input. This ash in the middle part of the seam is likely inherent ash in the vegetation (such as opaline silica), and airborne ash.

Sulfur values are also lowest in the central part of the coal seam. This trend may be due to the acidic conditions suppressing sulfate-reducing bacteria. Percentages of sulfur are highest at the base and top of the coal seam, and in the vicinity of partings (Williams and Keith, 1963; Esterle and Ferm, 1986). The increased levels of sulfur (in the upper part of the seam) may be diagenetic in origin, introduced by the flowthrough of fresh groundwaters at depth within the peat, and replenished by the encroaching fluvial source.

DISCUSSION

The Highvale No. 2 seam can be divided into a lower and upper part based on various characteristics. From both sample sites, palynology, petrography and geochemistry results indicate that peat which formed the lower half of the coal seam, accumulated under more stable conditions with very little fluvial influence. Mire waters were allowed to stagnate and acidify. These depositional conditions are reflected by the low ash and sulfur percentages, and high huminite values. The relatively high ash percentages at the base of the seam can be attributed to the uptake of inorganic material by colonizing vegetation. Sulphur enrichment at the base of the seam may be associated with diagenetic processes.

For the upper half of the seam, ash and sulfur values increase towards the top. Percentages of inertinite macerals also increase towards the top of the seam, along with Stereisporites sp. Abundant inertinites present in the Pit No. 4 profile, in particular, suggests that the surface of the mire was raised above the influence of groundwater for extended periods of time. The presence of Stereisporites sp. is likely due to acidification of the mire surface. This may appear to be in conflict with the discussion regarding a fluvial source and the replenishment of freshwater to the mire which supplied the clastic (ash) material making up the partings in the upper part of the seam.

Raising of the mire surface above the influence of fluvial activity is common in the normal course of peatland succession, resulting in the accumulation of thick, low ash peats. Stereisporites sp. presence and abundant inertinite maceral are products of this raised surface, in which the mire surface has acidified and the peat has been extensively oxidized.

A large percentage of the ash may have been airborne in origin, depositing mineral matter on the surface of the mire. Peat at the mire surface was oxidized, and through accumulation and aggregation was buried along with this ash. The resulting coal is thus relatively high in percentages of inertinite maceral, ash and sulfur within the upper half of the seam.

CONCLUSION

Establishment of coal facies through the interdisciplinary studies of coal petrography, palynology and coal geochemistry can lead to the development of a very detailed depositional scenario for a given coal seam. Each criterion reveals a different characteristic of that coal, and the vertical and lateral relationships provide insight as to the paleoecological framework, the association between organic and clastic sedimentology and their influence on coal quality.

Facies of the Highvale No. 2 coal seam reveal that the peat which accumulated and formed the upper half of this coal seam, underwent a much more complex depositional and diagenetic history, than peat which formed the lower half. For the lower half, peat accumulated under steady conditions in which mire waters were acidified, thus organic material was well-preserved, and ash and sulfur percentages were low.

As peat accumulated, the mire surface was raised, allowing for the oxidation of the peat (as indicated by the inertinite macerals) characterizing the upper half of the seam. Ash, possibly airborne in origin, was deposited and sulfur was introduced diagenetically to the peat by the flowthrough of fresh groundwaters from fluvial sources episodically encroaching upon the mire.

ACKNOWLEDGMENTS

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PETROLOGY AND DEPOSITIONAL ENVIRONMENT OF UPPER-PALEOCENE COALS FROM THE OBED-MARSH DEPOSIT, WEST-CENTRAL ALBERTA

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ABSTRACT

The Obed-Marsh coal deposit is of Upper Paleocene age, and contains over 200 million tonnes of subbituminous B to high volatile bituminous C coal.

Petrographic analysis of three sections from seams 1 and 2 reveals that the coal consists of high amounts of huminite and relatively low amounts of liptinite and inertinite, with the exception of some intervals in both seams.

The persistent high ratio of huminite to liptinite and inertinite indicates a relatively reducing environment, a feature also expressed by the relatively low inertinite content. Examination of the in-seam profiles indicates undisturbed peat accumulation over long periods of time and channel stabilization.

INTRODUCTION

The Obed-Marsh coal deposit is located approximately 24 kms northeast of Hinton, Alberta, at the boundary between the Alberta Plains and the Foothills (Figure 1). The coal-zone occurs in the Lower Tertiary Paskapoo Formation, is of subbituminous B to high-volatile bituminous C rank and the proven reserves are in the order of 226 million tonnes. Although there are five significant coal seams in the Obed and Marsh Blocks, the present study is concentrated on the organic petrology of seams 1 and 2. The thickness of the above seams ranges between 3.5 and 4.3 metres, and currently are striped-mined as feedstock for electrical generation plants. The life expectancy of the mine is 37 years (Dawson et al., 1986).

The main objectives of this study are:

(1) to establish petrographic zones based upon maceral group/mineral matter composition in three sections and evaluate the lateral continuity of the zones over a distance of 1.5 kms, and

(2) to interpret the depositional environment of the peat-forming swamp.

GEOLOGICAL BACKGROUND

The Obed-Marsh coal zone is approximately 13.5 metres thick, and is

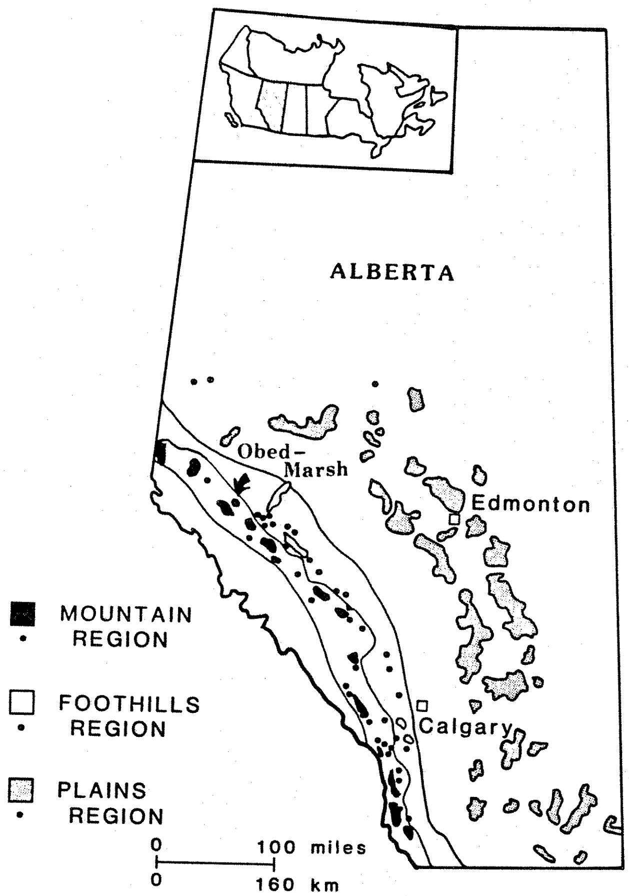


Figure 1. Location map of the Obed Marsh Coal deposit

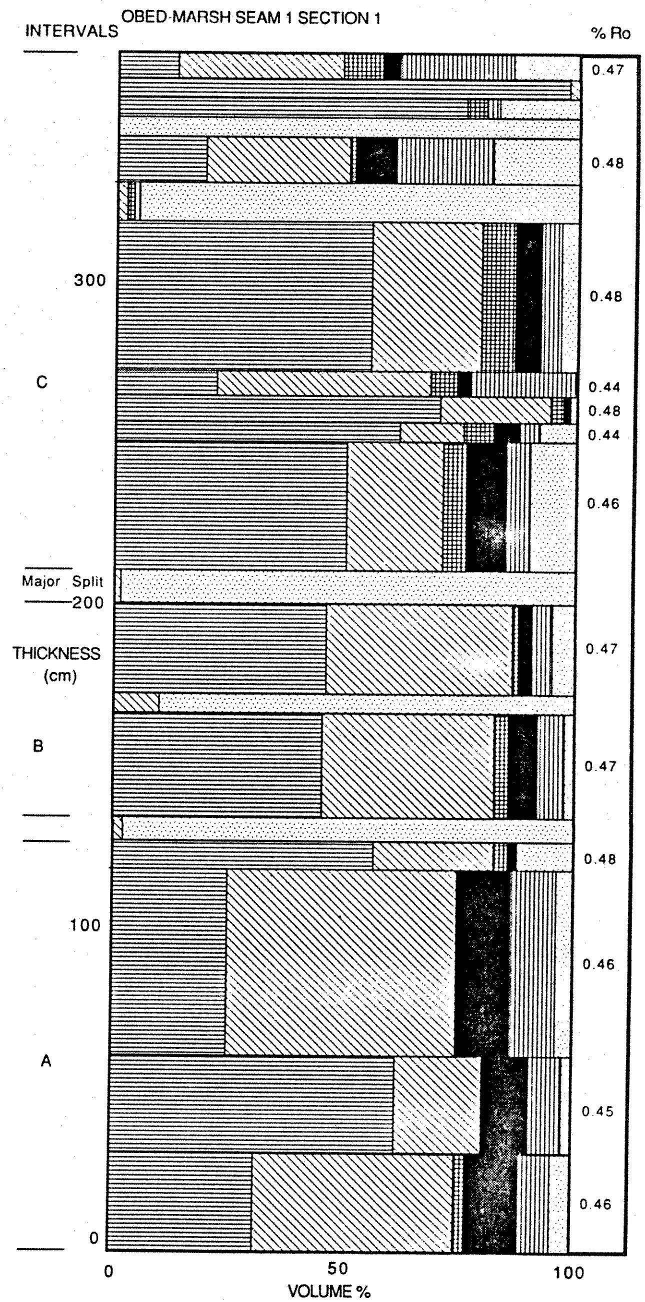


Figure 2. Maceral and reflectance profile of seam 1, section 1. Legend as in Figure 4.

situated in the uppermost part of the Upper Paleocene Paskapoo Formation. Strata in the area dip uniformly to the northeast at 0.5° and the axis of the Alberta Syncline lies to the east of the Obed-Marsh property (Dawson et al, 1986). Seams 1 through 5 are present in the Obed Block, but due to erosion only seams 1 and 2 are preserved in the Marsh Block. Only these two seams are considered economical at present.

The Obed-Marsh coal seams are mainly associated with fine-grained sandstones; siltstone, shale and claystone make up the interbedded sediments. Although the interbedded sediments exhibit no sedimentary structures apart from some faint cross-laminations, the fine sand and coarse silt may represent overbank channel deposits (Dawson et al, 1986).

Jerzykiewicz (1985) envisaged an anastomosing fluvial system and attributes the sediments to the fine-grained coaly termination of a major depositional cycle. Nevertheless, lateral continuity and uniform thickness of both the coal and interbedded clastics represent deposition in a relatively stable coal-forming environment.

METHODS

Three seam profiles taken from two exposures of seam 1 (sections 1 and 2, approximately 1.5 km apart) and one from seam 2 were measured. Only bands showing major lithotype changes were distinguished and each sample collected represents a lithotype interval within the seam profile. The coal and interbedded sediment samples were prepared, polished and analyzed for their maceral composition according to the ICCP (1971) procedures and classification.

A Zeiss MPM II petrographic microscope equipped with white (halogen), fluorescent (HBO) light sources, Zonax and a microcomputer and printer were used for maceral and reflectance analysis. A X40 Epiplan-Neofluar oil immersion objective (N.A. = 0.90; n_{oil} = 1.514), with resulting magnification of X640, was used for reflectance measurements. Photomicrographs were taken under plane-polarized light.

RESULTS

COAL RANK

The % Ro of eu-ulminite B in the Obed coal ranges from 0.43 to 0.52%, averaging 0.47%. Based on its reflectance, the coal is classified as subbituminous B to high-volatile bituminous C and it exemplifies maceral transformations typical of the first coalification 'jump'. The vertical variation in % Ro for seam 1 (sections 1 and 2) and seam 2 is shown in Figures 2 to 4.

PETROLOGY

Huminite macerals

Humotelinite and humocollinite are by far the dominant macerals observed in most samples, followed by humodetrinite. Humotelinite in the coal samples ranges from a minimum of 4.0% at the top of seam 1, section 2, to a maximum of 100.0% near the middle of seam 2. It averages 50.0% in seam 1, section 1, 45.0% in seam 1, section 2, and 58.0% in seam 2 (Figures 2 to 4). The cell structure of humotelinite (texto-ulminite) is visible and the cell lumens are often impregnated by porigelinite and resinite (Plate 1a and 1b).

Humocollinite has a range of 3.0% to 63.0% in the same samples, averaging 30.0% in seam 1, sections 1 and 2 and 25.0% in seam 2 (Figures 2 to 4).

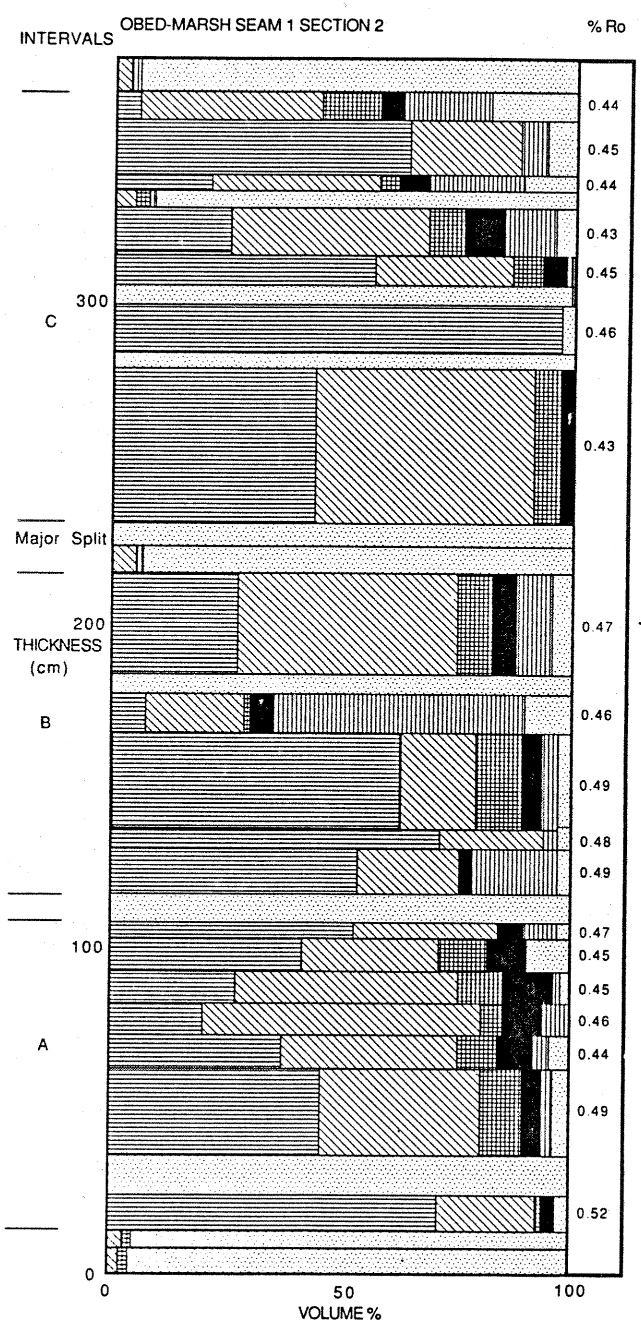


Figure 3. Maceral and reflectance profile of seam 1, section 2. Legend as in Figure 4.

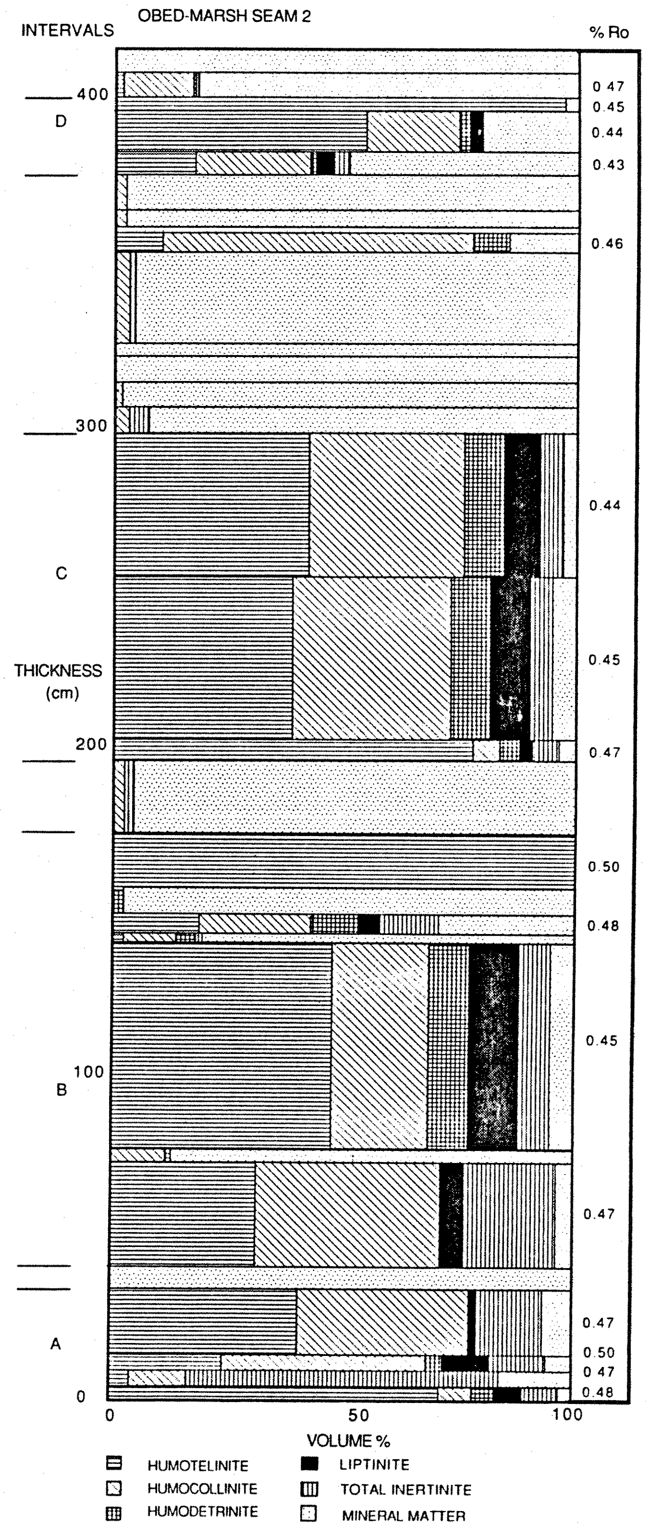
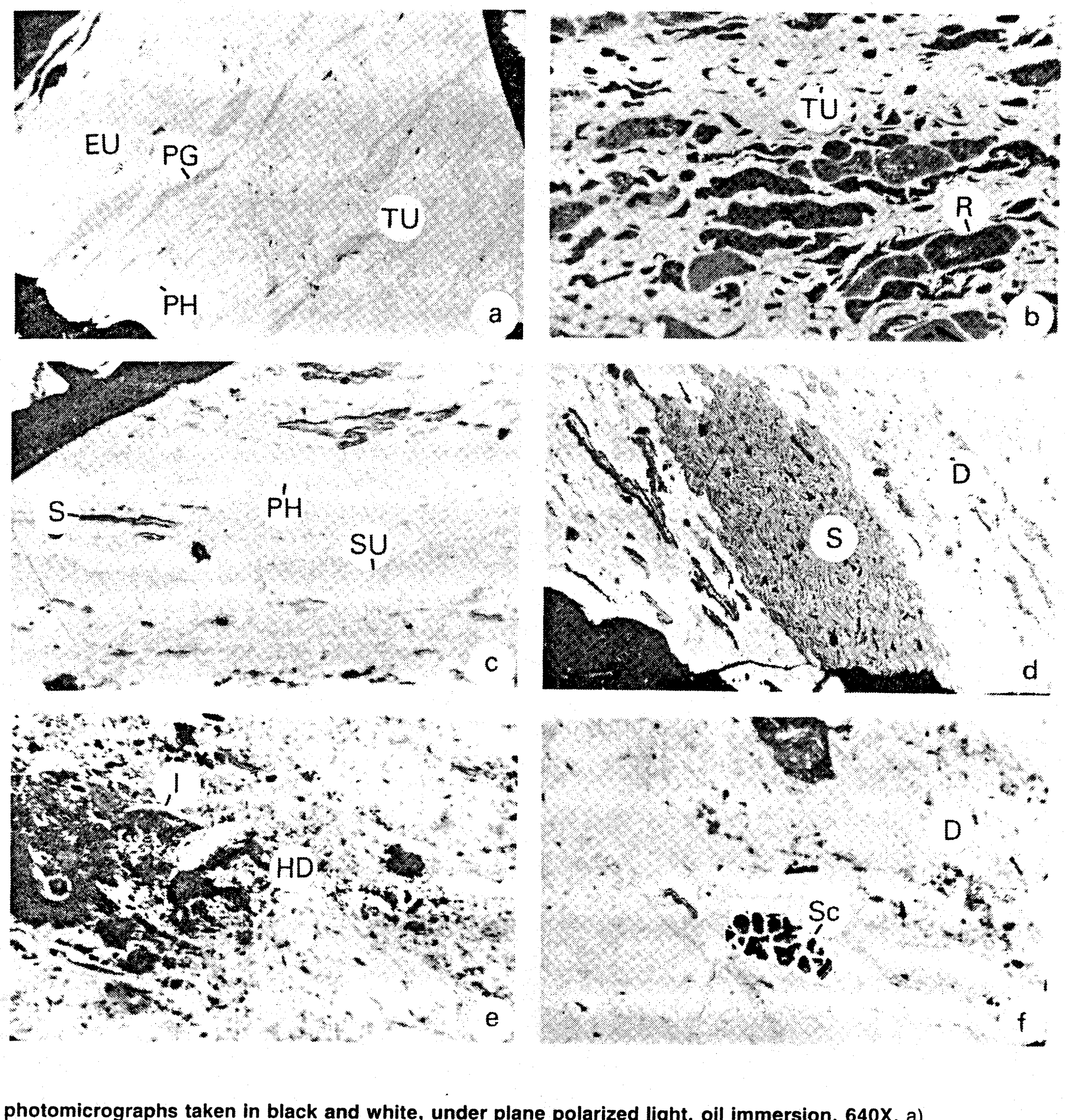


Figure 4. Maceral and reflectance profile of seam 2.

Plate 1



All photomicrographs taken in black and white, under plane polarized light, oil immersion, 640X. a) phlobaphinite (PH) and porigelinite (PG) infilling cell cavities of texto-ulminite (TU). Note the transition from texto-ulminite to eu-ulminite (EU). b) oval resinite bodies (R) infilling cell cavities of texto-ulminite (TU). c) association of phlobaphinite (PH) and suberinite (SU) in a cross section of a corkified cell wall. Note the presence of sporinite (S) in the huminitic matrix. d) a concentration of microspores (sporangia) (S) in association with densinite (D). e) humodetrinite (HD) enclosing fragments of inertinite (I). f) Sclerotinite (SC) in a densinitic groundmass (D).

Phlobaphinite (Plate 1a and 1c) is almost exclusively associated with texto-ulminite, suberinite or corkified cell walls and never exceeds 1.0%. Next to humocollinite, humodetrinite is the most abundant maceral ranging from 2.0% near the base of seam 1, section 2, to 13.0% near the top of the same section. It averages 5.0% in seam 1, section 1, 8.0% in seam 1, section 2 and 7.0% in seam 2. It is present in the form of densinite and forms the groundmass for the intimate mixing of humic detritus with other liptinite and inertinite macerals (Plate 1d, 1e and 1f).

Inertinite macerals

Inertinite macerals are present in minor quantities and most often in the form of inertodetrinite. Total inertinite averages approximately 11.0% in seam 1, section 1, 12.0% in seam 1, section 2 and 17.0% in seam 2, with the exception of two lithotype intervals, one near the middle of seam 1, section 2 (Figure 3), which contains an anomalously high percentage (56.0%) of fusinite and semifusinite and the other near the base of seam 2, containing 70.0% of total inertinite (Figure 4).

No increase in inertinite content is observed in the partings, but various forms of fungal remains or sclerotinite are consistently present in the huminitic groundmass (Plate 1f). Finally, low amounts of anisotropic inertinite occur throughout the coal seam. Pyrolytic carbon has been noted to be intimately associated with seemingly unaltered humocollinite.

Liptinite macerals

Primary macerals include sporinite (occasionally sporangia), cutinite, resinite, fluorinite, and suberinite. Exsudatinite or secondary resinite is generally associated with primary resinite and amorphous fluorescing matrix.

Total liptinite content ranges from 1.0% in seam 1, section 2 to 12.0% in seam 1, section 1, averaging 6.0% in section 1, 5.0% in section 2, and 6.0% in seam 2. Sporinite (Plate 1c and 1d) is the most abundant, followed by resinite (Plate 1b), cutinite, fluorinite and suberinite (Plate 1c).

Chitin has been informally, but suitably placed with the liptinite, and is very rare.

Mineral matter

Mineral matter content in coal averages 7.0% in seam 1, section 1, 6.0% in section 2 and 9.0% in seam 2, consisting mainly of clays with minor pyrite.

DISCUSSION

The organic petrology of the Obed-Marsh sections will be discussed in relation to:

a) The variation of organic petrology within the seams and between the seam 1 sections; and

b) The depositional environment of the coal deposit.

VARIATION OF ORGANIC PETROLOGY WITHIN THE COAL SEAMS

Humotelinite and humocollinite both form from the lignin and cellulose of plant cell walls. They are present in coal which has formed from peat that accumulated at a time when conditions in the peat-forming swamp were favourable for the preservation of woody tissue. Anaerobic conditions, generally regarded as a prerequisite for huminite and for vitrinite formation and preservation, translate to fairly low pH of the swamp water (<4.5) which suppresses bacterial degradation, and a high enough water table to prevent extensive oxidation (Renton and Cecil, 1979).

Inertinite macerals, on the other hand, are mainly derived from the same plant components that form huminite. They do not undergo humification and gelification but are subjected to the process of fusinitization which may be caused by oxidation, charring, mouldering and/or fungal attack either prior to or during peat accumulation. As a result, fusinite forms in peat layers which have been subjected either to swamp fires or strong oxidation. The high inertinite content of some intervals in seams 1 and 2 indicates severe oxidation and the overall predominance of fusinite over semifusinite is indicative of the strong oxidation which completely fusinitized plant cell walls.

The generally persistent high ratio of huminite macerals to liptinite and inertinite macerals indicates a relatively constant reducing environment, a feature also expressed by the relatively low inertinite content of the coal. The bright and brittle bands observed macroscopically were formed under stable preservation conditions, not allowing rafting, mixing and oxidation. The above features suggest that conditions in the Obed peat swamp were such that the peat was covered by stagnant water, most likely resulting from a locally high water table. In addition, the well preserved cell lumens in huminite, the phlobaphinite-suberinite association which indicates corkified tissues (Teichmuller, 1982) and the resinite bodies in particular attest to the presence of localized areas rich in tree-like vegetation. The presence of limited amounts of inertinite indicates that a certain fraction of the plant matter experienced drier conditions, possibly in areas of slightly higher elevation.

Humotelinite has formed in situ (autochthonous) in areas inhabited by trees, whereas humodetrinite and the intervals rich in sporinite and cutinite associated with densinite attest to the presence of a reed marsh type of coal depositional environment. This area was inhabited by herbaceous vegetation (mainly shrubs) which produce large quantities of spores.

Each section of the Obed Marsh coal seams was divided into petrographic zones based upon observed differences in the maceral composition and mineral matter content. Special consideration was given to the mineral matter content because mineral matter showed distinct changes in the vertical profiles. The depositional environment interpretations are based on both the maceral group percentages and the occurrences of individual macerals in each zone.

SEAM 1, SECTION 1

Section 1 contains numerous thick intervals consisting of clean, bright coal resulting from peat accumulation which remained uninterrupted for a long period of time (Figure 2).

Interval A shows the highest liptinite content (10.0-12.0%) throughout, except near the top where it decreases to 2.0%. Mineral matter content is low (3.0-12.0%), inertinite remains almost constant (7.0-10.0%), and humotelinite and humocollinite occur in similar amounts (Figure 2).

Interval B contains coal rich in humotelinite and humocollinite and low in inertinite and humodetrinite. Liptinite varies from 3.0-10.0% and is higher near the base. There is a 6 cm thick parting near the middle of this interval (Figure 2).

Conditions favouring peat accumulation and tissue preservation prevailed in interval C. Humodetrinite content is low (<10.0%), liptinite is approximately 10.0% near the base, decreases to 2.0% towards the middle and increases again to 7.0% near the top. Peat accumulation was interrupted by an influx of sediments represented by a thick (~ 12 cm) parting (Figure 2). Conditions for peat accumulation returned once more, resulting in the formation of a thick, uninterrupted interval, which contains high inertinite (4.0-24.0%) (Figure 2).

At the end, the water level in the channel rose rapidly, this resulted in an influx of inorganic sediments and 'drowning' of the peat surface.

SEAM 1, SECTION 2

As soon as conditions in the coal-forming environment were favourable for organic matter to accumulate, peat formation was initiated. The profile shows a relatively thick, bright coal interval between the base and the top of interval A with the occurrence of the first major parting (Figure 3). The presence of seat earth, and high amounts of humotelinite and humocollinite at the base of interval A indicate that the peat was autochthonous.

Peat accumulation was disrupted by the 9 cm thick parting which represents an influx of sediments into the coal-forming environment. Subsequently, the conditions that favoured peat accumulation returned and relatively clean and thick coal formed, with the exception of a 12 cm thick fusain band near the middle of interval B (Figure 3). The band contains more than 50.0% inertinite and pyrolytic carbon, indicating that the peat surface was exposed to the atmosphere and experienced higher temperatures, possibly due to fire (Goodarzi, 1985a).

Interval C contains thick intervals of clean, bright coal, rich in structured huminite and interrupted only three times by thin claystone partings. The presence of the thick sandstone at the top of seam 1 indicates the 'drowning' of the peat surface due to the sudden influx of inorganic sediments.

Interval A contains little inertinite (<7.0%), but the liptinite content is the highest of all intervals (4.0-12.0%) (Figure 3). Inertinite content increases in interval B to 18.0%, whereas liptinite never exceeds 5.0%. Liptinite content remains almost constant in interval C (6.0-10.0%), but inertinite increases from 2.0% near the base to 17.0% near the top of the interval.

SEAM 2

Seam 2 contains numerous intervals rich in inertinite near its base (Figure 4). Peat accumulation was disrupted by an influx of sediments represented by partings. The thickness of the partings varies between 4 and 22 cm in the lower 2/3 of the seam.

Intervals A and B contain almost equal amounts of humotelinite and humocollinite and are rich in inertinite. Interval B is also relatively rich in liptinite, and is characterized by a 17 cm thick interval consisting entirely of humotelinite (Figure 4).

In interval C, peat accumulation was once again favoured, resulting in the formation of clean and thick coal. This interval has equal amounts of humotelinite and humocollinite, moderate liptinite and humodetrinite and low inertinite contents.

The upper 1/3 of the seam is occupied almost entirely by thick parting intervals and only a few, thin intervals of coal represented by interval D can be seen (Figure 4). The sudden influx of sediments resulted in the 'drowning' of the Obed peat at that stage and deposition of clastics.

DEPOSITIONAL ENVIRONMENT

Peat accumulation can occur in river systems with well-developed floodplains (Jerzykiewicz and McLean, 1980). The prerequisites for accumulation of thick peat deposits are: 1) an adequate supply of plant matter, 2) a delicate balance between the groundwater level and peat surface, and 3) absence or limited presence of detrital clastic sediments (Teichmuller, 1982).

The Obed-Marsh coal depositional environment is envisaged as a floodplain isolated from an active channel, based on lithostratigraphic and sedimentological analyses (Macdonald, pers. commun, 1988). A stable, well developed floodplain has a great potential of producing clean coal and is protected by periodic introduction of clastic sediments because of its isolation from the channel and its floodwater by natural levees (Jerzykiewicz and McLean, 1980).

There was a balance between the water level fluctuation, rate of subsidence and accumulation of vegetal matter during peat deposition, which resulted in the formation of uninterrupted, thick, and clean coal with only minor quantities of mineral matter. The excellent preservation of cell structure, distinct floor and roof boundaries, presence of seat earth and thickness and continuity of the seam all tend to indicate a high degree of autochthony (Teichmuller, 1982; Goodarzi and Gentzis, 1987). The composition of the partings indicates very poor peat preservation conditions, the pH of the swamp water was probably high (>4.5) which, in turn, stimulated extreme biological degradation and subsequent accumulation of plant-derived inorganics which were the precursors of the mineral component of most of the partings. There is also a distinct possibility that few of the partings may represent airborne volcanic ash falls (Macdonald, pers. commun., 1989).

Examination of the maceral profiles suggests that the areas of peat accumulation were large and undisturbed for relatively long periods of time (i.e. a few thousand years), thus indicating that channels were stabilized and that sedimentation did not interrupt to any great extent peat accumulation.

High energy conditions, as indicated by the deposition of coarse clastics on the roof of seam 1 and occasionally within the seam, alternate with periods of quiescence which permitted the re-establishment of areas with tree-like vegetation.

TERNARY COMPOSITIONAL DIAGRAMS

An attempt has been made to establish a correlation between coal facies indicators and the environment of coal formation. A modification of Diessel's coal facies diagram for a variety of depositional settings (Diessel, 1986), has been attempted with limited success. The model takes into consideration two parameters, the gelification index (GI) and tissue preservation index (TPI) (Figure 5).

The Obed coal samples have relatively high gelification indices, an indication that they have a high content of wood-derived structured huminite (humotelinite), and a low content of inertinite. When total huminite is dominated by humotelinite, this results in high tissue preservation indices (Diessel, 1986; Figure 5). On the other hand, when unstructured huminite (humocollinite and humodetrinite) prevail, TPI values are low. The presence of unstructured huminite and considerable amounts of cutinite and sporinite in some of the Obed coal samples suggests peat formation from soft-tissue woody matter, probably herbaceous vegetation in a reed marsh environment.

Figure 5 shows the relationship between GI and TPI, and it becomes apparent that there is a drastic change in depositional environment within the 4 m thick seam 1. These changes are extreme, ranging from telmatic to wet forest swamp, to limnotelmatic and limnic environments. Such changes cannot be envisaged for the depositional environment of a single, relatively thin coal seam. Furthermore, GI and TPI of some samples are beyond the limits of the present model as indicated in Figure 5 (for example, GI of 312-321 and TPI 3.2-3.9).

An alternative ternary compositional diagram showing coal facies, where mineral matter occupies one apex and the three maceral groups occupy the other, is shown in Figure 6. The diagram, which is a modification of those used by Goodarzi (1985b) and Goodarzi and Gentzis (1987) clearly shows that the Obed coals plot mainly in the region which indicates good preservation conditions in an environment rich in tree-like vegetation.

Almost all Obed coal samples contain high amounts of huminite and, generally low amounts of liptinite and inertinite (Figure 7). This indicates that the peat swamp rapidly achieved conditions favourable for the preservation of organic matter and that only limited biological degradation of the woody tissues took place. A gradual shift towards drier conditions would

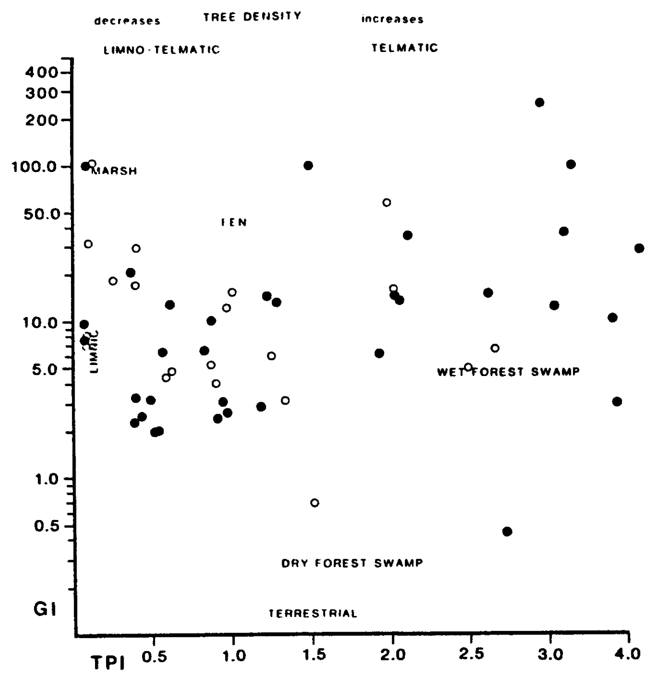


Figure 5. Coal facies diagram (modified after Diessel, 1986) seam 1 (●), seam 2 (O)

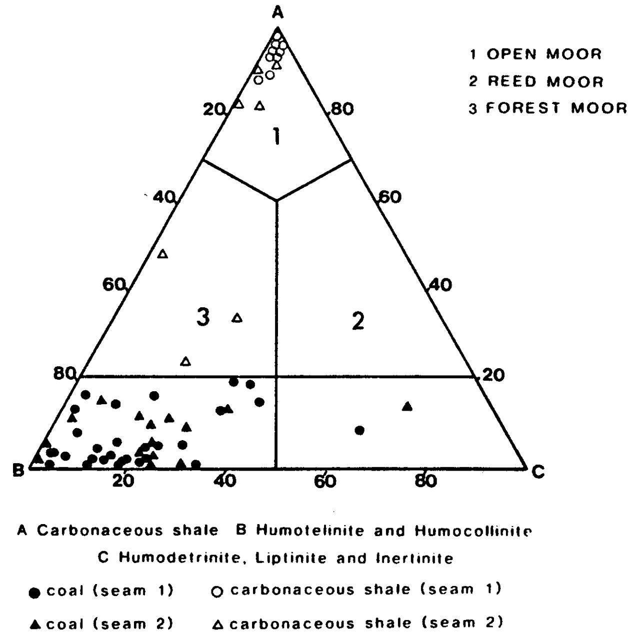


Figure 6. Ternary compositional diagram showing coal facies, Obed Marsh coal seams

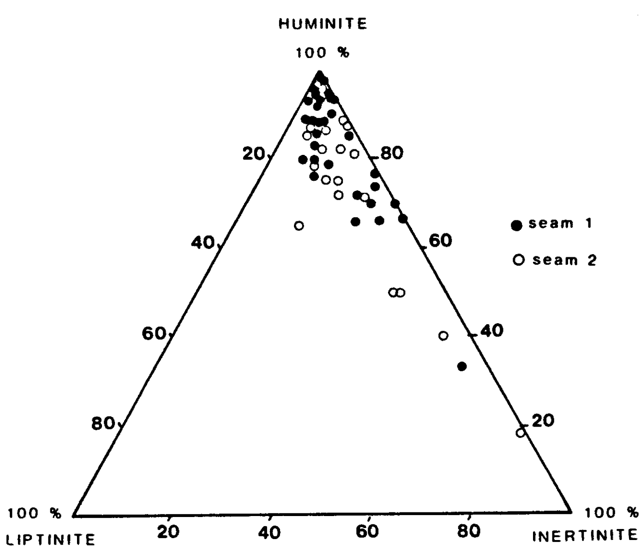


Figure 7. Ternary maceral composition diagram of the Obed Marsh coal seams

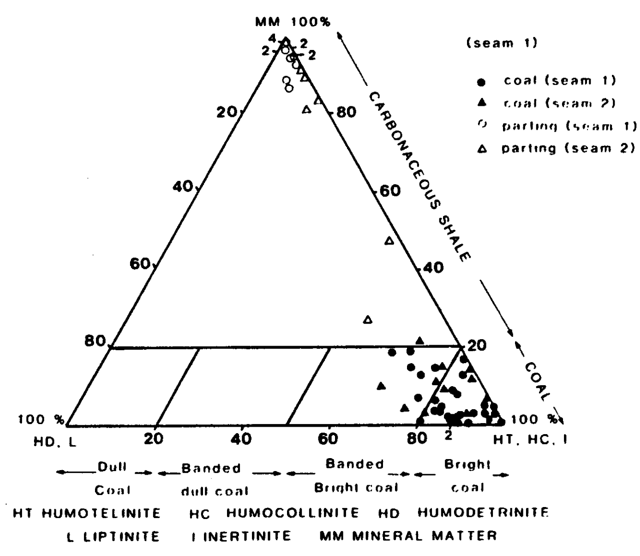


Figure 8. Ternary compositional diagram showing the relationship between macerals and microlithotypes, Obed Marsh coal seams

have caused the coal to increase in inertinite content at the expense of humotelinite and humocollinite. This did not happen in the Obed peat swamp, with the exception of some intervals in seam 2, and the water level was almost always covering the peat surface resulting in low inertinite content. In addition, the bright and banded bright nature of the Obed coal (Figure 8) indicates relatively 'wet' conditions, but not as wet if the coal contained abundant humodetrinite and liptinite. Therefore, the higher TPI values are largely maintained due to the high humotelinite content of the coal and not due to high semifusinite and fusinite, which could form even under mildly oxidizing conditions.

COMPARISON OF ORGANIC PETROLOGY BETWEEN THE SEAM 1 SECTIONS

Sections 1 and 2 of seam 1 are relatively similar in maceral composition, except for the following differences which indicate some localized events:

1) Section 1 has relative more liptinite, particularly in interval A than section 2 (Figures 2 and 3), indicating possible difference in accumulation of plant debris. Since sporinite and cutinite are the most dominant components of the liptinite content, the increase in liptinite in interval A, section 1 is mainly due to high sporinite and cutinite input, which may have been caused by directional action of wind or water.

2) A 9 cm thick inertinite rich interval is present only in the middle of interval B, section 2 (Figure 3). Pyrofusinite and pyrolytic carbon are present in the above interval and Goodarzi (1985a) reported that the occurrence of pyrofusinite and pyrolytic carbon in the Highvale coal seam in Alberta was due to peat fire. Therefore, a similar event can be envisaged for the presence of high inertinite in interval B of Obed Marsh. The limited extent of the inertinite interval indicates a localized occurrence of peat fire, which was limited to higher and drier elevations.

3) Section 1 has relatively clean coal due to the presence of five partings (4-10 cms), in contrast, section 2 has seven partings (5-14 cms).

SUMMARY

In-seam profile analysis of three sections from seams 1 and 2 in the Obed-Marsh coal deposit indicates undisturbed peat accumulation over long periods of time and infrequent inundation by clastic sediments. The coal is of subbituminous B to high volatile bituminous C rank and is characterized by high amounts of huminite and generally low amounts of liptinite and inertinite, except for some intervals in both seams.

ACKNOWLEDGEMENTS

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RELATIONSHIP OF PETROGRAPHIC AND CHEMICAL PARAMETERS IN COAL RANK EVALUATION FOR WESTERN CANADIAN COALS

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ABSTRACT

Reflectance measurements in the random mode were carried out on a suite of 110 western Canadian coals ranging in rank from lignite to anthracite. The reflectance data were compared with dry mineral-matter free fixed carbon data on the same coals. The best results were obtained when reflectance and fixed carbon data were compared for all the coals and for a population restricted to those with greater than 90 per cent vitrinite content. Correlation coefficients for 3rd order regression analyses on these two populations are 0.965 and 0.962 respectively. When the sample population was limited to those coals with less than 5 per cent inertinite the correlation coefficient is 0.936 and 0.884 when only samples with less than 10 per cent ash are considered. Reflectance boundaries related to ASTM rank thresholds agree fairly well with published limits. The study suggests a good separation of lignites, subbituminous and high volatile B/C bituminous coals on the basis of reflectance data.

RÉSUMÉ

Des mesures du pouvoir réflecteur ont été prises au hasard sur une série de 110 échantillons de charbons de l'ouest canadien, le type de charbon allant de lignite à anthracite. Les données du pouvoir réflecteur sont comparées aux données du carbone fixe, pur et sec, mesurées sur les mêmes échantillons. Les meilleurs résultats sont obtenus lorsque les données du pouvoir réflecteur et du carbone fixe sont comparées, d'une part, pour tous les charbons, et, d'autre part, pour une population restreinte à ceux dont le contenu en vitrinite excède 90%. Les coefficients de corrélations (régression de troisième ordre) sur ces deux populations sont de 0.965 et 0.962 respectivement. Lorsque la population des échantillons est restreinte aux charbons possédant moins de 5% d'inertinite, le coefficient de corrélation est de 0.936 et 0.884, et ce, seulement lorsque des échantillons avex moins de 10% en cendres sont considérés. Les limites du pouvoir réflecteur associées aux niveaux limites ASTM sont en accord avec les limites publiées jusqu'à maintenant. Cette étude suggère qu'une bonne séparation existe entre les lignites, les charbons sous-bitumineux et les charbons à haute teneur en volatile B/C tel qu'indiqués par les données du pouvoir réflecteur.

INTRODUCTION

The most commonly used approaches to describe coal composition are chemical and petrographic and a number of publications have discussed the relationship of characteristics measured in one method to those observed in the other. Routine chemical determinations include proximate and ultimate analyses and evaluation of calorific or heating value, whereas petrography includes measurement of maceral content and reflectance.

Assessment of maceral content, and occasionally microlithotypes, defines coal type which is based to a large extent on the composition of the original plant material and the varying degrees of geochemical and biochemical alteration to which the peat was subjected in the swamp. Reflectance and a number of the parameters measured by chemical analyses define rank, (e.g. fixed carbon or volatile matter and ultimate carbon), that is the degree of maturity which coaly material has achieved mainly through the influence of varying thermal regimes in its geological history. A third group of chemically derived measurements (ash, sulphur, and calorific value) define what has sometimes been described as coal grade, a characterization with strong utilization significance. The qualities of grade may be dependent partly on rank or on type or may not be related at all to these characteristics.

In the present paper an attempt will be made to relate coal rank as measured by vitrinite reflectance to coal rank as determined chemically. The specific chemical parameter used is fixed carbon on the dry mineral-matter free basis. A certain amount of sorting of the sample population was done to explore the effects of varying maceral and ash contents. The coals that form the subject matter of the report are all western Canadian coals and range in age from Lower Carboniferous (Mississippian) to Paleocene and in rank from lignite to anthracite.

SAMPLING AND ANALYTICAL PROCEDURES

A total of 110 samples was analyzed for this study. Chemical analyses, reflectance measurements and maceral content determinations were made on these samples. Table 1 summarizes sample origin including coal-bearing formation, age and geographic locality. Details on local stratigraphy and other geological features of these coals may be found in Smith (1989).

Table 1. Age and place of origin for samples used in this study

Number of Samples	Group or Formation	Age	Locality
2	Paskapoo	Paleocene	Obed Marsh, Alta.
12	Ravenscrag	Paleocene	S. Saskatchewan
14	Edmonton	L.* Cret.-Tert.	Wabamun Lake and Battle River areas, Alta.
8	Coalspur	Paleocene	Coal Valley, Alta.
4	Nanaimo	L.* Cret.	Vancouver Island
18	Gates	E.* Cret.	Luscar-Cadomin and Smoky River areas, Alta. Tumbler Ridge, B.C. **
5	Gething	E.* Cret.	E. Central B.C. **
4	Minnes	E.* Cret.	E. Central B.C. **
37	Kootenay	Jura./Cret.	Fernie & Elk Valley areas, B.C., Canmore area, Alta. **
2	Currier	Jura.	Groundhog field, B.C.
4	Kayak	E.* Carb.	Northern Yukon

* E. = Early, L. = Late
** Some or all of samples in these areas from exploration drillholes

Where possible, samples of fresh coal from active mines or boreholes were studied and many of the samples were canned in distilled water to prevent loss of moisture and oxidation. However, in many cases, especially with the lower rank coals, moisture was lost, presumably during preparation for analysis. With coals of anthracitic rank it was not possible to obtain much fresh material because coals of this rank are not being mined at present except in the Groundhog field. Thus the semianthracites of the Kootenay Group (from the Canmore field, Alberta) and the semianthracites and anthracites from the northern Yukon were from outcrop and, therefore, possibly weathered to some extent.

Petrographic analyses were carried out on polished particulate specimens prepared according to ASTM specifications (American Society for Testing and Materials, 1979) and analyzed following procedures and terminology outlined by the International Committee for Coal Petrology (ICCP, 1971) and Stach et al (1982). Maceral determinations were made by counting 500 points per sample. Reflectance measurements were carried out on vitrinite A for higher rank coals and eu-ulminite B for the lignites and subbituminous coals. Fifty points per sample were measured and averaged. Reflectance measurements on all samples were made in the random mode with the polarizer out. All the petrographic determinations were made on a Leitz Orthoplan microscope with MPV II photometric accessories at a magnification of x 625.

The chemical analyses were made according to ASTM specifications (ASTM, 1979).

RESULTS

One of the important criteria for establishing rank in higher rank coals is weight per cent volatile matter, dry mineral-matter free basis (dmmf) or dry mineral-matter free fixed carbon (100-volatile matter). Figures 1 to 4 illustrate this relationship for various sample populations.

POPULATION 1: ALL SAMPLES

Figure 1 shows the relationship between random reflectance and fixed carbon (dmmf) for all of the samples studied. The relationship is expressed by a third order regression line (solid). Superimposed on the diagram is a dashed line representing the relationship established by Kötter (1960) for a series of European coals. The points on Kötter's curve are not shown. Kötter's curve is frequently consulted when attempts are made to correlate reflectance with chemically determined ranks. Kötter's curves were drawn in the semi-log mode and Figure 1 is similarly framed for better comparison of the two curves.

Several observations may be made about this diagram. First, there is a fairly wide scatter of points about the western Canadian curve, although a third order regression analysis gave a correlation coefficient of 0.965. As will be mentioned later, this is thought to be due in part to rather widely varying maceral contents in these samples, including an inertinite range from 0 to 66 per cent. Inertinite has a higher carbon content than the other maceral groups and, therefore, high inertinite coals tend to yield higher fixed carbon on analysis. Also some of the anthracites and semianthracites of this study are from outcrop and this too may distort the position of the trend line. A second point to be noted is the relationship of the two curves to one another. They are only roughly parallel. At the low rank end the Kötter curve seems to suggest lower fixed carbon (higher volatile matter) than was measured in Canadian coals of the same reflectance.

The Canadian curve is pulled down at the lower rank end by the presence of two coals with reflectances below 0.20. These are high huminite lignites in which almost the entire composition is eu-ulminite A. The reflectance measurements were made on this material that has a significantly lower reflectance than eu-ulminite B. In this instance corresponding reflectances on eu-ulminite B would probably be between 0.25 and 0.30.

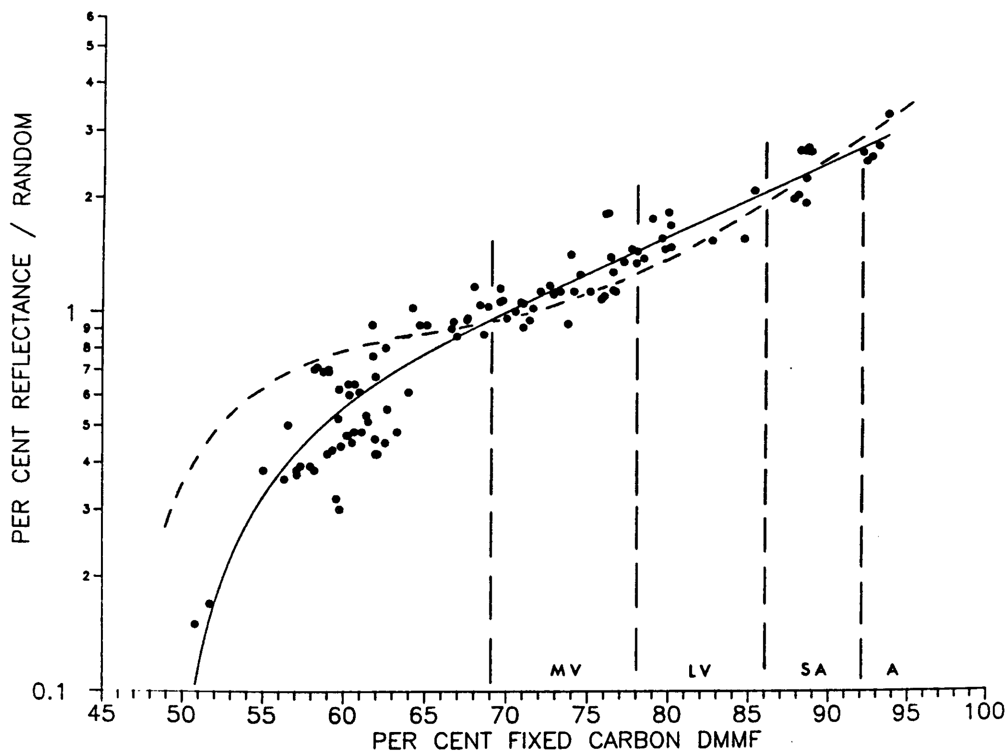

Figure 1. Relationship of fixed carbon (dmmf) to random reflectance for all coals of study. Unbroken line is 3rd order regression trend line; dashed line from Kötter (1960); MV and LV = medium volatile and low volatile bituminous; SA = semianthracite; A = anthracite.

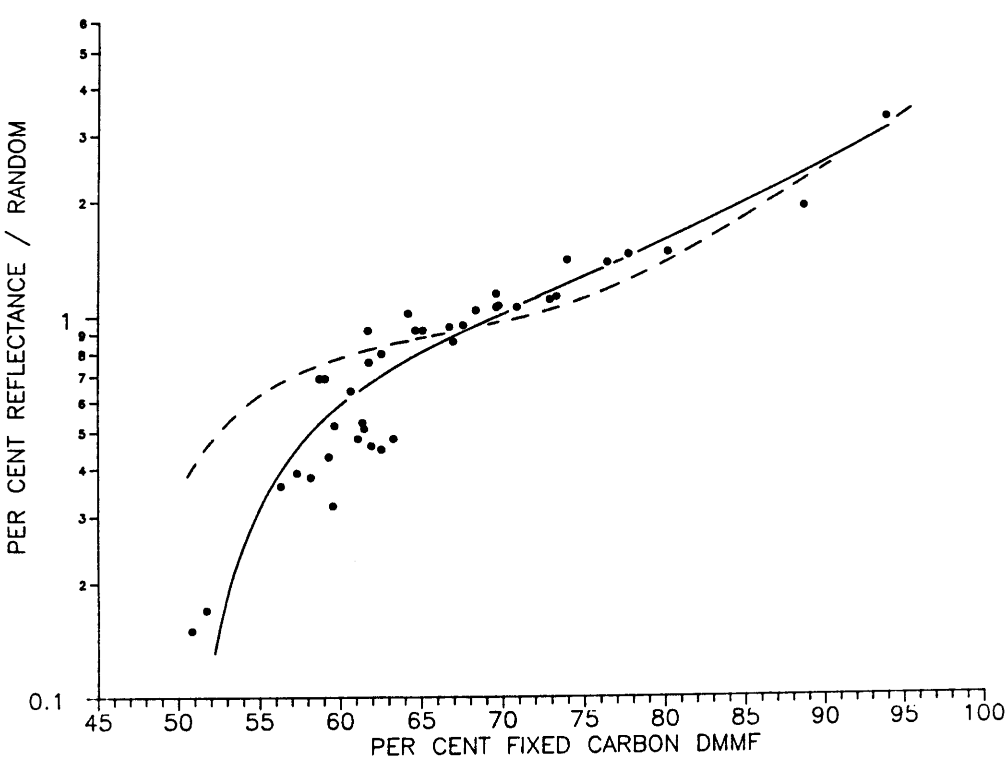

Figure 2. Relationship of fixed carbon (dmmf) to random reflectance for samples with >90 per cent vitrinite. Unbroken line is 3rd order regression trend line; dashed line from Kötter (1960).

A relatively dense cluster of Canadian points below the trend line, roughly between 55 and 65 per cent fixed carbon, is almost entirely composed of Saskatchewan lignites and subbituminous coals from Alberta. They seem to constitute a separate population.

In the medium and low volatile bituminous range the Kötter curve is slightly below the Canadian curve indicating that for similar reflectances the European coals analysed by Kötter would have somewhat higher fixed carbon contents. However, these actual and postulated differences should be regarded with due caution. Differences in analytical procedures, analytical errors, sample history as well as real differences in the mainly Mesozoic and Tertiary coals of western Canada, compared with the mainly Carboniferous coals Kötter studied, are all composited in the relative positions of the two curves.

POPULATION 2: SAMPLES WITH >90 PER CENT VITRINITE CONTENT

Figure 2 again displays a cross plot of random reflectance versus fixed carbon, but the Canadian coals shown are restricted to those with greater than 90 per cent vitrinite on the mineral-matter free basis.This restricted series of samples is more similar to Kötter's material than the samples shown in Figure 1; apparently he examined hand-picked vitrinites, or at least vitrinite concentrated in some fashion. The scatter of points around the trend line appears less pronounced than in Figure 1. However, the 3rd order correlation coefficient is 0.962, almost identical to Figure 1. Apparent again is the cluster of points below the Canadian trend line representing vitrinite or huminite-rich lignites and subbituminous coals. There is an unfortunate dearth of samples at the upper end of the curve that prevents a proper discrimination of the curve position in the low volatile bituminous to anthracite range. Again the Kötter curve has been superimposed to show comparison with the western Canadian curve.

POPULATION 3: SAMPLES WITH <10 PER CENT ASH

The relationship shown in Figure 3 represents another sorting of the original 110 samples whereby random reflectance and fixed carbon values for only those samples with less than 10 per cent ash (dry basis) have been plotted. The ash restriction was imposed in an attempt to diminish the influence of mineral matter (particularly carbonates) on the determination of volatile matter and hence fixed carbon. This figure contains more detail than Figures 1 and 2 in that the rank of the coals is identified as determined by ASTM standards. Also plotted on the Figure are best-fit reflectance boundaries that appear to match separation of the ASTM rank classes. It should be noted that there are few, if any, natural breaks apparent in the distribution of points with the possible exception of the coals at the lower end of the rank scale, that is high volatile bituminous B/C and lower. It is of interest that these lower rank coals seem to divide fairly well along reflectance boundaries though certainly not along fixed carbon thresholds. This latter characteristic has, of course, long been recognized and is the reason why the ASTM has classified coals below 69 per cent fixed carbon according to calorific value. Figure 3 suggests that reflectance might also be useful in discriminating these lower rank classes.

There is considerable overlap in reflectance between the high volatile A and medium volatile bituminous groups and a reflectance threshold is difficult to place, at least for the group of samples included in this study. The 0.95 random reflectance threshold is somewhat lower than that suggested by other authors, e.g. Davis (1978) and McCartney and Teichmüller (1972) made the division at 1.12. The 0.95 boundary may be too low due to the maceral composition of some of the medium volatile coals included in the study. Calculation of the mean inertinite content for the coals of this rank that plot below the trend line of Figure 3 shows a value of 36 per cent while the coals plotting on or above the trend line have inertinite contents of only 14 per cent. Thus the high inertinite coals appear to show elevated fixed carbon contents though their reflectances suggest a lower rank category.

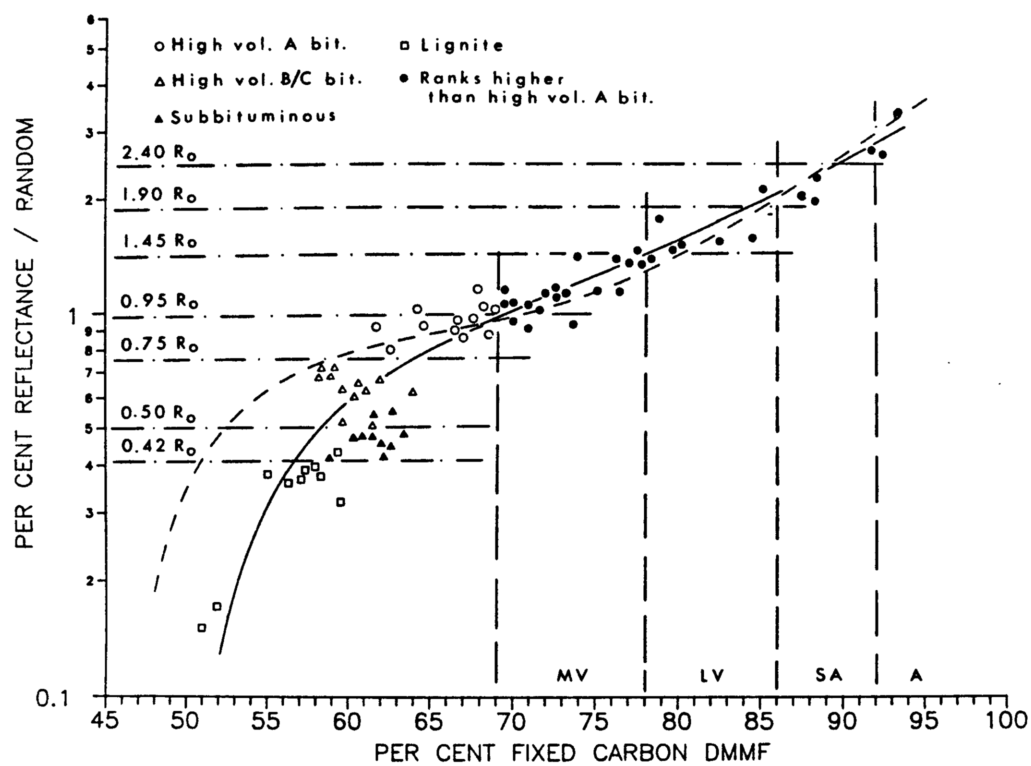

Figure 3. Relationship of fixed carbon (dmmf) to random reflectance for samples with <10 per cent ash (dry). Unbroken line is 3rd order regression trend line; dashed line from Kötter (1960). MV, LV, SA and A as in Figure 1.

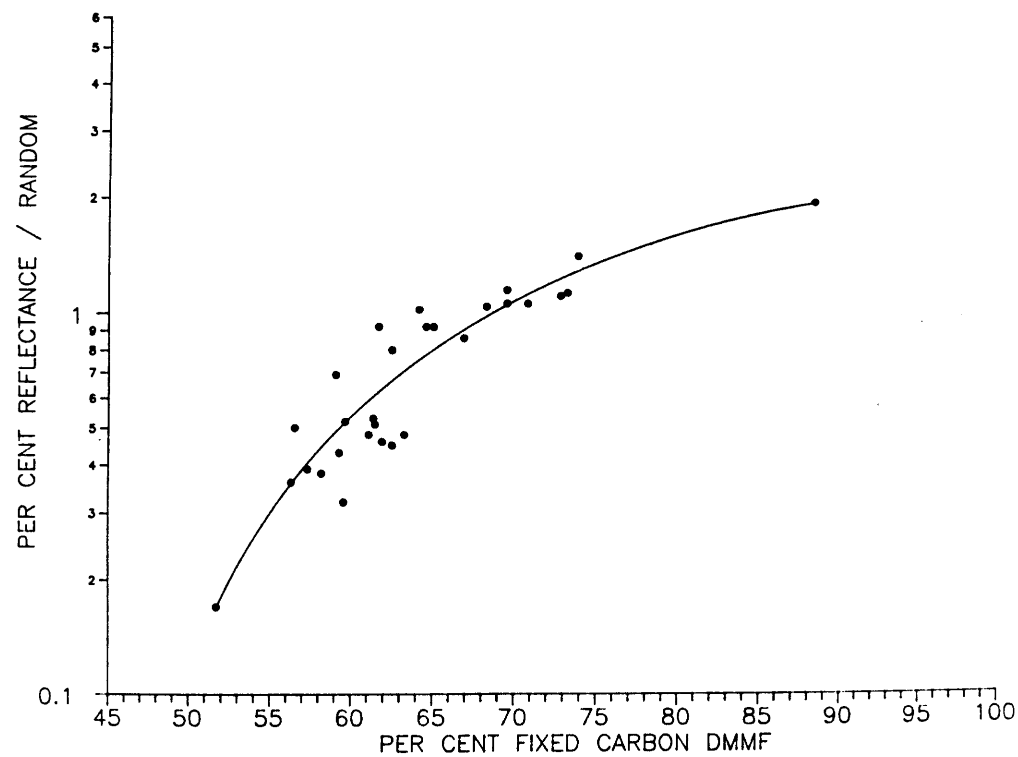

Figure 4. Relationship of fixed carbon (dmmf) to random reflectance for samples <5 per cent inertinite. Unbroken line is 3rd order regression trend line.

Despite the overlap in reflectance between some of the rank classes, a comparison of the rank thresholds with those proposed by other authors shows rather good correlation. These comparisons are shown in Table 2. The thresholds suggested in this paper should be regarded as tentative for the moment and have been included in Table 2 for the sake of comparison. Some need to be better established such as the high volatile A bituminous and medium volatile bituminous boundary. Also better anthracite samples should be studied so as to determine the upper end of the curve with more confidence.

The correlation coefficient of a third order regression for population 3 is 0.884. This would suggest that maceral composition rather than variations in ash content was more important in controlling variation in fixed carbon/volatile matter content for the total sample population of this study. It should be mentioned that the original selection of samples for the study was restricted to material with a maximum of 20 per cent ash.

POPULATION 4: SAMPLES WITH <5 PER CENT INERTINITE

Figure 4 represents yet another sorting of samples based on maceral content. This time only those samples with less than 5 per cent inertinite (mineral-matter free) were chosen for plotting, that is samples with combined vitrinite and liptinite contents of 95 per cent or more. This select group of samples is relatively small and with one exception, are all medium volatile bituminous or lower rank. The population of samples represented on this figure are all reactive-rich, so that the rather wide scatter of points about the trend line is somewhat surprising. The correlation coefficient is 0.936. However, again differences in maceral composition may explain divergence from the line. Those samples on or above the line have a mean content of vitrinite B/humodetrinite plus liptinite of 28 per cent while those below the line average about 18 per cent. This combination of macerals probably has higher volatile matter contents (lower fixed carbon) than vitrinite A/humotelinite. Thus the samples that plot above the line have lower than average fixed carbon contents relative to their reflectances while the reverse is true for those samples below the line.

Table 2: Comparison of reflectance thresholds with ASTM Rank Classes
(all reflectances random)

Rank	Kötter (1960)*	McCartney and Teichmüller (1972)	This Paper
Lignite			< 0.42
Subbituminous			0.42 - 0.50
High vol. B/C bit.		0.50 - 1.12	0.50 - 0.75
High vol. A Bit.			0.75 - 0.95
Med. vol. bit.	1.02 - 1.39	1.12 - 1.51	0.95 - 1.45
Low vol. bit.	1.39 - 1.82	1.51 - 1.92	1.45 - 1.90
Semianthracite	1.82 - 2.56	1.92 - 2.50	1.90 - 2.40
Anthracite	> 2.56	> 2.50	> 2.40

* Estimated from Kötter's curve

CONCLUSIONS

Comparison of reflectance data and fixed carbon contents for a series of western Canadian coals indicates good correlations when all samples are considered and when the population is restricted to samples with more than 90 per cent vitrinite. The correlation is slightly poorer when the sample population is restricted to coal with less than 5 per cent inertinite and poorest when the population is limited to samples with less than 10 per cent ash.

Correlation coefficients are dependent on the number of samples involved in the calculations. A proper comparison of coefficients should be made on sample populations that are equal in number. Thus a comparison of coefficients from populations 1 and 4 where the difference in numbers of samples is pronounced is not as valid as comparison between populations 1 and 2 where the sample numbers are more nearly equivalent.

Reflectance limits related to ASTM rank boundaries compare favourably with threshold values published by other authors except for the boundary between high volatile A bituminous and medium volatile bituminous where a considerable overlap in values makes the placement of such a threshold difficult. The data on western Canadian coals also suggest that reflectance boundaries might be useful in separating the lignite, subbituminous and high volatile B/C bituminous rank classes.

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EFFECTS OF STRUCTURE AND TECTONICS ON COAL GEOCHEMISTRY - SOME EXAMPLES FROM BRITISH COLUMBIA

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ABSTRACT

Geochemical variations in British Columbia coals are well known, and have been attributed to a variety of factors such as rank and depositional environment. This paper examines the effects of tectonic setting and smaller-scale structure on coal geochemistry in selected British Columbia deposits.

Average major and trace element characteristics from complete channel sections of two Intermontane coals - Tulameen and Hat Creek, are compared with mean values of all major seams in four Foreland basin type coals - the Nanaimo and Comox deposits of the Insular Belt and the Monkman and Quintette coals of the Northeast Coal Basin. Results indicate that similarities exist in coal deposits formed in similar tectonic settings. For example, the Intermontane coals examined exhibit low B and W, intermediate Ba, Sr, Br, Se, Fe and S, and high Mo, Mn and Na. The Northeast deposits have low Cu, intermediate Sr, and high Ba, Rb, Zn, K and Al. Characteristic patterns for tectonic settings are more common for trace elements than major elements, indicating that the latter are more likely to be influenced by local conditions.

Geochemical effects of local structures in the Wellington Seam, Nanaimo Basin and the Blakeburn Opencast Mine, Tulameen coal deposit are also examined. Elevated Au and Platinum Group Element values were noted in highly slickensided and sheared Wellington coal and faulted Blakeburn coal respectively. These enrichments, relative to undeformed sections, are thought to be due to increased rates of groundwater flow in the deformed coal, the exposure of greater numbers of bonding sites, and access to deeper groundwaters which are more enriched in certain elements.

INTRODUCTION

Coal is deposited and preserved in two major tectonic settings (Stach 1982, Rahmani and Flores 1984) - Foredeeps such as the Cretaceous Rocky Mountain Foredeep or the modern SW coast of New Guinea; and Continental Intermontane basins such as the Carboniferous basins of the French Central Plateau or the Tertiary Basins of northern Thailand. Coal deposits formed in each of these settings have several general distinguishing characteristics. These include deposit size, numbers of seams, and seam thicknesses and lateral extents. Intermontane coals are typically limited in lateral extent and contain fewer seams which however may attain considerable individual thicknesses. Depositional setting of the coal-bearing sequence is also influenced by tectonic setting, with freshwater lacustrine or fluvial environments dominating in Intermontane basins,and coastal plain paralic settings, ranging from fluvial to deltaic, in Foredeep basins.

The purpose of this paper is to demonstrate, using some examples from British Columbia, that geochemical characteristics of coal are also affected by tectonic setting. In addition the effect of intrabasinal smaller-scale structures on elemental variation in coal deposits is examined.

TECTONIC SETTING

The coal deposits of British Columbia are related to two primary tectonic settings - Intermontane and Foredeep or Foreland basins (Van der Flier-Keller and Goodarzi 1988A:B). The Tertiary Similkameen, Bowron, Chu Chua and Telkwa coal deposits of the Intermontane Belt are examples of the former (Long 1981), while the Cretaceous Vancouver Island and Rocky Mountain coals may be classified as Foreland Basin in style.

Geochemical characteristics of six coal deposits, two from Intermontane settings and four from two examples of Foreland basins in Western Canada, are examined; Nanaimo and Comox from the Insular Belt, Hat Creek and Tulameen from the Intermontane Belt, and Monkman and Quintette from the Northeast Rocky Mountain Belt. The general characteristics of deposits in similar tectonic settings are comparable, i.e. depositional environments, age, interbedded strata, and structural style are similar. However, local variations in adjacent source rocks and therefore groundwater characteristics do occur.

Intermontane Coals

The Intermontane coal deposits examined are small in size and are formed by accumulation of Tertiary sediments and volcanics in extensional strike slip fault-bounded basins. Thick lignitic to high volatile B/C bituminous coal sequences of limited lateral extent result. For example, the Hat Creek deposit contains 50, 70 and 160m thick seams, in which the maximum thickness of clean coal is 30m. Adjacent lithologies are diverse ranging from a Cretaceous ultramafic complex to Eocene basalts and Triassic Nicola Group volcanics. Interbedded lithologies include lacustrine and alluvial fan sediments (Long 1981, Goodarzi and Van der Flier-Keller 1988). Freshwater deltaic environments are often found associated with Intermontane deposits worldwide (Long 1981), however, they are not present in the Canadian Cordillera.

Foreland Basin Coals

The Foreland Basins include the Northeast and Southeast Rocky Mountain deposits and the Insular coals. These coal-bearing sequences are more extensive, and on average contain a greater number of seams (average number of economic seams in the Northeast Coalfields is six) which are also generally thinner (less than 9m and more commonly around 4m) than the Intermontane coal seams. Structural settings of the Foreland basins vary from thrust faulted blocks containing anticline syncline pairs in the Northeast Coalfields, to relatively uniformly easterly dipping faulted strata in the Vancouver Island coalfields. Deltaic depositional environments dominate, however fluvial strata are also recognised (Carmichael 1983). Adjacent lithologies in Foreland basins are also variable however sedimentary and metasedimentary units are more typical than in the Intermontane situations.

RESULTS

When average elemental concentrations for coal in the six deposits (Table 1) are examined it is evident that similarities exist between

Table 1. Mean major (%) and trace element (ppm) concentrations in the six Western Canadian coal deposits

Element	Nanaimo	Comox	Hat Creek	Tulameen	Monkman	Quintette
Al_2O_3	2.85	3.50	3.21	9.8	4.96	4.5
Ash	15.6	13.9	17.8	8.55	17.21	22.8
CaO	1.73	1.65	0.26	0.70	2.77	1.14
Fe_2O_3	0.68	1.51	0.54	0.60	1.42	0.86
K_2O	0.17	0.06	0.085	0.996	0.41	0.39
MgO	0.63	0.12	0.10	0.33	0.08	0.3
MnO	0.0062	0.0045	0.0075	0.036	0.001	NA
Na_2O	0.12	0.02	0.27	0.35	0.32	0.09
P_2O_5	0.06	0.16	NA	NA	0.14	0.045
S	0.70	2.07	0.50	0.50	0.94	B.D.
TiO_2	0.15	0.25	0.17	0.57	0.50	1.28
As	3.8	55.9	11.4	2.6	NA	2.1
B	106	70	9	44	NA	37
Ba	499	109	161	198	1092	958
Br	1.9	2.0	11.8	9.1	NA	6.9
Cl	128.0	261.8	42.5	93.2	NA	101.7
Co	4.1	4.2	9.2	3.7	9.1	3.9
Cr	28.9	19.1	30.3	7.4	29.6	24.1
Cu	12.2	18.2	35.4	NA	12.9	11.4
Mo	2.2	2.3	3.5	2.8	NA	2.4
Rb	12.8	10.5	6.0	10.1	33.1	24.8
Sb	0.6	0.6	0.5	0.3	NA	0.8
Sc	3.9	6.1	6.4	3.0	NA	4.9
Se	0.6	0.9	1.1	0.9	NA	3.0
Sr	368	337	107	105	151	178
Th	1.0	1.0	2.5	1.8	3.0	6.2
U	0.7	0.6	1.5	1.0	2.1	2.9
V	31.8	43.2	100.8	30.6	576	44.3
W	1.7	1.0	0.6	0.6	NA	1.5
Y	11.0	16.4	NA	NA	7.3	15.0
Zn	9.6	11.3	26.0	29.7	30.6	39.7
Zr	21.0	27.3	NA	NA	60.9	56.7

deposits formed in similar tectonic settings (Van der Flier-Keller and Goodarzi 1988A:B). The Nanaimo and Comox coals show groupings for certain elements, and the same is true of the Monkman and Quintette, and Hat Creek and Tulameen coal deposits. Specific trends are outlined in Table 2.

Table 2. Regional trends in coal geochemistry (modified from Van der Flier-Keller and Goodarzi 1988B)

Tectonic Setting	Element Characteristics (relative to mean values for all the deposits)			
	Low	Low to Intermediate	Intermediate	High
Insular	Th Br U Zn		Sb Co Mo	Sr Rb Ca B
Northeast	Cu		Sr	Ba Rb Zn K Al
Intermontane	B W	Ba Sr Br Se Fe S		Mo Mn Na

Major elements are not strongly grouped by tectonic setting, however high Ca appears to be characteristic of the Insular coals, high K and Al of the Northeast coals and intermediate to low Fe and S of the Intermontane coals. Other major element concentrations are therefore probably controlled by more local factors. Trace elements, in contrast, are strongly grouped by tectonic setting. This indicates that conditions within the coal bearing basins are such that distinctive geochemical patterns, particularly for trace elements, are produced. These patterns may be related to a number of factors (Van der Flier-Keller and Goodarzi 1988) which are all directly or indirectly controlled by the tectonic setting of the coal-bearing succession. For example, B, S and Sr variations may be related to depositional environment with highest values occurring in most brackish deltaic settings. Low values of these elements would therefore be expected in Intermontane basin tectonic settings. The effect of source rocks on geochemistry may also be ultimately related to tectonic setting. Typical source rocks for the Northeast coals are sedimentary and metasedimentary while a wide range of diverse lithologies are more commonly associated with the Intermontane coals. While individual elements may be related to certain factors such as rank or depositional environment, the total association of elemental variation characteristic of any set of coal deposits must be related to the overall tectonic setting of the deposits.

LOCAL STRUCTURE

Smaller scale structure of a coal basin may also impact coal composition. For example, faults directly associated with the coal-bearing succession may provide conduits for circulating groundwaters leading to depletion or enrichment of particular elements in the coal adjacent to the fault. Similarly the reduction in coherence of a seam or coal section resulting from folding or faulting may give rise to variations in permeability which may also ultimately result in changes in coal composition.

Two examples of the effects of local structure on coal composition are given. They are the Wellington Seam in the Nanaimo coal Basin and the Blakeburn Openpit in the Tulameen coal deposit.

WELLINGTON SEAM - NANAIMO BASIN

The coal occurrences on Vancouver Island may be subdivided into the Nanaimo and Comox subbasins. The Nanaimo Coalfield contains three major seams, the lowermost of which is the Wellington Seam. The seam is located in the Extension Formation of the Nanaimo Group (Upper Cretaceous in age) and outcrops to the west of Nanaimo in a northsouth striking belt. The coal is exposed at the Wolf Mountain Colliery and at the Nanaimo Waterworks, approximately four kilometres to the south, where it is intensely deformed. The coal section at the Waterworks contains a heavily slickensided and sheared upper unit which overlies a band of hard coal. The latter rests on a moderately slickensided seam base. The seam is underlain and overlain by carbonaceous mudstones. Basal mudstones are structurally deformed.

The section is overlain by thick, hard, and resistant sandstones and conglomerates and is underlain by a resistant unit of sandy siltstones. The less competant coaly unit has acted as a zone of weakness between the two more resistant units and has become severly deformed as a result of stresses applied. No distinct continuous shear planes were recognised in outcrop, however, sigmoidal structures and minor shear planes were noted in addition to abundant slickensides and listric surfaces.

RESULTS

Major and trace element geochemistries of the major benches of the seam are compared with the average geochemistry of the Nanaimo coals (Van der Flier-Keller and Dumais 1988) and also with the whole seam geochemistry of the laterally equivalent Wellington seam at Wolf Mountain.

Ash contents of the samples vary from 46% to 4.2% in the deformed Wellington seam, and average 15.6% and 28.2% for the Nanaimo coals in general and the Wellington seam at Wolf Mountain respectively. Major element values for all the samples are comparable. A number of trace elements are enriched or depleted in the deformed coals compared to either the Wolf Mountain or average Nanaimo coals (Table 3). Gold is considerably enriched, while Co, Ni, Pb, Rb, Sb, Sc, U, Th and the REE are moderately enriched in at least 75% of the deformed coal samples. Elements which are consistently depleted in the deformed coals include B, Cl and Sr.

BLAKEBURN OPENCAST MINE - TULAMEEN COALFIELD

The Tulameen coal deposit is located in south central British Columbia in the Intermontane Belt. The thirty metre coal-bearing sequence is of Eocene age and where best exposed in the Blakeburn Opencast mine contains approximately 18 metres of coal. The entire section was sampled in 1987 and geochemical and petrographic results have been reported (Goodarzi and Vander Flier-Keller in press). The 200 m long section is disrupted by a major fault which offsets the entire coal-bearing sequence by approximately 30 m. In addition a number of smaller normal and thrust type

Table 3. Enrichment and depletions of elements in the deformed Wellington seam (in ppm)

	Element	1	2	3	4	5	6
	LOI*	84.4	71.8	53.9	95.8	73.9	84.3
>>	Au**	5	14	73	130	48	52
>	Co	4.1	2.8	3.4	6.6	9.1	11.0
	Ni	13	10	23	11	18	59
	Pb	1		7	2	5	2
	Rb	13	13	36	16	5	5
	Sb	0.6	0.4	6.8	0.2	2.7	1.5
	Sc	3.9	3.3	14.1	1.8	5.1	7.2
	U	0.74	0.63	1.25	0.36	2.69	0.93
	Th	1.0	1.1	2.7	0.5	5.3	2.1
	La	4.3	3.4	7.5	4.4	9.6	15.3
	Ce	8.7	6.5	18.3	8.8	22.0	27.6
	Nd	4.4	2.0	8.6	4.1	11.0	33.5
	Sm	0.90	0.51	1.90	0.56	2.11	6.58
	Eu	0.24	0.16	0.52	0.14	0.55	1.62
	Tb	0.14	0.05	0.42	0.40	0.52	1.44
	Yb	0.60	0.44	1.38	0.22	1.46	2.47
	Lu	0.12	0.07	0.26	0.04	0.29	0.38
<	B	106	90	46	26	30	10
	Cl	128	60	30	10	60	50
	Sr	368	380	30	130	80	70

* %
** ppb
LOI Loss on Ignition

1 Average Nanaimo coal
2 Wolf Mountain Wellington Seam
3
4 Nanaimo Waterworks Wellington Seam
5
6

faults have been identified. Samples of coal from and adjacent to these subsidiary faults have been analysed for a wide range of elements including Au and the Platinum Group Elements (PGE).

RESULTS

Results indicate that in certain of the minor faults the PGE are substantially enriched compared to the rest of the coal-bearing sequence. Table 4 lists the Pt and Pd values for the faulted coal. Three faults in the central portion of the section are enriched in Pt. The remaining faults have concentrations comparable with the general section (Table 5). Palladium values, in contrast, are significantly enriched in the majority of the faulted samples compared to the background section where only one coal sample contained Pd above detection limits (Table 5). The highest Pt values correspond to maximum Pd values. No comparable enrichments were noted for any other elements.

Table 4. Pt and Pd values in Blakeburn faulted coal (ppb)

	Pt	Pd		Pt	Pd
BL88-01	-	8	BL88-13	>10,000	750
BL88-02	30	38	BL88-14	10	-
BL88-03	20	50	BL88-15	160	55
BL88-04	-	10	BL88-16	-	-
BL88-05	10	3	BL88-17	10	-
BL88-06	10	17	BL88-18	20	4
BL88-07	-	-	BL88-19	10	4
BL88-08	-	2	BL88-20	-	-
BL88-09	-	-	BL88-21	-	-
BL88-10	210	13	BL88-22	-	-
BL88-11	190	14			
BL88-12	10,000	6,100	Average Blakeburn	17	-

- below detection limits

Table 5. Pt and Pd values in the background Blakeburn section (ppb)

	Pt	Pd		Pt	Pd
C1/C2	67	-	C29	-	-
C7	29	-	C31/32	-	-
C8	-	-	C34/36	-	-
C10	-	-	C38	9	-
C11	170	-	C40/42	8	-
C13	-	-	C44/45	19	-
C16/19	12	-	C50	-	-
C21/23	-	-	C51	-	-
C25	23	70	C52	-	-
C27	-	-	C54/56	-	-

DISCUSSION

These geochemical anomalies may be explained in a variety of ways. First the coal as a result of deformation may be more permeable and therefore may allow a greater quantity of groundwater through flow. Secondly the deformation may have exposed a greater number of bonding or adsorption sites for certain elements. If the groundwaters are of similar composition throughout the entire coal basin then these factors alone might give rise to higher values of certain elements in the most deformed samples. In addition, faults which extend deeper into the subsurface may access groundwaters which are more enriched by virtue of having flowed through different source lithologies (Freeze and Cherry 1979). This is proposed to be the case for the Blakeburn section, where the groundwaters accessed by the faults are those which have flowed through or been associated with the Tulameen ultramafic complex and are therefore more enriched in the PGE. Local variations in groundwater composition may also occur in the Nanaimo Basin.

A combination of increased flow of groundwater through the deformed coal and possible variations in groundwater geochemistry are though to be the main factors involved in producing the enrichments observed.

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INFLUENCES OF STRUCTURAL DEFORMATION ON COAL QUALITY IN THE NORTHERN ALBERTA FOOTHILLS

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ABSTRACT

Regional variation in volatile matter contents and vitrinite reflectance for the base of the lower Cretaceous Gates Formation in the northern Alberta Foothills show a consistent pattern, indicating a gradual decrease in rank from northeast to southwest. Coalification resulted largely from stratigraphic burial, but tectonic burial also played a role, as illustrated in the Cadomin area. The amount of tectonic burial may increase from northwest to southeast. The presence of optically biaxial vitrinite anisotropy, with Rmax parallel to fold axes, indicates the presence of a tectonic stress field during the later stages of stratigraphic burial and subsequent deformation.

Structurally thickened coal can be attributed to at least two structural positions: fold hinges and fold limbs. Dilation occurs at chevron fold hinges and incompetent material, such as coal, flow into these dilation zones. Duplexes are present in fold limbs, where the roof thrust is the top and the floor thrust the bottom of the coal seam, resulting in tectonic thickening of the coal. These structurally thickened coals are important exploration targets. Prediction of structurally thickened coal by computer constructed down-plunge cross sections has proved useful in coal exploration in the Canadian Rocky Mountain Foothills.

INTRODUCTION

The tectonic setting of sedimentary basins influences burial and degree of coalification of organic-rich layers. In addition, structural deformation may alter the thickness of coal seams. Consequently, structural geological studies may assist in explaining coal quality variations and predicting the location of thickened coal seams.

The degree of coalification (rank) is governed primarily by rise of temperature during burial and the length of time during which this occurs. Data on coal rank in the Canadian Rocky Mountains and Foothills of the Grande Cache area suggests that the degree of coalification was largely achieved prior to deformation (Haquebard and Donaldson, 1974; Kalkreuth and McMechan, 1984 and 1988; Langenberg et al., 1987). Langenberg et al. (1988) reported syn-deformational coalification in the Cadomin area. Components of post-thrusting coalification were documented in the southern Alberta Foothills (England and Bustin, 1986).

This article will discuss effects of structural deformation on volatile matter contents, vitrinite reflectance and thickness of seams. Some effects of structural deformation on ash contents are discussed by Macdonald (this volume).

GEOLOGIC SETTING

This paper is concerned with coals from the Grande Cache Member of the Gates Formation, which forms part of the Luscar Group of the central and northern Foothills of western Alberta (figure 1). The Luscar Group is largely confined to the Inner Foothills, which consists largely of folded and faulted lower Cretaceous rocks and is topographically higher than the Outer Foothills. In the Outer Foothills and in the Interior Plains the Luscar Group is at depth and information on rank pattern can be obtained from oil and gas wells. The boundary between Foothills and Mountains is formed by the McConnell Thrust in the south and the Rocky Pass Thrust in the north (figure 1). West of Hinton the boundary steps northeastward to the Boule Thrust and consequently the coal deposits of Rock Lake and Pocahontas (25 km west of Hinton) are situated in the Mountains.

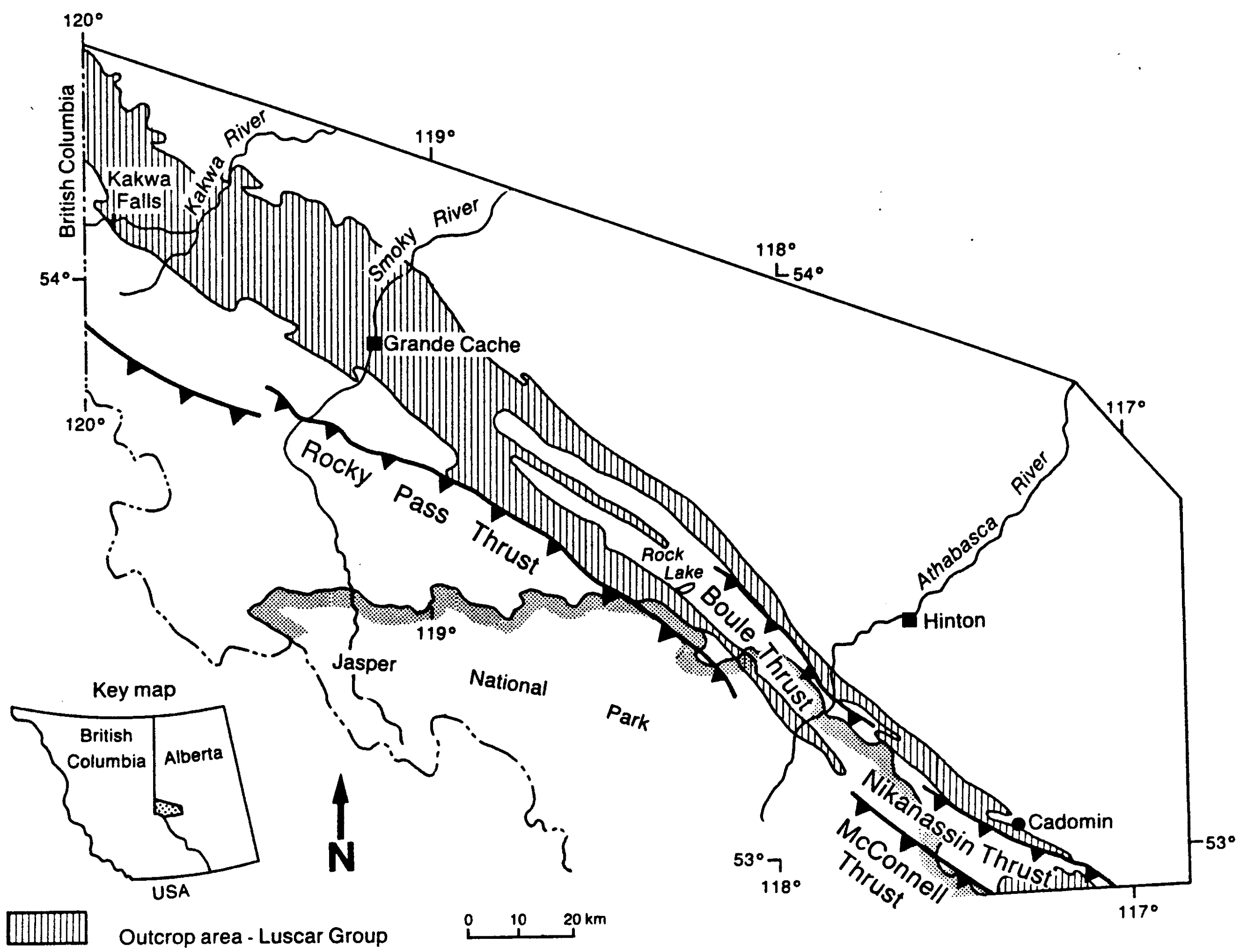

Figure 1. Map of study area with outcrop of Luscar Group and traces of major thrust faults.

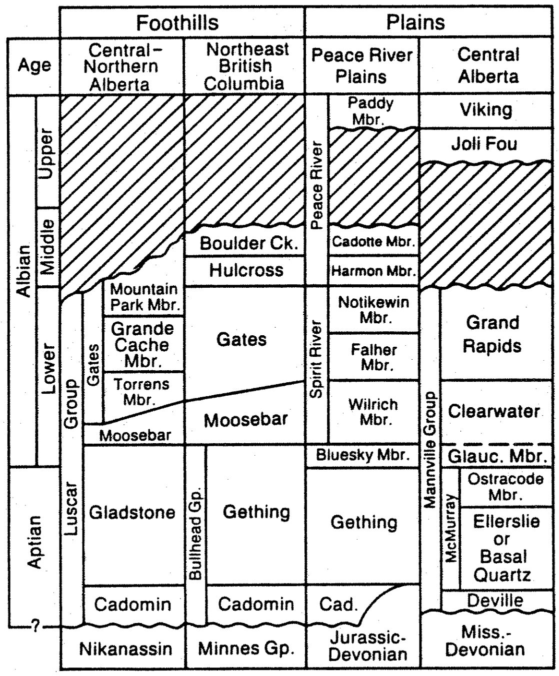

Figure 2. Lower Cretaceous stratigraphic nomenclature of the northern Foothills and neighbouring areas.

The largely nonmarine Gates Formation can be divided into three members: Torrens, Grande Cache and Mountain Park members (figure 2). The age of the Gates Formation ranges from early to middle Albian. The basal Torrens Member, which is thin (about 30 m) compared to the other members, consists of sandstones deposited in a shoreface environment. The Grande Cache Member is characterized by coastal plain sandstones, shales and major economic coal seams. It grades into the Mountain Park Member, which consists of fluvial, fining-upward sandstone, shale and minor coal seams. Depositional environments of the Gates coals are discussed by Kalkreuth and Leckie (this volume) and Macdonald et al. (1988).

Strata in the region are complexly folded and cut by numerous thrust faults. Thrust faults generally do not have as much displacement as faults in the southern Rocky Mountains Foothills. Deformation is thought to have proceeded from southwest to northeast and it is estimated to have reached the Foothills during the Paleocene (Kalkreuth and McMechan, 1984).

REGIONAL COALIFICATION

Data on regional coalification patterns of the Luscar group can be obtained by determination of volatile matter contents and vitrinite reflectances. Volatile matter contents were summarized from Energy Resources Conservation Board and Alberta Geological Survey files, and maximum vitrinite reflectance from files at the Institute of Sedimentary and Petroleum Geology in Calgary. The data have been released previously in an open file report (Macdonald et al., 1989).

Most of the analyses are obtained from seams in the basal part of the Gates Formation of the Luscar Group, i.e. the Jewel Seam of the Cadomin area, the Kennedy Seam of the Mountain Park area, the No. 3 and 4 seams of the

Grande Cache area and equivalent seams of adjacent areas. The maximum vitrinite reflectances for the base of the Grande Cache Member range from 0.86 % (west of Rock Lake) to 1.97 % (from 2779 m depth in a well in the Outer Foothills). These reflectances indicate a rank range from high-volatile A to low-volatile bituminous. To produce a regional rank map based on one parameter, all vitrinite reflectances were converted to volatile matter contents (dry and ash free). This relationship is not linear (Bustin et al., 1983), but for restricted rank ranges it can be approached by a linear curve. For the Cadomin area the relationship is: VM(daf)=58-27*Rmax for the range of 0.9 to 1.4 % Rmax (Langenberg et al., 1988). For the range of 1.4 to 1.8 % Rmax the relationship is VM(daf)=38-11*Rmax, as estimated from unpublished data from the Grande Cache area. The volatile matter contents estimated from vitrinite reflectance, together with volatile matter from proximate analyses are summarized on the map of figure 3.

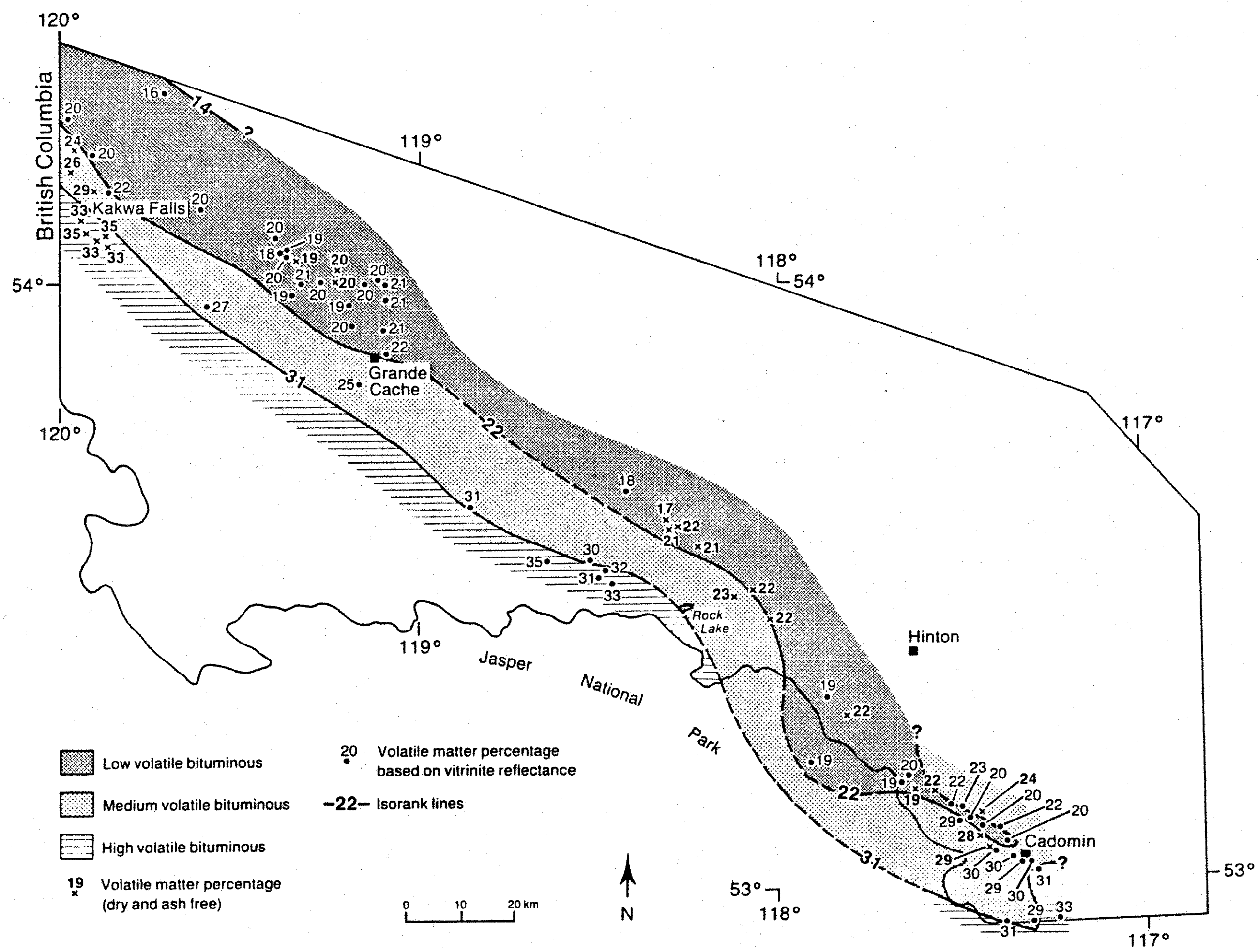

Figure 3. Coal rank variation at the base of the Grande Cache Member based on dry and ash free volatile matter contents.

The contoured map of figure 3 shows a very consistent rank pattern, where the highest rank (low volatile bituminous) is along the northeastern side and the lowest rank (high volatile A bituminous) along the southwestern side of the area. It should be noted that no sudden changes in rank across major thrust faults can be observed. A pattern of westwards decreasing rank for the Gates Formation was observed by Kalkreuth and McMechan (1984 and

1988) in the area northwest of Grande Cache.

The rank variation at the base of the Grande Cache Member displayed on figure 3 can be explained by variation in three possible parameters: 1) paleo-geothermal gradients, 2) depth and duration of stratigraphic burial, 3) tectonic burial history, or a combination of these parameters (see also Kalkreuth and McMechan, 1988). Unfortunately, no detailed information on paleo-geothermal gradients is available for the study area (some suggestions can be found in Hitchon, 1984). Kalkreuth and McMechan (1988) assumed paleo-geothermal gradients similar to the present day geothermal gradients for the area northwest of Grande Cache. This may also apply for the present study area. However, the variation in geothermal gradients are insufficient to explain the rank variation observed.

Little information is available on variation in depth of statigraphic burial because of extensive erosion. It seems reasonable to assume about 5500 m of burial for the base of the Gates Formation (see Kalkreuth and McMechan, 1984). The isorank lines run largely parallel to the trend of the Foothills (figure 3), suggesting that the degree of coalification is entirely related to stratigraphic burial in a foreland basin. The broad areas of

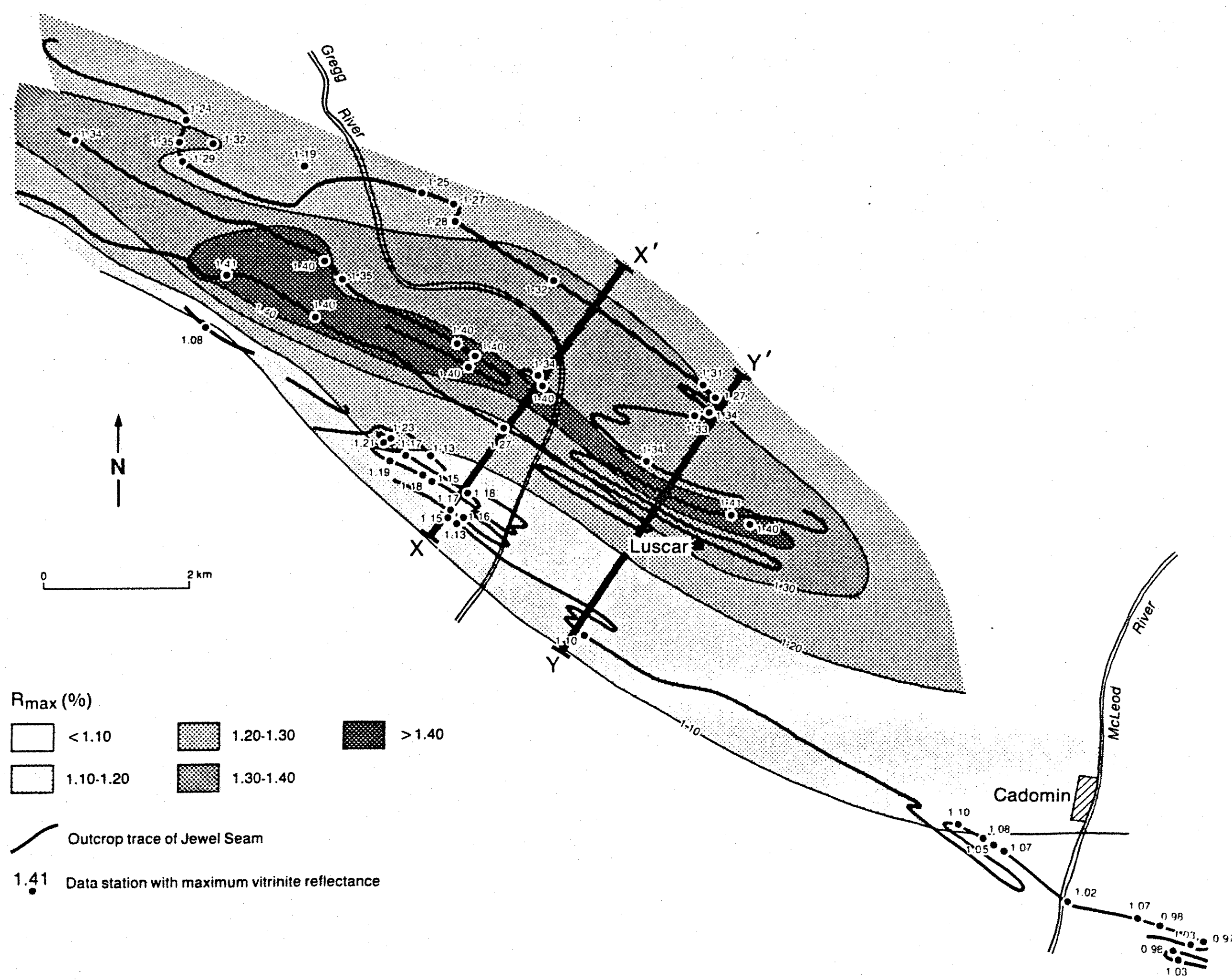

Figure 4. Maximum vitrinite reflectance variation of the Jewel Seam in the Cadomin area.

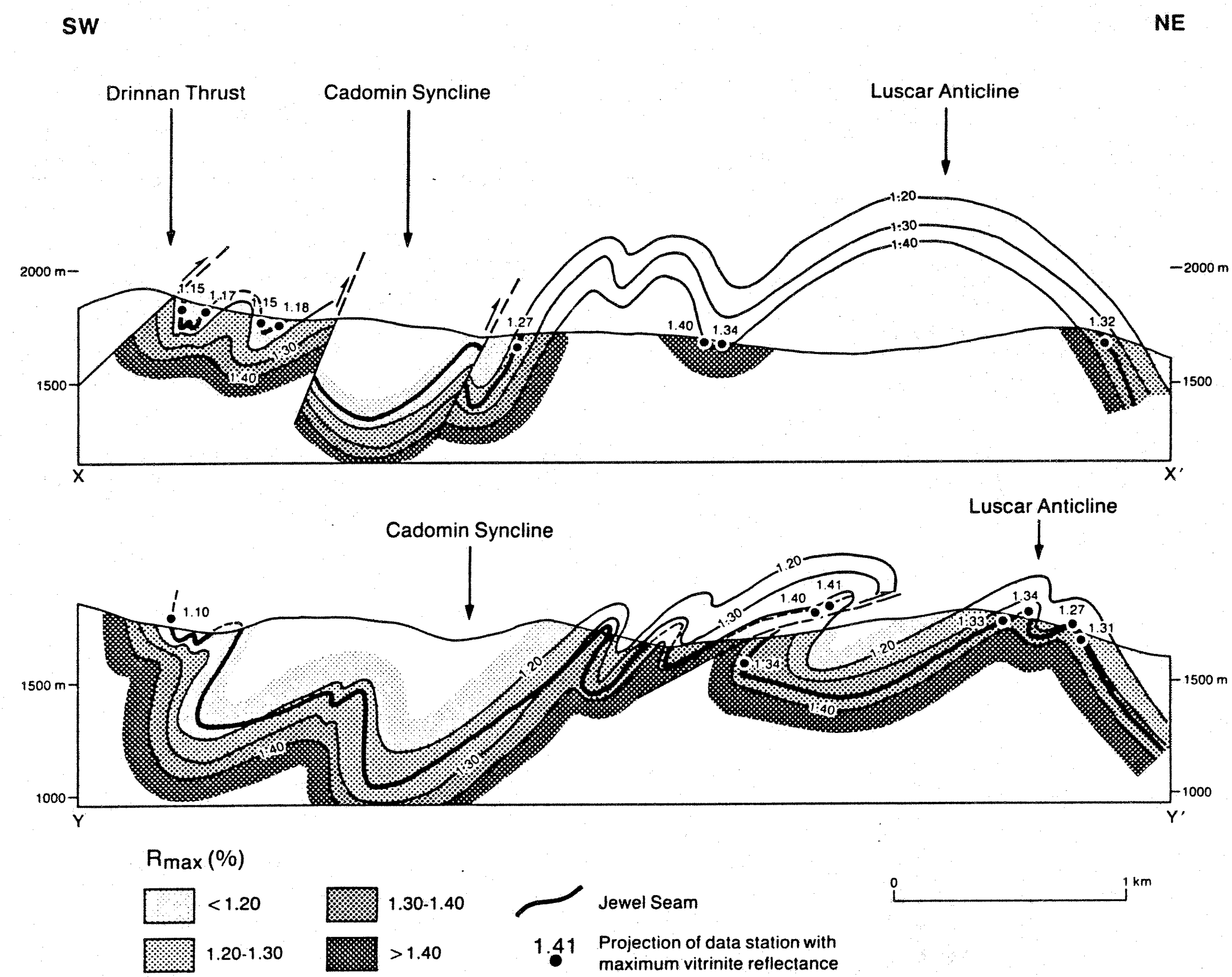

Figure 5. Cross sections through the Cadomin area, showing the relation between rank of the Jewel Seam and deformed strata. The cross section lines are shown on figure 4.

equal rank in the Kakwa Falls, Grande Cache and Rock Lake areas support this interpretation. However, significant rank changes over short distances in the Cadomin area (figure 4) are more difficult to explain and may be related to tectonic burial.

SYN-DEFORMATIONAL COALIFICATION

In the Cadomin area maximum vitrinite reflectance for the Jewel Seam ranges from 0.97 to 1.43 % (figure 4). The highest rank is found in the central part of this area, with a decrease in rank both to the southwest and the northeast (Langenberg et al., 1988). The intersections of isorank surfaces and the folded Jewel Seam, as illustrated in figure 4 and 5, indicate that the central part of the area was buried somewhat deeper, resulting in the higher rank. This configuration of rank surfaces is generally described as syn-deformational coalification (Bustin et al., 1983). Consequently, coalification in the Cadomin area results partly from tectonic burial. It should be noted that the highest rank levels are not along the axis of the Cadomin Syncline, as would be expected in the syn-deformational coalification model, but along the southwestern flanks of the Luscar Anticline (figure 5). This might be explained by a late stage adjustment of the structure, where parts of the Cadomin Syncline have moved upwards by secondary folding and thrusting.

The rank pattern in the Cadomin area (figure 4) may be compared with the regional westward and eastward decrease in maturation of the lower Cretaceous strata from a maximum near the edge of the deformed belt (Kalkreuth and McMechan, 1988). The interesting fact to notice is that the maximum rank is exposed at the surface in the Foothills of the Cadomin area, while in the Grande Cache area the highest rank is present in the subsurface of the Interior Plains. Information from oil wells has to be collected to verify if the decrease in rank eastward continues in the subsurface northeast of Cadomin.

It is concluded that the rank variation shown on figure 3 is largely controlled by stratigraphic burial, with tectonic burial playing a lesser role. The amount of tectonic burial may have increased from northwest to southeast, resulting in syn-deformational coalification in the Cadomin area.

BIAXIAL VITRINITE REFLECTANCE

Another indication of influences of structural deformation on coalification is the presence of biaxial vitrinite reflectance in coals of the area. Traditionally vitrinite is considered to have a uniaxial negative reflectance indicatrix. However, an increasing number of biaxial reflectance indicatrices have been reported (Levine, 1983; Kilby, 1988). To investigate the relationships between the principal reflectance axes of vitrinite and the structural position of the coals, a series of oriented coal blocks were collected from diverse structures in the Grande Cache area. From these blocks the orientation and magnitudes of the three principal reflectance axes (maximum, intermediate and minimum reflectances) were determined using a method modified from Levine (1983). The results of three samples from the Grande Cache area are illustrated in the stereoplots of figure 6. These samples (one each of the Nos. 4, 10 and 11 seams, where No. 4 is near the

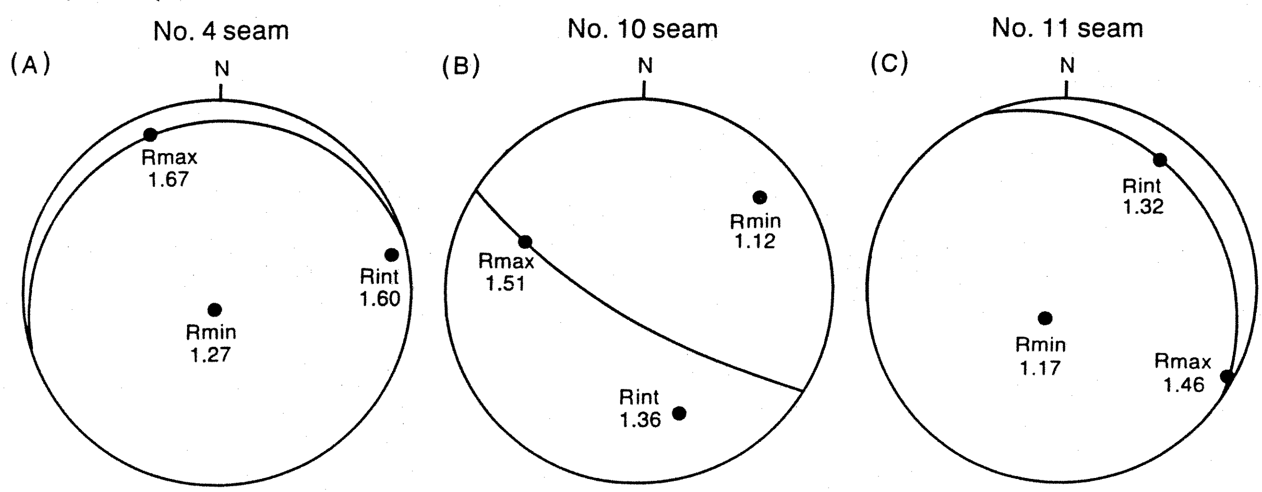

Figure 6. Orientations and magnitudes (percent reflectance) of principal reflectance axes of vitrinite for samples from (a) No. 4 seam, (b) No. 10 seam and (c) No. 11 seam.
The orientation of the bedding plane is indicated by the solid curve.

base of the Grande Cache Member and No. 11 at the top) are considered representative for the optical anisotropy encountered in the area. The maximum reflectances (Rmax) of these samples are significantly higher than the intermediate reflectances (Rint), proving that biaxial coals are present in the Grande Cache area. Only about 20 percent of the blocks collected show uniaxial anisotropy. The orientation of Rmax is, in all biaxial cases, parallel or subparallel to the macroscopic fold axis (as shown by the stereoplots of figure 6). Biaxial and uniaxial coals were generally found together with no clear relationship between structural position and anisotropy, except some samples close to one of the major thrusts. Biaxial coals were also found in the Cadomin and Mountain Park areas.

The biaxial nature of the vitrinite has implication on the determination of maximum reflectance (Rmax) in pellets made from crushed coal particles. Rmax of the pellet will only be the "true" Rmax if vitrinite is optically uniaxial (Kilby, 1988). For biaxial coals, Rmax of the pellet is expected to be between the "true" Rmax and "true" Rint. To test this, pellets were made from crushed particles of the oriented blocks and Rmax magnitudes of these pellets were measured. Rmax values determined on these pellets of crushed coal and on oriented blocks from the same sample show that reflectances from the crushed coal are generally lower. The pellets made from crushed coal from the samples shown in figure 6 obtain Rmax magnitudes of 1.64% (No. 4 seam), 1.37% (No. 10 seam) and 1.35% (No.11 seam) reflectance, respectivily. The standard deviations are 0.06, 0.06 and 0.05%, respectively. Only in the case of the No. 4 seam (figure 6a) is the value of the pellet reasonably close to the "true" Rmax as determined from the oriented block. The reason is that this particular sample has a relatively low degree of biaxiallity.

The biaxial nature of the vitrinite anisotropy with Rmax parallel to fold axes is interpreted to result from preferential orientation of aromatic lamellae in coal in the direction of minimum compressive stress (Levine, 1983). This stress field is different from that resulting from simple stratigraphic burial. Because there is no clear relationship between the degree of anisotropy and structural position, biaxial coals of the Grande Cache area are explained to result from coalification during burial (before folding and thrusting started) with the presence of a tectonic stress field. In addition, isoreflectance lines run parallel to the folded strata of the Grande Cache area and indicate pre-deformational and not syn-deformational coalification. It might be reasonable to assume that this tectonic stress field was present during the later stages of burial, relatively shortly before deformation started in the Grande Cache area. Coalification with the presence of a stress field probably continued during deformation, but rapid erosion ended coalification soon thereafter. Effects of syn-deformational coalification are more clearly present in the Cadomin area. Measurements on additional oriented coal blocks from the Cadomin area is in progress.

STRUCTURALLY THICKENED COAL

Structurally thickened coal pods can be found in many places, where it forms important exploration targets for the development of open pit mines. Presently there are two structural positions identified where thickening occurs, in fold hinges resulting from dilation and in fold limbs resulting from duplex faulting. These two positions will be discussed separately. Coal pods along fold hinges have been known and explored for many years, while coal pods resulting from duplex thrusting have only been recognized recently.

DILATION IN FOLD HINGES

The prominent deformation process in this part of the Foothills was flexural slip folding, which resulted in chevron folds (Dahlstrom, 1970; Langenberg et al., 1987). Dilation took place at the fold hinges. The dilation zone can be filled in two ways, either by flow of incompetent material (such as coal) into the void or by hinge collapse (Ramsay, 1974). In the Foothills a combination of these two processes took place.

Good examples of hinge dilations are exposed in open pits of the Grande Cache and Cadomin areas. One of these examples has been recently outlined in the South Pit area (figure 7), which is located about 20 km north of the town of Grande Cache. Here considerable reserves of metallurgical coal were found

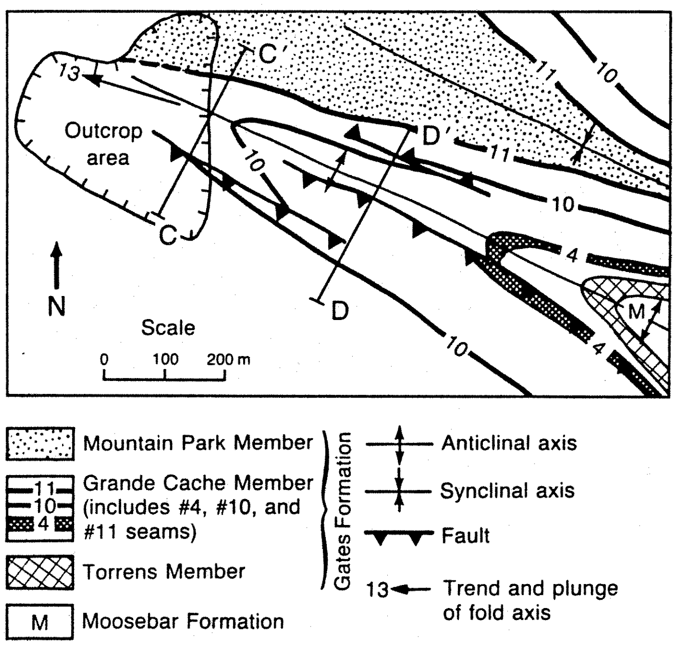

Figure 7. Geological map of the South Pit area, Smoky River Coal Ltd.

utilizing down-plunge projection techniques which are available in the TRIPOD mapping software (Charlesworth et al., 1989). Mapping in the outcrop area of figure 7 determined that the fold axis plunges in northwestern direction. Information from the outcrop area, which included two drill holes, was projected parallel to the fold axis onto a vertical section along CC'. The interpreted cross section (figure 8a) showed a thickened No. 4 coal seam at about 150 m depth. The information west of section line CC' was projected another 300 m onto a vertical section along DD' (figure 8b). From this down-plunge cross section, No. 4 seam was estimated to be about 75 m deep in the hinge of the anticline and to be about 30 m thick as a result of structural thickening. This cross section predicted a potentially surface mineable area east of DD' towards the estimated subcrop of coal below Quaternary sediments (figure 7).

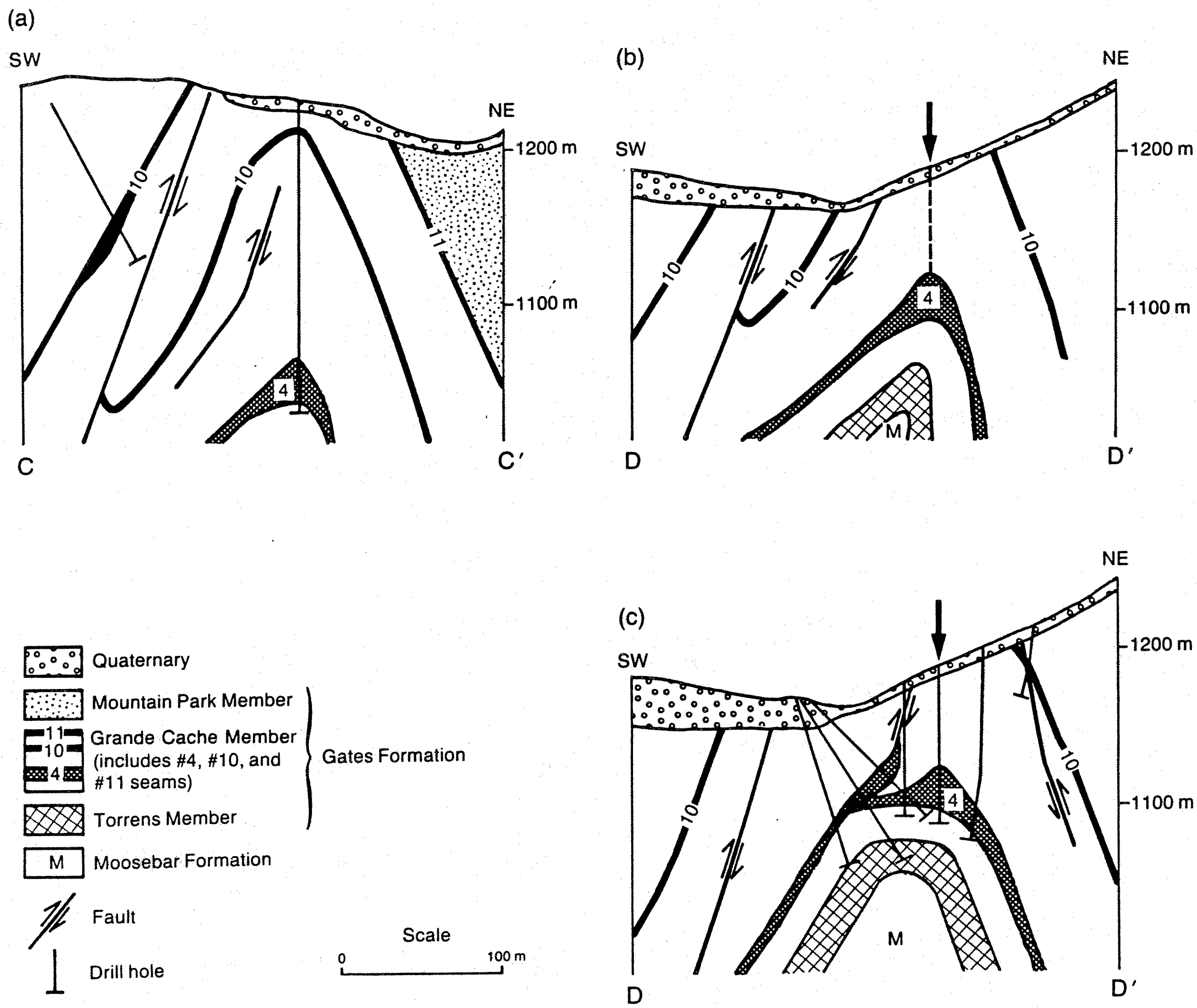

Figure 8. Cross sections through the South Pit area, Smoky River Coal Ltd. The lines of section are shown on figure 7. (a) Section CC' based on outcrop mapping and two drill holes. (b) Section DD' as predicted from Section CC'. The location of the first drill hole to test the structure is indicated with an arrow. (c) Section DD' based on seven drill holes.

A drill hole site (indicated by the arrow on section DD') was selected and drilled to a depth of about 110 m. The No. 4 seam was encountered at 70 m depth with a thickness of 29 m, which is about four times normal stratigraphic thickness. Subsequently the structure was drilled out with a total of 7 drill holes along line DD' (figure 8c). The predicted geometry of the thickened No. 4 seam was confirmed at the predicted depth, although the geometry was found to be more complicated as a result of hinge collapse faulting, with possible subsequent fault movements. Additional drilling confirmed the presence of mineable coal.

DUPLEXES IN FOLD LIMBS

A duplex is an imbricate thrust system where each subsidiary thrust joins two common thrusts, an upper roof thrust and a lower floor thrust. Charlesworth and Gagnon (1985) give an example of duplexes in a coal seam of the Outer Foothills at the Coal Valley Mine (Alberta) where the seam has been thickened 20 times the stratigraphic thickness. In the Grande Cache area duplexes are found in the limbs of macroscopic folds (Langenberg et al., in press).

A good example of a duplex in coal is present in the No. 12 Mine area (figure 9) about 20 km north of Grande Cache. Eight drill holes and some outcrop information were used in the construction of a down-plunge cross section (figure 9b). No. 4 seam is 30 m thick in the thickest part of the

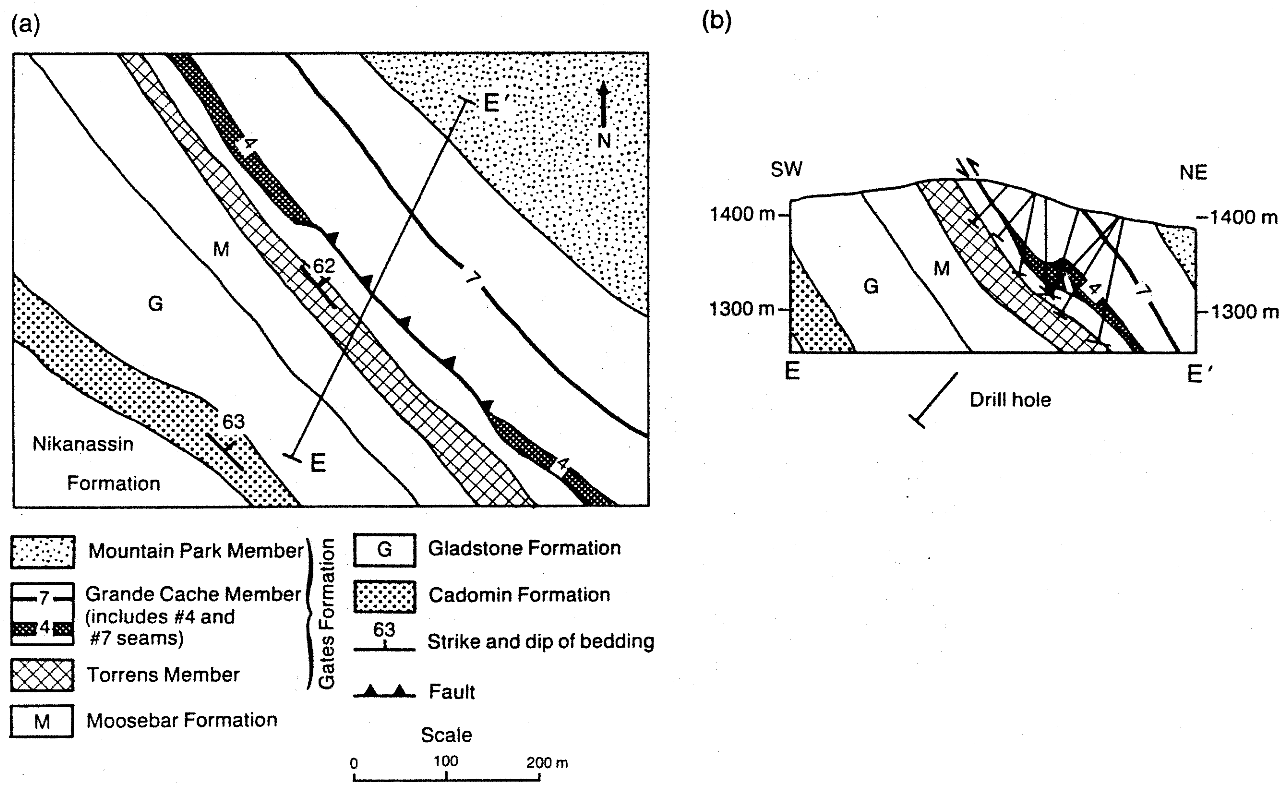

Figure 9. Geological map (a) and cross section EE' (b) of part of the No. 12 Mine area, Smoky River Coal Ltd. The cross section, which is based on eight drill holes, illustrates the presence of a duplex in the No. 4 coal seam

structure, which is about four times normal thickness, and is faulted out at the surface. The coal has been thickened by the stacking of thrust slices (also called horses) in a duplex. The roof thrust is assumed at the top of the coal and the floor thrust at the bottom. The presence of a rock wedge indicates that the floor thrust of the duples is locally below the base of the coal. At least four stacked thrust slices must be present to explain the observed thickness of the coal. However, the exact position of the subsidiary thrusts cannot be determined in the uniform coal pod. The coal reserves in the No. 12 mine area are significantly enhanced by the presence of the duplex. Duplexes are generally located in limbs of folds. Because duplexes have only been recognized recently in the Smoky River coalfield, they may become the major exploration target in the near future.

CONCLUDING REMARKS

The degree of coalification in the study area resulted largely from stratigraphic burial. However, tectonic burial also played a role in some areas. A tectonic stress field was probably present during the later stages of stratigraphic burial and subsequent deformation, resulting in biaxial anisotropy of vitrinite. Regionally, the coalification pattern can be described as synorogenic.

Numerical mapping techniques such as employed by the TRIPOD software are strong tools for unravelling the geometry of deformed coal bearing rocks. This methodology has been successfully applied in the Grande Cache area, significantly adding to existing coal reserves. Consequently, these techniques provide a basis for the establishment of exploration targets. These targets include coal thickened in fold hinges and in duplexes. Further work is needed to understand why duplexes form in some locations and not in others.

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PARTICLE SIZE DISTRIBUTION IN COAL AND ITS CONTRIBUTION TO RESULTS OBTAINED THROUGH AUTOMATED IMAGE ANALYSIS

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ABSTRACT

The contribution of particle size distribution to the results of automated image analysis of coal is investigated. This is studied in two parts. In the first part of the study, error between runs and between samples is tested using the reflectance histogram as the primary tool. Coals crushed to two particle sizes are tested to determine the role of particle size in automated analysis. Between runs error can be controlled through proper preparation and selection of analysis parameters. Between samples error is quite noticeable in comparisons made. However, this error source is independent of methods used in image analysis. In the second part, the possibility that specific macerals may concentrate at certain size fractions is investigated. The reflectance histogram is used to compare variations in the composition of samples resulting from sieve analysis. A concentration of inertinite macerals in the larger particle sizes of one coal is observed. In another coal, one series of size fractions showed an increase of inertinite with decreasing particle size. In both parts of the study, quantitative data is used to support observations made concerning behaviour of the reflectance histograms. Image analysis is an effective method if proper attention is given to factors considered in this study. Because image analysis does not rely on morphology to determine maceral contents of coal, subjective influences are eliminated. Through the use of reflectance histograms, the ability to evaluate maceral distributions provides new methods of assessing coal quality.

RESUME

On recherche la contribution apportée par la distribution granulométrique aux résultats de l'analyse automatisée des images charbonnières. La recherche a été divisée en deux parties. Dans la première partie de l'etude, l'erreur établie entre des essais et des échantillons est examinée en se servant en premier lieu de l'histogramme de réflectance. Des charbons concassés à deux dimensions granulométrique distinctes sont examinés afin de déterminer le rôle que joue la dimension granulométrique dans l'analyse automatisée. En ce qui concerne des essais, l'on peut contrôler l'erreur par moyen de la bonne préparation et la sélection apte des paramètres d'analyse. Quant aux échantillons, l'on remarque une erreur marquante. Cependant, cette source d'erreur ne se rapporte pas aux procédés d'analyse des images. Dans la deuxième partie de l'étude, l'on examine la possibilité que des macéraux particuliers se concentrent aux fractions de taille spécifique.
L'histogramme de réflectance est employé afin de comparer des variations en

composition des échantillons qui proviennent de l'analyse granulométrique. Une concentration de macéraux d'inertinite aux tailles des particules plus grandes est examinée. Dans un autre charbon, une série de fractions de taille a révélé une augmentation d'inertinite au fur et à mesure que diminue la dimension granulométrique. Les données qualitatives servaient à confirmer des observations faites aux deux parties de l'étude susmentionée en ce qui concerne le comportement des histogrammmes de réflectance. L'analyse des images constitue une méthode efficace pourvu que l'on prête de l'attention suffisante aux facteurs mentionnés dans cette étude. Puisque l'analyse des images ne compte pas sur l'aspect morphologique pour déterminer les contenus macéraux des charbons, des influences subjectives ont été éliminées. L'usage des histogrammes de réflectance pour faciliter l'évaluation des distributions des macéraux pourvoit des nouvelles méthodes qui aident à l'évaluation de la qualité des charbons.

INTRODUCTION

The use of automated image analysis to determine the maceral content of coal has been described by a number of authors (Pratt (in press), Goodarzi (1987), Riepe and Steller (1984), Zeiss(1979)). Using this method, reflectance distributions are constructed from systematic traversing of the polished surface of a particulate block of coal. The resulting histogram represents the nature (composition) of the coal itself (Pratt, in press). These histograms offer a new means of investigating coal quality, and the automated methods used provide results in considerably shorter times than manual analysis.

At the Geological Survey of Canada, a Zeiss IBAS 2 is used to perform automated image analysis. The system has been described by Goodarzi (1987), and Pratt (in press), to which the reader is referred for details on the methods used. Its product, the reflectance histogram, consists of 256 classes of reflectance frequency data describing a mixture of distributions of the three basic coal macerals. Most commonly, vitrinite is the dominating distribution that forms a peak from which the mean random reflectance can be determined. The other macerals usually form shoulders or subsidiary peaks around the vitrinite distribution. In some cases an 'artifact wedge' forms on the left of the histogram as a result of the systems inability to completely eliminate such unwanted image features as mineral matter, edge effects and epoxy binder. A band fitting technique is used to determine thresholds between the coal macerals. From the cumulative frequencies occurring between these thresholds maceral percentages can be calculated.

Advantages of the method include rapidity of analysis and elimination of subjective involvement during the data collection phase. The resulting reflectance histogram can be used for rapid qualitative assessment of the nature of the coal. Although quantitative results will be presented and discussed, this paper will concentrate on the use of the histogram as a comparative tool, and demonstrate the ability to observe differences in the nature of samples using automated image analysis.

The Canadian Coal Petrographers Group has been discussing the problems of particle size and stepping distances as sources of error between operators in conventional point counting techniques used to determine coal composition.

Pratt (in press) suggests that such factors must also be considered in the selection of measuring parameters used in automated image analysis. In both methods, if the stepping distance chosen is less than the maximum particle size, the possibility of repeated measures on individual particles may cause increased error. Either a large stepping distance or a small particle size must be used to overcome this effect. In image analysis, areas are evaluated from entire microscopic fields. For this reason, large particles that dominate entire fields may bias a reflectance distribution. Also, for any given particle size distribution there is a representative equivalent area (REA) that must be evaluated to obtain accurate and repeatable results. Measuring less than this area will cause increased error, whereas measuring a greater area is redundant and unnecessary. Experience has shown that repeatable results are obtained in image analysis if a minimum of some four million pixels can be evaluated on a given pellet surface. Since most analysis performed to date has been performed using -20 mesh coals, this number of pixels is likely to be a close approximation to the representative equivalent area for such a particle size. At the time of the experimental phase of this study, the corresponding figure for other particle sizes was not known. The first part of this paper addresses such factors as repeated measures, dominated fields and REA in considering error between samples and between runs using the reflectance histogram as a comparative tool.

Various macerals behave differently during the process of crushing bulk samples of coal (Cameron and Botham, 1966). It has also been observed that fusain (inertinite rich) particles concentrate in certain size fractions of coals that have been passed through a series of sieves (Cameron, personal communication). This may indicate that more than one particle size distribution may exist in a sample of crushed coal, each having different composition characteristics. If certain macerals tend to concentrate at a particular particle size, then their likelihood of being encountered during analysis may be affected. In the second part of this study an attempt is made to detect such phenomena using the reflectance histogram.

In consideration of all of the above factors, the ability to achieve reliable and repeatable results using image analysis is shown. Implications of this work on manual methods is discussed.

EXPERIMENTAL

Two blocks of coal were selected that were known to be relatively low in ash content. One was a high volatile bituminous B-C coal from the Val D'Or seam of the Paleocene Coalspur formation of west central Alberta (Jerzykiewicz, 1985). The other was a medium volatile bituminous coal from the Greenhills #10 seam of the Jurassic-Cretaceous Kootenay group of south eastern British Columbia (Gibson, 1979).

Each block was treated as follows: A jaw crusher was used for initial crushing to approximately one-quarter inch particle size to allow representative splitting using rifflers. The resulting sample was split into two samples of approximately one hundred grams. One of the halves was then crushed further using a mortar and pestle and was carefully sized to -20 mesh (mesh size equivalents in microns are shown in table 1). The other half was crushed using a Reinsch ZM-1 centrifugal grinding mill until a -80 mesh grain size was achieved. At this point four representative splits of both the -20 and -80 mesh samples were made for pelletizing and analysis using the automated system. Thus there were four groups of four samples; Val D'Or -20 and -80 mesh, and Greenhills -20 and -80 mesh coal, resulting in sixteen pellets. The use of two different crushing methods was intended to provide samples having considerably different particle size characteristics. These sixteen pellets would be used for comparing between samples error for the two particle distributions. One pellet of each of the four groups of samples would then be run an additional three times to provide four runs on a single pellet from each group. This would provide four runs on one pellet for the Val D'Or -20 and -80 mesh samples, and the Greenhills -20 and -80 mesh samples. This was intended to provide information regarding between runs error for each particle size.

The remainder of the original four samples (i.e. Val D'Or -20, -80 and Greenhills -20, -80 mesh) were subjected to sieve analysis. Since rifflers had been used to split the portions required for pelletization from the original samples, the remainder of each was still representative. They were passed through a series of sieves having standard sizes of -20, -40, -60, -80, -100, -120, and -140. Obviously, the -80 mesh samples were only passed through the latter four sieves. The resulting size fractions were weighed and then a split of each was taken for pelletizing and analysis on the automated system. This resulted in eleven pellets each of the original two coals. It is important to note that these are size fractions derived from the original crushed samples, and not separate samples crushed to the particular mesh sizes.

The samples obtained were mounted in polyester resin and polished using a Beuhler Ecomet IV/Euromet polishing system. During the mounting process, efforts were made to obtain the maximum possible compaction of coal grains on the surface of any given pellet. This was done by using the minimum amount of polyester resin possible to obtain wetting of the coal grains yet minimizing formation of air bubbles.

Image analysis was performed in a similar fashion as described by Pratt (in press). One hundred and forty four fields were evaluated on each pellet. A stepping distance of approximately one-half millimetre was used in the scanning of the pellet surface. This distance is smaller than the maximum particle size of a -20 mesh coal (840 microns) yet larger than that of a -80 mesh coal (180 microns). This would test the effect of stepping distance in relation to maximum particle size.

RESULTS AND DISCUSSION

The results of the sieve analysis are shown in table 1. It can be seen that the goal of obtaining differing particle size distributions was achieved. In both cases the distributions of -20 mesh samples are skewed towards the large end of the particle size range, whereas the -80 mesh samples both have large amounts of fine material. Some difference in the particle size distributions of the two coals may be relatable to their respective Hardgrove Indices. The Greenhills #10 coal would most likely have a higher Hardgrove Index than the Val D'Or coal on the basis of rank.

The purpose of analyzing four pellets of each of the original samples was to determine the between samples error, meaning the error introduced in

Mesh size	Opening in microns	Val D'Or -20	Val D'Or -80	Greenhills #10 -20	Greenhills #10 -80
20 x 40	840	45.1	-	35.8	-
40 x 60	420	23.9	-	26.0	-
60 x 80	250	7.8	-	8.7	-
80 x 10	180	4.7	14.9	5.6	6.8
100 x 120	150	3.0	12.5	3.3	10.9
120 x 140	125	2.8	13.2	3.3	12.0
-140	105	12.7	59.4	17.3	70.3

Table 1: Results of sieve analysis. Size fractions are shown in percentages.

the process of crushing and splitting of samples. Similarly, four runs were performed on one pellet of each sample to determine between runs error, or the error that occurs when the same prepared sample is run more than once. In order to assess both types of error for the two particle sizes of both coals, sixteen histograms were used. These fell into four groups: histograms used to evaluate between runs error for -80 mesh coal, between runs error for -20 mesh coal, between samples error for -80 mesh coal and between samples error for -20 mesh coal. Normalizing the histograms within each group to the same population size and then plotting them on the same set of axes provided a convenient means of graphically comparing the results for each group. This is done in figures 1 and 2. Figure 1 contains the four comparison diagrams for the Val D'Or seam, each containing four histograms. Figure 2 is the same, illustrating the diagrams for the Greenhills #10 seam. If there were no error of any kind, all histograms from any sample or run would be identical. In the comparisons, the area between the lines forming the histograms represents the error of the type addressed by that diagram. For instance, in figure 2 a considerable amount of between samples error is visible in the reflectance range of 1.5 to 2.0 in the upper right diagram.

Inspection of figures 1 and 2 provides the following information:

For both coals the best agreement between histograms occurs in the -80 runs situation. Error in the -20 runs diagrams is not severe but is more visible than the -80 case. It is suspected that this is a result of the combined effects of individual fields being dominated by single particles, or repeated measures on the same particle due to the particle size being slightly larger than the stepping distance used. The high degree of repeatability achieved in the -80 runs illustrate the basic soundness of the methods of automated image analysis. The error seen in the -20 runs diagrams indicates that in spite of larger areas assessed in analysis (see discussion of table 2, below), the effects of dominated fields and repeated measures are difficult to overcome.

In both cases the worst error is apparent in the between samples test. In the Val D'Or case, the -80 samples show considerable variations in the shape and size of the dominating vitrinite peak, which occurs at a reflectance of about 0.58 Ro. There is considerable error in the Greenhills

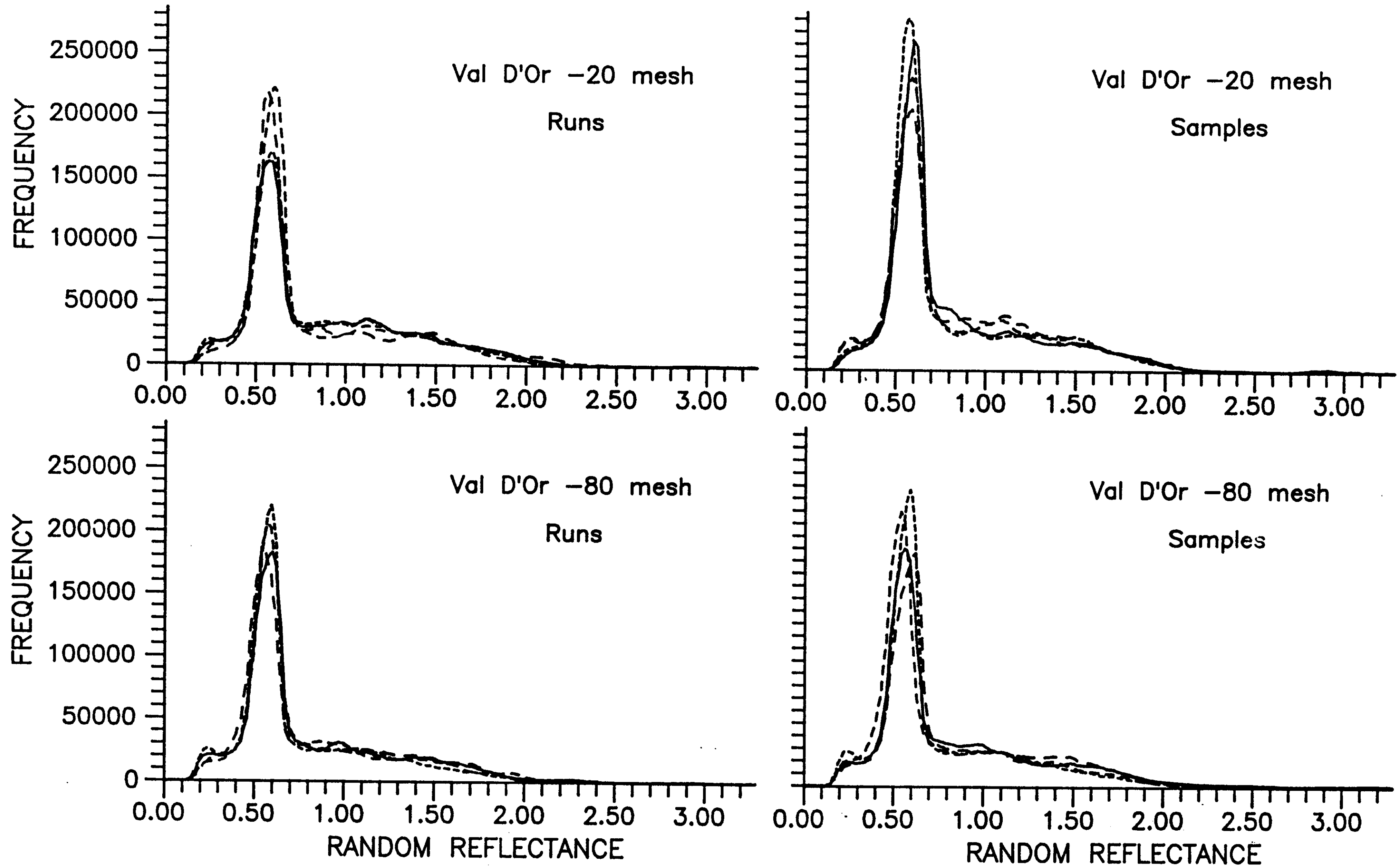

Figure 1: Comparison diagrams for between runs and between samples error for Val D'Or coal. Error between runs is tested in diagrams to the left, error between samples is tested on the right. In both cases -20 mesh samples are on top and -80 mesh samples are below.

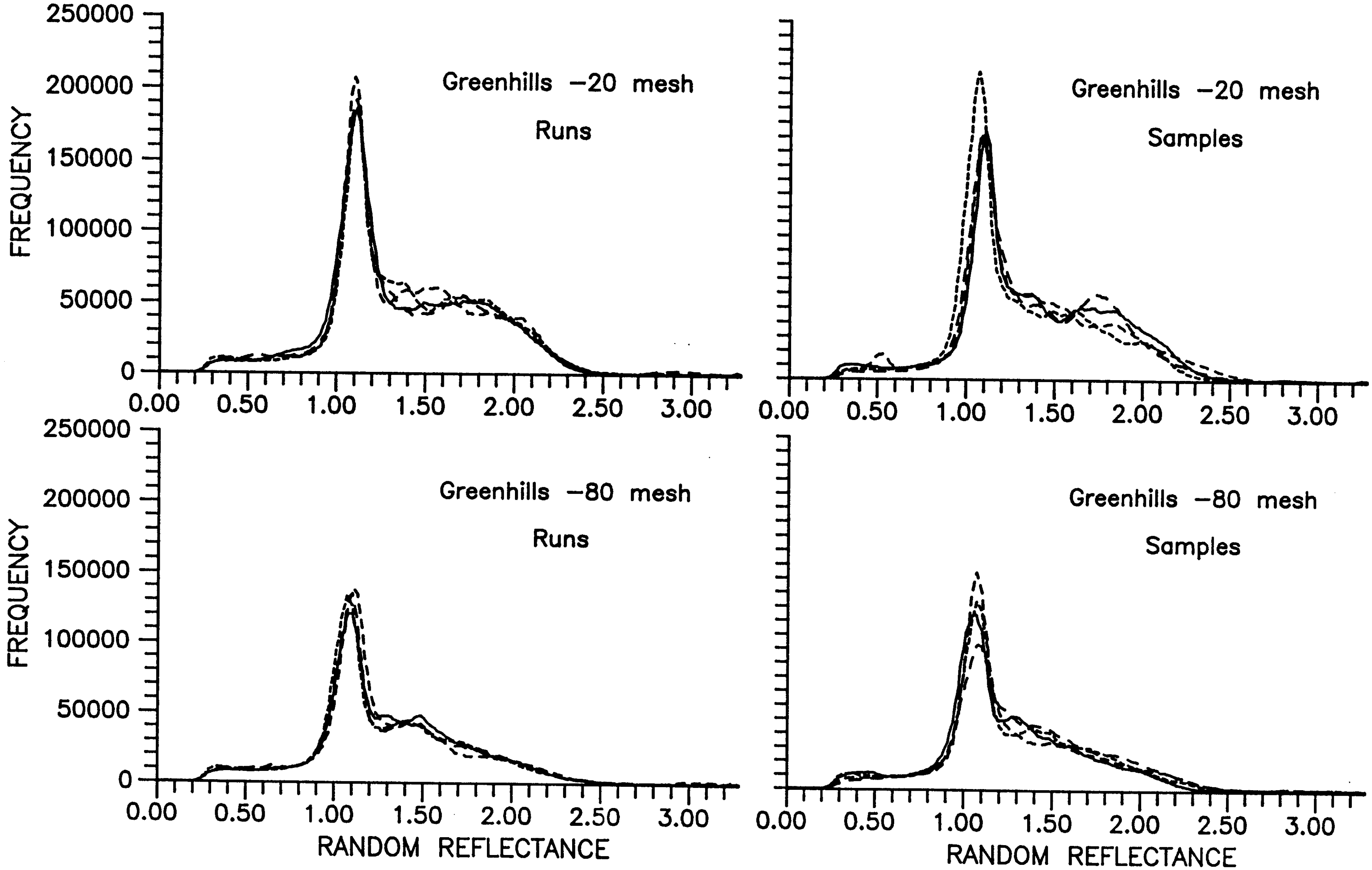

Figure 2: Comparison diagrams for between runs and between samples error for Greenhills #10 coal. Error between runs is tested in diagrams to the left, error between samples is tested on the right. In both cases -20 mesh samples are on top and -80 mesh samples are below.

#10 samples diagram at a reflectance range of 1.5 to 2.0 Ro, representing a portion of the inertinite macerals. The higher inertinite content of this coal probably contributes to a higher frequency of dominated fields or repeated measures in this reflectance range. This results in greater irregularity in the shape of the corresponding portion of the histograms. The increase in this irregularity from the -20 runs case to the -20 samples case illustrates the added effect of between samples error. The between samples diagrams for both coals show that there can be a considerable amount of between samples error. Although this error source occurs independently of the techniques used in image analysis, the histogram comparisons provide an effective means of detecting such error.

The fact that the -80 between runs results are most consistent implies that image analysis is most effective when the samples are of a particle size that allow several grains to be assessed in any given field. Keeping particle size smaller than the maximum stepping distance is also important. These are factors that can be considered during the preparation phase. If a small particle size is selected, then it is important to prepare pellets in such a way that the particles will be well compacted allowing several to be visible in any given field during analysis. If this is not the case, a larger number of fields will have to be evaluated to obtain accurate results causing increased processing time. Fundamental statistics dictates that the goal of analysis should be to sample the largest number of particles as is practically possible.

The preceding discussion raises the question of how much area must be evaluated to obtain repeatable, accurate results without redundant and unnecessary measurements. It was suggested above that this representative equivalent area is a minimum of four million pixels for -20 mesh coals. Table 2 provides some insight into this question by providing quantitative results on maceral content from the interpretation of the histograms shown in figures 1 and 2, as well as the number of pixels evaluated in each case. Once again it can be seen that the -80 between runs data is in best agreement for both coals. It is difficult to draw conclusions from the remaining cases since these percentages are fairly close and there is a third source of error introduced in the manual interpretation of the histograms. However, it is noteworthy that the improvement in the -80 between runs figures occurs in spite of considerably lower numbers of pixels measured. This implies that the representative equivalent area for -80 mesh coals is somewhat lower than for -20 mesh coals. On the basis of data in table 2, the REA for -80 mesh coals is in the vicinity of 3.5 to 4.5 million pixels. The -80 between runs data also indicate good machine repeatability. However, such results do not necessarily reflect the true composition of the original bulk sample. That will depend on how well the actual specimen represents the sample from which it has been split. This is seen in the -80 between samples series of data. In spite of excellent agreement in between runs data for samples of the same particle size, there is a noticeable increase in error in the between samples series.

On the basis of the data in table 2, it is likely that the REA for -20 mesh coals is somewhat higher than four million, possibly in the range of five to six million pixels. Even when this high number of pixels are analyzed, considerable error still occurs as shown in the data for the Greenhills -20 mesh between runs group of samples. These data confirm the

	BETWEEN RUNS ERROR				BETWEEN SAMPLES ERROR			
	Vit. %	Inert. %	Lipt. %	N $x10^6$	Vit. %	Inert. %	Lipt. %	N $x10^6$
	53	45	2	4.4	57	40	3	5.0
Val D'Or	55	43	2	4.1	60	38	2	4.4
-20 mesh	49	49	2	4.6	57	41	2	5.6
	59	38	3	4.4	53	45	2	4.4
Difference:	10	11	1	0.5	7	7	1	1.2
	62	34	4	3.8	56	41	3	4.5
Val D'Or	60	38	2	3.9	61	36	3	4.3
-80 mesh	59	39	2	4.2	58	40	2	4.0
	59	39	2	3.5	62	34	4	3.8
Difference:	3	5	2	0.7	6	7	2	0.7
	45	54	1	5.6	53	46	1	4.6
Greenhills	54	45	1	6.0	50	48	2	4.6
-20 mesh	50	48	2	5.0	46	53	1	5.4
	47	52	1	5.3	45	54	1	5.6
Difference:	9	9	1	1.0	8	8	1	1.0
	50	48	2	3.8	45	54	1	4.1
Greenhills	50	48	2	3.9	55	43	2	4.1
-80 mesh	49	49	2	4.1	49	49	2	4.2
	54	44	2	4.1	50	48	2	3.8
Difference:	5	5	0	0.3	10	11	1	0.4

Table 2: Quantitative results from histograms shown in figures 1 and 2.

suggestion that it is desirable to sample the largest number of particles possible. Better results are obtained if a large number of smaller areas are used as opposed to a smaller number of large areas.

The implications of these observations on conventional point counting methods are difficult to assess. In the discussions of the Canadian Coal Petrographers Group it has been suggested that error may be predicted using the binomial distribution, provided the basic assumption that there is an equal probability of success on every trial is met by keeping the maximum particle size smaller than the stepping distance used (Bustin, personal communication). If this assumption is not kept, error will increase. The between runs data in figures 1 and 2, and table 2 confirm that this is true, at least in the case of image analysis.

In the second part of this study, size fractions from sieve analysis of the coals were analyzed. These were splits of the size fractions shown in table 1, as opposed to separate samples crushed to a specific size. The reason for performing this test was to determine if certain macerals concentrate at particular size fractions in the crushing process. The histograms of samples from each of the size fractions in table 1 were normalized to a uniform population size. In figures 3 and 4 the histogram for all four groups of samples (Val D'Or -20, -80 and Greenhills -20, -80) are aligned in series to facilitate comparison. The dashed curve in these illustrations represents an average based on the frequencies in the normalized histograms for that particular group. As such this represents the 'average shape' of the histograms, rather than the average composition based on frequencies in the original histograms weighted according to proportions of sieve fractions. For the Val D'Or -20 series (figure 3, left) the amount of variation seen in all seven fractions could be attributed to either between runs or between samples error. For instance, in the 40 x 60 fraction, a small hump appears at a reflectance range of approximately 1.5 to 2.25. However, this is not severe enough to be considered a significant change in the fundamental shape of the histogram. However, in the equivalent Greenhills series (figure 3, right) the 20 x 40 fraction yields a histogram that is considerably different from those of smaller size fractions. There is a large hump visible in the reflectance range of 1.5 to 2.5 that deviates from the 'average' histogram (dashed line) significantly. The material this represents is most likely high reflecting semifusinite and fusinite. Observing the two histograms of smaller fractions immediately below, a tendency for the inertinite distributions to move towards the vitrinite peak can be seen. In these cases the inertinite components are progressively enriched in lower reflecting semifusinite. At the 100 x 120 histogram, the inertinites seem to have a more diffuse pattern. It would appear that in this coal (Greenhills #10), there is a concentration of higher reflecting inertinites around the 20 x 40 particle size fraction. More reactive semifusinites are seen as particle sizes become smaller, with the higher reflecting inertinites returning in the very fine portions.

Examining the histograms of the -80 mesh analysis, both the Val D'Or and the Greenhills samples show little deviation from their respective 'average' histograms, although the Val D'Or samples appear to have an increase in inertinite as particle size decreases. In both cases there are few histogram features that are distinct enough to warrant consideration.

At the time of analysis, separate, manually determined thresholds had originally been applied to the individual histograms in each of the four groups of samples. Using these for reference, standard thresholds were determined for each group and applied to the frequency data of each sample to re-calculate the maceral composition of each. In other words, the same set of thresholds were applied to every histogram within a group. The results are shown in Table 3. It can be seen that there is a nine percent drop in inertinite content from the 20 x 40 to the 40 x 60 fractions of the Greenhills -20 mesh samples. A certain amount of this difference may be attributed to error factors discussed above. However, this is controlled by good numbers of pixels counted during analysis so the pattern shown is probably the result of real effects. It can be seen that viewing the histograms in series provided more information than a table of maceral proportions. The table data indicates that inertinite content remains fairly constant at particle sizes less than -40 mesh. Although this is true, the increase in low reflecting semifusinites seen in the histograms is not

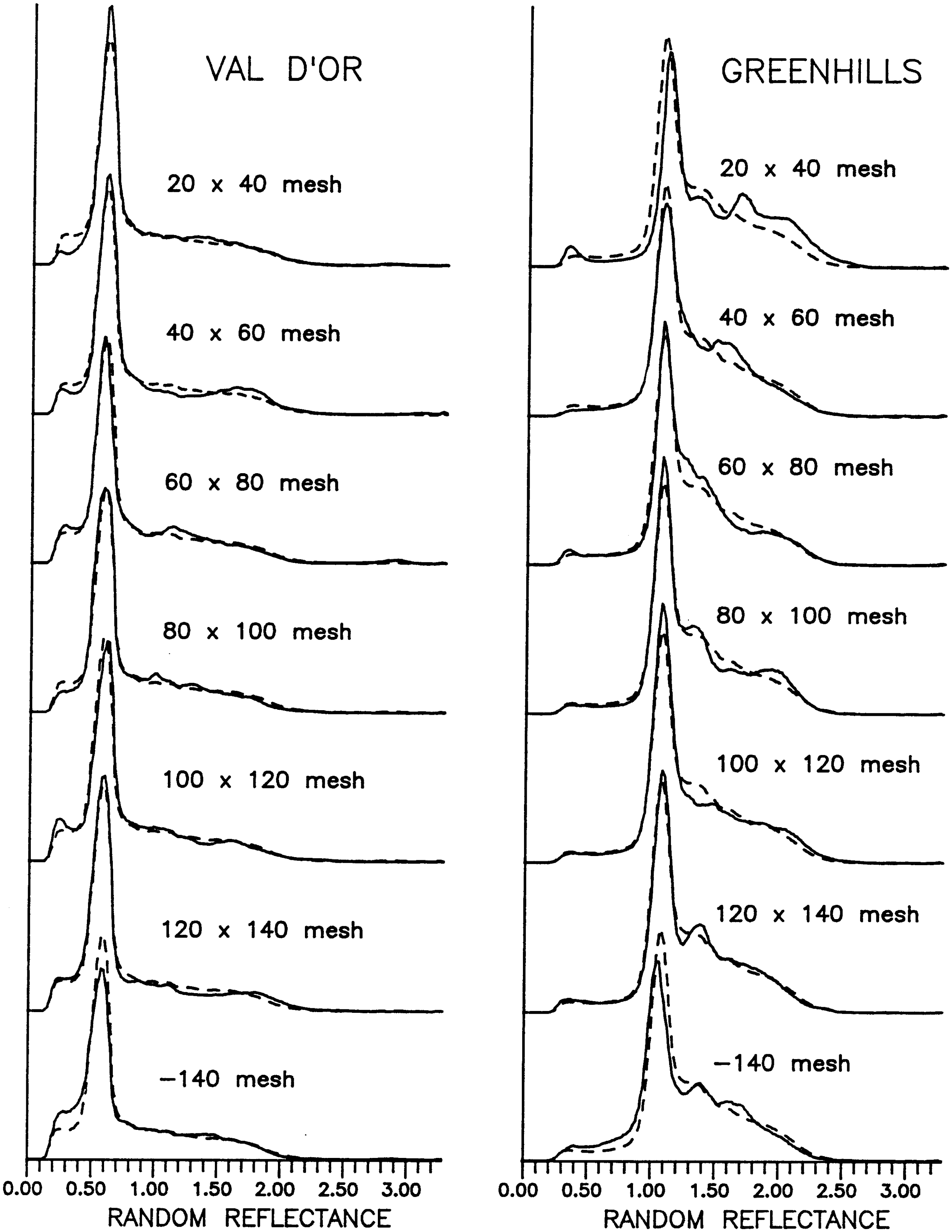

Figure 3: Reflectance Histograms of -20 mesh sieve fractions from table 1.

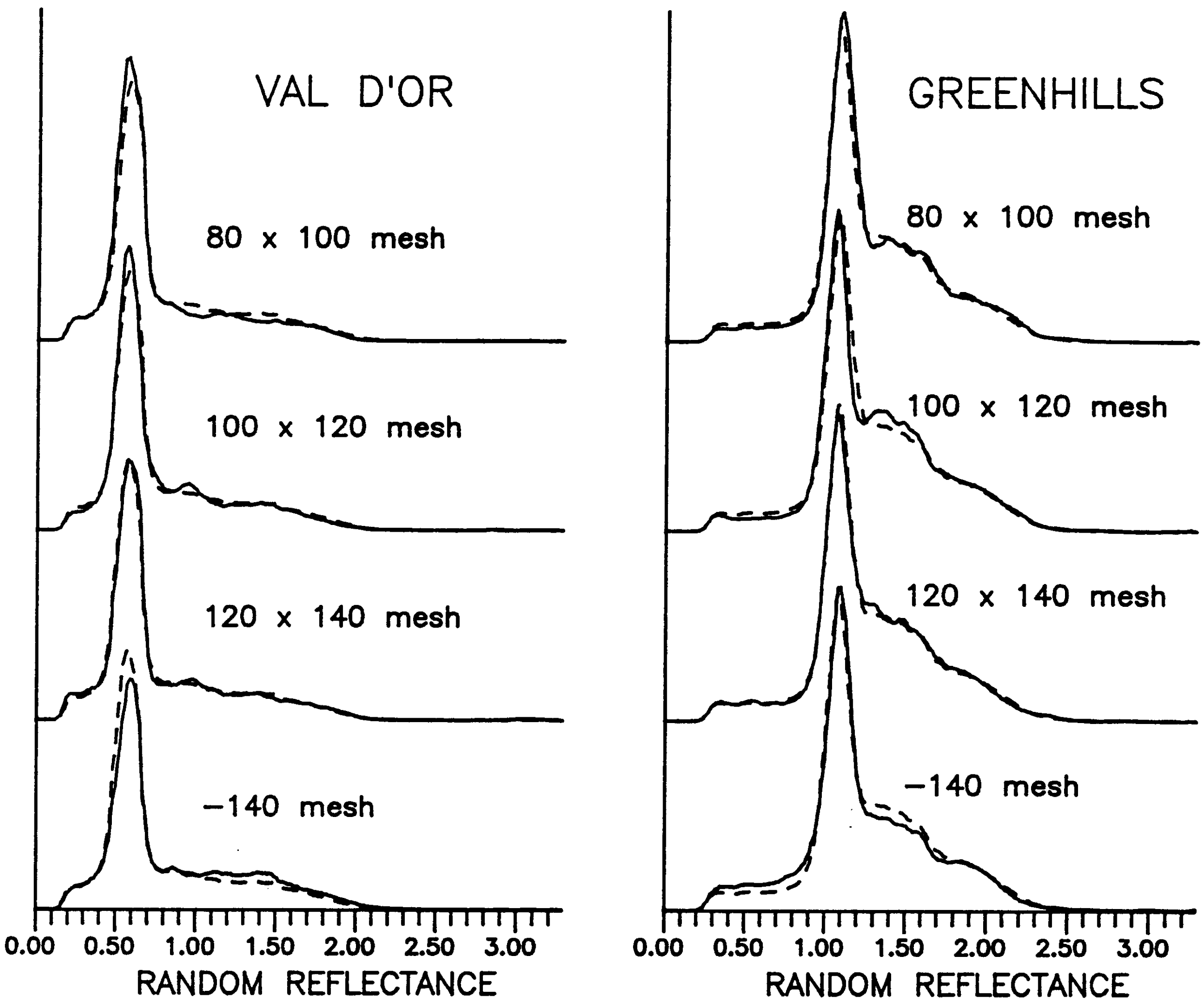

Figure 4: Reflectance histograms of -80 mesh sieve fractions from table 1.

apparent in the table data. All fractions of the Greenhills -80 sample are very similar, as are the Val D'Or -20 fractions. An increase in the liptinite content of the Val D'Or -20 mesh fractions is probably due to image processing difficulties caused by the lower rank of the coal in combination with increased edge effects as particle size decreases. As observed in the histograms, the Val D'Or -80 fractions show a gradual increase in inertinite as they become smaller in size.

Because inertinite components of coal are brittle, it is possible that in some cases they may be the first macerals to crush out of the bulk sample. This has been observed macroscopically and may explain the observations in the Greenhills -20 sieve analysis. A secondary occurrence of this phenomenon may be the cause of the return of the higher reflecting material in the fine fractions of this coal. Similar effects may have occurred in the Val D'Or -80 sample. However, it is not as obvious as the Greenhills #10 case in both the histograms and the tabular data, and for this reason a conclusion can not be made.

	Mesh size	-20 MESH Vit. %	Inert. %	Lipt. %	-80 MESH Vit. %	Inert. %	Lipt. %
	20 x 40	59	39	2	-	-	-
	40 x 60	59	38	3	-	-	-
Val D'Or	60 x 80	56	40	4	-	-	-
	80 x 100	60	37	3	69	28	3
	100 x 120	58	37	5	64	34	2
	120 x 140	60	36	4	62	35	3
	-140	55	39	6	56	42	2
	20 x 40	44	55	1	-	-	-
	40 x 60	53	46	1	-	-	-
Greenhills	60 x 80	55	44	1	-	-	-
	80 x 100	55	44	1	55	44	1
	100 x 120	56	43	1	52	47	1
	120 x 140	52	47	1	53	45	2
	-140	53	45	2	54	44	2

Table 3: Quantitative data derived from standardized maceral thresholds applied to histograms in figures 3 and 4.

If there is indeed a concentration of specific macerals at certain particle sizes, particularly the larger sizes, then the liklihood of repeated measures and dominated fields is increased for that particular component, creating the possibility of a weighted histogram. In this experiment, this phenomenon was controlled to some degree by sieving out the smaller particles and by ensuring large numbers of pixels were evaluated. In routine analysis, this could be overcome by using a smaller particle size, although this may not be popular amongst workers using conventional methods since it creates difficulty evaluating the morphology of smaller particles encountered. However, morphology is a further source of error in manual analysis due to inconsistency between operators. Image analysis does not rely on morphology in any way, eliminating bias in the collection of data, although it may contribute to the resulting histograms. Voids in the inertinite macerals may cause artifact buildup (Pratt, in press). This can be controlled through good samples preparation and proper image processing technique.

The use of reflectance histograms as a comparative tool to detect differences in sample characteristics has been shown in both parts of this study. By superimposing histograms, or by studying them in series, many uses may be found in the field of quality control both in laboratories or industry. The ability to observe the actual reflectance distributions provides additional advantages. Using the distributions, it is possible to derive statistical parameters such as the mean, standard deviation and population size for various macerals (Pratt, in press). In contrast, manual methods simply provide the proportions of maceral components, which are only indicators of relative population size. For example, in order to determine the mean and standard deviation of the reflectance distribution of vitrinite, a completely separate measurement must be performed in addition to the point counting required to determine maceral composition. Using automated image analysis, all of this information is available in a fraction of the time. Although detailed maceral analysis will always require the discretionary skills of trained human observers, automated image analysis provides rapid and accurate assessment of coal quality in a form that is amenable to many types of analysis.

CONCLUSION

The reflectance histogram is a convenient means of comparing the quality of groups of coal samples. Testing error between runs and between samples was shown as an example. Between samples error can be significant. Between runs error is controllable, illustrating the basic soundness of the image analysis technique. Quantitative results confirm conclusions drawn from comparisons of histograms.

Comparisons of reflectance histograms of particle size fractions arranged in series suggests that some macerals concentrate at certain particle sizes. This may be due to different crushing characteristics between macerals. If more than one particle size distribution exists having different maceral composition characteristics additional sources of error may be introduced. Smaller particle sizes may reduce this error or at least reduce other sources.

Automated image analysis provides results in a form that is useful in a number of ways. This study shows that sources of error are controllable and easy to trace, and the reflectance histogram is a valuable comparative tool having a variety of applications. The ability to examine actual distributions provides an advantage over manual methods that simply provide proportions of the various coal components. Since image analysis does not rely on particle morphology, inconsistencies between operators is eliminated. Trends in the behaviour of maceral distributions can be detected providing insight into the behaviour of a coal through various processes.

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COMPUTER MODELLING OF THE JUDY CREEK SOUTH COAL DEPOSIT

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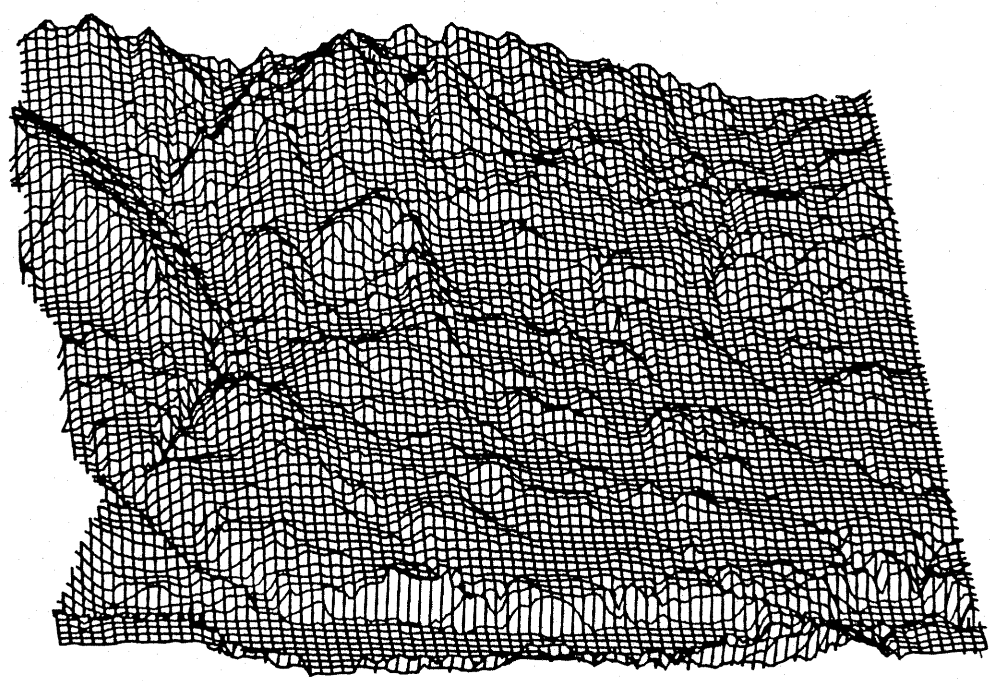


ABSTRACT

A computer based geological model is a set of gridded surfaces - depositional, structural and erosional - which are arranged in space to represent one possible realization of the underlying geology.

Geological computer modelling is neither a definitive or a mature science - it is an evolving art. However recent trends in computer modelling embrace a probablistic or statistical approach and strive to integrate all data, be it exact or inexact.

This study describes the construction of a computer based geological model of the Judy Creek South coal deposit. An effective and geologically reasonable approach is presented. Stacked isopachs, indicator mapping and model operations are discussed. The model is well suited to coal resource/reserve generation and mine planning. The algorithms discussed are easily extendable and provide a sound base on which to build more sophisticated applications.

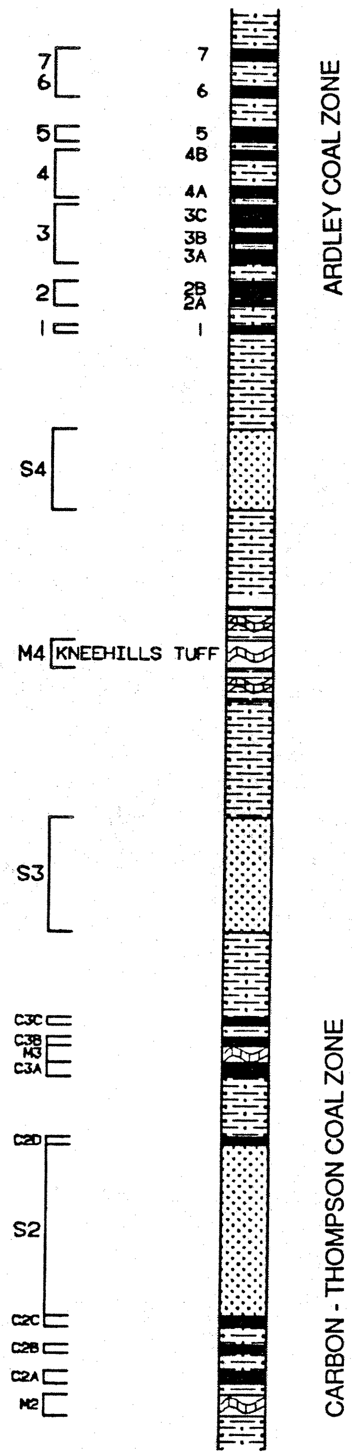


Figure 1. Typical stratigraphic section in the Judy Creek South area

INTRODUCTION

Figure 1 illustrates the generalized stratigraphic package in the Judy Creek South area. Seams 1 through 7 belong to the Ardley coal zone of the Scollard Formation. Seams C2 (A, B, C and D) and C3 (A, B and C) belong to the upper Horseshoe Canyon Formation and are thought to be equivalent to coals of the Carbon-Thompson coal zone (Dunn, 1988). Only the Ardley coals are of economic interest in the Judy Creek South area. The computer model was generated using all individual Ardley seams (Seams 1 through 7) as well as the combined C2 interval (base of C2A to the top of C2D) and also includes glacial tills and gravels.

Figure 2 illustrates the distribution of drillholes across the Judy Creek South study area. A southwest - northeast drilling trend can be observed as drilling generally follows the Ardley subcrop. If we select a number of different seams or seam interburdens using all the drillhole data in the study area and isopach that data (a "naive" approach) *three important limitations* become apparent;

1) Problems in areas where drill data is scarce or absent (non-informed areas) *(Figure 3).*

i) Isopach lines may not extend into non-informed areas (this is largely a function of the search radius specified in the gridding algorithm).

ii) The gridding algorithm extrapolates wildly into non-informed areas (ie isopach values at the northwest and northeast corner of the map far exceed the seam's mean thickness of <1 meter.

2) The isopach does not account for situations where the seam is absent. For example *Figure 4* is an isopach of Seam 4A - a very discontinuous seam in the Judy Creek South area - yet the isopach suggests seam continuity over a very large portion of the study area. This is because only Seam 4A thickness values are gridded. Clearly a technique is needed beyond simple isopaching of raw data to account for seam absence or discontinuity in "informed" areas.

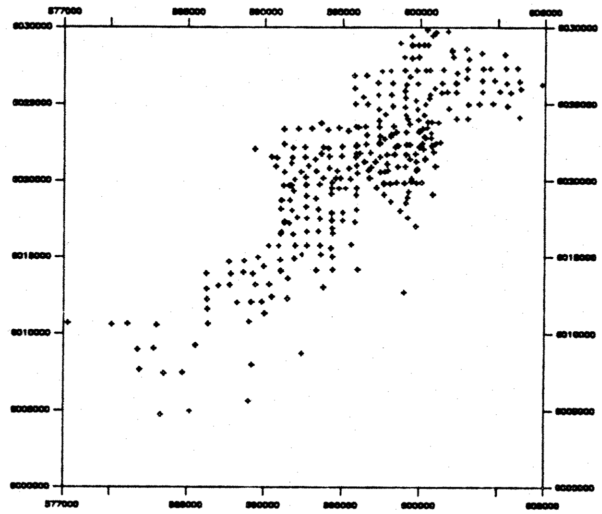


Figure 2. Distribution of drillholes, Judy Creek South area

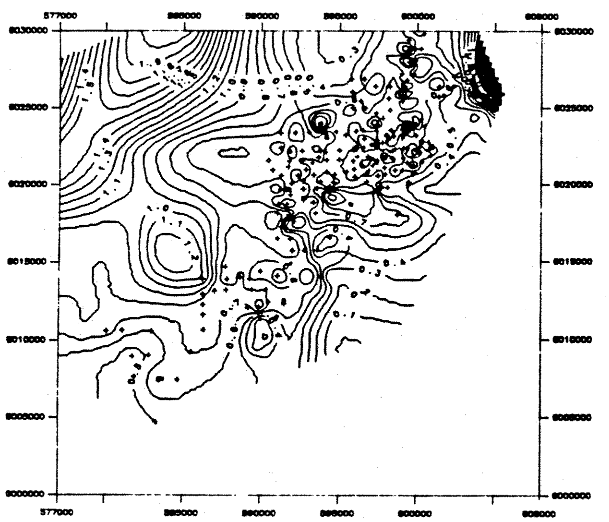


Figure 3. Isopach of Seam 3A

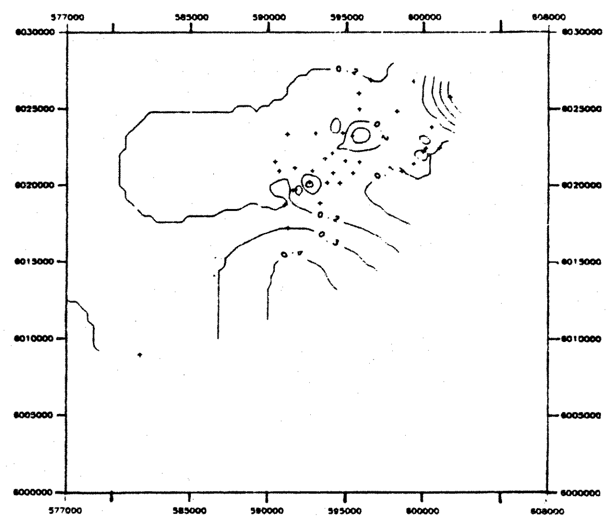


Figure 4. Isopach of Seam 4A

3) Naively gridding the elevation of the tops and bases of a number of seams will result in "swimming surfaces" *(Figure 5).*

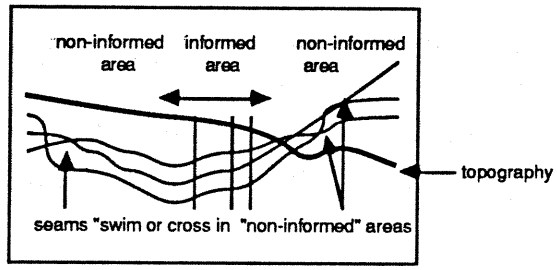


Figure 5. Crossing of surfaces in "non-informed" areas

The ability to reasonably predict the thickness or elevation of a coal seam in areas where there is little or no drilling data is necessitated primarily because of two reasons;

1) The need for resource/reserve estimation in areas where there is little or no drillhole data.

2) Extrapolation of seams beyond subcrop and outcrop so the areal extent of the deposit can be defined (ie so the seams are accurately truncated).

If these two primary requirements are to be fulfilled then the problems of wild extrapolation of surfaces and recognition of seam absence have to be addressed. This requires that a more sophisticated approach be taken other than just the gridding and displaying of raw data as discussed above - it requires the construction of a computer model. A variety of different modelling techniques can be taken to address the problems outlined above. A first generation approach to computer modelling of the Judy Creek South coal deposit is discussed below.

MODEL BUILDING

Figure 6 illustrates the basic steps in model building. Importantly the model building process imitates natural geologic processes; it firsts builds depositional surfaces, then tilts them (tectonic activity) and finally truncates them (glacial erosion). In nature since faulting and folding, and erosion postdate initial deposition they have no influence on original depositional surfaces. Post depositional structural influence is "filtered out" in the model building process by interpolation of unit thicknesses from drillhole information (isopaching) as opposed to interpolating the elevations of unit tops and bases. The Judy Creek South model represents a simple case; one uninterrupted period of deposition followed by tilting and finally erosion. More complex situations can easily be imagined, however the basic principles would remain the same; in effect you would execute a number of iterations of the modelling process as opposed to a one pass approach discussed here.

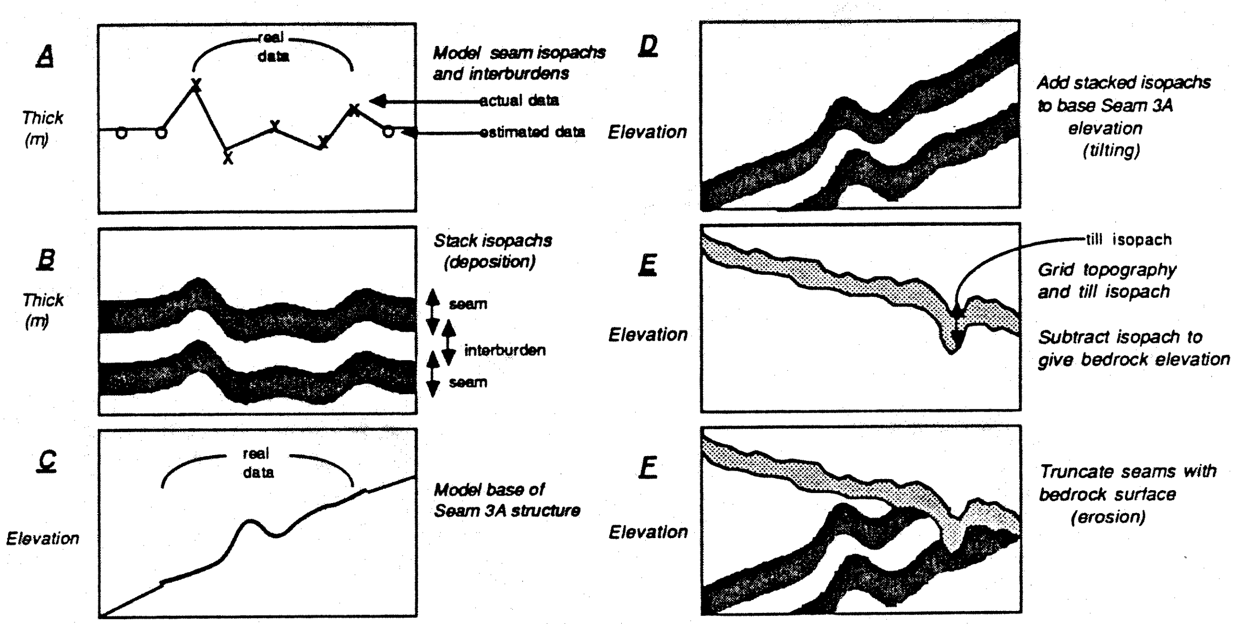


Figure 6. Basic Modelling Concepts

The following schematic illustrates the key elements in the construction of the Judy Creek South computer model. Steps A through E concern mainframe operations and will be the primary focus of the model building discussion. SAS ®(Statistical Analysis System) software and proprietary Exxon developed SAS mapping procedures were run on an Amdahl 5890 mainframe computer. Procedures to display and evaluate the model were run in a PC environment. MEDSYSTEM®(Mineral Evaluation and Design System) software developed by Mintec Inc. was run on a Compaq 386.

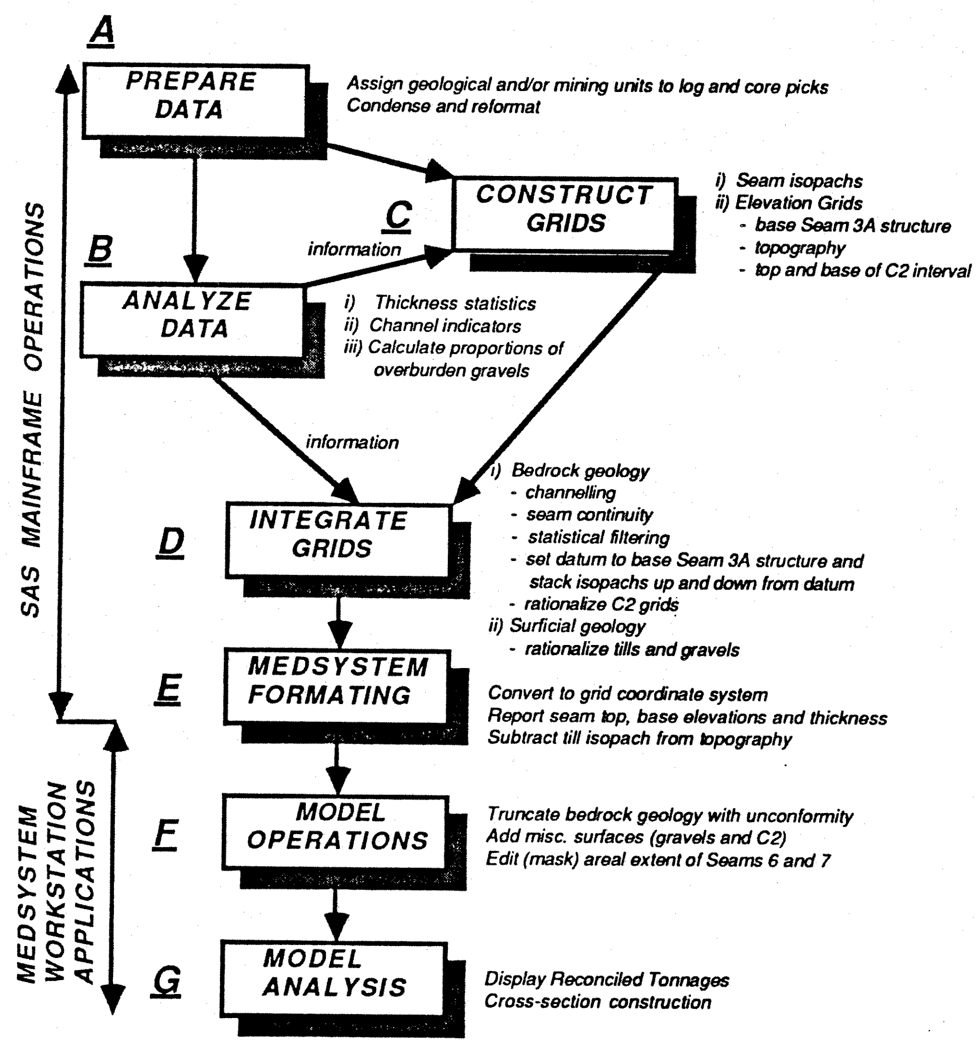
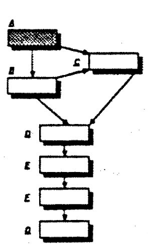
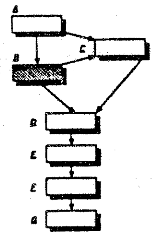


Figure 7. Geological Modelling Flowchart



A DATA PREPARATION

Several programs not discussed in this paper condense the original picks into a mappable format. Preliminary mapping and statistical analysis help in recognizing and correcting data errors. The importance of data integrity cannot be overemphasized, typically over 70% of time spent in the geological modelling process is spent working and re-working the original data to bring it as close to a "clean status"as possible.



B DATA ANALYSIS

Three SAS programs were written to analyze and summarize drillhole data for information needed in the gridding and model integration process.

1) Thickness statistics (mean, minimum and maximum) *(Figure 8)*

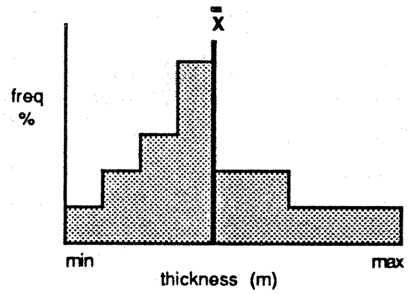


Figure 8. Thickness statistics

2) Channel Indicators

If a seam is not present in a hole and there are seams present above and below the missing seam interval then the channel indicator is set to 0 (ie the probability of the seam being present is nil). If the seam is present the channel indicator is set to 1 *(Figure 9).*

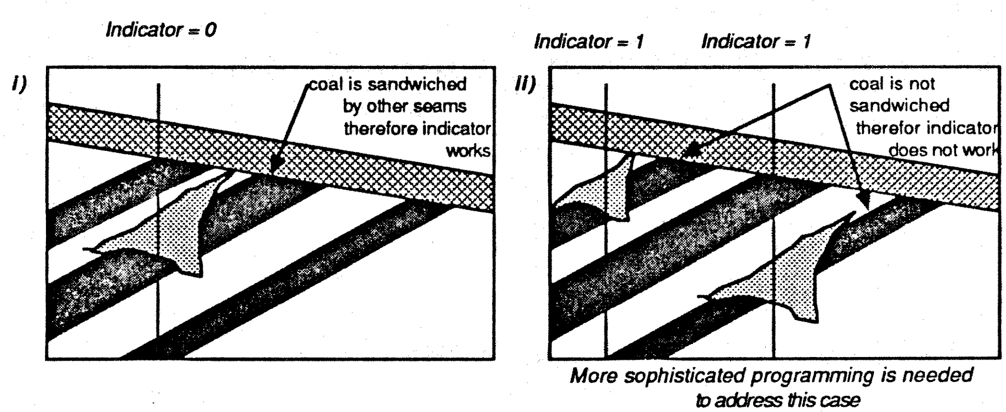


Figure 9. Channel Indicators

This technique only "picks up" some channels; the uppermost or lowermost coal horizons are not bracketed by other coal horizons therefore the channel indicator logic will not work. Even if the coal is discontinuous the channel indicator will still be set to 1 and the coal horizon will extend through areas where drillhole information suggests that it is not present. This problem is addressed in the Judy Creek South modelling process by manually interpreting where the upper and lowermost seams are not present, digitizing those areas and then removing them from the essentially completed model after it was downloaded to the workstation environment. More sophisticated programs such as those developed by J. D. Hughes of the Geological Survey of Canada is needed to better address this problem.

3) Overburden Stratigraphic Proportions

The percentages of five distinct glacial units (as a function of total till thickness) is calculated for each hole. If a unit is not present in a hole a 0% value is reported *(Figure 10)*.

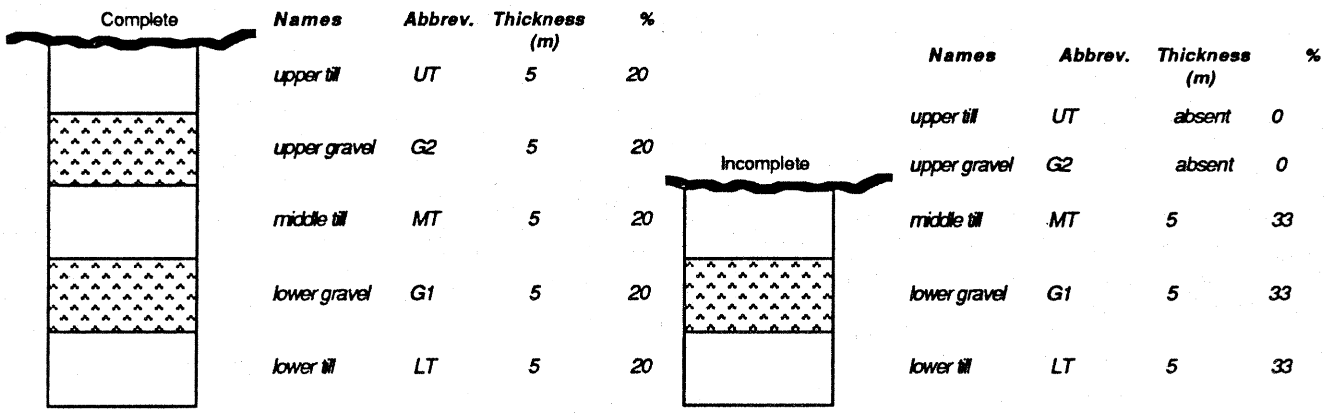
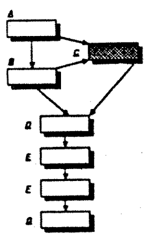


Figure 10. Overburden stratigraphic proportions



C CONSTRUCT GRIDS

Gridding is divided into two basic types; i) isopaching of depositional units and ii) structure contouring of elevations. All gridding uses the same Exxon SAS algorithm (two pass least squares with an octant search; course grid multiplier is 4 times the 200 meter grid). Grids produced at this stage provide the raw data for the subsequent grid operations needed to build a geologically reasonable model.

i) Isopaching

Figure 11 illustrates the process involved in generating fieldwide isopachs. The technique adds pseudo data (the field mean) in non-informed areas to prevent wild extrapolation.

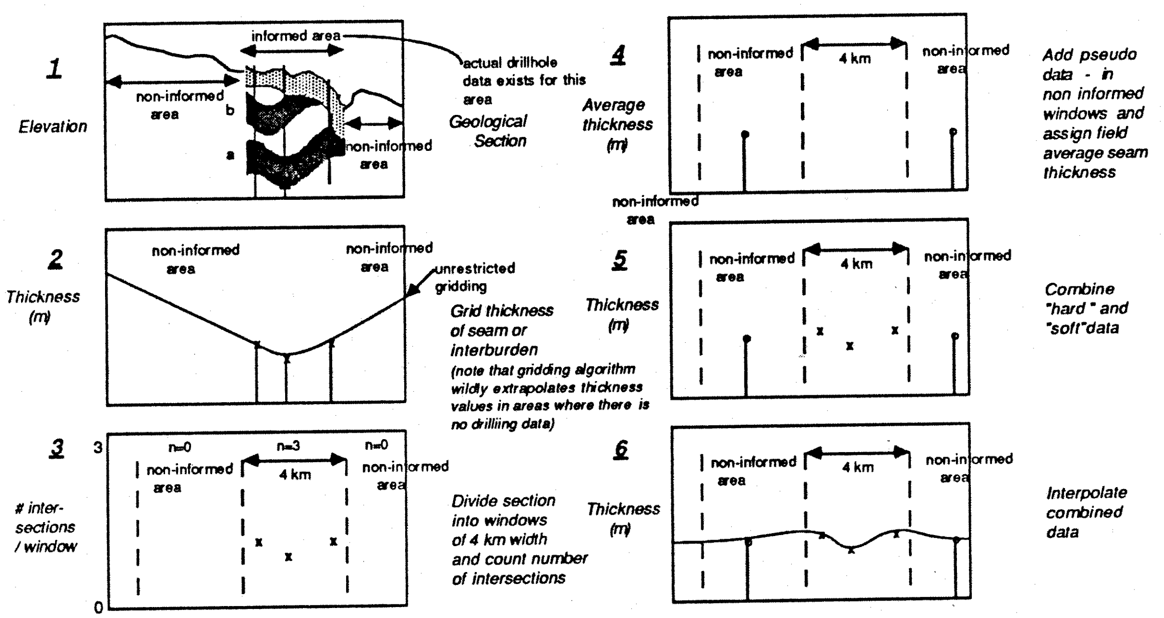


Figure 11. Fieldwide isopach generation

An important variable in the algorithm is the width of the counting window. The window width used for this study is 4 km, which is about the average range of seam thickness variograms (in other words, beyond the range of spatial correlation the mean is as good a guess as any).

In addition to a thickness value several other grids are calculated and used in later processing. The number of intersections per window is gridded (*Figure 12)* providing a measure of the confidence of the thickness estimate.

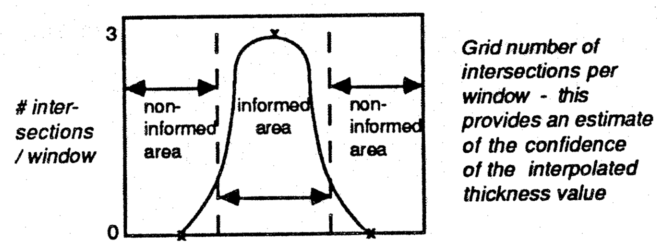


Figure 12. Number of intersections per window

The channeling indicator is also gridded for all coal seams *(Figure 13).* If the coal seam is thought to be discontinuous in non-informed areas a flag is set and the channel indicator becomes 0 (seam not present) in those areas. Use of these grids is discussed further below.

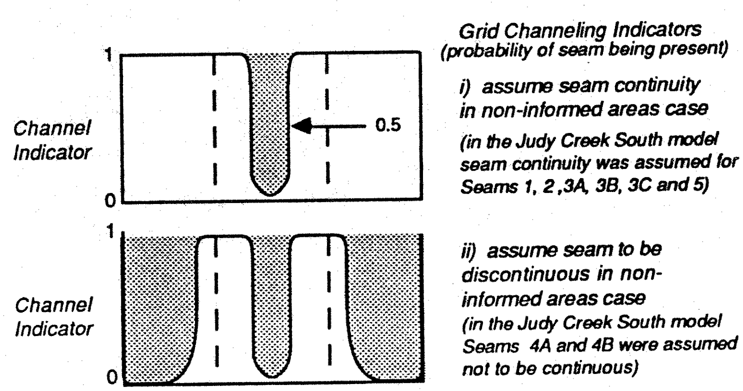


Figure 13. Gridding of channelling indicators

ii) Elevation Grids

a) Base Seam 3A structure is created using "pseudo-data" or dummy holes in conjunction with the actual elevation data. The dummy holes are in effect just geologist predicted x y z coordinates of the base Seam 3A surface at the four corners of the study area. The result is a field wide grid that extends beyond subcrop to the east and to depth in the west. *Figure 14* illustrates this concept in section view. *Figure 15* shows the structure contour map of base Seam 3A without pseudo-data. *Figure 16* shows the structure contour map with pseudo data. Note that the final structure contours covers the entire study area.

b) Topography is re-gridded from a 5 meter contour interval digital terrain model constructed by The Orthoshop of Calgary. Original grid spacing of the digital terrain model is 120 meters. In terms of resource assessment this is the most important grid.

c) The top and basal elevations of the C2 seam interval is gridded in a straightforward manner (no pseudo-data was used).

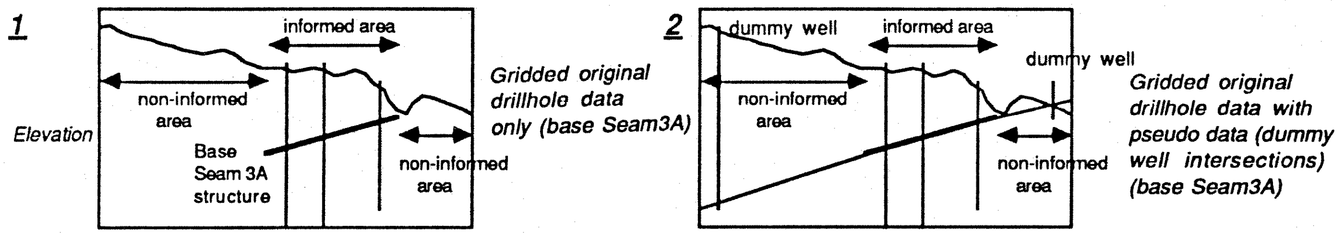


Figure 14. Construction of structure contour of base Seam 3A

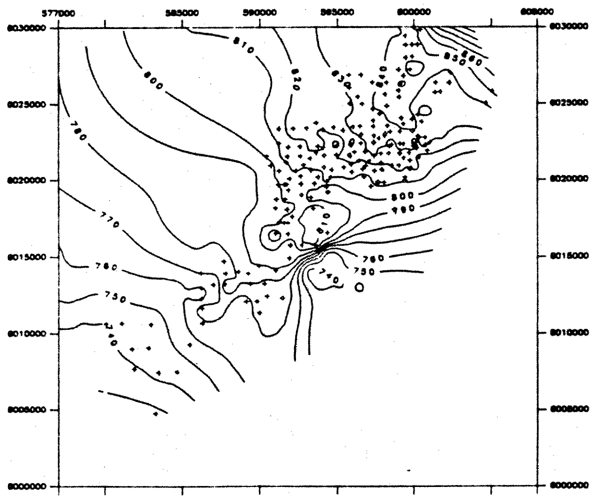


Figure 15. Structure contour map of base Seam 3A without pseudo-data

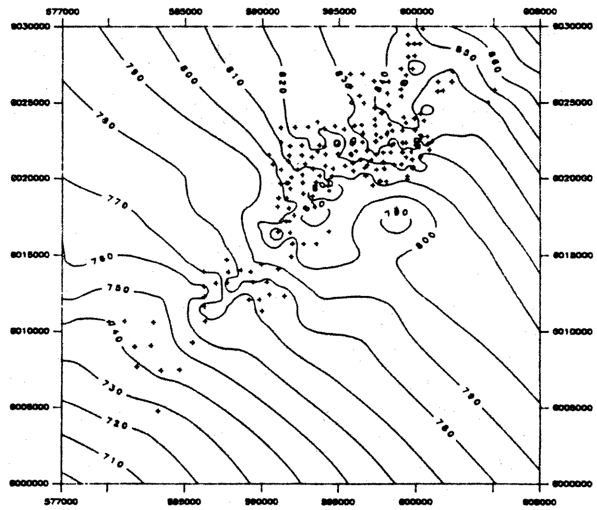
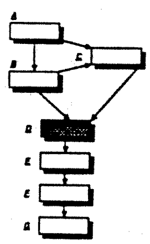


Figure 16. Structure contour map of base Seam 3A with pseudo-data



D INTEGRATE GRIDS

This portion of the modelling process combines the grids constructed in the previous steps into an "almost complete" geological model and can be broken into two components; i) bedrock geology and ii) surficial geology.

i) Bedrock Geology

The process of creating an integrated model of bedrock geology requires the following steps;

a) Statistical Filtering of Fieldwide Isopachs

At this stage the isopach grids are essentially passed through a high and low pass filter to remove any wild extrapolations *(Figure 17).* The high pass filter corresponds to the minimum thickness observed in the drillhole database while the maximum thickness forms the cutoff for the low pass. Only Seam 4A and Seam 4B were assigned a minimum of 0 meters (ie allowed to pinch out).

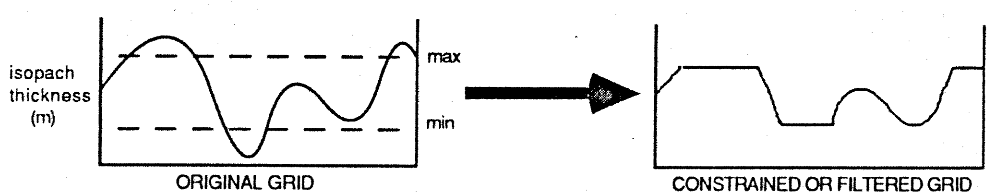


Figure 17. Isopach grid filtering

b) Channelling

Channelling removes coal by using the channel indicator grid as a type of "probablistic cookie cutter." If the channel indicator grid value is less than .5 (50% probability) the coal is assumed to be channelled out and the volume of coal removed is added to the overlying interburden *(Figure 18).* Note that this method results in vertical seam truncation - varying the cutoff function will give different channel geometry.

c) Seam Continuity in Non-Informed Areas

If coal is thought to be discontinuous in an undrilled (non-informed) area it can be removed by setting a flag in the isopaching program that sets channel indicators (or continuity flag) to 0 thereby removing estimated coal *(Figure 19).* The original model only uses this technique on Seam 4A and Seam 4B due to their very discontinuous nature across the drilled portion of the study area. In hindsight the method should have been used on Seam 6 and Seam 7 as well.

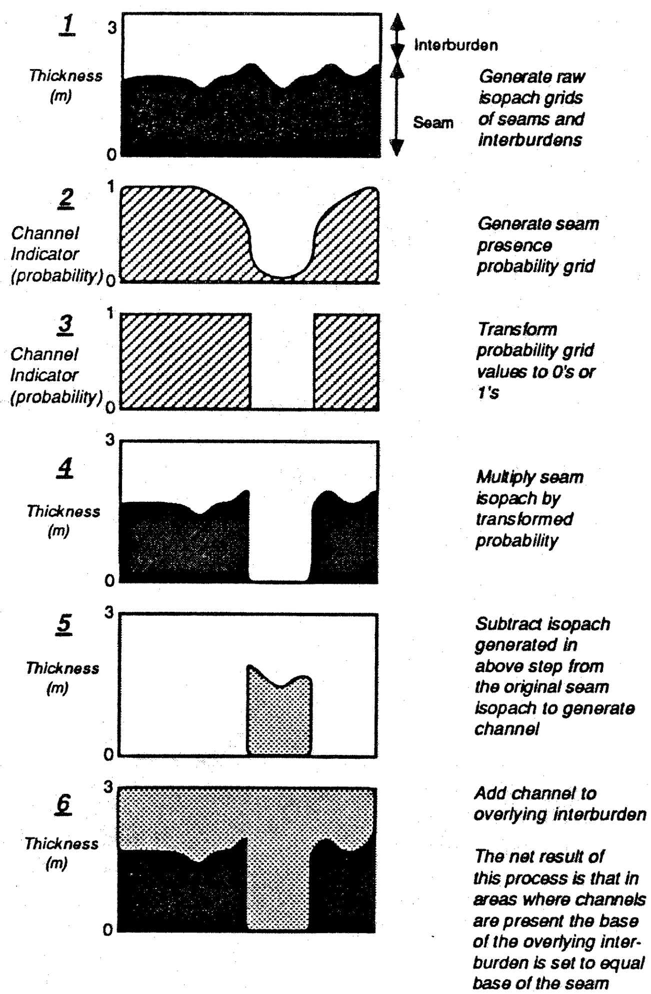


Figure 18. Modelling Channels

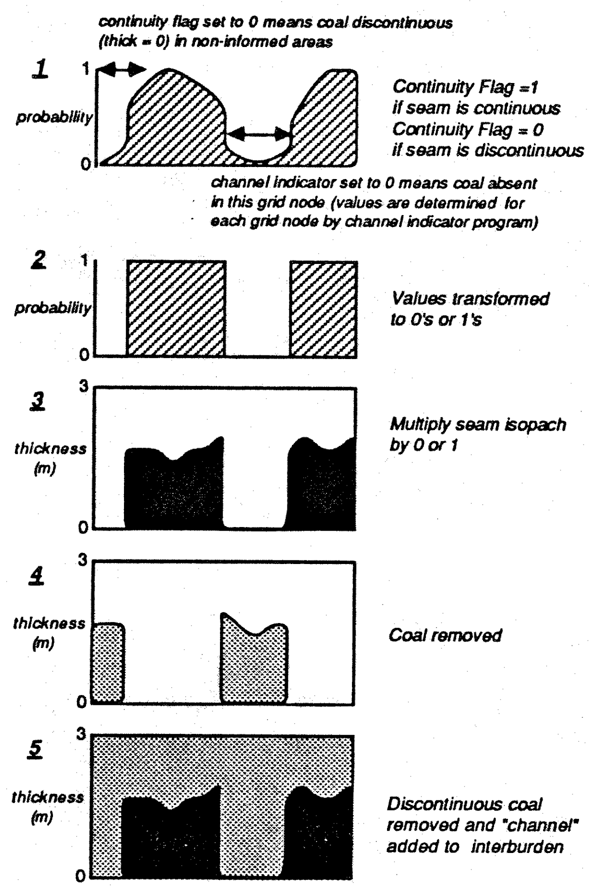


Figure 19. Setting seam discontinuity flags in non-informed areas

d) Stacking Isopachs

This step creates a depositional model (ie pre-tilting) in a layer cake fashion. At this stage all seams and interburden isopachs have been constructed and refined. Seam and interburden isopachs are successively added (or subtracted) from the base of Seam 3A *(Figure 6B).*

e) Re-datum to Base Seam 3A Elevation

Adding the elevation of the base of Seam 3A to the stacked isopachs has the effect of tilting the model to the orientation of the geologic structure *(Figure 6C and D).*

f) Special Considerations

Due to the discontinuous nature of Seam 4A and 4B, and the C2 interval, slightly different techniques are used in their modelling;

Seams 3 to 5 Interburden
Reproportioning of isopachs within the Seam 3 to Seam 5 interval was performed to reduce the error introduced by the isopaching process of several thin discontinuous intervals *(Figure 20).* Seams 4A and 4B are allowed to coalesce with each other but not with the underlying Seam 3C or overlying Seam 5. The reproportioned estimates are not filtered further.

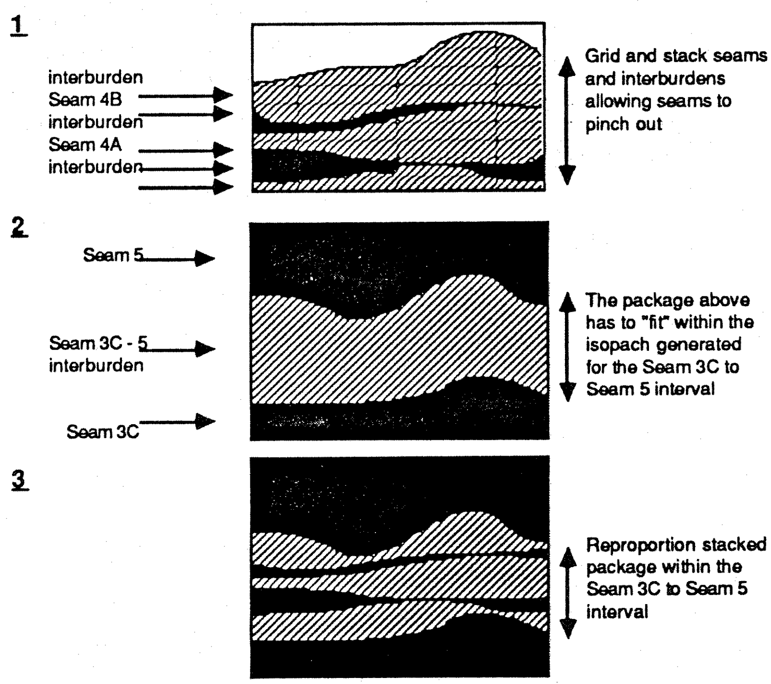


Figure 20. Seams 3 to 5 interburden modelling

Seam C2 Package
Seam C2 of the Carbon-Thompson coal zone was modelled by first gridding the top and base elevation and subsequently rationalizing the grids to remove crossing tops and bases *(Figure 21).* Considerably more effort would be required to do a complete Carbon-Thompson model. Note the model includes all C2 seams (C2A, C2B, C2C and C2D and all interburden as one package).

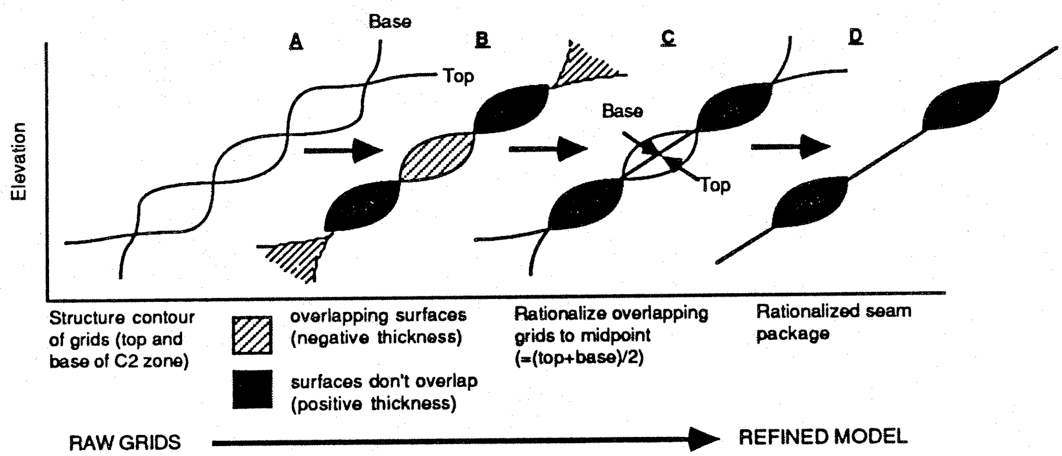


Figure 21. Modelling C2 package

Surficial Geology
Integration of the grid models of topography, total till thickness and till composition/stratigraphic percentage provides a model of the buried glacial topography and a model of the distribution of the two gravel units (G1 and G2).

a) Bedrock/Till Unconformity
This surface is easily generated by subtracting the total till isopach (including gravels) from the topographic elevation grid. Remember the till isopach is a fieldwide estimate outside the informed area.

b) Gravels
Gravels are added to the model through the use of the percentage grids of the 5 surficial units (LT, G1, MT, G2, UT). The iso-percentages are constrained to be greater than 0, stacked and normalized to 100%. These percentages are then multiplied by the total till thickness and added to the glacial unconformity to provide elevations of the gravels *(Figure 22).*

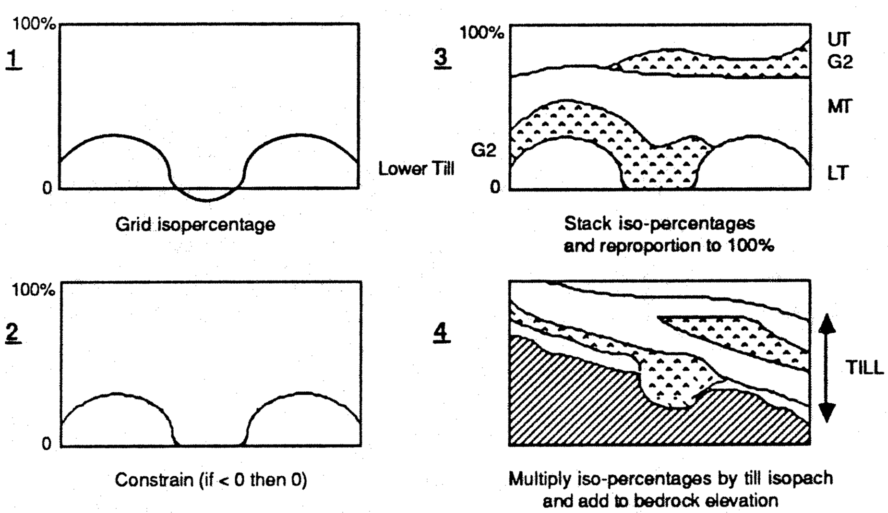
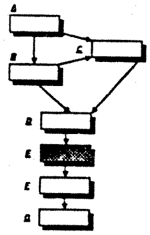


Figure 22. Modelling gravels



E MEDSYSTEM FORMATTING

This step converts UTM coordinates to grid coordinates *(Figure 23)*, converts seams to benches *(Table 1)* and reports data to a Medsystem ready file. Data for the Ardley unit are put out in a FILE 15 format while the remaining grids (surfaces) are put out in FILE 19 style.

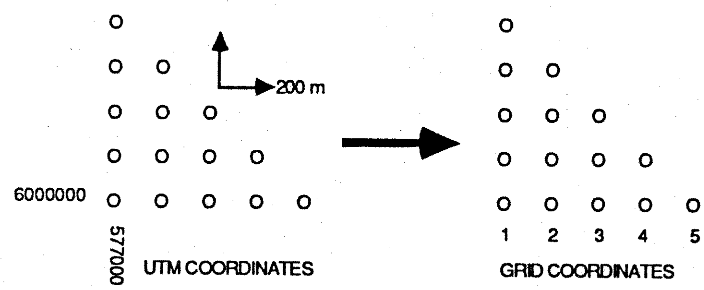
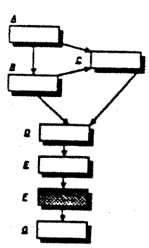


Figure 23. Grid origin

Seam	Bench
7	1
6	2
5	3
4B	4
4A	5
3C	6
3B	7
3A	8
2B	9
2A	10
1	11

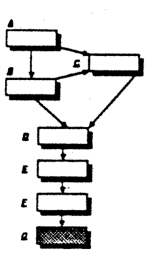
Table 1. Seam to bench naming

These transformations are typical of what is involved in moving data from one system to another.



F MEDSYSTEM MODEL OPERATIONS

Medsystem programs complete the modelling process by truncating the seams at subcrop and removing incorrectly modelled Seam 6 and Seam 7 where they are discontinuous (as discussed previously).



G RECONCILIATION AND VALIDATION

Volumes of coal and rock have been compared between Medsystem reports and the original mainframe SAS model (after truncation at subcrop). Results are virtually identical. Furthermore tonnages also compare favorably with previous manual efforts as well as an earlier Medsystem generated model.

Visual checking of cross sections *(Figure 24)* suggests a reasonable model has been made. One obvious but simply fixed error is that the gravels do not pinch out in non-informed areas. In hindsight the gravels should pinch to 0 in non-informed areas.

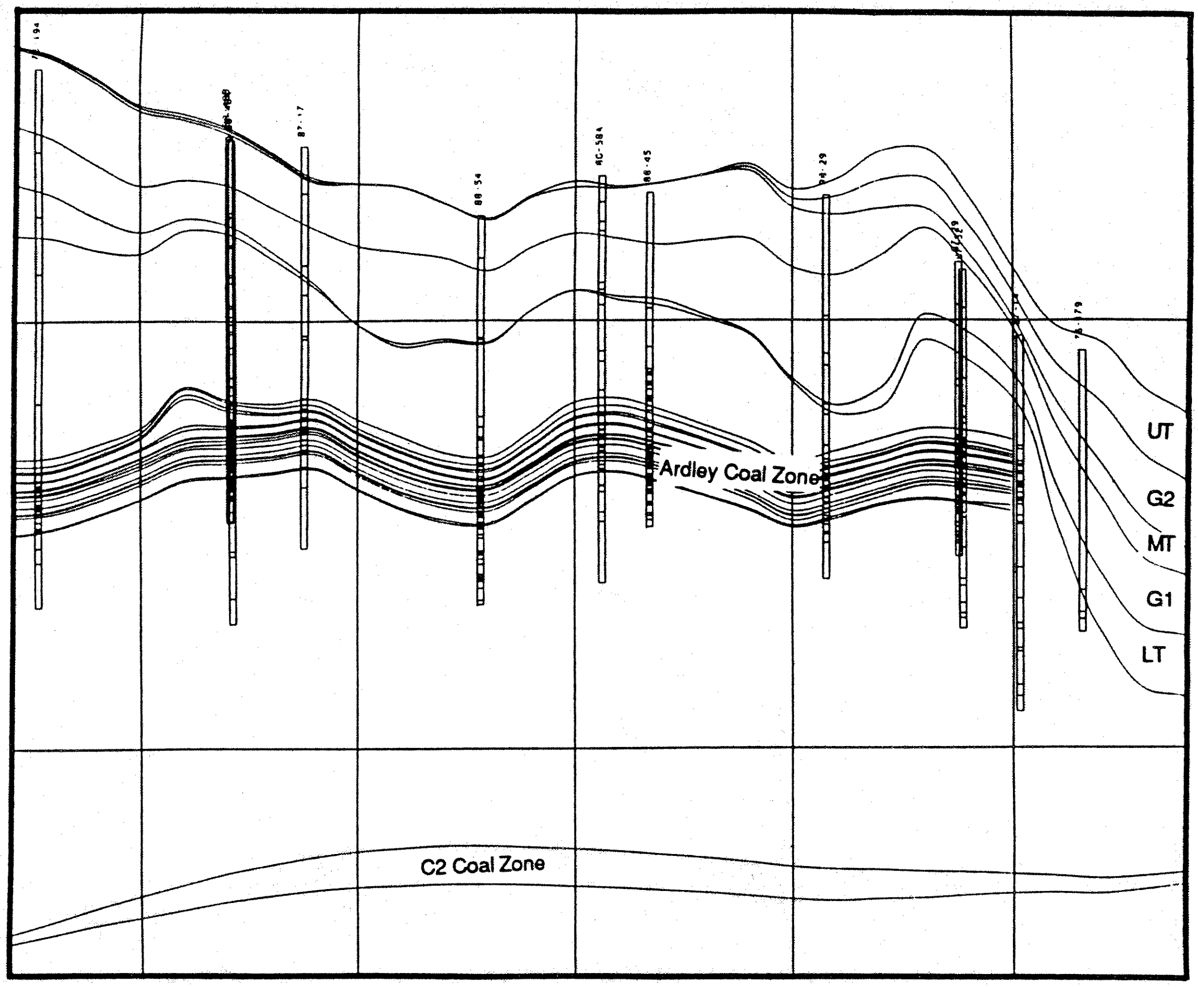


Figure 24. Example of west-east Medsystem generated cross-section across Judy Creek South area

DISCUSSION

The realism or level of detail achieved in a geological model (be it computer or paper based) is constrained by several factors;

1. Available information is often complex, incomplete and/or incorrect.

2. Modelling methods may be physically or conceptually weak.

3. Manpower, computer power and time may be limited.

4. The required resolution of the model is related to the end use of the model.

A pragmatic approach is taken in the construction of the Judy Creek South model;

1. Most of the complexities and deficiencies in the data are adequately handled. Further sophistication in the analysis of borehole data would provide more comprehensive use of the data.

2. The modelling technique is conceptually simple and is geologically and geostatistically sound.

3. Effective use of both the geologist's time and the computer resources is achieved.

4. Resolution of the model is more than satisfactory for downstream geological and engineering applications.

Furthermore the modelling technique can be easily modified or extended to address a need for more complex modelling requirements. Importantly it provides a prototype from which to develop more rigorous and effective modelling tools.

Application of Geostatistics

Ideally geostatistical estimation techniques (ie kriging and/or conditional simulation) should be used in the isopaching algorithm. However the effort needed versus the improvement in model precision does not justify the use of geostatistics at this stage.

Nonetheless the modelling method used incorporates some geostatistical techniques which could easily be extended to incorporate kriging or simulation. Indicator functions are used to limit seam continuity while a simple type of conditional simulation is used to estimate thickness values in non-informed areas. The use of "poor man" geostatistics, although slightly compromised, is effective in light of the real life constraints faced in the construction of the Judy Creek South model.

CONCLUSIONS

1) A computer based geological model of the Judy Creek South coal deposit has been built.

2) The model satisfies downstream geological and engineering requirements and represents an effective blend of human and technological resources.

3) The modelling technique is simple, geologically reasonable and offers several advantages over other techniques. Problems with crossing seams are non-existent and the modelling method can easily incorporate geostatistical applications such as kriging.

ACKNOWLEDGMENTS

The authors thank Dave Hughes of the I.S.P.G. for assisting with drillhole data analysis and encouraging and influencing our modelling efforts. Dave has also provided a number of completed geological models of the entire Judy Creek area - it is hoped that in the near future a direct comparison of his model with the model discussed in this paper will be undertaken. Don Guglielmin is thanked for invaluable Medsystem assistance. Esso Resources Canada Limited is thanked for permitting us to publish this paper. David Hallas and Allister Peach are thanked for reviewing the manuscript.

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Statistical Evaluations of Coal Quality in the Ardley Coal Zone

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ABSTRACT

Exploratory statistical evaluations of the Ardley coal zone in Alberta, indicate that significant coal quality variations occur at regional and detailed scales. With the objectives of characterizing central tendencies and variability, the study was divided into the following three phases: (1) detailed analysis within a mine site (Highvale Mine), (2) regional comparison of prospective mining areas and (3) comparison of coal quality variation in the Highvale Mine to regional results.

Regional coal quality data sets contain the weighted average based on thickness, of all seams combined in each drill hole location. Median ash values for regional samples are 30.7% (Ardley Bend), 27.0% (Wetaskiwin), 18.5% (Low Water Lake), 14.8% (Genesee), 15.9% (North Highvale), 17.4% (South Highvale), 19.8% (Whitewood), 29.5% (Swan Hills), 36.7% (Fox Creek) and 34.9% (Musreau Lake) all on a dry basis. Similar variation is observed for median sulphur values between study areas. These large variations suggest that no single area or sample site can be considered "typical" of Ardley coal quality.

At Highvale Mine, coal quality is evaluated on a seam by seam basis. Results from the Highvale study indicate significant variations in coal quality between seams. Median ash values for seams 1 to 6, are 18.4%, 13.9%, 19.3%, 22.2%, 38.0% and 20.3%, respectively, all on a dry basis. The comparison between individual seam values to the composite median for the entire Highvale area (16.0%), indicates that statistical results must be interpreted carefully. Accuracy and confidence in the predicted values are dependent on the scale of investigation and amount of data the estimates are calculated from.

The coal quality data sets examined typically display non-normal distributions, widely varying skewness and spatial dependencies. Nonparametric statistical techniques, with no distributional assumptions, are recommended because of these data characteristics.

INTRODUCTION

Between 1986 and 1989, the Coal Geology Group of the Alberta Geological Survey has been involved in a program investigating coal quality in the province. The objectives of this study are to characterize Ardley coal quality in the plains region of Alberta and to quantify observed variations. This investigation was done in three phases: (1) a detailed analysis of coal quality within a mine site (Highvale Mine); (2) a comparison of coal quality between a series of minesites and prospective mining areas; and

(3) a comparison between coal quality variation in the Highvale Mine to regional data.

The Ardley coal zone is lower Tertiary in age and lies near the base of the Scollard Formation (Gibson, 1977). Ardley coals are found throughout the Alberta plains, from Township 30 in the south to Township 66 in the north, and from the outcrop edge of the Scollard Formation to the deep subsurface (Richardson et al., 1988). It is mined extensively and is one of Alberta's most important sources of thermal coal. Coal quality studies are considered the key to better understanding of these valuable resources, and essential for resource planning over the next few decades.

Exploratory statistical evaluations from this study clearly illustrate significant variation in coal quality at all scales. Detailed evaluations within a mine site (Highvale Mine), indicate large variations in coal quality between seams and significant lateral changes in quality within individual seams. On a regional scale, large differences are observed for composite coal quality data (weighted averages of all seams) between study areas. A summary of results for ash, fixed carbon, volatile matter (proximate analyses), heat content (calorific value) and sulphur (ultimate analyses), all on a dry basis, is presented.

DETAILED STATISTICAL EVALUATION OF THE HIGHVALE MINE

The Highvale Mine is located about 80 kilometres west of Edmonton, Alberta and supplies coal for the Keephills and Sundance thermal electric power plants (Figure 1). With over 315 core holes having coal quality information, it represents one of the best explored coal deposits in Alberta. TransAlta provided their coal geology and coal quality data for this detailed evaluation. The abundant coal quality data, detailed geological information and the laterally extensive nature of the seams, make the Highvale Mine ideal for detailed study.

In the Highvale Mine, seams 1, 2, 3, 4 and 6 are mined (Figure 2). These seams are laterally continuous and easily identified by their unique geophysical log signatures. Coal isopach maps and cross sections, based on over 500 development and exploration holes, describe the lateral continuity, thickness variation and geometry of these seams (Lyons et al., 1987; Wong et al., 1988). The seams are numbered sequentially, from the shallowest (Seam 1) to the deepest (Seam 6).

Seams 1 and 2 stand out as the thickest and most economic of all the seams. Seam 1 is generally 2.0 to 4.0 m thick over most of the mine site and seam 2 ranges in thickness from 3.0 to 4.0 m. Seams 3, 4 and 6 are much thinner, varying from 0.3 to 1.2 m, generally contain more partings and have higher ash contents. Seam 5 which is not a recoverable unit, is commonly less than 0.4 m thick, and contains very high ash contents. It is included in this discussion for comparison purposes only. Within the Highvale Mine boundary, these seams can be correlated with a high degree of geologic assurance. Outside of Highvale many of the seams, including seams 1 and 2 thin and split, making correlation more difficult.

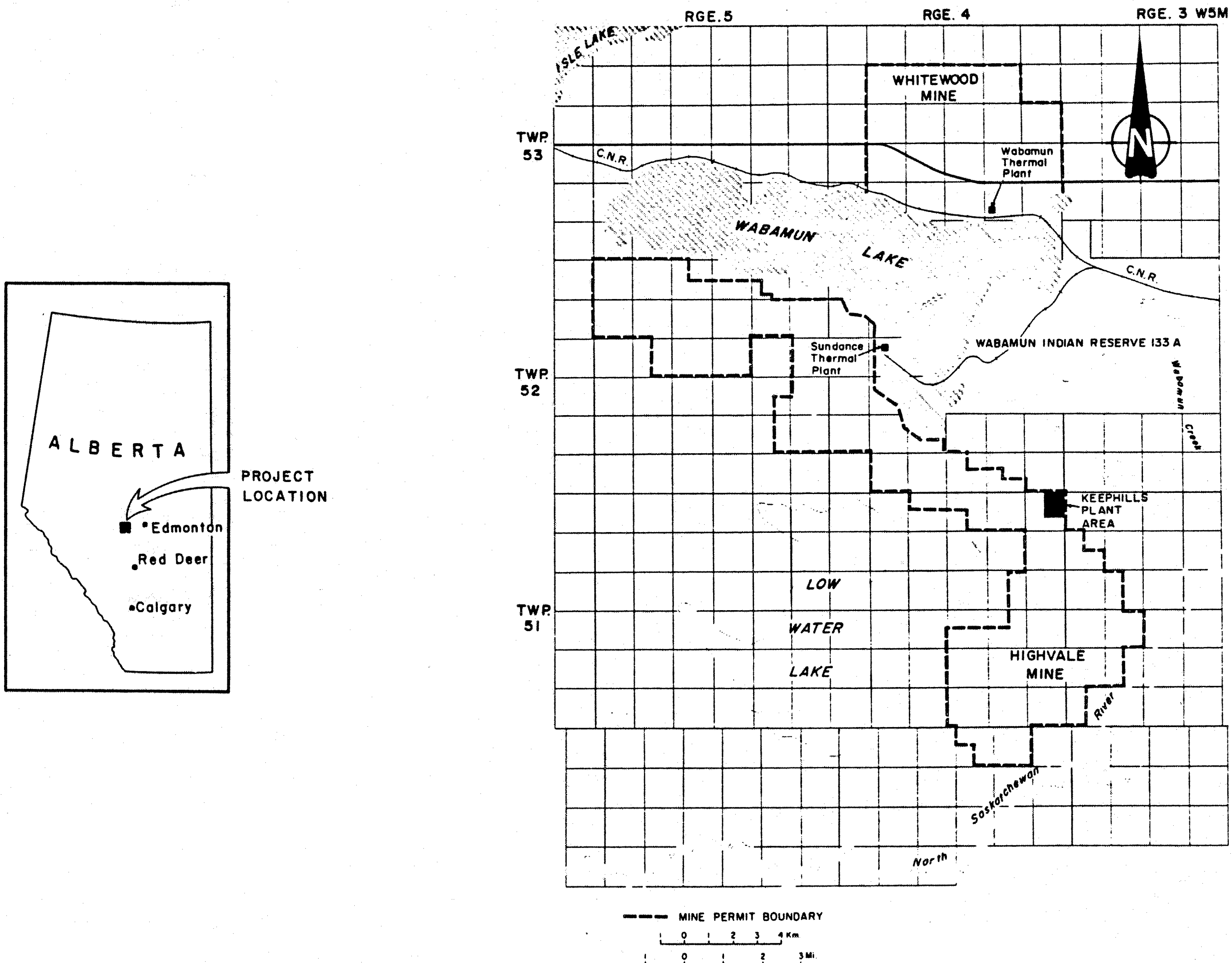

Figure 1. General location map of the Highvale Mine and locations of the Sundance and Keephills thermal electric power plants (modified from Lyons et al., 1987).

The first step in this evaluation is the separation of the data into geologically homogeneous groups. The data are subdivided on a seam by seam basis and seam correlations confirmed. Some of the data from areas along the subcrop are not included in the evaluation because of the possible effects of weathering, oxidation and erosion. Statistical results were carefully examined to see if variations observed were due to sampling bias, differences in analytical procedures, or due to geologic controls. Geological interpretations were applied in each step of the statistical evaluation, since the quality of the coal is closely tied to the geologic controls.

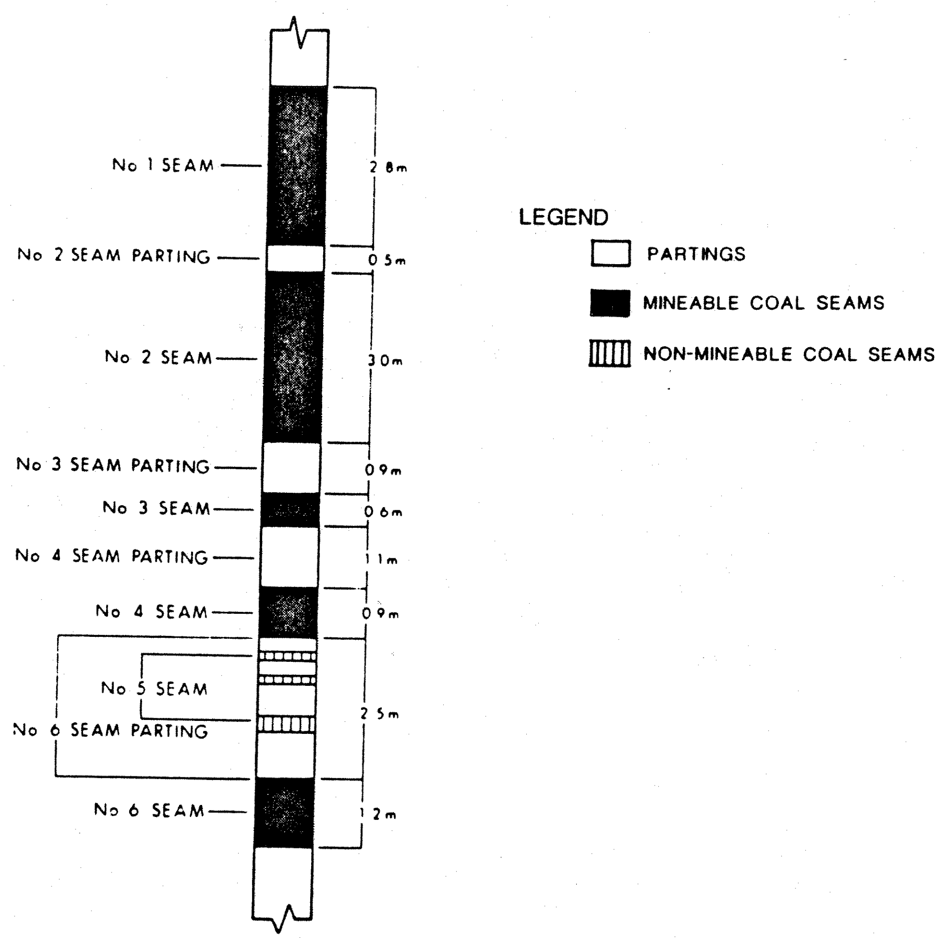

Figure 2. Numbering system and thickness comparison of the Ardley coal seams in the Highvale Mine. Seams are numbered 1 through 6, from the top to base, respectively, in the succession (after Taylor, 1985).

For the purpose of visual comparisons, multiple box plots were prepared. Box plots are simple diagrams showing the maximum, minimum, 75th percentile, the median (or 50th percentile) and the 25th percentile (Figure 3). The percentile is the value which is not exceeded by a certain portion of the sample population. The median or 50th percentile, for example, is the halfway point in a set of values. The median is less affected by outliers, and therefore, can be a better measure of central tendency than the mean for skewed data distributions. In the present study, a series of multiple box plots are used to summarize seam to seam variations.

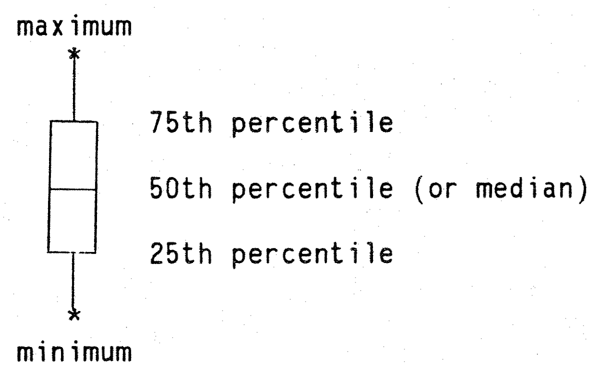

Figure 3. Features of box plots used in this study.

In Figure 4 the relatively low variability in proximate analyses of seams 1 and 2 is indicated by the smaller size of the boxes. The relative positions of the boxes indicate that these seams have the highest quality of all seams in the Highvale Mine, in terms of their thermal properties. Seams 1 and 2 are not only the thickest seams, they also have higher levels of volatile matter, fixed carbon, and heat of combustion and the lowest levels of ash and sulphur. Seam 5, which is not mineable, stands out with the highest variability and lowest quality of all seams. Seams 3, 4 and 6 generally fall between these two extremes.

The variation in seam 1 illustrates the importance of detailed geology and the level of confidence associated with the coal quality estimate. Subsequent investigations by the authors indicate that the northern half of the mine (Highvale North) differs significantly from the southern half (Highvale South). In Highvale North seam 1 and seam 2 display very similar coal quality characteristics. Both are considered high quality thermal coals, with relatively low ash and sulphur contents and low variability. In Highvale South, seam 1 has higher ash and sulphur contents and is more variable in quality. Because of significant differences in the geology and associated coal quality characteristics between Highvale North and Highvale South, more accurate estimates of coal quality in seam 1 can be offered by studying the two areas separately. Geostatistics performed after the seam comparisons were made concentrated on North Highvale because of the noted differences between areas.

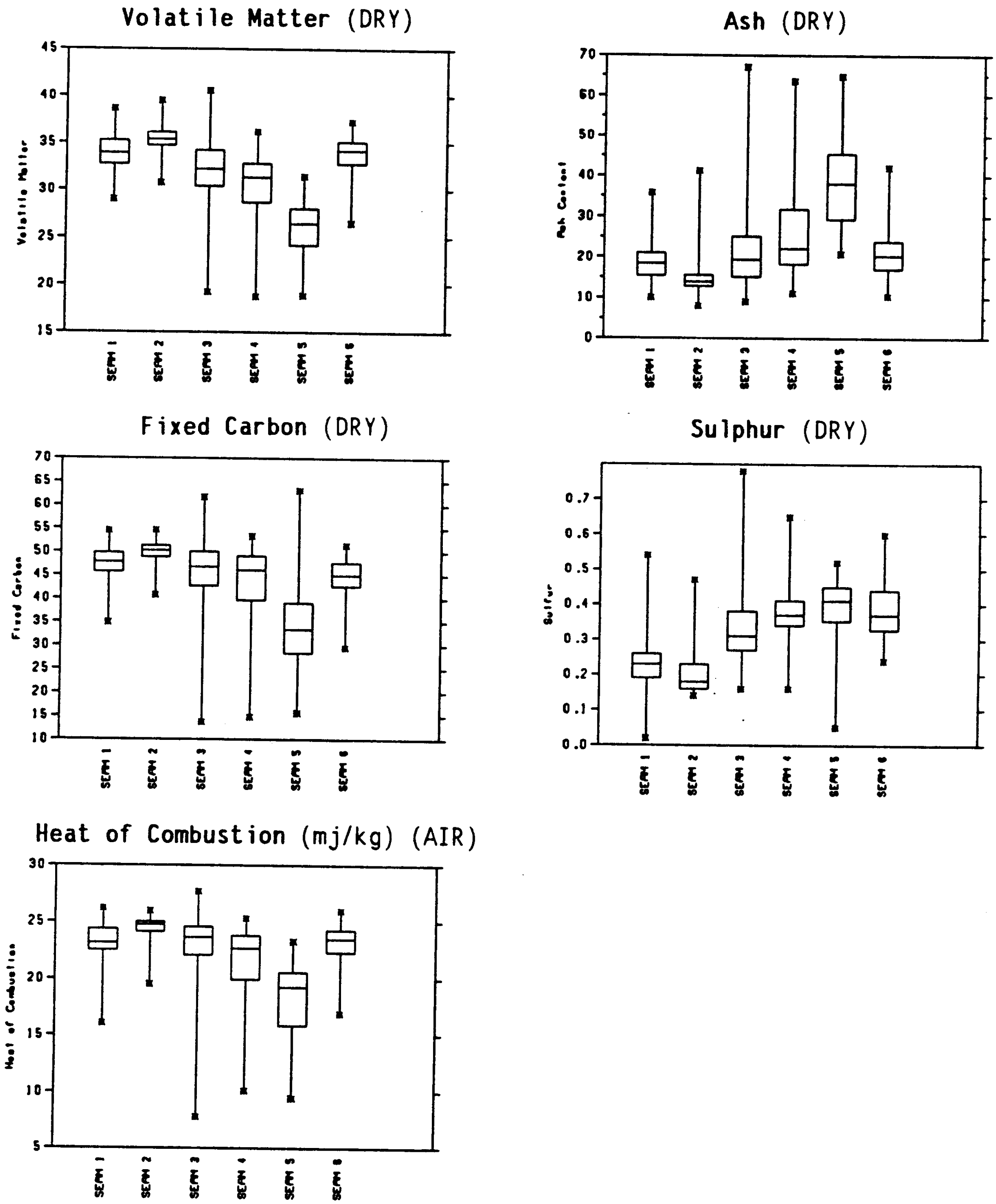

Figure 4. Multiple box plots of proximate analyses for seams 1 to 6 in the Highvale Mine. The data are from raw/untreated samples. Proximate values are reported on a moisture free (DRY) basis. Calorific value is reported on an air-dried basis (AIR).

The skewness of the distribution is represented by the spacings between the horizontal bars of the box and the lengths of the "whiskers" that link the box to the maximum and minimum points. The plots for sulphur distribution for seam 5, for example, is negatively skewed and seam 2 is positively skewed (Figure 4). In the seam 5 example, there are more larger values (negatively skewed) above the median. For seams 1 and 2, there are more smaller values (positively skewed) above the median in the data distribution. The preference for nonparametric techniques is due to these varying frequency distributions of samples.

Interseam comparison is facilitated using a series of histograms in Wong et al., (1988) and the box plots (Figure 4). One general observation is the frequent departures from the normal distribution. Care must be taken in any analysis relying on the normality assumption because of these test results. Limitations are also imposed because the varying types and degrees of skewness in the data distribution. This means that one cannot apply a systematic technique to transform each data set for processing or predictive modeling, because the transformation appropriate for one seam may not be so for another.

High seam to seam variability is observed for all variables. Variations are expressed in terms of levels (central tendencies), variance and frequency distributions. When evaluating coal quality, "representativeness" is an important consideration. On a deposit scale, coal quality values should be clearly differentiated as to which seam they are from. Ash analyses for Highvale, for example, will vary from as low as 11% by weight (Seam 2) to 40% or more (Seam 5) in the same drill hole location. In addition, some deposits must be further subdivided into separate study areas (Highvale North and South, for example), for more accurate estimates of coal quality on an individual seam basis.

COMPARISON BETWEEN MINESITES

Data for this study is derived from the Energy Resources Conservation Board (ERCB) coal quality file. Although detailed company data for Highvale is available, ERCB data for Highvale was used instead for consistency in the comparison. It is recognized that seam by seam differentiation is not practicable in regional comparisons mainly because of difficulties in correlating seams over broad areas. In this regional study, coal quality variables were reported on a weighted average basis. This removes the bias contributed by the sample length to the composite value. The resulting data sets for the regional study represent coal quality for all seams combined at each drill hole location, and assumes that the drill holes reach the base of the coal zone.

Coal quality data from ten deposits were compared. The areas are Ardley Bend, Fox Creek, Genesee, Low Water, Musreau Lake, Swan Hills, Wetaskiwin, Whitewood, North Highvale and South Highvale. The locations of these areas are shown in Figure 5. These areas were chosen because of their mining potential and relatively abundant sample locations. Table 1 lists the median value and the number of sample locations for ash, fixed carbon, volatile matter and calorific value (all on a dry basis). Median sulphur values (dry basis) are included, which were derived from the ultimate data set.

Table 1. The median (weighted average basis) for proximate variables and ultimate sulphur. These values are derived from data available through the Energy Resources Conservation Board. Analysis results are from raw/untreated coal samples. The proximate variables ash, fixed carbon (FxC), volatile matter (VM) and ultimate sulphur (S) are expressed in weight percent. Calorific Value (CV) is expressed in mj/kg.

	Ardley Bend	Fox Creek	Genesee	Low Water	Musreau Lake	Swan Hills	Wetaskiwin	Whitewood	North Highvale	South Highvale
Ash (dry)	30.7	36.7	14.8	18.5	34.9	29.5	27.0	19.8	15.9	17.4
FxC (dry)	39.2	35.9	51.5	48.6	37.8	38.4	42.4	45.2	47.9	48.6
VM (dry)	30.1	27.4	33.7	32.9	27.3	32.1	30.6	35.0	36.2	34.0
CV (dry)	20.4	18.4	25.4	23.7	19.5	19.6	21.7	22.9	24.1	23.9
Number of Locations	147	15	62	38	23	50	25	49	148	18
Ultimate S (dry)	0.36	0.35	0.26	0.25	0.48	0.34	0.39	0.31	0.24	0.25
Number of Locations	68	16	62	10	16	52	25	48	54	18

Significant variation in ash is observed between minesites. The median ash values (weighted average basis, all seams combined), indicate that the ash level is highest from the Fox Creek area (36.6%), followed by Musreau Lake (34.9%). The lowest ash values are observed in the Genesee (14.8%) and North Highvale (15.9%) areas. The remaining areas, Ardley Bend (30.7%), Swan Hills (29.5%), Wetaskiwin (27.0%), Whitewood (19.8%), Low Water (18.5%) and South Highvale (17.4%) fall in between.

Coal quality trends are detected from a regional perspective in the Ardley coal zone. Coal quality variations on this scale may reflect regional geologic and tectonic controls acting on the basin during deposition of the Ardley coal zone. The relatively thick, low ash coal seams within the Highvale and Genesee areas, for instance, are associated with the relatively low median ash values of the composite data set. Highvale and Genesee also stand out as areas with the thickest cumulative coal and thickest seams on regional resource maps (See Richardson et al., 1988). North and south of the Highvale/Genesee area, coal resource maps indicate that the Ardley coal zone consists of thinner seams with lower cumulative coal. The higher median ash

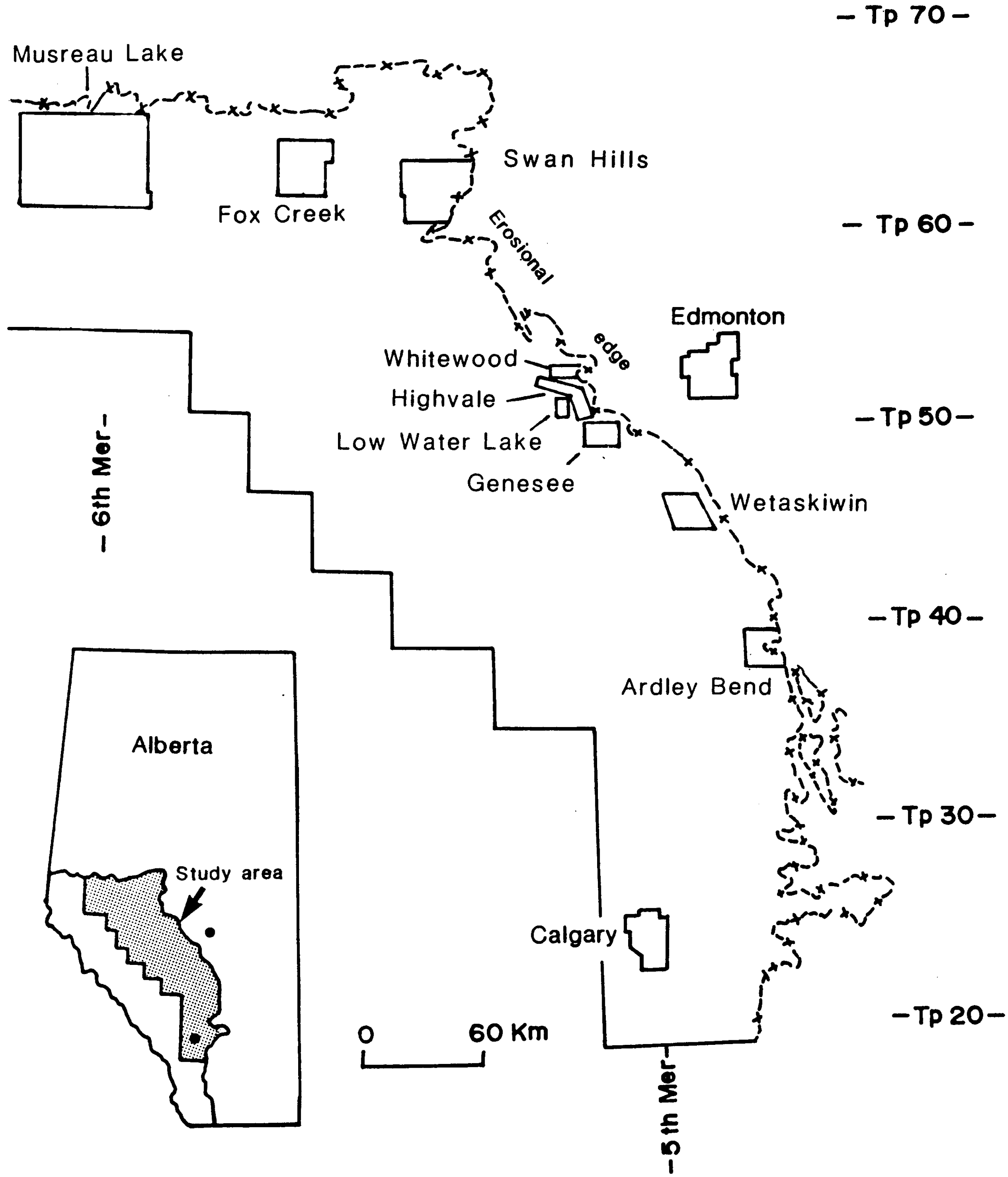

Figure 5. Locations of the mine sites and potential mine sites used in the regional comparison.

values north and south of the Highvale/Genesee area, may reflect these regional trends.

Further detailed studies of coal quality within additional minesites, similar to the study done for Highvale, are needed to verify the spatial dependence and regional trends. Through more detailed studies and better understanding of the geological controls, we will be able to estimate coal quality more accurately.

COMPARISON BETWEEN HIGHVALE MINE AND REGIONAL TRENDS

The purpose of this part of the analysis is to examine differences in coal quality parameters between Highvale and the rest of the Ardley coal zone. This evaluation combines North and South Highvale into one data set because of the relatively small number of data locations in Highvale South. Comparisons were made between data obtained inside Highvale and that obtained outside to see if the observed differences are statistically significant and to find out what the nature of those differences are. Since most of the coal quality data is not normally distributed, the Wilcoxon (Mann-Whitney) nonparametric test was applied in each case (SAS Users Guide, 1985; Kalbfleisch and Prentice, 1980). From the P-values listed in Table 2, one can assume that all proximate variables and ultimate sulphur show significant differences at the 5% level.

Table 2. Comparisons between Highvale Mine data and the rest of the Ardley coal zone (Entries are P-values from the Wilcoxon test).

Proximate Analysis	P-value
Ash (dry)	0.0000
FxC (dry)	0.0000
VM (dry)	0.0000
CV (dry)	0.0000
Ultimate Analysis	**P-value**
S (dry)	0.0000

To illustrate the differences between values, Table 3 lists summary statistics for each variable. The statistics presented are the median and the interquantile range. The median (or 50th percentile) is a measure of central tendency and interquantile range is a measure of the amount of variability. Interquantile range is defined as the difference between the 25th percentile and 75th percentile of the data distribution.

Since the Wilcoxon test only detects whether the data came from the same population without giving details of the nature of the differences, it is useful to examine such summary statistics for indications of where the differences are. From Table 3, one can see that differences in ash content between samples obtained inside and outside Highvale, can be attributed to both the central tendency and the variability in the observations.

Table 3. Summary Statistics of Coal Quality From Inside Highvale (IN) and Outside Highvale (OUT). Analysis results are from raw/untreated coal samples. Proximate variables ash, fixed carbon (FxC), volatile matter (VM) and sulphur (S) are expressed in weight percent. Calorific value (CV) is expressed in mj/kg. All values are reported on a dry basis.

Variable	Median		Interquantile Range	
	IN	OUT	IN	OUT
Proximate				
Ash (dry)	16.0	24.5	2.8	12.1
FxC (dry)	48.0	44.2	4.7	8.9
VM (dry)	36.1	31.3	4.7	4.0
CV (dry)	24.1	22.2	0.9	3.7
Sample size	140	699		
Ultimate				
S (dry)	0.24	0.33	0.11	0.12
Sample Size	55	145		

The median ash content inside Highvale is much lower than that observed regionally, with a value of 16.0% (dry) compared with 24.5% (dry) outside Highvale. Less variability is also observed, with an interquantile range for ash inside Highvale of 2.8% compared to 12.1% outside Highvale. Similar trends were observed for sulphur. Median sulphur inside Highvale is 0.24% (dry) and outside Highvale, median sulphur is 0.33% (dry). The interquantile range for sulphur inside Highvale is 0.11% and 0.12% for outside Highvale. Comparison of fixed carbon, volatile matter and calorific value, indicate that the major differences are associated with variability.

The results from the above comparison show that there are significant differences in sulphur (dry) and ash (dry) between Highvale and other areas of the Ardley coal zone. In terms of thermal properties, the Ardley coal zone in the Highvale area stands out as having better quality than that observed regionally. As discussed earlier in the paper, the Highvale mine is situated within a trend of thick cumulative coal (Richardson et al., 1988). From a geological and statistical perspective, the Highvale Mine appears to be anomalous. It contains some of the thickest and most laterally continuous seams compared to the other study areas, and consistently shows up in statistical analysis as having some of the lowest ash and sulphur values.

CONCLUSIONS AND RECOMMENDATIONS

It is clear from the results of this exploratory study that classical statistical methods based on the normality assumption, may not be appropriate in the analysis of coal quality data. Statistical methods should be carefully chosen based on the associated geological models, and the results of exploratory statistical evaluations of each data set. Understanding the geology of the deposit is critical to interpreting results and for the selection of study areas.

In this study the preferred measure of central tendency is the median. Variability based on the departures from the sample median is used to indicate the range of values likely to be encountered when evaluating a coal deposit. For general analysis of both the regional and detailed mine site data sets, nonparametric methods with no distributional assumptions are likely to be most appropriate. Another consideration is the spatial dependence of coal quality variables. Geostatistical studies are needed to complement exploratory statistical analysis. Again, a detailed understanding of the geology is critical.

One concern in this study is the "representativeness" of the data. Central tendencies and range in coal quality values vary depending on the scale of investigation and amount of accuracy desired. On the regional scale of investigation the median ash and sulphur values for the Highvale area are 16.0% (dry basis) and 0.24% (dry basis), respectively. Individual seams within the Highvale area, however, have a relatively large range of values. On the minesite scale, median ash values vary from 18.4% in seam 1, 13.9% in seam 2, 19.3% in seam 3, 22.2% in seam 4, 38.0% in seam 5 and 20.3% in seam 6 (all on a dry basis). Comparison of median sulphur values indicates similar trends. Median sulphur values vary from 0.25%, 0.18%, 0.31%, 0.37%, 0.41%, and 0.37% (dry basis) respectively, for seams 1 through 6.

So what is representative and how do we interpret statistical results? Since seam correlations and detailed geology are not available in the ERCB coal quality data set, studies using these data are limited to regional evaluations. Coal quality values reported on a regional scale serve only as a guide to measure expected ranges in values. Data derived directly from companies which differentiates seams and provides detailed geological information provides a higher confidence level for studying central tendencies and variation. Detailed studies on a mine site scale are recommended for more reliable estimates and to gain a better understanding of coal quality variation and its controls.

ACKNOWLEDGMENTS

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GATES FORMATION (LOWER CRETACEOUS) COALS IN WESTERN CANADA; A SEDIMENTOLOGICAL AND PETROGRAPHICAL STUDY*

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ABSTRACT

Coal seams formed on Lower Cretaceous wave-dominated strandplain sediments in Western Canada are characterized by great lateral continuity, substantial thicknesses, relatively low ash and low sulphur contents. The coals formed behind an active shoreline in areas undergoing subsidence due to shale compaction and dewatering. The zone of peat accumulation was generally protected from fluvial flooding and storm/tidal inundations. Statistical evaluation of petrographic properties, by correspondence analysis, of the Lower Cretaceous Gates Formation coals shows that the strandplain coals form distinctive petrographic groups characterized by relatively low vitrinite contents and high inertinite contents. Liptinite contents are negligible. Tissue preservation indices and gelification indices indicate a forest-type depositional environment in which a relatively low water table allowed the accumulation of oxidized and partly oxidized components. Significant amounts of detrital components indicate that some transportation of the organic material took place prior to deposition.

INTRODUCTION

Although many models have been proposed for the formation of coal (e.g., Stach et al., 1982; McCabe, 1984), there is no satisfactory explanation for thick and widespread coal deposits resting directly on regionally extensive sheets of sandstone and conglomerate which were deposited along wave-dominated coastlines. Yet coals formed in this depositional setting are economically significant, being thick and having relatively low ash and sulphur contents.

Laterally continuous, extensive sheets of coal up to 12 m thick, sitting directly on littoral sandstones have long been recognized as generally having formed on broad coastal plain deposits (Spieker and Reeside, 1925). Interpretations for deposition of the coal have varied from coastal plain swamps (Spieker and Reeside, 1925), barrier island lagoons (Young, 1955; Doelling, 1972), delta plains (Cotter, 1976) and delta-front foreshore deposits (Levy, 1985). More recently, many of these coastal deposits have been interpreted as deposits of progradational wave-dominated deltas and associated strandplains (Balsely and Parker, 1983; Levy, 1985; Leckie, 1986).

Petrographic composition of low rank coals has been used extensively to describe the environments of deposition in ancient peat swamps (e.g., Teichmuller, 1962; Schneider, 1978, 1980; von der Brelie and Wolf, 1981; Hagemann and Wolf, 1987). For bituminous coals, such as the Lower Cretaceous coals of the Rocky Mountain Foothills, comprehensive data and interpretations as to the relationship between petrographic composition and paleoenvironments of peat formation are found less frequently (Hacquebard and Donaldson, 1969; Cameron, 1972; Allshouse and Davis, 1984; Diessel, 1982, 1986; Hunt et al., 1986). The methods which have been used to relate coal petrographic characteristics to environments of deposition include lithotype, microlithotype and maceral analyses.

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In the present study, maceral analyses have been used to relate petrographic composition of the coals to environments of deposition. Diessel (1982), in a study on Australian coals, discussed the diagnostic values of individual coal macerals. In the vitrinite group, the occurrence of vitrinite A (telenite, telocollinite) indicates an origin from wood-producing plants. Vitrinite B (desmocollinite), although commonly representing a major proportion of the total vitrinite component, is less diagnostic because this maceral may have been derived from a variety of organic sources. Liptinite macerals such as sporinite, resinite, cutinite and alginite all refer to specific sources and some, like alginite, are also indicators of the relative position of the water table during peat accumulation. In the inertinite group, macerals such as semifusinite and fusinite refer to an origin from woody sources, but also indicate slightly drier to very dry conditions in the peat swamp where these components were exposed to oxidation processes and/or fungal attacks. There is also a possibility of forest fires contributing a substantial amount of fusinite (pyrofusinite) to the overall coal composition. The other facies-diagnostic maceral of the inertinite group appears to be inertodetrinite which represents broken-up pieces of fusinite and semifusinite, thus indicating an origin from woody precursors. The association of inertodetrinite with degraded vitrinite (vitrinite B) and sporinite in Carboniferous and Permian coals has previously been interpreted to represent a reed-type moor environment characterized by substantial degradation of the organic matter (Teichmüller, 1962; Diessel, 1982). In a more recent study, Diessel (1986) defined a Tissue Preservation Index (TPI) and a Gelification Index (GI) for a number of Australian coals and was able, in comparison with sedimentologically well-characterized associated strata, to assign specific depositional environments (dry forest swamp, wet forest swamp, fen, marsh).

The objectives of this paper are to relate coal characteristics to depositional environments of the coals in the Lower Cretaceous Gates Formation in Western Canada. A north-south cross section along the Lower Cretaceous interval in the Rocky Mountain Foothills is shown in Figure 1. Locations of outcrop sections analyzed for a larger, more regional study (Kalkreuth and Leckie, in press) are shown. The present study provides a detailed example of coal characteristics and depositional environments of Gates Formation coals from the Luscar coalfield of the southern study area (Fig. 1, location 3) and a more general description for regional occurrences of Gates Formation coal.

CHARACTERISTICS OF WAVE-DOMINATED DELTAS AND STRANDPLAINS

Characteristics of wave-dominated deltas and strandplains are shown in Figure 2. The coals formed on regionally extensive sheets of shoreface sand and/or gravel that were deposited along the coast of wave-dominated deltas and associated strandplains (Fig. 2). Sediment brought to the shoreline by the distributaries was reworked and redistributed by wave action and longshore drift. Riverine flow transporting sediment to the coast is concentrated in one or two major distributary channels (Coleman, 1981) that generally remained fixed over long periods of time. Representative vertical sequences which resulted from shoreline progradation are shown in Figure 3.

LOWER CRETACEOUS GATES FORMATION, WESTERN CANADA

The Albian Gates Formation consists of several upward-coarsening sequences (Fig. 1), formed on the western margin of the North American Cretaceous epeiric seaway. Gates shorelines prograded northwards as a series of sand and gravel wave-dominated deltas and strandplains (Leckie and Walker, 1982; Leckie, 1986) that extended as a sheet sand laterally along strike for at least 230 km and downdip for up to 90 km. The lowermost shoreline sediments of the Gates Formation are underlain by 206 m of marine shales of the Moosebar Formation at Bullmoose Mountain and 42 m at Mt. Torrens (Fig. 1).

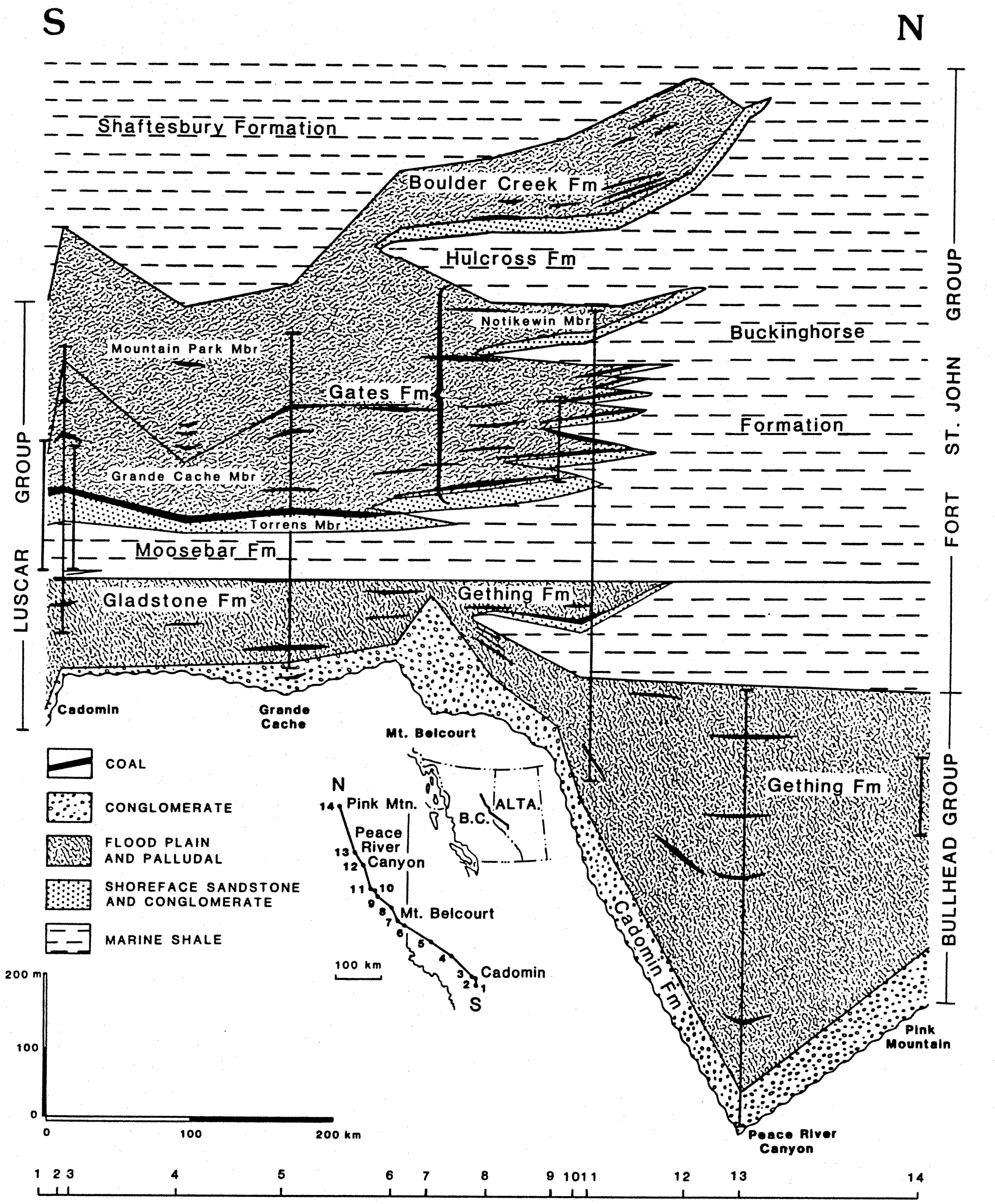

Figure 1. North-south cross section along the Foothills of western Alberta and northeastern British Columbia. Vertical bars in section represent locations used for detailed coal petrographic analyses. Location of sections used for control are 1 = Mountain Park; 2 = Cadomin; 3 = Luscar; 4 = Little Berland and South Berland Rivers; 5 = Grande Cache; 6 = Mt. Torrens and Torrens Ridge; 7 = Mt. Belcourt; 8 = Duke Mountain; 9 = Mesa, Shikano and Wolverine Pits, Tumbler Ridge; 10 = Mt. Spieker; 11 = Bullmoose Mountain; 12 = Dokie Ridge; 13 = Peace River Canyon; and 14 = Pink Mountain. Data from Stott (1968, 1984), Carmichael (1983), Leckie (1983) and Gibson (pers. comm., 1987).

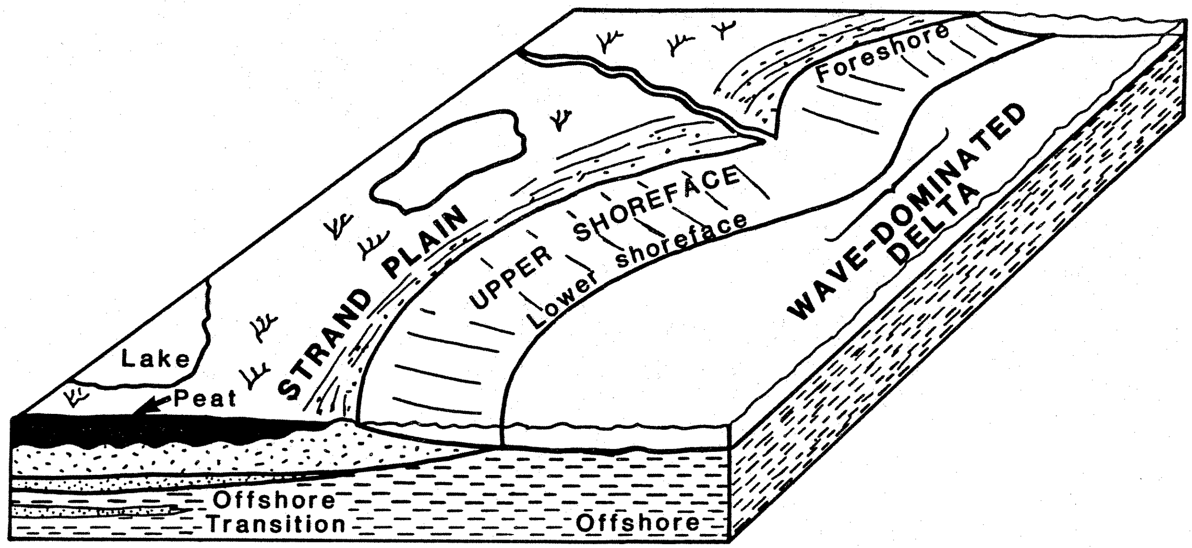

Figure 2. General characteristics of wave-dominated deltas and strandplains which form a laterally continuous sheet of sandstone and/or conglomerate.

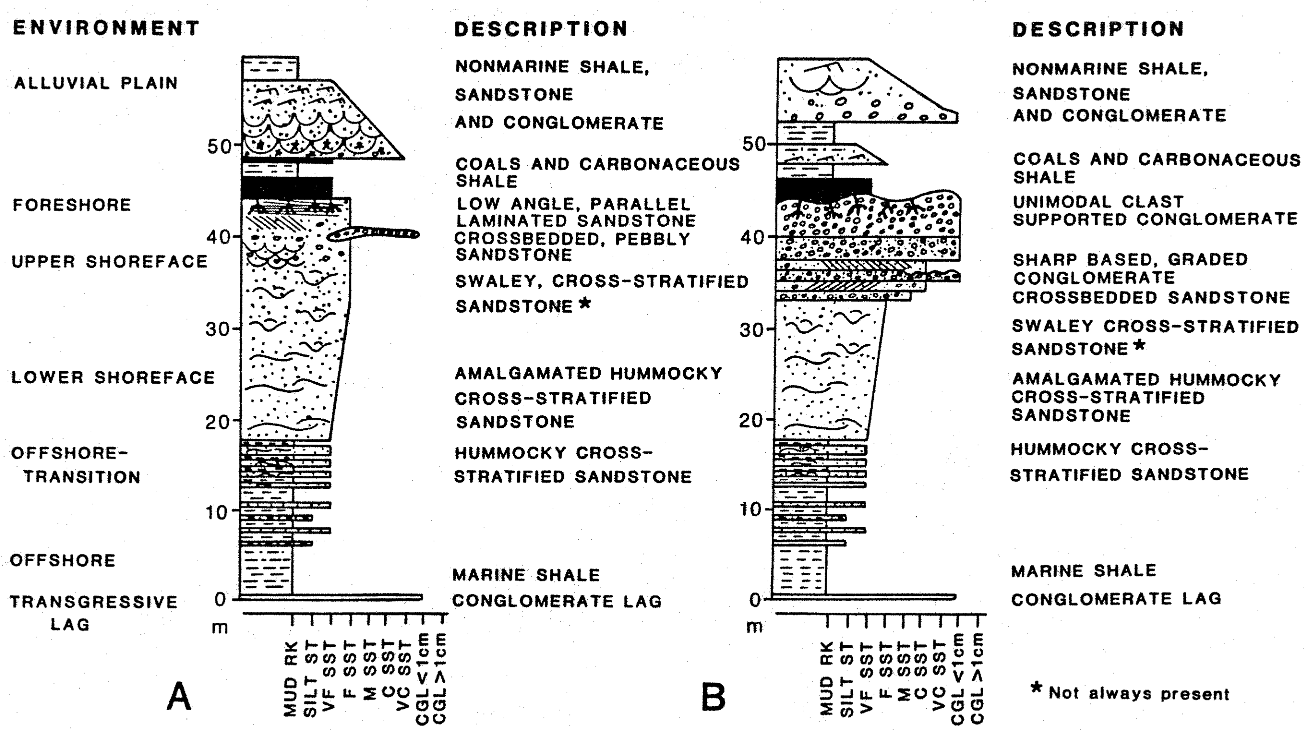

Figure 3. Generalized vertical sections resulting from the progradation of wave-dominated coastlines.

The shoreface sandstones are overlain by a coal-bearing unit with coals in excess of 12 m thick, which can be traced laterally for 230 km, directly above the underlying sheet sandstone. The upper Gates Formation in the south and central portion of the study area (Fig. 1, Locations 1 to 8) can generally be considered as having been deposited in an upper delta-plain to fluvial environment.

The marine to nonmarine cycles of the upper part of the Gates Formation at its northern limit (Fig. 1, Locations 9 to 12) also contain sheet sandstones and conglomerates 30 to 40 km wide and greater than 150 km long. They are capped by thin coals or carbonaceous shales a few centimetres to decimetres thick (Cant, 1984; Leckie, 1986).

PETROGRAPHIC CHARACTERISTICS OF LOWER CRETACEOUS COALS

In the context of the present study 357 whole seam samples were analysed petrographically. Coals were collected in the Rocky Mountain Foothills over a distance of approximately 600 km from Mountain Park in the southeast to Pink Mountain in the northwest (Fig. 1). The samples represent a number of depositional environments, ranging from the alluvial fan deposits of the Cadomin Formation and the deltaic-fluviatile/coastal plain successions of the Gething Formation to the alluvial to coastal plain sequences of the Gates Formation (Mountain Park Member and Grande Cache Member, respectively).

Sampling and petrographic analysis

The samples were collected as channel samples from outcrop and mine sites. In cases where a number of successive samples had been taken from a seam, a composite sample was prepared according to the thickness of the individual layers. The samples were then processed according to standard procedures (Bustin et al., 1985). Petrographic composition was determined by maceral analyses based on 500 counts/sample using a slightly modified Stopes-Heerlen system (ICCP, 1963) for the classification of coal macerals. Maceral contents are expressed in volume per cent on a mineral matter free basis (m.m.f.).

Correspondence analyses

In order to facilitate a comparison and interpretation of the large number of samples the petrographic data and a number of additional variables such as the vitrinite/inertinite ratio obtained from the maceral analyses were first evaluated for similarity levels and significance using correspondence analysis. For details of calculations and applications in geology see Lebart et al. (1984) and David et al. (1977). In general, in this type of statistical analysis, groups of sample points can be interpreted as a result of the same processes or belonging to a specific family. Similarly, nearby variable points will indicate high similarity levels between the variables. A group of sample points will be characterized by the variable points close to that group. Points plotting near the centre of gravity represent undifferentiated distributions and are considered to be of low significance. In general the greater the distance from the centre of gravity the greater the significance of variables and samples. However, loadings (proportional to frequencies) and absolute contributions to the principal axis must be checked before final judgement is made (Tables 1 and 2). For further details, see Kalkreuth and Leckie (in press). The strandplain coals form distinct groups in the correspondence diagram (Fig. 4).

Table 1. Masses and absolute contributions from macerals and mineral matter to the first six principal axes (correspondence analysis, 1st run).

Vari-ables	Masses	Distri-bution	Absolute Contributions					
			F1	F2	F3	F4	F5	F6
VITA	.158	.29	25.1	1.5	11.8	10.3	9.7	.2
VITB	.154	.10	.1	4.6	24.2	22.8	8.5	.0
VDET	.003	12.54	1.6	19.4	38.3	28.6	11.0	.2
VTOT	.314	.07	11.8	3.8	.2	2.2	.0	.3
SF	.072	.38	16.0	.0	3.1	.0	1.5	14.3
FUS	.021	.44	1.9	.0	.1	1.6	5.7	18.1
IDET	.051	.41	8.9	2.6	.0	4.0	.7	49.5
MAC	.008	.84	2.3	.3	1.2	.6	.1	.0
MIC	.003	1.74	.3	.0	.0	.3	.0	4.5
ITOT	.156	.28	28.7	.5	2.6	.8	1.3	.0
SPOR	.004	1.33	.0	.4	.5	5.4	14.1	.7
CUT	.000	1.00	.0	.0	.0	.0	.0	.0
RES	.000	8.59	.3	.3	.0	5.0	11.8	1.6
OTH	.000	12.43	.0	.2	.4	2.1	4.9	3.6
LTOT	.006	1.56	.0	.7	.4	11.7	30.7	3.4
MIN	.049	1.10	3.0	65.6	17.2	4.5	.1	3.4

Absolute contribution levels of macerals and mineral matter show that the first principal axis (F1; Fig. 4) is composed of vitrinite contents on the one side and inertinite contents on the other (Table 1). The second principal axis (F2; Fig. 4) has the highest contribution from mineral matter contents with only minor contributions from liptinite macerals (Table 1). Close similarity levels are indicated for many of the Gates coals by proximity and overlapping areas that are characterized by large amounts of inertinite macerals. The contributions of mineral matter and liptinite macerals to these inertinite-rich coals is generally small. A few subgroups also exist. One subgroup has greater contributions of mineral matter whereas maceral distribution (inertinite vs vitrinite) stays more or less constant. Another subgroup has significantly increased vitrinite contents commonly associated with higher amounts of mineral matter.

Coal seams collected from the underlying Torrens Member and some examples from coals developed within the upper part of the Grande Cache Member in the south are generally characterized by increased vitrinite contents and substantial amounts of mineral matter. Regionally there appears to be more similarity between the coals of the Grande Cache Member in the south than in the north, where lower similarity levels are

Table 2. Masses and absolute contributions from macerals, mineral matter contents and petrographic indices to the first six principal axes (correspondence analysis, 2nd run).

Vari-ables	Masses	Distri-bution	Absolute Contributions					
			F1	F2	F3	F4	F5	F6
VITA	.128	.16	5.4	.3	10.4	.6	1.6	18.9
VITB	.137	.09	.5	3.7	1.7	12.9	.8	17.1
VDET	.002	11.20	.5	15.2	2.2	.0	54.8	6.2
VTOT	.267	.04	1.4	.4	9.0	9.4	.9	.0
SF	.068	.35	9.5	.8	1.7	8.7	.0	2.0
FUS	.020	.41	1.2	.0	1.9	.3	.0	2.8
IDET	.048	.40	5.9	.4	8.0	.1	.5	2.6
MAC	.008	.80	1.3	.9	.3	1.4	.0	.5
MIC	.002	1.76	.3	.1	.0	.0	.0	1.2
ITOT	.146	.26	17.9	.4	4.7	5.3	.0	.1
SPOR	.004	1.32	.0	1.0	1.4	.0	.5	11.0
CUT	.000	1.00	.0	.0	.0	.0	.0	.0
RES	.000	8.88	.1	.5	.4	.3	.0	6.0
OTH	.000	15.05	.0	.3	.3	.0	.3	3.1
LTOT	.005	1.55	.0	1.7	2.4	.0	.5	18.6
MIN	.043	1.03	.7	58.7	7.8	4.2	15.3	.1
A/B	.004	.45	.3	.2	.4	.4	.0	2.9
SF/F	.017	.79	2.1	.0	3.6	1.0	1.0	1.2
V/I	.016	1.63	10.7	2.0	5.3	.0	.2	.6
T/F	.017	3.31	21.1	5.6	18.7	1.0	.0	1.5
I-RATIO	.008	.39	.0	.0	1.9	2.1	.0	1.4
W/D	.030	1.24	7.6	3.1	9.7	48.4	5.6	.3
TPI	.007	1.79	.5	1.0	.0	2.7	17.2	.0
GI	.017	1.83	13.0	3.5	7.9	.0	.4	1.3
S/D	.005	.17	.0	.0	.4	1.0	.0	.7

CORRESPONDENCE ANALYSIS (68.94% of total variance)

INPUT: 357 samples, 16 variables (macerals and mineral matter content)

HISTOGRAMS OF THE FIRST EIGENVALUES

	EIGENVALUE	%	% CUM.
1	.14722440	47.55	47.55
2	.06619453	21.38	68.94
3	.02458061	7.94	76.88
4	.02217416	7.16	84.04
5	.01848809	5.97	90.01
6	.00880679	2.84	92.85
7	.00620995	2.01	94.86
8	.00458683	1.48	96.34
9	.00421238	1.36	97.70
10	.00387766	1.25	98.96
11	.00284707	.92	99.87
12	.00029741	.10	99.97
13	.00004946	.02	99.99
14	.00004036	.01	100.00
15	.00000011	.00	100.00

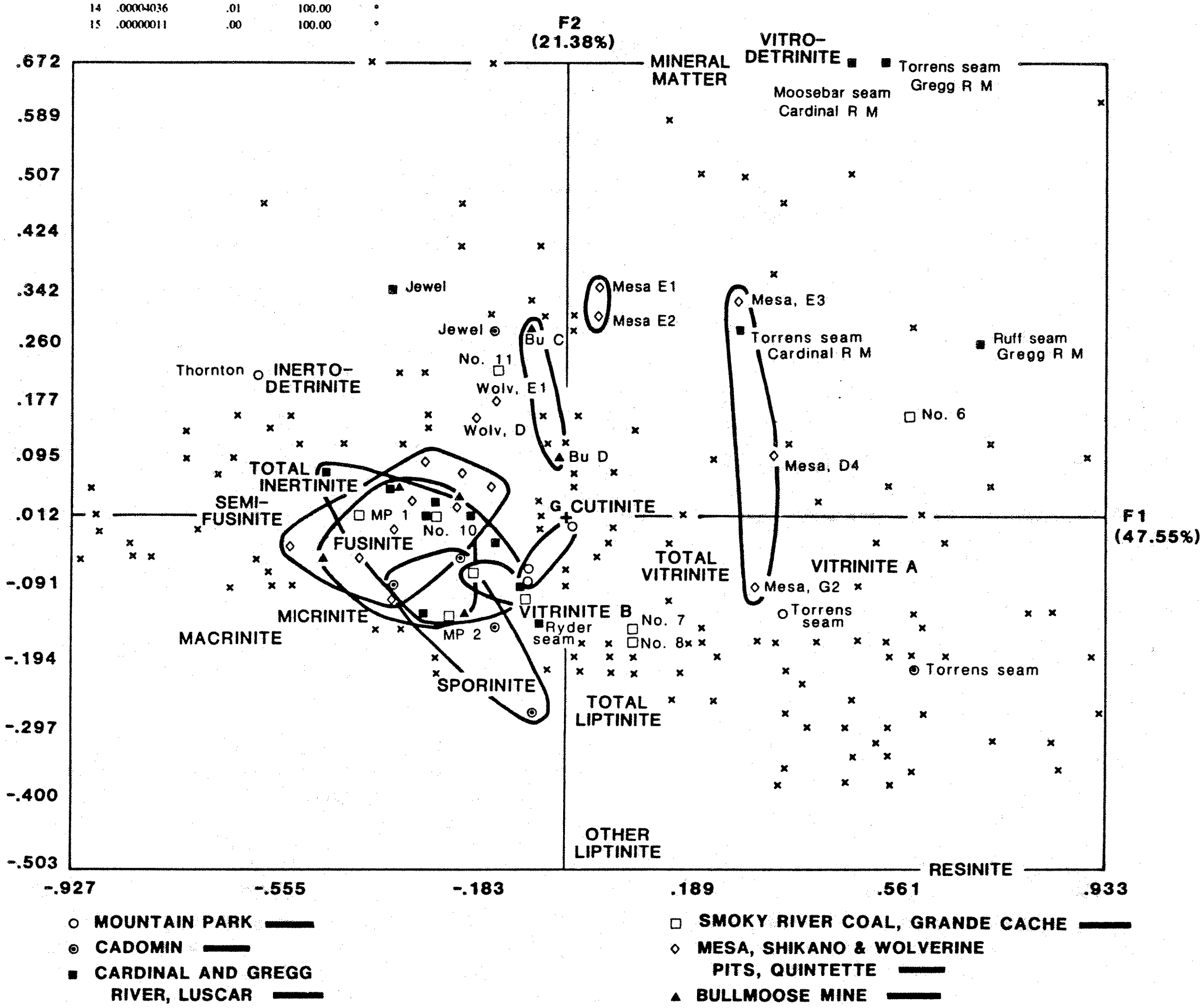

Figure 4. Diagram illustrating similarity levels of Lower Cretaceous coals with respect to maceral contents and mineral matter content. The encircled areas indicate ranges for Lower Cretaceous Gates coals from locations 1, 2, 3, 5, 9 and 11, Figure 1. "x" = point of undefined sample.

CORRESPONDENCE ANALYSIS (59.15% of total variance)

INPUT: 334 samples, 25 variables (macerals, mineral matter, ratios)

HISTOGRAMS OF THE FIRST EIGENVALUES

	EIGENVALUE	%	% CUM.
1	.18711610	45.01	45.01
2	.05877273	14.14	59.15
3	.04273815	10.28	69.43
4	.02895065	6.96	76.39
5	.02148402	5.17	81.56
6	.01628027	3.92	85.48
7	.01320793	3.18	88.65
8	.01115207	2.68	91.34
9	.00711949	1.71	93.05
10	.00672826	1.62	94.67
11	.00447071	1.08	95.74
12	.00376298	.91	96.65
13	.00357801	.86	97.51
14	.00335086	.83	98.34
15	.00289114	.70	99.04

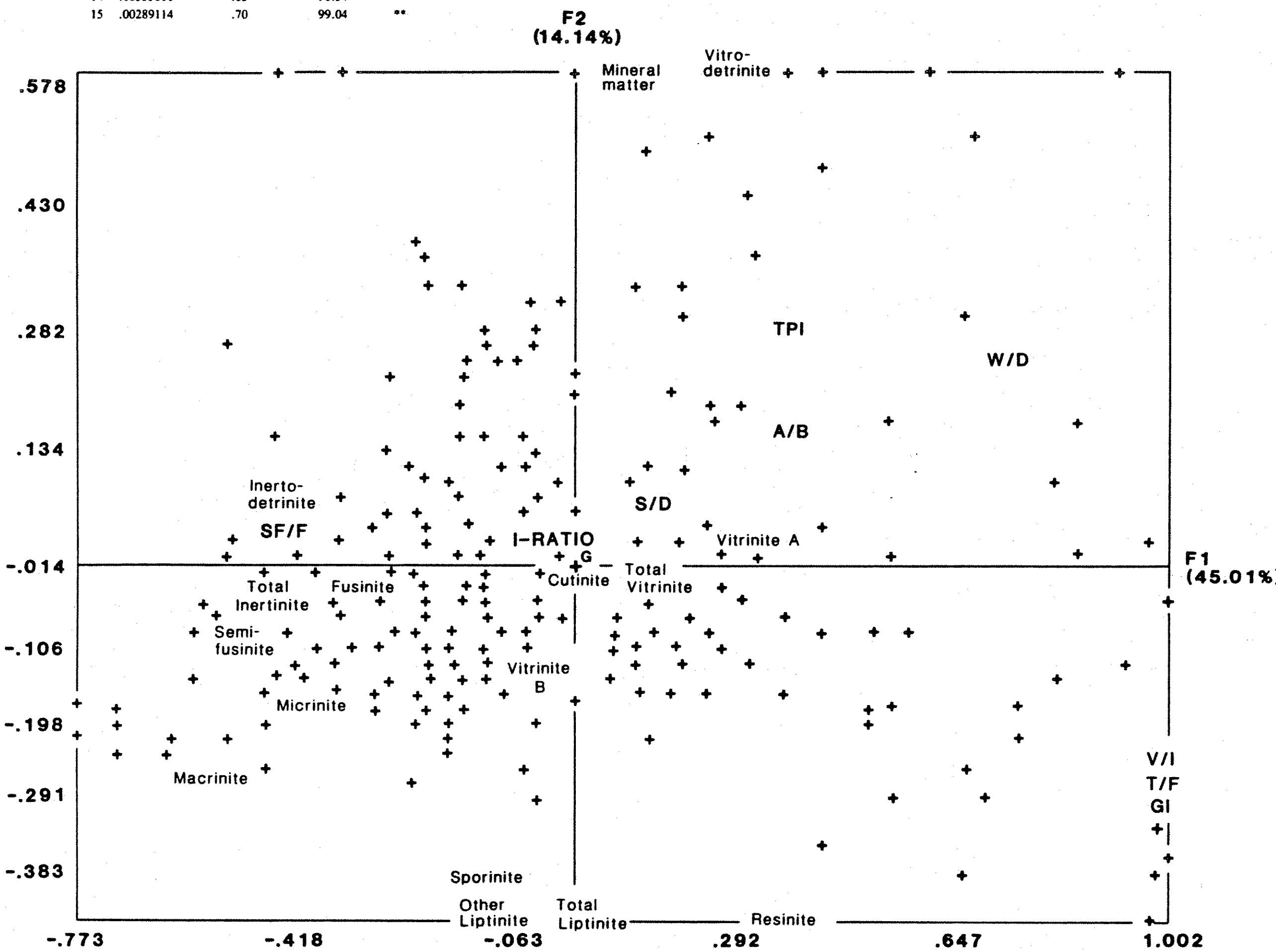

Figure 5. Diagram illustrating similarity levels for petrographic indices with respect to samples and maceral data. "x" = point of undefined sample. Petrographic Indices are: GI ratio = (Total Vitrinite + Macrinite)/(Semifusinite + Fusinite + Inertodetrinite); IR ratio = (Semifusinite + Fusinite)/(Inertodetrinite + Macrinite + Micrinite); S/D ratio = (Vitrinite A + Fusinite + Semifusinite)/(Alginite + Sporinite + Inertodetrinite + Vitrinite B + Vitrodetrinite); SF/F ratio = Semifusinite/Fusinite; T/F ratio = Total Vitrinite/(Fusinite + Semifusinite); TPI ratio = (Vitrinite A + Fusinite + Semifusinite)/(Vitrinite B + Macrinite + Inertodetrinite); V/I ratio = Total Vitrinite/Total Inertinite; VA/VB ratio = Vitrinite A/Vitrinite B; W/D ratio = (Vitrinite A + Fusinite + Semifusinite)/(Alginite + Sporinite + Inertodetrinite).

indicated by the formation of subgroups as illustrated in the correspondence analysis graph (Fig. 4).

In a second correspondence analyses a number of petrographic indices (Fig. 5) were tested for similarities and significance levels among themselves and their relation to the original variables (macerals and mineral matter). The correspondence analyses graph (Fig. 5) shows that the absolute contributions to the first two principal axes are highest for parameters such as V/I ratio, T/F ratio and Gelification Index which describe the variations in vitrinite and inertinite contents (Table 2). These parameters have the highest significance in the context of this study. Less significant, with only minor contributions to the first two principal axes, are the parameters SF/F ratio, W/D ratio and Tissue Preservation Index (Table 2); the latter two describe variations in preserved tissue versus detrital components. Negligible contributions come from parameters such as IR ratio, VA/VB ratio and S/D ratio which means that these parameters are highly insignificant in the interpretation of the coals investigated (Fig. 5, Table 2).

Coal characteristics and depositional environments of the Gates coals

Gregg River Mine, Luscar

The section sampled (Fig. 1, location 3) is shown in Figure 6 and represents a composite separated by 650 m. Samples were collected from a thin coal seam developed in the shoreface sandstone of the Torrens Member, the Jewel seam directly on the

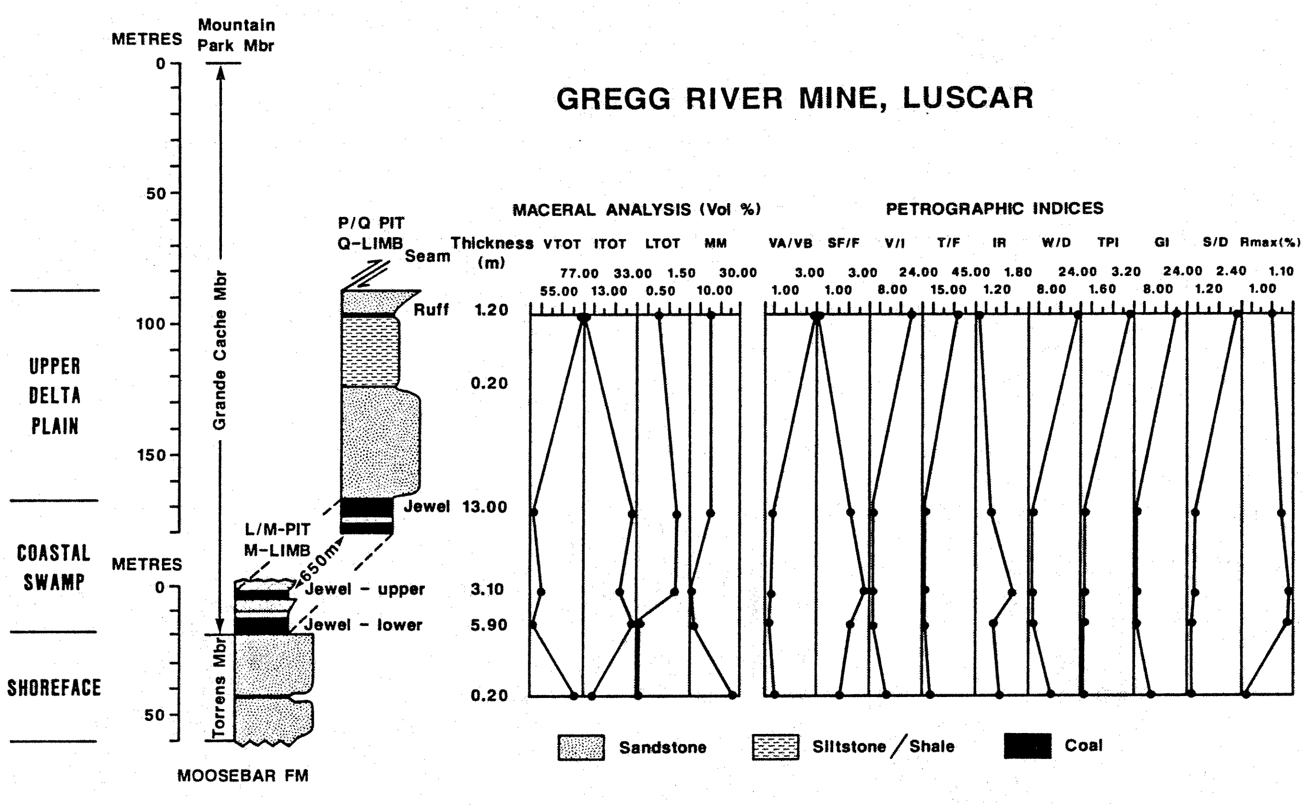

Figure 6. Maceral data,mineral matter contents and petrographic indices for Lower Cretaceous Gates coals, Gregg River Mine, Luscar (stratigraphic section from Langenberg, Macdonald and Strobl, Alberta Geological Survey, unpublished). Rmax % = mean maximum vitrinite reflectance. For abbreviations of petrographic indices, see Figure 5.

shoreface sandstones, and the Ruff seam from the upper delta plain deposits. Within this sequence, systematic trends in maceral contents, mineral matter content and in the petrographic indices are apparent (Fig. 6). The seam from the Torrens Member has a very high vitrinite content (93%) whereas inertinite content is low (7%). Liptinite macerals were found only in traces. The mineral matter content is very high (47%). In contrast, the samples collected from the Jewel seam show a drastic decrease in vitrinite contents (46 to 58%) whereas inertinite macerals account for 40 to 52%. Macerals of the liptinite group (in the form of sporinite) are still rare (up to 2%). Mineral matter contents in the Jewel seam range from 2 to 23%. Higher vitrinite content is indicated for the Ruff seam (96%) that contains only minor contributions of inertinite (3%) and liptinite (1%). The Ruff seam at this location has a mineral matter content of 21%. Many of the petrographic indices, show distinct changes with respect to the stratigraphic position of the coal seams. Related to the overall contents of vitrinite and inertinite macerals, the Jewel seam has a very low V/I ratio, whereas the Torrens seam and the Ruff seam have high ratios. Preservation of the organic matter appears to be best in the Ruff seam, which is characterized by a high VA/VB ratio, a high W/D ratio, a high S/D ratio and a very high Tissue Preservation Index. In contrast, the Jewel seam appears to have a lesser degree of plant preservation, mainly because of substantial amounts of inertodetrinite (low W/D and S/D ratios) and vitrinite B (low VA/VB ratio). Within the inertinite group, semifusinite is the predominant maceral (22 to 24%, high SF/F ratios, Fig. 6), whereas the total amount of structured inertinite (fusinite and semifusinite) is always greater than inertodetrinite (IR ratios = 1.35 to 2.02, Fig. 6).

To assess the type of prevailing moor during accumulation of the organic matter, the Gelification and Tissue Preservation Indices for the five coals were plotted in a facies diagram (Fig. 7) as proposed by Diessel (1986). The three samples of the Jewel seam plot very close to each other which indicate a similar type of depositional environment for these strandplain coals. They must have been formed under relatively dry conditions as indicated by the high amounts of inertinite macerals (semifusinite, inertodetrinite, to a lesser extent fusinite). The major split of the seam as illustrated in Figure 6 might be a result of local flooding adjacent to distributary channels or a result of lacustrine conditions caused by temporarily and locally increased subsidence rates. The Torrens seam has a much higher Gelification Index (Fig. 7) due to a very high vitrinite content and low amounts of inertinite. The formation of the Torrens seam most likely reflects slight sea level fluctuations during deposition of the Torrens Member in which peat accumulated while a relatively high water table level was maintained, as indicated by the large amounts of gelified plant remains. The Ruff seam in the Gregg River Mine area is highly variable in thickness, ash content and lateral continuity. Very high Gelification and Tissue Preservation Indices (Fig. 7) are the result of the Ruff seam being made up almost entirely of vitrinite. As such, the Ruff seam might represent a locally flooded moor of the upper delta plain which had a significant influx of mineral matter associated with a relatively high water table.

General petrographic characteristics of Gates coals

In addition to the detailed examination of the coals from the Gregg River Mine, three other sections of the Gates Formation (Fig. 1, locations 5, 9 and 11) were examined by Kalkreuth and Leckie (in press). The results indicate that the coals which accumulated on the strandplain above the marine sandstones of the Torrens Member form distinct groups (Fig. 4). However, considerable petrographic variation occurs among these groups and there is also some overlapping of petrographic characteristics for the overlying coals from the upper and lower delta plains.

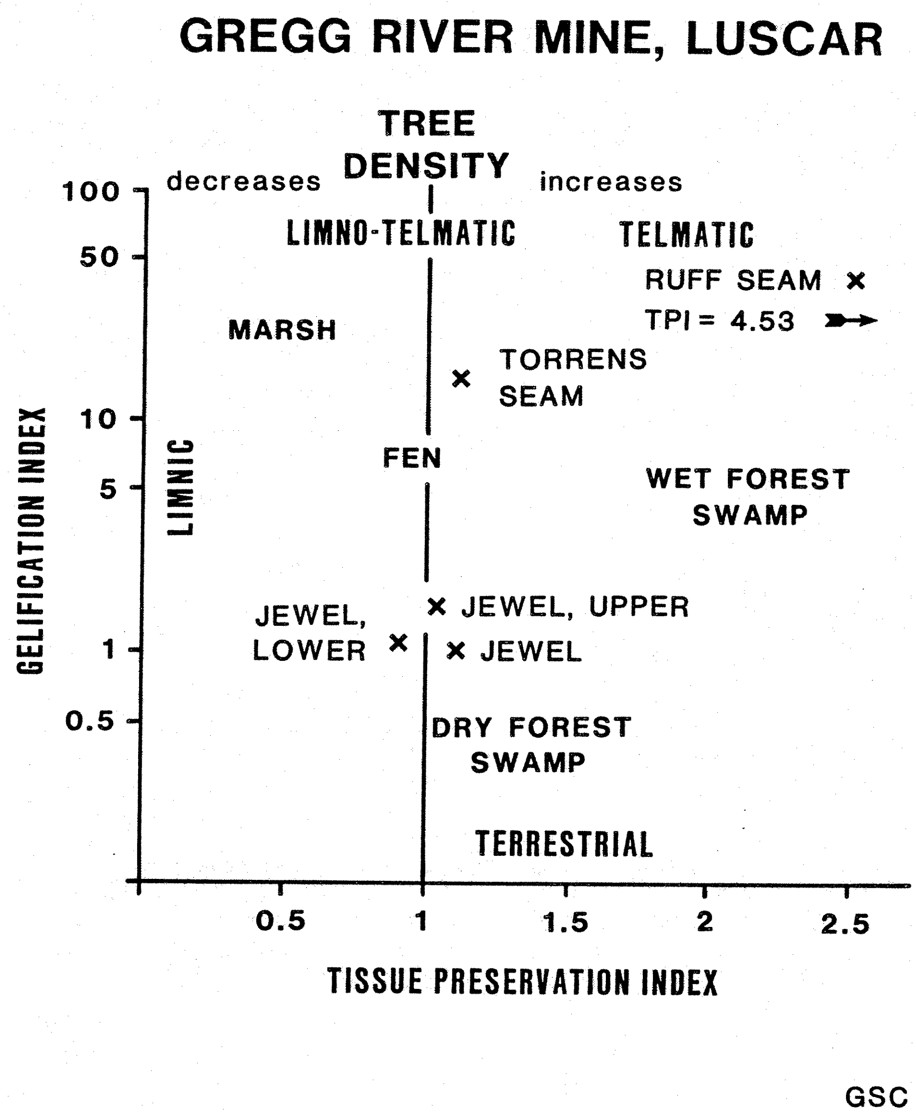

Figure 7. Facies diagram for Lower Cretaceous Gates coals at Gregg River Mine, Luscar.

The coals are generally characterized by relatively low vitrinite contents from 45 to 66% with a mean of 57%. In contrast, inertinite contents are relatively high (31-53% mean = 42%). Within the inertinite group, major components are semifusinite (14-24%, mean = 20%), inertodetrinite (8-19%, mean = 13%) and fusinite (3-10%, mean = 5%). Liptinite content is low, (nil to 9%, mean = 2%). The relatively low vitrinite contents and high amounts of inertinite macerals, in particular semifusinite, indicate rather low water tables during peat accumulation in which substantial part of the organic matter was oxidized prior to final burial.

Mineral matter in most of the coals is low, ranging from 2 to 11% with a mean of 6%. Three seams form a separate group for which increasing amounts of mineral matter were determined (23-29%). The high mineral matter content in these seams may be related to local flooding adjacent to fluvial channels.

Overall, petrographic indices vary from one sample to the other. The V/I ratios range from 0.85 to 2.00 (mean = 1.40) which indicates for most of the coals the predominance of gelified components (vitrinite) over non-gelified (inertinite macerals). Within the vitrinite group, the VA/VB ratio indicates a slight dominance of vitrinite B over vitrinite A (mean = 0.86), which suggests that substantial amounts of woody materials were decomposed prior to burial. The same holds true for the relatively high proportion of inertodetrinite which is derived from mechanical breakdown of fusinite and semifusinite precursors. The IR ratios (semifusinite + fusinite/inertodetrinite) range for the strandplain coals from 1.16 to 2.64 with a mean of 1.58. That means that in all of these coals the sum of semifusinite + fusinite macerals is greater than inertodetrinite. IR ratios <2 were considered by Diessel (1982) to reflect hypauthochtonous and allochthonous conditions in the ancient peat swamps where dominantly semifusinite, fusinite and inertodetrinite were deposited. This indicates that some transportation took place during the accumulation of the Gates Formation shoreface/strandplain peats. Tissue preservation indices are low to intermediate (T/F: 0.22 - 2.01, mean = 1.02; TPI Index: 0.64 - 1.54, mean = 1.14). These values indicate for the strandplain coals a forest-swamp type of depositional environment with periods of low water tables during which substantial amounts of oxidized and partly oxidized materials were formed. The relatively high contents of the non-gelified macerals semifusinite, fusinite and inertodetrinite relative to the amounts of gelified components (i.e., vitrinite) leads to relatively low gelification indices (1.00 - 2.27, mean = 1.59). Applying a coal facies diagram, as proposed by Diessel (1986), for many of the shoreface/strandplain coals of the Lower Cretaceous, a forest-moor type of depositional environment is envisioned (Fig. 8). Some coals are characterized by somewhat higher gelification indices but similar TPI indices, which indicates a shift to a less forested, fen-like depositional environment characterized by a larger input of aquatic plants such as reeds and sedges.

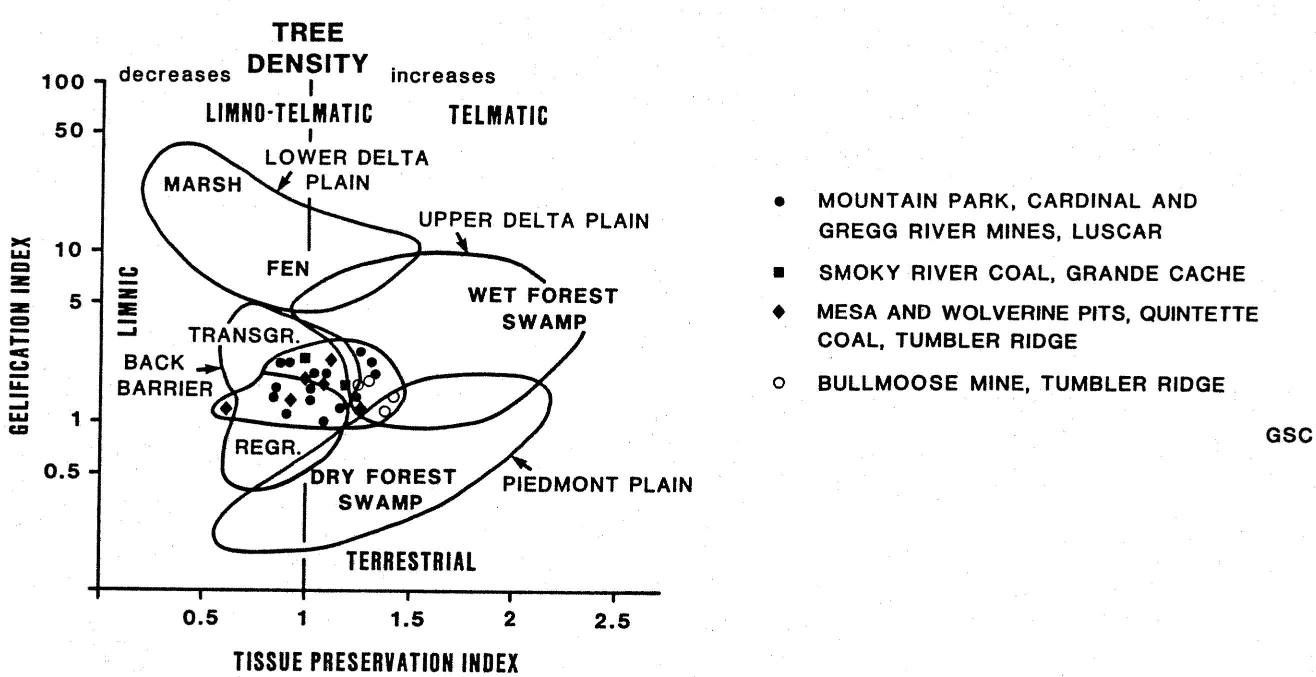

Figure 8. Coal facies and depositional environments for the Lower Cretaceous Gates Formation strandplain coals (modified from Diessel, 1986).

PROPOSED MODEL FOR FORMATION OF STRANDPLAIN COALS

A model for coal formation on progradational wave-dominated deltas and strandplains is shown in Figure 9. For this model, the shoreline deposits of the prograding deltaic/strandplain system are considered to be similar to a tea saucer (Fig. 9). The zone of active sediment supply and high wave energy was represented by the high energy beaches which acted as the saucer rim. Sediment brought to the shoreline by distributaries was redistributed along the coast by longshore drift. Even though the coastlines were high energy ones, with high rates of sediment supply, all the wave energy was expended on the foreshore and shoreface and none was transmitted landward of the beach except when large storms, perhaps combined with high tides, occurred. Many of the coals show large amounts of components such as inertodetrinite and vitrinite B, which are probably related to occasional flooding and storm events, at which time mechanical breakdown of original source materials took place during transport. Although mineral matter content is generally low (averaging Vol. 6%), some seams have mineral matter contents up to 30 Vol. %, perhaps due to flooding and storm events.

The shoreface sandstones formed a platform on which the coal and peat accumulated. The platform was relatively flat with gentle undulations due to paleobeach ridge topography (e.g., Leckie and Walker, 1982; Young, 1976; Curray et al., 1969). This relief would have affected the water table which in turn, played a major role in the preservation of source materials (gelified organic materials such as vitrinite versus nongelified materials such as fusinite and semifusinite). Although the coals formed directly on coastal deposits, they would not have formed at the shoreline. The presence of brackish or salt marshes having a high H_2S content would have generated sulphur-rich, pyritic coal (Postma, 1982; Cohen, 1984). Instead, the coals are characterized by low sulphur contents, and, thus were probably not affected by aqueous sulphate from marine waters which would produce high sulfur coals (Cohen, 1984). The low sulphur content indicates that the peats were removed from the active shoreline and there was minimal brackish or no marine influence.

The shoreface sandstones of the strandplain began to subside almost immediately after their deposition and, as a result, it is only the immediate coastal sands which are at sea level. The marine muds in front of the wave-dominated delta were initially

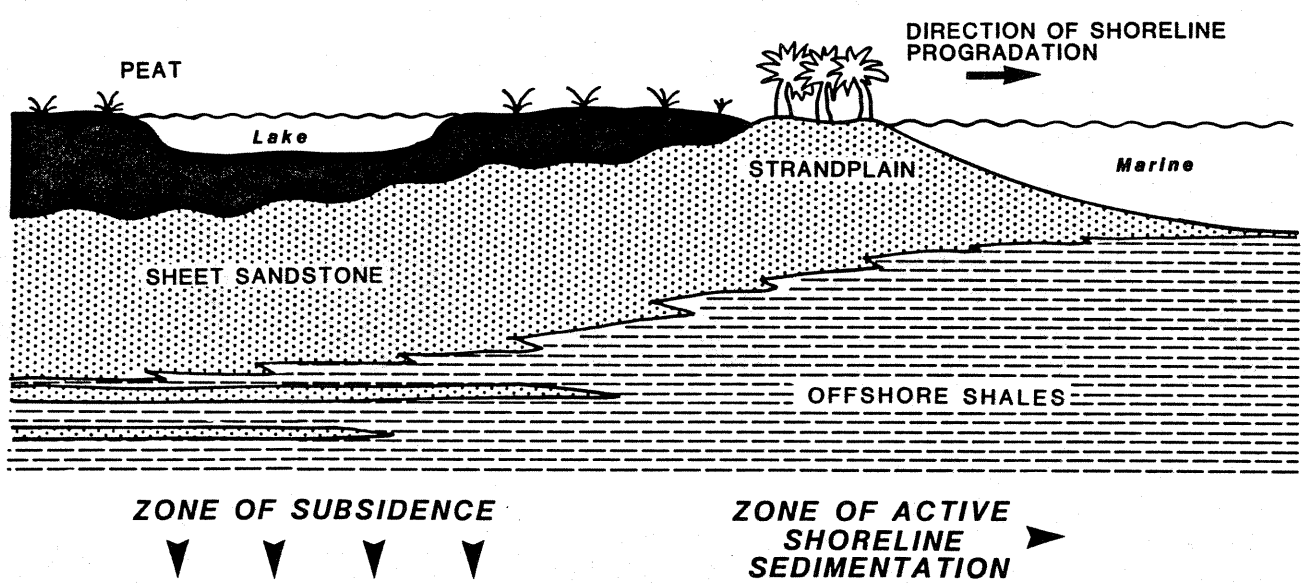

Figure 9. Depositional model to illustrate the formation of laterally continuous coals above regionally extensive strandplain deposits.

deposited with a high porosity, typically exceeding 50% (Hamilton, 1976). Compaction of the muds was rapid during the initial stages of burial, there typically being a porosity reduction of 15 to 17% in the first 200 m (Hamilton, 1976). Mechanical compaction squeezed out interstitial water and the increased temperature and confining pressure also released chemically bound water from clays and other hydrated minerals. The expelled waters flowed updip and landwards and may have contributed to recharging the strandplain water table (Galloway and Hobday, 1983). The subsidence was largely the result of compaction of the underlying shales by dewatering and clay particle rearrangement with a lesser tectonic contribution. The shoreline zone of active sedimentation was, in effect, a hingeline which migrated seawards.

This model satisfies the two major requirements for peat accumulation: 1) protection from active sedimentation; and 2) a high water table for the formation and preservation of organic matter (McCabe, 1984). The petrographic characteristics of the coals indicate fluctuating water tables that led to high amounts of oxidized to partially oxidized components (semifusinite and fusinite contents, averaging 20 and 5 Vol. %, respectively) which were formed during periods of relative dryness. Protection from active sedimentation landward from the shoreline is inherent in the wave-dominated coastline model (Fig. 9).The wave dominated delta had only one or two active distributaries (Coleman, 1981) and consequently large areas were removed from active clastic sedimentation. Thus, this reduced the detrital influx and produced low-ash peats. Furthermore, the rapidly subsiding strandplain sands were the platform (i.e. inner, lower portion of the tea saucer) on which the peats accumulated.

It is critical to the model that the rate of subsidence matches the rate of peat accumulation. If the rate of upward growth of the peat swamp is matched by subsidence due to shale compaction, then substantial thicknesses of peat can accumulate. If the rate of subsidence exceeds the rate of peat formation then the area will be submerged and a large, probably shallow lake will form instead of a peat forming swamp.

A reasonably high ground water table is a prerequisite for high organic productivity and preservation of peat. Wave-dominated deltas and strandplains have a shallow water table and contain one of the most highly transmissive and laterally uniform aquifers (Galloway and Hobday, 1983). Upper shoreface sands have a low mud content due to persistent wave agitation above fair weather wave base. As such, they form an isotropic and homogeneous medium bounded above and below by the less permeable lower shoreface sands and shales of the offshore zone. Porosities through the nonindurated shoreface sands are typically 30 to 50% (Freeze and Cherry, 1979). The climate during deposition of Gates Formation sediments was generally humid to subhumid, providing an ample meteoric source for groundwater recharge. Discharge of meteoric-derived groundwater dominates water table circulation and a meteoric recharged groundwater system can maintain a very large area having a shallow to emergent water table that is ideal for plant growth and peat preservation. Preliminary investigations on lithotype variations within the Gates Formation seams suggest that the coals are characterized by great variations in vertical succession, indicative of fluctuating water tables. The groundwater rises or maintains its position as compaction of the peat mat takes place and the strandplain subsides. The peat essentially develops and maintains its own water table. In the examples described above, the coals formed over progradational shoreface sediments at a time when relative sea level would have been at a stillstand or beginning to fall. Thus, the high water tables were not the result of sea level rise.

CONCLUSIONS

Coal seams formed on the wave-dominated, strandplain sediments of the Gates Formation are characterized by great lateral continuity (tens to hundreds of kilometres), substantial thicknesses (up to 12 m), relatively low ash and low sulphur contents. The coals formed behind an active shoreline in areas undergoing subsidence due to shale compaction and dewatering. The zone of peat accumulation was removed from the shoreline and generally protected from fluvial flooding and storm/tidal inundations. Statistical evaluation, by correspondence analysis, of the Gates Formation showed that strandplain coals formed distinctive statistical groups that are characterized by relatively low vitrinite contents and high inertinite contents. In the inertinite group, semifusinite and inertodetrinite dominate. Liptinite contents are negligible. Tissue preservation and gelification indices for the strandplain coals indicate a forest-type depositional environment in which relatively low water tables allowed the accumulation of oxidized and partly oxidized components (fusinite and semifusinite). Fair amounts of detrital components such as inertodetrinite and vitrinite B are diagnostic that some transportation of the organic material took place prior to burial.

ACKNOWLEDGMENTS

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OVERBURDEN DIGGABILITY CRITERIA FOR SURFACE COAL MINES

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ABSTRACT

By establishing correlations between various geotechnical, geological and geophysical parameters for the overburden at Highvale Mine in central Alberta, criteria are developed for assessing the diggability of the various geologic formations when using different types of stripping equipment including bucketwheel excavators, walking dralines and power shovels. A procedure for applying equipment-specific criteria is outlined to generate plans showing the areal extent and thickness of difficult-to-dig strata which require blasting.

BACKGROUND

Highvale Mine is located just south of Wabamun Lake about 70 km west of Edmonton, Canada. Maximum coal reserves exploitable by conventional surface mining techniques have been estimated to be about 750 million tonnes which will be mined from fourteen separate pits by stripping up to 3.7 billion bm^3 of overburden. The general layout of the current mine is illustrated on Figure 1.

About 12 million tonnes of coal per annum are presently mined from three pits designated 02, 03 and 04. All the output from the mine is consumed by two mine mouth thermal generating plants. This surface mining operation constitutes one of the largest in Canada and, with depths to coal currently up to 30 m increasing ultimately to 60 m, reliable geotechnical assessment of the overburden characteristics has become a necessary part of mine design and planning.

The overburden materials at Highvale are composed of gently dipping sequences of mudstones, siltstones, sandstones and coal of Upper Cretaceous and Tertiary age. Overlying this succession are Pleistocene deposits consisting of clay till containing ice thrusted blocks of Tertiary rock.

Glaciation has resulted in varying degrees and depths of bedrock distrubance, evidence of which includes minor faulting, folding, fracturing, crushing and shear plane formation.

The coal is generally won from five of the six seams present, which vary from one to three metres in thickness. The overall coal and interburden thickness between Seams 1 and 6 is almost constant at 14 m throughout the mine area. The strata immediately above the coal are characterized by a mudstone and siltstone sequence between 4 and 8 m thick, containing a number of thin calcareous and sideritic bands. Overlying this sequence is a massive, poorly indurated sandstone enveloping a number of hard, calcareous/ferruginous bands of variable thickness to about 1 m. Overburden is currently stripped in all three pits by draglines operating in both the chopcut mode (excavating above the dragline bench level) and bankcut mode (excavating below the bench), the extent of each mode depending on the relevant geotechnical constraints and the depth to coal in the particular pit. Prestripping by scraper is presently carried out to recover and stockpile topsoil and subsoil for reclamation purposes. The typical mining method used at Highvale Mine is shown on Figure 2 (Wade et al, 1988).

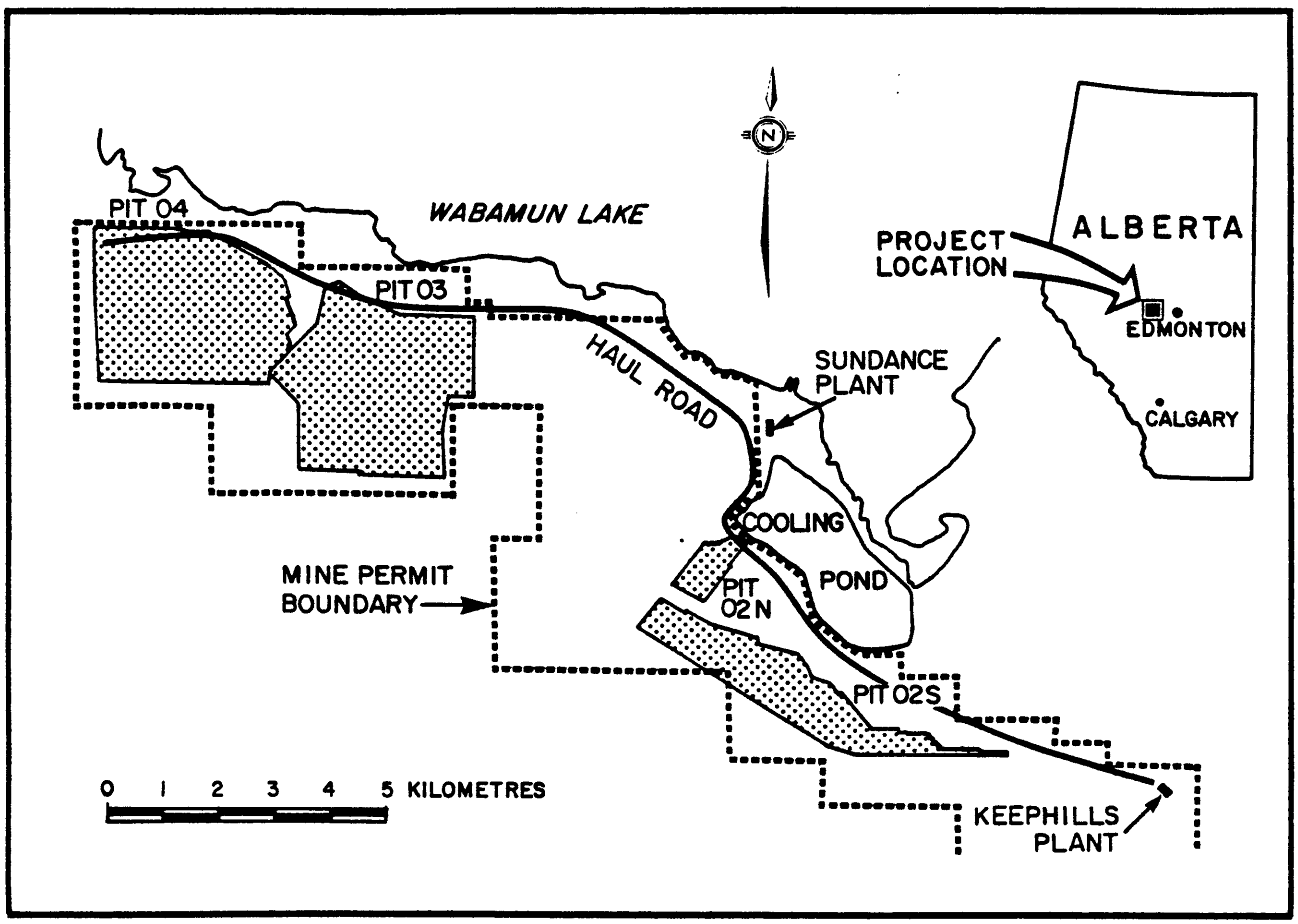

Fig. 1 General layout of Highvale Mine

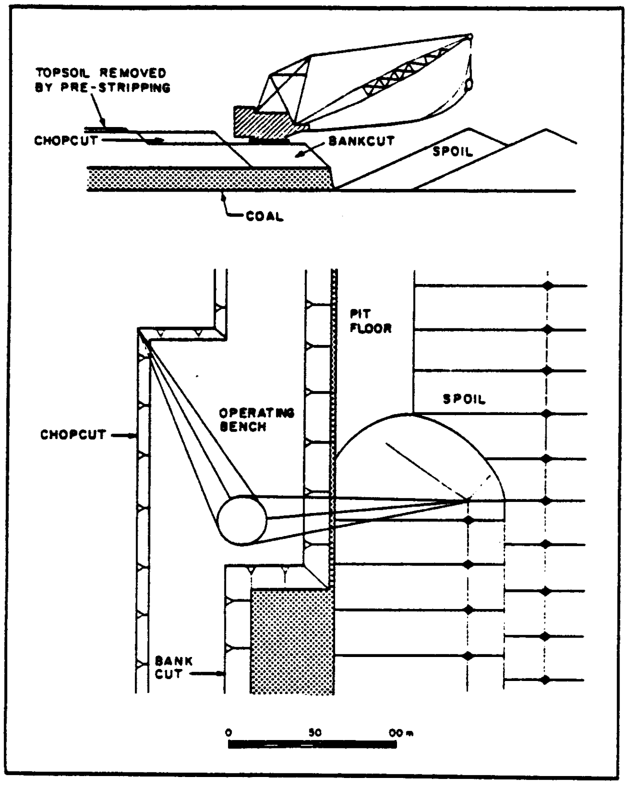

Fig. 2 Mining method at Highvale

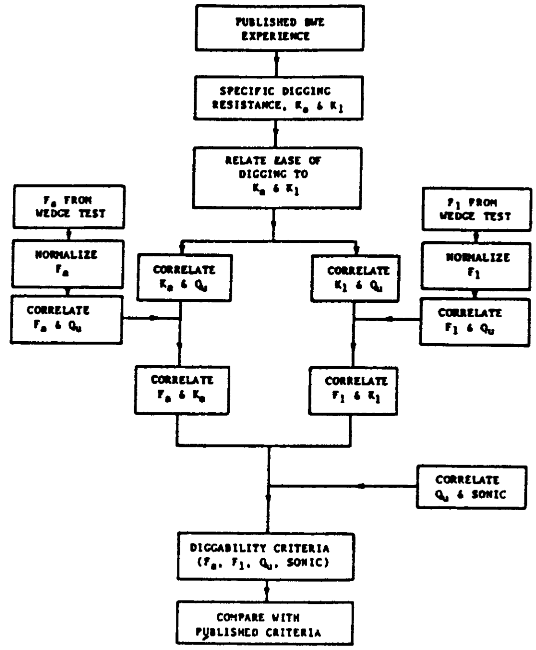

Fig. 3 Diggability assessment model

INTRODUCTION

The assessment of material diggability at Highvale Mine, where different types and sizes of stripping equipment are being used or contemplated, first required an evaluation of the digging capability of each machine. Then criteria were established in terms of the overburden formation parameters, uniaxial compressive strength and sonic transit time, relating these parameters to equipment digging capability. Using equipment-specific digging criteria, it then becomes possible to subdivide each pit into zones according to degree of digging difficulty for the stripping equipment designated for that pit.

The digging capacity of, and corresponding digging criteria for, different types of stripping equipment are formulated in this paper. Also presented is a computer based procedure for applying the criteria to generate plans showing areas of the mine which contain difficult-to-dig strata that require blasting prior to stripping.

METHODOLOGY OF ASSESSING DIGGABILITY

Based on the approach described by Rodenberg (1987a), the specific digging force exerted by a bucketwheel excavator (BWE) or power shovel was defined as the bucket breakout force divided by either the cut area of the chip (K_a) or the bucket lip length (K_l). For draglines the breakout force was assumed to be equal to the maximum operating drag pull force. Formation digging resistance was characterized by specific cutting resistance values, F_a and F_l from the O&K wedge test (O&K, undated), and the compressive strength. Published information relating the specific digging forces for an operating BWE Model SchRs 1800 to formation compression strengths at Goonyella Mine permitted correlations to be established with the compressive strength and O&K specific cutting resistance values for Highvale materials.

Based on experience at Goonyella, Neyveli and other mines, BWE operation at near maximum operating breakout force is required to excavate hard ground and results in machine productivity of less than 50% of rated capacity. Adopting this as the criterion for the upper bound of hard digging for both draglines and shovels, and by prorating the equivalent specific digging force per lip length in accordance with corresponding K_a values reported (Rodenberg 1987b), additional productivity ratings were established for the remaining digging categories. Development of the individual equipment-specific criteria is outlined in the following paragraphs.

CRITERIA FOR BWE

The proposed BWE diggability criteria is given in Table 1. The procedure used to develop the criteria, which is outlined on the diggability assessment model (Fig. 3), differed somewhat from that used previously (Wade et al, 1987) and consisted of the following steps:

- values of specific digging resistance (i.e. K_a and K_l) for different BWE models were obtained from a review of published information on operating mines (Table 2);
- these values were categorized according to relative diggability and equipment productivity (Table 1);
- published specific digging resistance values were correlated with the corresponding uniaxial compressive strengths of the sedimentary strata being excavated (Figs. 4 & 5);

Table 1. Proposed BWE diggability criteria for Highvale Mine.

Digging Resistance	K_a (MPa)	Est. Productivity* (%)	Proposed Criteria Q_u** (MPa)	F_a** (MPa)	F_1** (kN/m)	Sonic**** (u-sec/m)
Easy	0-0.25	100	0-8	0-0.6	0-70	410+
Diggable	0.25-0.5	75-100	8-16	0.6-1.1	70-150	375-410
Hard	0.5-0.75	50-75	16-20	1.1-1.4	150-200	360-375
Marginal	0.75-1.0	50-	20-25	1.4-1.8	200-250	345-360
Undiggable	1.0+	-	25+	1.8+	250+	345-

* Estimated for a BWE with a rated output similar to the O&K SchRs 1800 operating at Goonyella Mine from adapted Rodenberg, 1987b).
** From Fig. 2
*** From Fig. 3
**** From Fig. 6

Table 2. Cutting forces for different types of equipment.

Type	Model	Rated Capacity (BCM/Hr)	Breakout Force (kN)	Bucket Width (m)	K_a (MPa)	K_1 (kN/m)	Mine Location
BWE	O&K	5400	358	-	1.1	-	Neyveli, India
	SchRs 1800	5200	340	-	0.84	118-135	Goonyella, Australia
	Krupp 1420	-	272	-	-	-	Loy Yang, Australia
	Krupp 1150	-	217	-	-	-	Frimmersdorf, Germany
	VABE 400e	1040	-	-	-	60	Unong, Philippines
	Krupp C7005	-	-	-	-	100	Omarska, Yugoslavia
	SchRs 650/5-28	-	-	-	-	110	Kosovo, Yugoslavia
Hydraulic Excavator	Demag 285	-	1079	3.6	-	200**	
Shovel P&H	2800 X P	-	1366	4.29	-	212**	
Dragline	M8750-37A	-	2000*	4.27	-	312**	
	M8050-14B	-	1325*	3.69	-	239**	
	M7800	-	625*	3.19	-	130**	
	BE1360-W	-	1130*	3.51	-	214**	

* Breakout force = 1/2 Stall Drag Pull
** Computed assuming bucket lip length = 1.5 x bucket width

- the cutting resistance parameters, F_a and F_l, from O&K wedge tests on overburden specimens from Highvale were correlated with the Highvale compressive strength values (Figs. 4 & 5);
- with uniaxial strengths as a basis, the laboratory determined specific cutting resistance parameters (F_a and F_l) were correlated with specific digging resistance parameters (K_a and K_l) (Figs. 6 & 7);
- for Highvale data a relationship was established between compressive strength and sonic transit time (Fig. 8);
- the developed BWE diggability criteria for Highvale Mine were tabulated in terms of compressive strength, specific cutting resistance and sonic transit time (Table 1);
- the Highvale BWE criteria were compared with criteria published by others (Table 3).

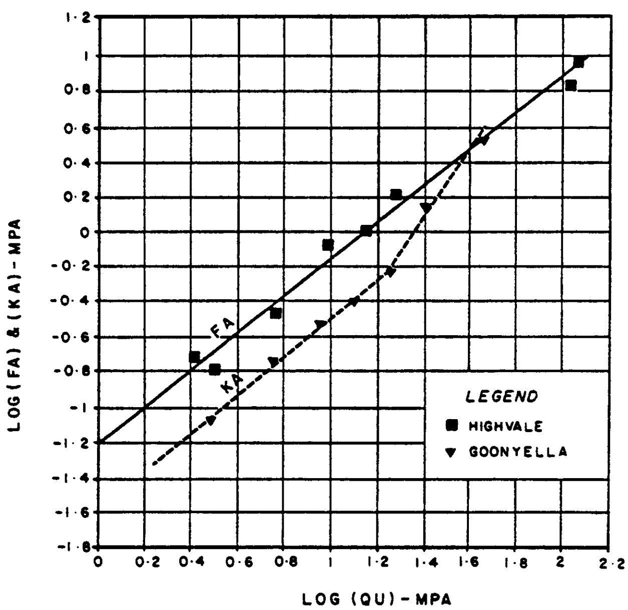

Fig. 4 Variation of F_a & K_a with compressive strength

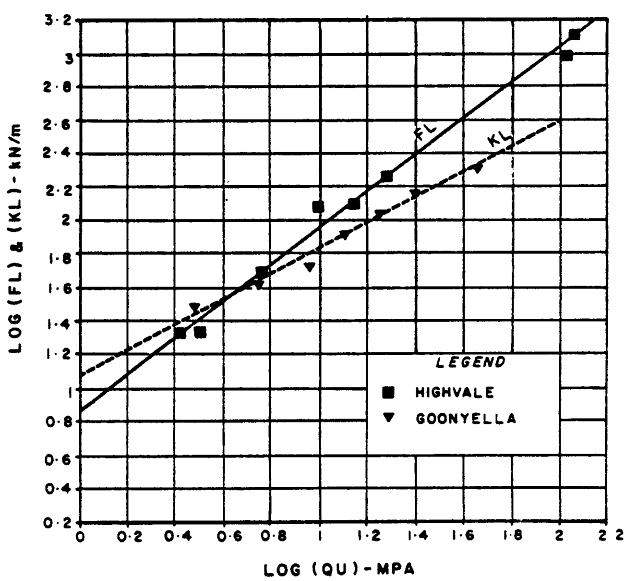

Fig. 5 Variation of F_l & K_l with compressive strength

CRITERIA FOR DRAGLINE & SHOVEL

The maximum specific digging force, K_l (max), for the draglines operating at Highvale was computed by dividing the maximum operating drag pull obtained from equipment specifications by the bucket lip length (Table 4). The procedure for developing marginal and hard digging criteria, once K_l values are known, is illustrated in Table 5 for the shovel and different dragline models. Other diggability ratings were determined by prorating the respective compressive strength and sonic values given for hard digging conditions for each machine. A summary of the diggability criteria for different stripping equipment is given in Table 6.

Table 3. Comparison of BWE diggability criteria.

Class	Digging	Compressive Strength (MPa)			Specific Cutting Resistance, K_a (Mpa)				
		Highvale	Goonyella	Gorylewicz	Highvale	Goonyella	Neyveli	Canmet	Kozlowski
1	Easy	0-8	-		0-0.6	0.15-0.45	-	-	0-0.17
2	Diggable	8-16	-	0-5	0.6-1.1	0.45-0.6	1.1	0-1.0	0.17-0.36
3	Hard	16-20	10	5-10	1.1-1.4	0.6-0.75	2.3	1.0-1.5	0.36-0.54
4	Marginal	20-25	15	10-45	1.4-1.8	0.75-1.0	-	1.5-2.4	0.54-0.8
5	Undiggable	25+	-	45+	1.8+	1.0+	-	2.4+	0.8+

References:
- o Goonyella criteria - after O'Regan et al (1987)
- o Gorylewicz criteria - after Gorylewicz (1977)
- o Neyveli criteria - after Rodenberg (1987b)
- o CANMET criteria - after Weise (1981)
- o Kozlowski criteria - after Kozlowski (1980)

Table 4. Drag pull for various dragline models.

Model	Max. Operating Drag Pull* kN	Bucket Size m^3	Bucket Lip** m	K_1 (Max) kN/m
M8750-37A	2,000	68.8	6.41	312
M8050-14B	1,325	44.3	5.54	239
M7800	625	28.7	4.79	130
BE1360-W	1,130	38.2	5.27	214

* Max. operating drag pull = 1/2 stall drag pull.

** Bucket Lip length was assumed to be proportional to the cube root of the bucket size.

Table 5. Procedure used to assess diggability for draglines & shovel.

Equipment	K_1* (kN/m)	Q_u** (MPa)	Sonic*** (u-sec/m)	Relative Diggability
BWE-SchRs 1800	126.5	22	360	Hard
Shovel -	212(max)	45	290	Marginal
P&H 2800 X P	141****	25	350	Hard
D/L-M8750	312(max)	70	240	Marginal
	208****	40	310	Hard
D/L-M8050	239(max)	50	280	Marginal
	159****	29	340	Hard
D/L-M7800	130(max)	23	355	Marginal
	87****	13.5	390	Hard
D/L-BE1360	214(max)	45	290	Marginal
	143****	25	350	Hard

* from Table 2
** from Fig. 3
*** from Fig. 6
**** K_1 (max) value reduced by 33% to approximate sustained hard digging conditions.

Table 6. Diggability criteria for different stripping equipment.

Equipment	Diggability Rating									
	Easy		Diggable		Hard		Marginal		Undiggable	
Type	Qu	Sonic	Qu	Sonic	Qu	Sonic	Qu	Sonic	Qu	Sonic
BWE Sch Rs 1800	0-8	410+	8-16	375-410	16-20	360-375	20-25	345-360	25+	345-
Shovel P&H 2800XP	0-9	400+	9-18	375-400	18-25	350-375	25-45	290-350	45+	290-
D/L M8750-37A	0-15	380+	15-30	335-380	30-40	310-335	40-70	240-310	70+	240-
D/L M8050-14B	0-11	395+	11-22	360-395	22-29	340-360	29-50	280-340	50+	280-
D/L M7800	0-5	425+	5-10	410-425	10-13.5	390-410	13.5-23	355-390	23+	355-
D/L BE1360-W	0-9	400+	9-18	375-400	18-25	350-375	25-45	290-350	45+	290-

Notes:

- Q_u = formation compressive strength, MPa
- Sonic = formation sonic transit time, micro-sec/m

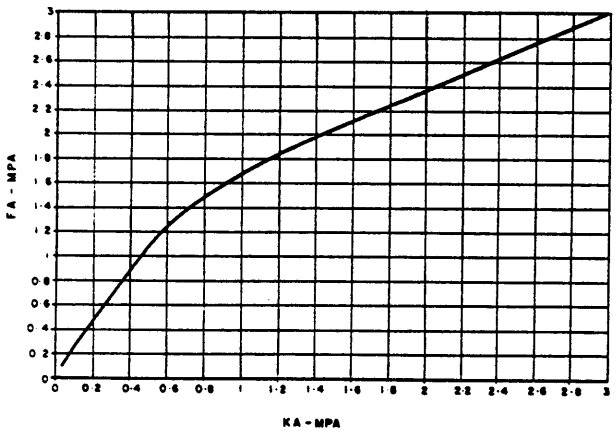

Fig. 6 Relationship between F_a & K_a

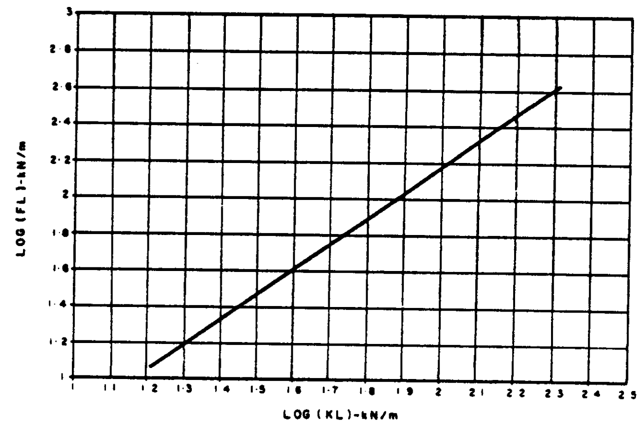

Fig. 7 Relationship between F_l & K_l

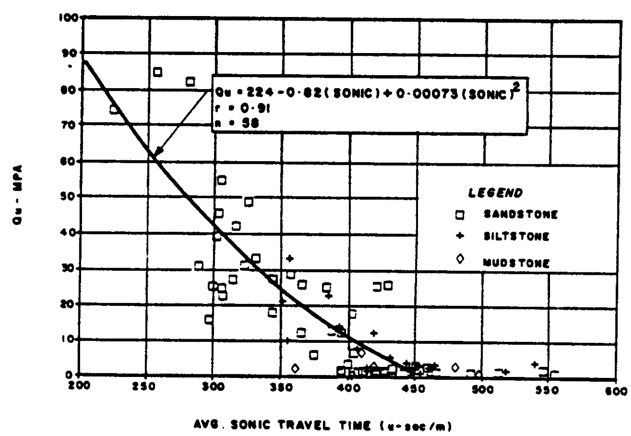

Fig. 8 Compressive strength vs. sonic travel time relationship

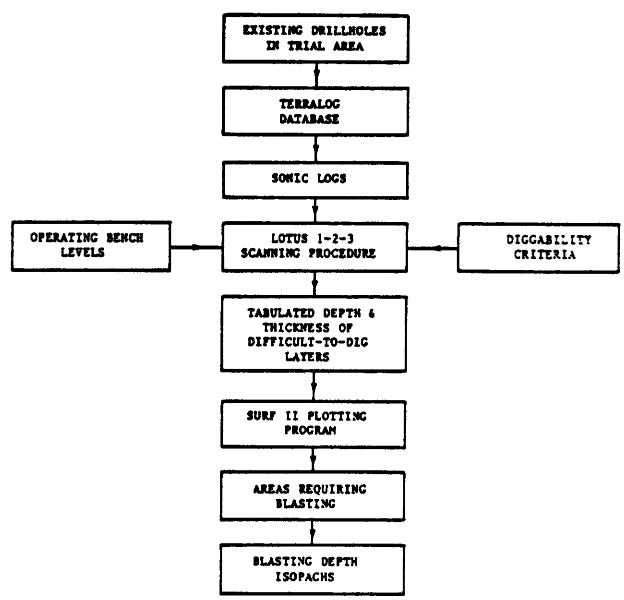

Fig. 9 Procedure for applying diggability criteria

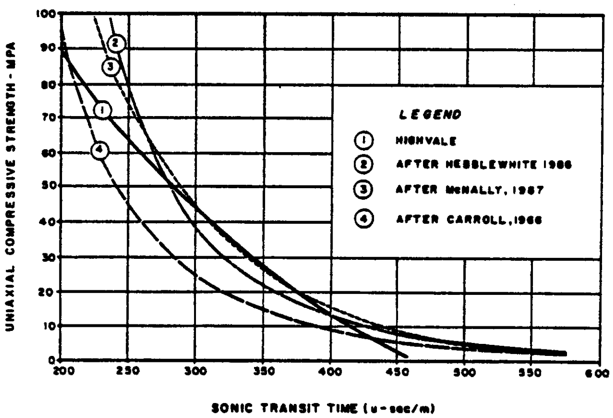

Fig. 10 Comparison of Highvale and published data

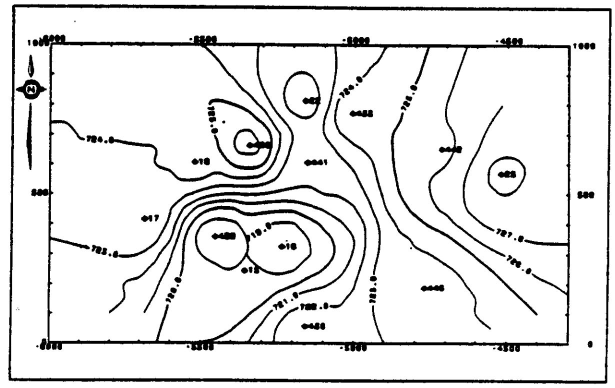

Fig. 11 Thickness of difficult-to-dig strata for M8750 dragline in trial area

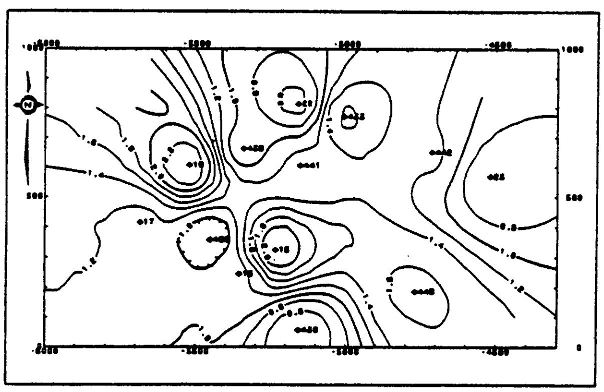

Fig. 12 Bottom contours of difficult-to-dig strata

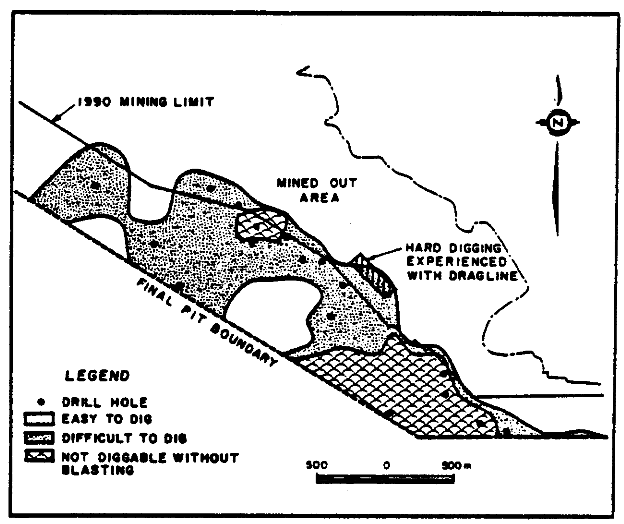

Fig. 13 Diggability map for BE1360 dragline

APPLICATION OF CRITERIA

The procedure for applying the diggability criteria and generating plans showing difficult-to-dig areas which require blasting is illustrated schematically on Fig. 9 and summarized as follows:

- a trial area about one kilometre square was selected which contained several drillholes with good sonic log data;
- digitized sonic transit time profiles for the drillholes were downloaded onto floppy disks from the geophysical database;
- macro subroutines for the Lotus 1-2-3 program were developed to automatically scan each sonic profile on the floppy disks and print out the depth and thickness of difficult-to-dig strata for the stripping equipment being considered;
- after transforming depths to elevations and incorporating drillhole coordinates, the tabulated data (Table 7) were processed by the SURF II plotting program to create plans showing cumulative thickness isopachs of the difficult-to-dig strata as well as elevation contours of the base of the deepest hard band.

Table 7. Cumulative thickness & base elevation of hard layers in trial area.

				Difficult-to-dig Layers			
				D/L M-8750		D/L M-7800	
	Coordinates		Ground	Cum.	Bottom	Cum.	Bottom
Hole No.	N	E	Elev.(m)	Thick	Elev.(m)	Thick	Elev.(m)
15	244.90	-5356.00	762.40	1.11	719.04	3.24	719.69
16	324.2	-5235.30	760.90	2.23	718.41	4.31	717.47
18	606.50	-5520.80	749.50	2.38	724.22	3.77	723.00
22	812.80	-5160.80	754.30	0.51	721.44	1.32	720.55
25	568.40	-4520.30	754.00	0.64	728.11	1.44	728.35
428	357.32	-5452.95	760.41	0.79	718.42	3.42	716.75
439	662.61	-5342.14	759.21	0.87	726.29	1.93	722.91
441	604.88	-5153.29	755.97	1.24	722.18	2.74	722.94
442	650.67	-4715.10	755.68	1.23	725.88	3.40	718.64
446	187.86	-4770.26	773.78	1.62	723.82	4.22	724.19
17	414.90	-5684.70	749.30	1.16	723.81	2.27	722.79
430	56.58	-5158.28	760.79	0.44	722.52	3.74	721.86
433	770.92	-5006.88	769.80	1.657	24.80	3.36	724.13

DISCUSSION

As indicated in Table 3, the specific cutting resistance criteria for BWE diggability agrees reasonably well with published criteria. Relatively poor agreement occurs, however, with the compressive strength criteria due in part to the paucity of published compressive strength data from operating mines.

In assigning appropriate sonic transit times for different overburden strata, one has the choice of three different sonic logs (i.e. long, medium and short representing, respectively, the largest, intermediate and shortest spacing between the acoustical receivers on the sonic probe). It was found that the average value of the long spacing signature over a depth interval of 1 to 2 m encompassing the strength test specimen provided the best correlation with uniaxial strength. On the other hand, poor correlations were experienced if:

- the drillhole diameter varied by more than 2.5 mm over the depth interval considered (as denoted by the caliper log), or
- any one of the three sonic signatures remained constant over the depth interval.

As shown on Fig. 10, reasonably good agreement between Highvale and published data from other mines was obtained for the compressive strength vs. sonic transit time relationship.

It should be noted that the presence of hard bands above the water level in drillholes cannot be detected by sonic logging due to poor acoustical coupling between the sonic probe and surrounding formation. This is not a serious shortcoming of the diggability criteria, however, since the water level in most drillholes is generally less than 5 m from the ground surface during sonic logging and the occurrence of hard bands in the uppermost formations at Highvale is infrequent.

The F_a and F_l cutting resistance values used for Highvale were determined from O&K laboratory wedge tests conducted on frozen and unfrozen specimens of different overburden lithologies. Since in most cases the specimen dimensions varied from the 15 cm cube or 15 cm dia x 15 cm high cylinder specified by the O&K procedure, the calculated cutting resistance values were "normalized" by multiplying the measured F_a by the ratio of the specified area (15 x 15 cm) to the tested area, and F_l by the ratio of the specified cut length (15 cm) to the actual cut length. This approach materially decreased the scatter in the results and brought the data closer to the field-determined K_a and K_l values reported in the literature (Figs. 4 and 5).

The criteria for hard digging adopted for the trial area at Highvale correspond to the upper limit of the dragline 'diggable' category shown in Table 6 and represent equipment productivity less than 75%. If it is assumed that sustained dragline productivity should exceed 75% during stripping operations, then for the M8750 dragline the cumulative thickness of hard strata that has to be blasted in the area studied is denoted by the isopachs on Fig. 11. Since the trial area selected contains numerous hard bands, it is not surprising that the analyses indicate blasting is required over the whole area. When, on the other hand, an assessment of overburden diggability is made on the entire mine, it is expected that appreciable portions of the area will not require blasting. This assessment is scheduled to be carried out over the next few months.

If the dragline bench is established about 25 m above the coal zone, all of the hard strata detected in the trial area will occur below the bench level. The required depth of blast holes can be computed as the difference between the bench elevation and the elevation of the base of the lowermost hard layer, shown as contours on Fig. 12.

The criteria in Table 6 indicate that hard digging with the BE1360 dragline would be experienced in formations with an average sonic transit time less than 375 micro-sec/m. Approximately half of the area in Pit 02 between the 1983 and 1990 mining limits has hard bands with sonic transit times much less than 375 micro-sec/m and, as depicted on Fig. 13, hard digging with this dragline has been experienced in the area since 1986. Since the specific cutting force for draglines is generally higher than that for BWE's (Table 2), it is considered that the difficult-to-dig areas for a BWE in Pit 02 would be larger than that shown on Fig. 13. However a more thorough test of the criteria will be possible when isopachs of hard digging thickness are prepared from the sonic logs and compared with areas where hard digging has been experienced in each pit.

CONCLUSIONS

Diggability criteria for different types of stripping equipment, expressed in terms of formation compressive strength and sonic transit time, have been developed for Highvale Mine (Table 6) based on experience gained with BWE operation in similar mines elsewhere. The BWE criteria developed compare favourably with published BWE criteria (Table 2) and the dragline criteria accurately predicted, at least in one area, the location where hard digging would be encountered.

A workable procedure for applying the diggability criteria to the Highvale Mine area has been developed and plans showing depth contours and thickness isopachs for difficult-to-dig zones can readily be generated for different types of stripping equipment.

ACKNOWLEDGEMENTS

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ADVANCES IN REFLECTION SEISMIC METHODS FOR SHALLOW COAL EXPLORATION IN WESTERN CANADA

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ABSTRACT

Several reflection seismic programs have been conducted in the Plains regions of Alberta over the past 5 years. Improvements in data acquisition techniques have been accomplished as a result of these surveys. Of greatest significance has been the increase in frequency bandwidth of reflections from coal zones. This has been achieved through better energy coupling at the seismic source, improved receiver spread geometry, a larger number of recording channels, higher subsurface multiplicity, and the use of recording instruments with fast digital sampling rates (4 kHz) and a wide dynamic range.

The improvements in the seismic method for coal exploration are illustrated with a comparison between two seismic data sets from the Dodds-Round Hill coalfield. One survey was conducted in 1981 and part of that program was repeated in 1988. The dominant frequency of the 1981 data was 70 Hz whereas that of the 1988 data was over 110 Hz. Improved resolution in the recent data has enabled all of the major coal zones in the field to be mapped, including partings in the Dodds coal zone.

INTRODUCTION

The objective of this paper is to review the current capabilities of the reflection seismic method for coal exploration and development in the Plains region of Alberta.

The basic purpose of a reflection seismic program over a coal deposit is to map the continuity of the coal seam(s). Most coal seismic programs undertaken throughout the world in the 1970s were aimed at establishing the presence or absence of the coal zone (Clarke, 1976; Lepper and Ruskey, 1976; Scherba, 1977; Peace, 1979; Ziolkowski and Lerwill, 1979). In the 1980s, the acquisition and processing of high resolution seismic data has continued to improve, and the interpretation of the data has consequently become more refined.

Over the past 5 years, several reflection seismic programs have been undertaken over coalfields in Alberta. The goals of the surveys were to map coal subcrop, and to resolve the structural and stratigraphic details of the coal seams. A high-resolution seismic survey near Camrose was discussed by Lawton (1985), who attempted to relate the character of reflections to the depositional environment of the coal. Sartorelli et al (1986) provided overviews of high resolution seismic techniques and discussed their applicability in coal-mining operations. More recently, Lyatsky (1988), and Lyatsky and Lawton (1988) made a quantitative interpretation of reflection seismic data from the Whitewood mine in south-central Alberta.

The main advances made in the seismic method for coal exploration have primarily been improvements in data acquisition. State-of-art seismic recording instruments are capable of faster digital sampling rates, greater dynamic range, and more recording channels than their counterparts of only five or six years ago. This has resulted in improved vertical and lateral resolution from the data, and better signal to noise ratios due to higher subsurface coverage. Greater attention to the seismic source and to the geometry of the recording spread have now enabled very shallow (<50 m) targets to be mapped successfully (Sartorelli, et al, 1986; Lyatsky and Lawton, 1988).

RESOLUTION

The thickness of an individual coal seam is significantly less than the wavelength of a seismic pulse in the subsurface. Hence, a seismic reflection observed from a coal zone can be viewed as the superposition of many discrete, overlapping events from the tops and bases of individual seams within the coal zone. Vertical resolution is the ability to identify these individual events in the total seismic response, and it depends on the frequency bandwidth of the recorded data and the seismic velocity in the interval of interest. Widess (1973) showed that the resolvable thickness of a layer is equal to one-quarter of the wavelength of the seismic pulse, provided that the total frequency bandwidth is twice the central frequency of the data. Velocity (v), frequency (f) and wavelength (λ) are related through the simple expression

$$\lambda = v/f$$

Hence, the higher the central frequency of broad-band seismic data, then the smaller will be the wavelength in the subsurface, resulting in greater vertical resolution. This relationship is illustrated in Figure 1, in which resolvable thickness is plotted versus interval velocity for a range of seismic frequencies. Figure 1 shows that if the velocity through a coal zone is 2000 m/s, then seismic data with a central frequency of 50 Hz would resolve layers 10 m thick, whereas data with a central frequency of 100 Hz would resolve layers only 5 m thick. Synthetic seismograms further illustrating this effect are shown in Figure 2. These data are based on a seismic modelling study of the Highvale coalfield in south-central Alberta, described by Lyatsky and Lawton (1988).

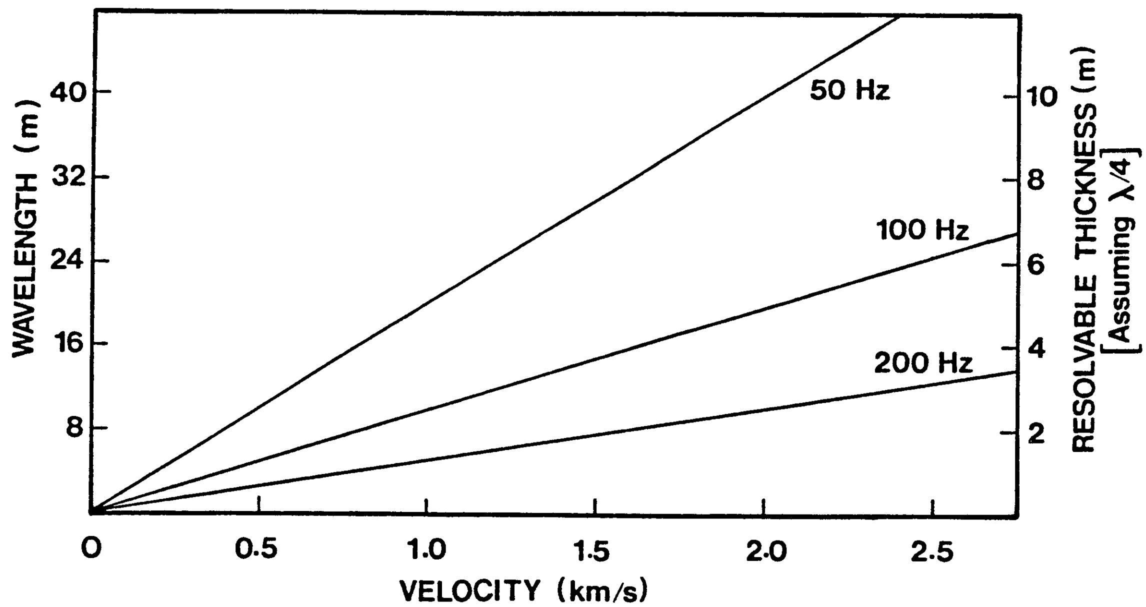

Figure 1. Resolvable thickness as a function of velocity and wavelength for a range of seismic frequencies (from Lawton, 1985).

Because of the need for improved vertical resolution, the greatest effort made in seismic surveys over coalfields has been to increase the central frequency and the total frequency bandwidth of the recorded data. This has been achieved through high subsurface coverage, small energy sources (explosive), careful attention to shot coupling, small receiver group intervals and more recording channels. Specialized data processing, particularly static corrections and multichannel filtering techniques have also contributed to the improved bandwidth of shallow reflection data. In this paper, the impact of these parameters is shown for a seismic line which was acquired in late 1988 over part of the Dodds-Round Hill coalfield near Camrose in central Alberta. For comparison purposes, this line re-occupied part of an older program which was shot in 1981 and described by Lawton (1985).

CAMROSE SEISMIC SURVEYS

GEOLOGY

The study area lies within the Dodds-Round Hill coalfield and is located 20 km north-east of Camrose and 9 km south of the community of Round Hill (Figure 3). Coal seams of this coalfield belong to the Upper Cretaceous Horseshoe Canyon Formation, and accumulated within interdistributary and interchannel areas of a prograding delta complex (Hughes, 1984). Five coal zones occur in the area of seismic coverage, which Hughes (1984) termed, in ascending order, as the Dodds, Round Hill, Dusty, Burnstad and Demay coal zones. Logs from drillhole WLS-116 (Figure 3) show that the coal zones in this area vary in thickness between 1 and 3 metres, with interseam thicknesses between 5

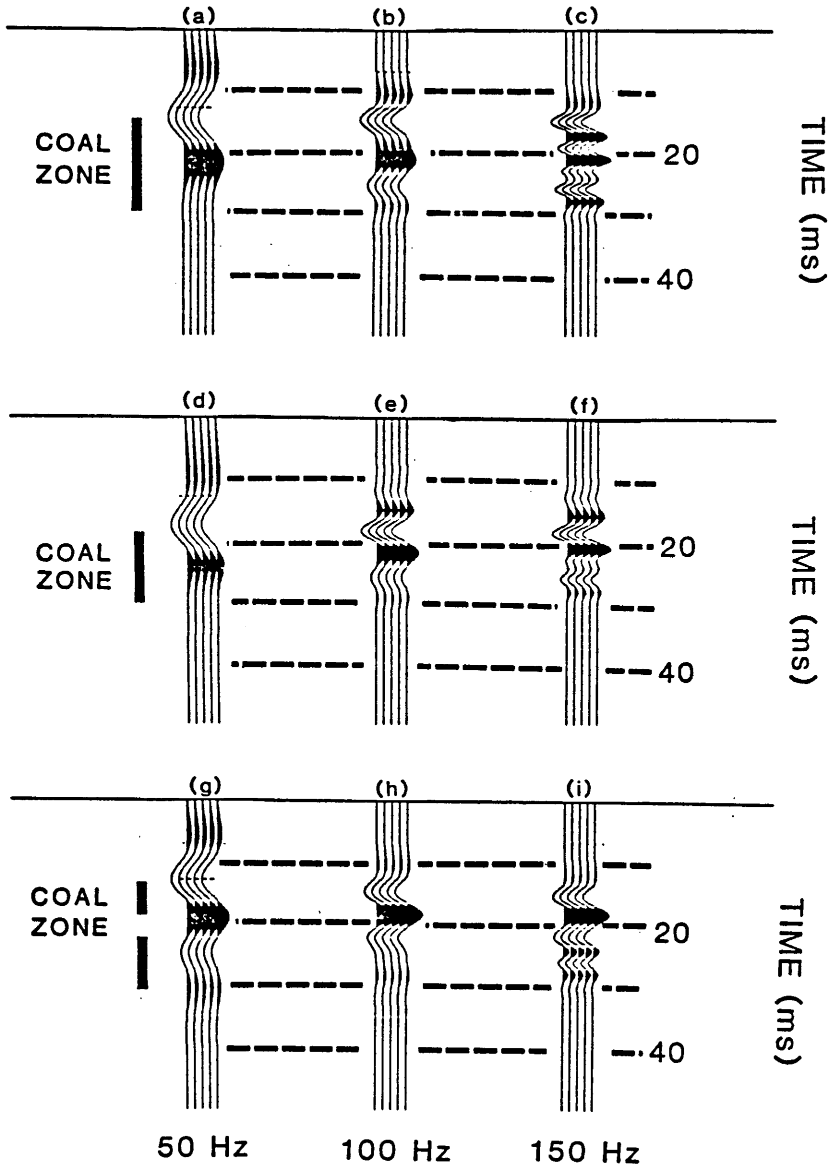

Figure 2. Synthetic seismograms from a well in the Highvale coalmine, illustrating the increase in resolution with greater frequency bandwidth and higher central frequency. Each row represents a different coal seam stratigraphy, as indicated on the left margin of the figure. Seismograms were generated with 50-Hz Ricker wavelets (left column), 100-Hz Ricker wavelets (middle row), and 150-Hz Ricker wavelets (right column). (from Lyatsky and Lawton, 1988).

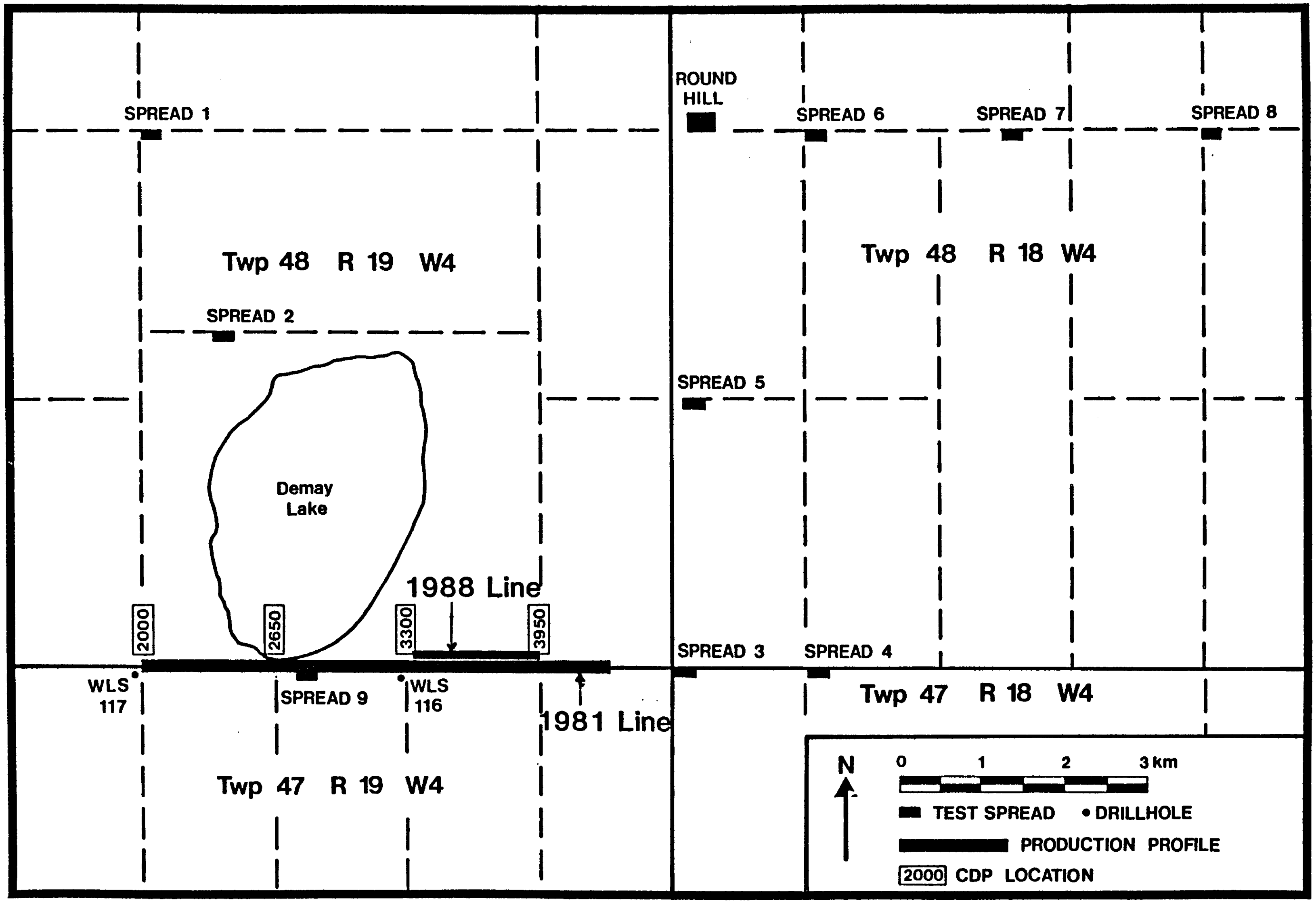

Figure 3. Location map showing the 1981 and 1988 reflection seismic programs in the Dodds-Round Hill coalfield near Camrose.

and 12 m. Some of the coal zones contain up to 3 individual seams, with partings several metres thick. Along the seismic line, the coal zones occur in a depth range 40 m to 90 m below the ground surface. The seams dip gently to the southwest and subcrop below glacial till to the southeast of Round Hill.

DATA ACQUISITION

Figure 3 shows the locations of seismic lines acquired in 1981 and 1988. The 1981 profile was 5.7 km long and the data were collected by the University of Calgary. The 1988 data were acquired by Geo-Physi-Con Co. Ltd, of Calgary; the line was 1.6 km in length, and coincided with the 1981 line between CDP locations 3380 and 3950 (Figure 3). Drillhole WLS-116 provided information about the coal zone stratigraphy at the western end of the 1988 line, as noted above.

Table 1 shows the acquisition parameters used in the 1981 and 1988 seismic surveys.

Table 1. Seismic data acquisition parameters.

Parameter	1981 survey	1988 survey
Number of channels	48	96
Spread geometry	120-5-SP-5-120 m	240-5-SP-5-240 m
Receiver interval	5 m	5 m
Source interval	10 m	15 m
Subsurface coverage	12 fold	16 fold
Geophone type	40 Hz, single	27 Hz, cluster
Sampling interval	2 millisec	1/4 millisec
Instruments	DFS-III	Geometrics ES-2400
Amplifier	Binary gain	Floating Point
Instrument filters	Out - 125 Hz	20 - 720 Hz
Source type	Betsy seisgun	Primacord
Source size	4 oz. shell	50 gm
Source depth	surface	3 m shothole

As indicated in Table 1, the major differences between the 2 surveys concern the source, spread geometry and the data sampling rate. The seisgun, used in the 1981 survey, is a low-energy surface source which fires a lead alloy slug into the ground. Although adequate energy penetration was obtained, the recorded data had a central frequency of only about 70 Hz. This was attributed to severe attenuation of the high frequency components of the signal in the near-surface layers. In the 1988 survey, a small primacord explosive charge was used, buried to a depth of 3 m. Observations of field monitor records showed that data with frequencies of up to 200 Hz were recorded. The improvement in frequency bandwidth is considered to be due to the buried charge, which reduces the travelpath through the highly-attenuating near-surface layers

DATA PROCESSING

A standard data processing flow was followed for both data sets. The 1981 data were processed at the University of Calgary, whereas the 1988 data were processed by Reilly's Seismic Data Processors, of Calgary. The 1988 data benefitted from processing software for noise reduction and weathering static corrections which was not available at the time that the 1981 data were processed.

INTERPRETATION

Figure 4 shows processed final sections from the seismic line (Figure 3) which was common to both surveys. There is a dramatic improvement in overall quality of the 1988 data (Figure 4b) compared with the 1981 data (Figure 4a). This is due primarily to the greater frequency bandwidth. The peak frequency of the 1988 data is about 100 Hz, occasionally up to 140 Hz, whereas that of the 1981 data is only about 70 Hz. The 1988 section also shows greater reflection continuity and coherency than the 1981 section. This improvement is due to removal of residual static errors in the recent data.

The processed seismic section from the 1981 data (Figure 4a) is characterised by hummocky, subparallel, high-amplitude reflections. Because of the limited bandwidth of the data, reflections from individual coal zones cannot be distinguished, and the data can interpreted only in terms of the presence or absence of the major coal zones. Lawton (1985) inferred from the reflection data that the coals were deposited in a delta plain environment, and attributed the hummocky reflection pattern to differential compaction and minor faulting. A channel washout was also interpreted to be present (Lawton, 1985). A much clearer picture of the subsurface is provided by the 1988 data (Figure 4b). Reflections show greater continuity and coherency, and the short wavelength structural variations seen in the 1981 data are not present, due to the removal of residual static errors. Long wavelength features are visible in the data and these are inferred to be caused by drape over sandstone partings between seams of the Dodds coal zone.

An interpretation of the final section from the 1988 data is provided in Figure 5. The 5 coal zones mapped by Hughes (1984) can now be identified clearly, and these are marked on Figure 5. Control of the interpretation was provided by the logs from drillhole WLS-116 (Figure 3). Note that this level of interpretative detail was not possible from the 1981 data.

Several significant features are evident in Figure 5. Firstly, the event from the Demay coal zone terminates about half way across the section. This is interpreted to be the position of the Demay subcrop and is in close agreement with the subcrop position proposed by Hughes (1984). Secondly, splits in the Dodds coal zone are clearly visible

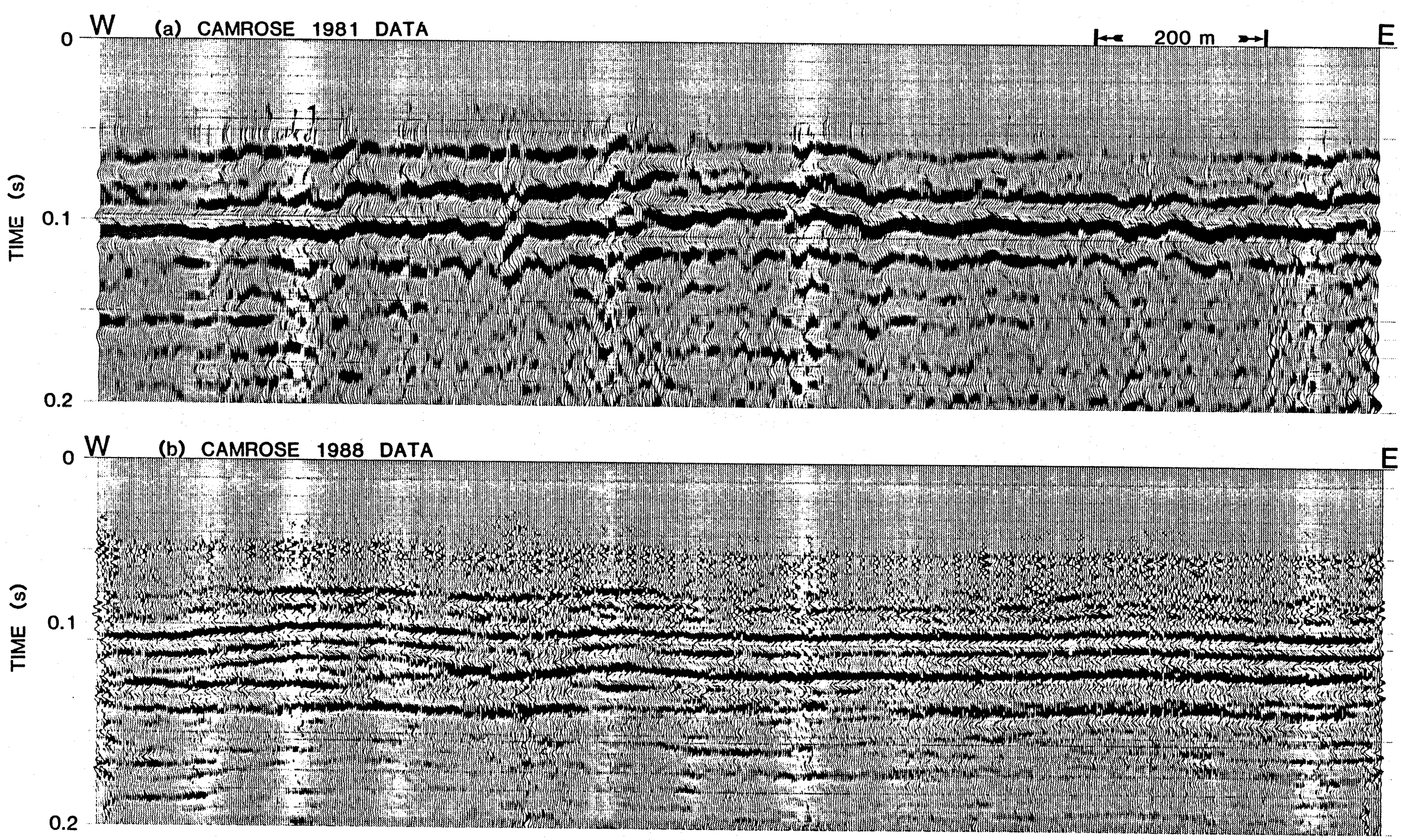

Figure 4. Final stacked sections from the seismic surveys over the Dodds-Round Hill coalfield. (a) 1981 survey, (b) 1988 survey.

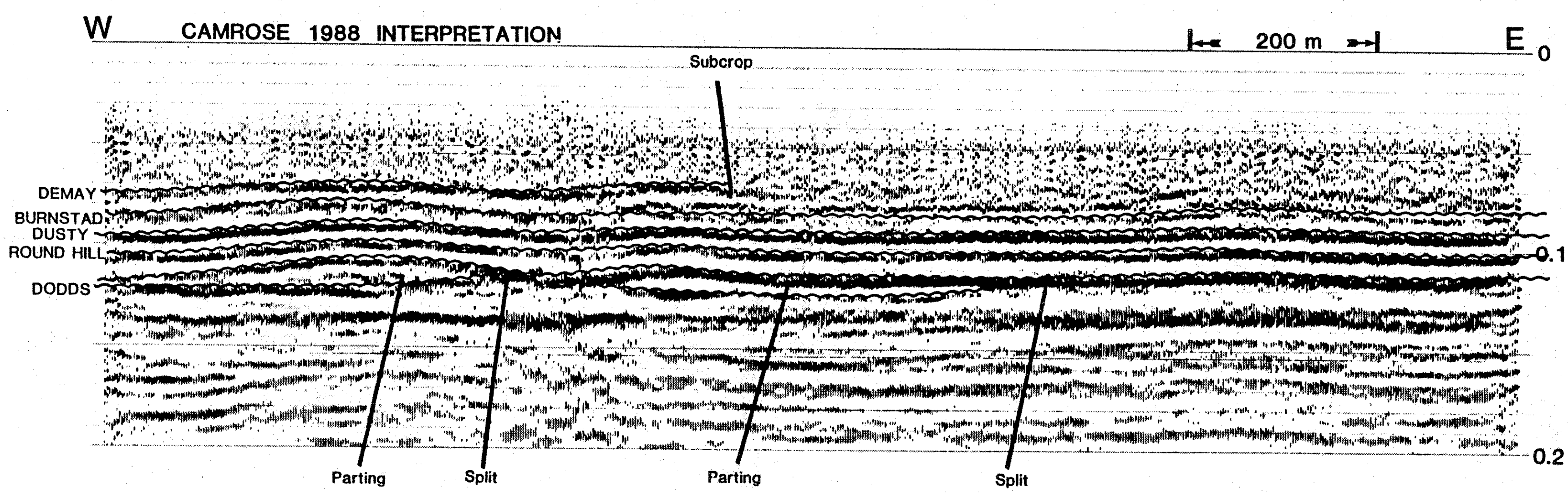

Figure 5. Interpreted seismic section from the 1988 survey over the Dodds-Round Hill coalfield. Individual coal zones are labelled on the left side of the section.

near the centre and at the western end of the line. Dodds seams A to C are separated from Dodds seams I to J (Hughes, 1984) by partings which are likely to be crevasse-splay sands. The upper Dodds seams, as well as the overlying coal zones, drape over the partings as a result of differential compaction. This interpretation is supported by the fact that the isochron between the Dodds and Round Hill coal zones decreases over the structural high. Based on the seismic data, the maximum thickness of the parting is calculated to be about 15 m, and the maximum structural drape is calculated to be about 8 m.

The horizontal, low-frequency reflection below the Dodds event is considered to mark the boundary between the Horseshoe Canyon Formation and the underlying Bearpaw Formation.

CONCLUSIONS

This study has illustrated the improvements that have made in the use of the reflection seismic method for coal exploration in Alberta. Better field data acquisition techniques for high resolution programs have resulted in reflections with increased frequency bandwidth being recorded. These high frequency data have been preserved and enhanced by careful data processing, particularly by the special attention given to static corrections. Targets as shallow as 20 m can now be imaged successfully.

In an experimental program near Camrose, Alberta, reflections with central frequencies of over 110 Hz were recorded from coal zones in the Dodds-Round Hill coalfield. Data with this frequency enables individual coal zones to be mapped with confidence, including splits and partings.

It is considered that the high resolution reflection seismic method has evolved to the level whereby it can now be used on a production basis, in conjunction with drilling programs, for mine planning purposes. It provides continuous depth information along a profile and should enable the number of drillholes required to define a coalfield to be reduced, or at least targeted to specific problem areas.

ACKNOWLEDGMENTS

Financial support for this project through the Alberta/Canada Energy Resources Research Fund, a joint program of the Federal and Alberta Governments and Administered by Alberta Energy and Natural Resources, is gratefully acknowledged. Well log data used for the synthetic seismograms were provided by TransAlta Utilities Corp. and Monenco Consultants Ltd. The cooperation shown by the staff of Geo-Physi-Con Co., and Mr. Bob LaBun of Reilly's Data Processors Ltd. contributed significantly to the success of the 1988 Camrose survey.

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GEOPHYSICS FOR PLAINS COAL MINING: SOME RECENT DEVELOPMENTS

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ABSTRACT

Since the last Coal Geoscience Forum (Calgary, 1987) there has been increased use and testing of both downhole and surface geophysical techniques. This paper highlights the results of some of this.

Surface geophysical methods that have been used most extensively for coal mapping purposes are direct current soundings and profiling, and reflection seismic profiling. Direct current methods exploit the electrical resistivity contrast of coal, while reflection seismic profiling relies on the acoustic impedance contrast.

Direct current data acquisition arrays now used are symmetrical with respect to current injection and potential measurement probes. This symmetry data to be directly compared to direct current soundings data, increases the rate at which terrain can be covered and provides data to an increased number of depths of exploration.

The most significant improvement to the reflection seismic profiling method has been in data recording. A present recording system having dynamic range and data storage capabilities that are large even in comparison to typical oil industry systems is now used on a routine basis for coal exploration and mine planning.

The neutron probe, a downhole geophysical tool that is widely used in the soil sciences, has been tested to measure moisture content and density changes in sediment to depths of 10 m. The probe used is a Campbell Pacific Nuclear (CPN) model 501DR Depthprobe, capable of measuring bulk density and volumetric moisture of subsurface materials (CPN Corp., 1984).

Two test sites were chosen and both moisture and wet density readings were collected in December, 1988 and January, 1989. The December and January readings within each data type from both sites show a strong reproducibility. The moisture ratios and the density ratios are generally within 0.1 of 1. The correspondence between the neutron probe data and that obtained from samples was relatively poor compared to the similarity between the December and January probe readings. However, a consistent relationship between the readings is: (i) the probe moisture readings are generally higher than those from the samples, and (ii) the probe density values are generally less

than those from the samples.

Advantages of the neutron probe are being able to (i) take a larger number of readings within a single test hole, and (ii) to return to the same site later to repeat these readings. This probe may be useful for long term monitoring of the moisture and density conditions within a mine site.

INTRODUCTION

Since the last Coal Geoscience Forum (Calgary, 1987) there has been increased use and testing of both downhole and surface geophysical techniques. This paper highlights the results of some of this. Additional information will be presented at the Forum during poster sessions.

NEUTRON PROBE

TOOL DESCRIPTION AND DATA COLLECTION

The neutron probe, a downhole geophysical tool, is widely used in the soil sciences,to measure moisture content profiles through the near surface soil horizons (Black et al., 1968; Chanasyk, 1986 and 1988; Holmes, 1966). Its' use here is being tested to measure moisture content and density changes in sediment to depths of 10 m.

The probe used for this study is a Campbell Pacific Nuclear (CPN) model 501DR Depthprobe, capable of measuring bulk density and volumetric moisture of subsurface materials (CPN Corp., 1984). The unit is lightweight (approximately 20 kg), self contained and very portable. Density measurements are made from a 10 mCi Cesuim-137 gamma source and gamma detector. A 50 mCi Americium-241/B3 fast neutron source and thermal neutron detector is used for moisture readings. The probe is 57 cm long and has a diameter of 4.7 cm. Data is transmitted to the surface recording instrument through a multiconductor cable.

The surface electronic assembly records and displays the density and moisture data, and also acts as a shield for the probe upon retraction from the hole. The assembly comes equipped with a 10 m long cable and moveable cable stops to secure the probe at preselected depths. Longer cable lengths are also available.

The probe requires operation in a dry close-fitting cased hole. An undersized pilot hole was first drilled to the target depth using a Brat22 auger drilling rig. The rig then pushed a single length of casing down the undersized hole to ensure a tight fit between casing and formation. The casing was constructed of 5.1 cm diameter schedule 40 aluminum tubing. Prior to insertion in the hole the end of the casing was plugged and all joints were welded together to provide a sealed moisture free hole.

The tool assembly was positioned onto the casing head protruding 25 cm above ground surface. The probe was then lowered down the cased hole to the selected depth. Moisture and density readings were recorded after a counting time interval of 64 seconds. Measurements were taken at 15 cm depth intervals between surface and 4 m, and at 25 cm intervals below 4 m. Additional readings were taken at 5 cm intervals at particular zones of interest.

Coring was carried out at each site with the auger rig to obtain lithologic descriptions of the sediment and to collect continuous samples for gravimetric moisture content determination. The core hole and neutron probe holes were drilled about 6 m apart. Core samples were 6 cm in diameter and 15 cm long. The volume of the sample was calculated by carefully selecting and measuring the core in the field. Samples were then quickly bagged and sealed to prevent moisture loss and delivered to the laboratory for analysis within four days.

Gravimetric moisture content was determined in the Alberta Research Council soils laboratory following procedures (McKeague, 1978). The samples were first weighed to determine gross wet weight, then oven dried at 105° C for 48 hours to drive off moisture, and finally weighed again dry. Total volume, wet weight and dry weight measurements of each sample were used to calculate the density and moisture content by weight and volume.

DATA PRESENTATION

Two test sites were chosen. The geology at Site 1 consisted of about 25 m of till overlying bedrock; the top 10 m was instrumented. Site 3 consisted of a comparatively thin till cover (6.7 m) overlying sandstone: the top 7.5 m was instrumented. The lower 0.5 m of till at Site 3 consisted mainly of sandstone.

Both moisture (volume %) and wet density readings were collected at the two sites in December, 1988. The sites were revisited about one month later (January, 1989) and another set of data collected. The measurement depths were the same except a few additional readings about 5 cm apart were taken within zones of particular interest. The data sets from each site were compared to determine their reproducibility. These data were also compared to moisture and wet density data obtained from the samples collected.

The December and January data from Site 1 are similar (figure 1). Both the moisture and density decrease markedly in the upper 1.5 m. The principal differences between the curves are the result of the extra readings taken during the January, 1989 measurements. The correspondence between the two sets of data is demonstrated by the ratio of the December to January readings (figure 1).

The data from Site 3 exhibits a similar internal consistency (figure 2). The density readings are similar to those at Site 1 in that they decrease noticeably within the upper 1.5 m. The moisture however, does not show a similar trend. The spike in the January moisture data, about 6.2 m, is a correct reading as the probe was returned to that depth

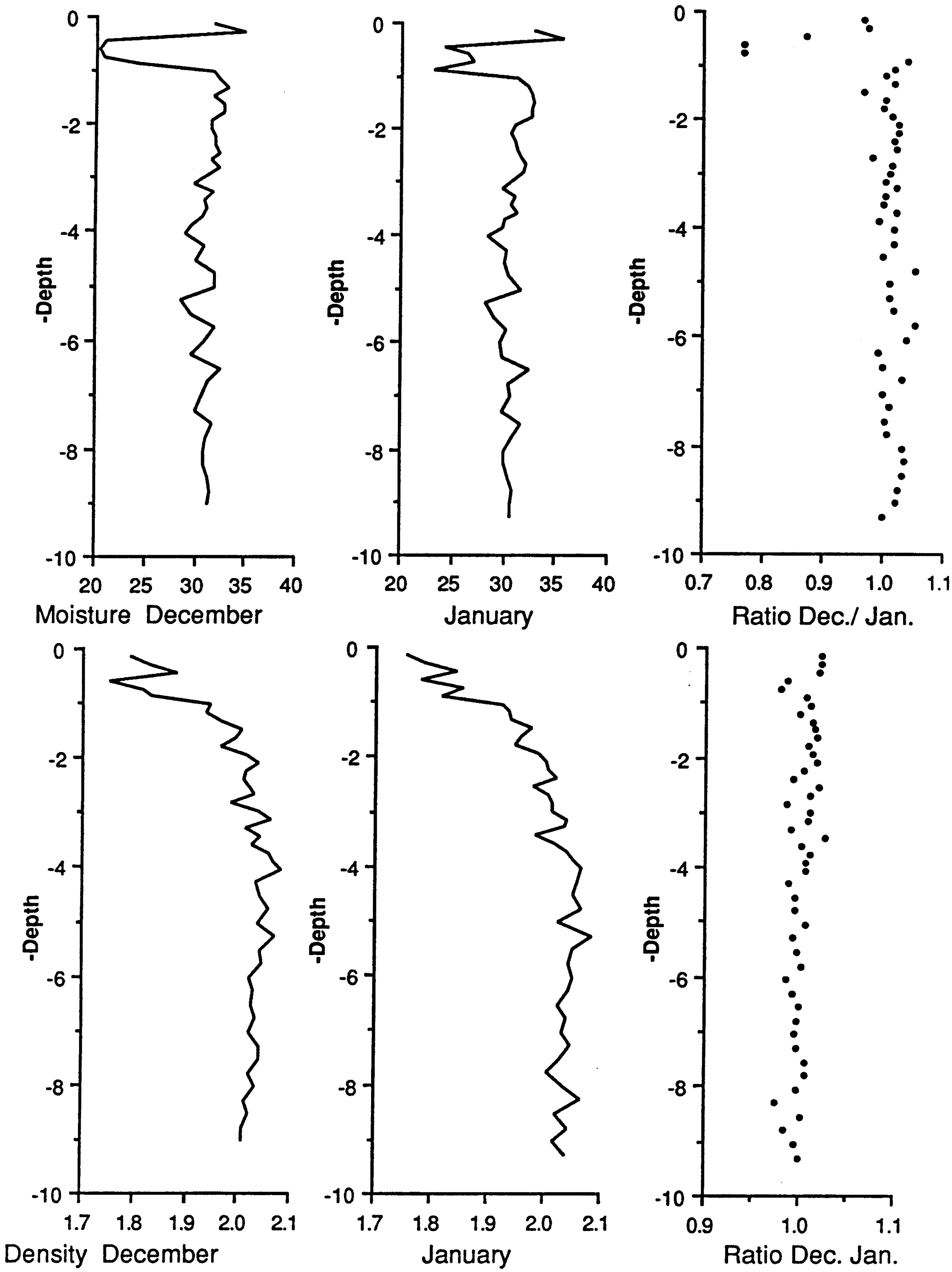

Figure 1. Site 1, comparison of December, 1988 and January 1989 data from neutron probe for volume percent moisture and wet density to demonstrate data reproducibility.

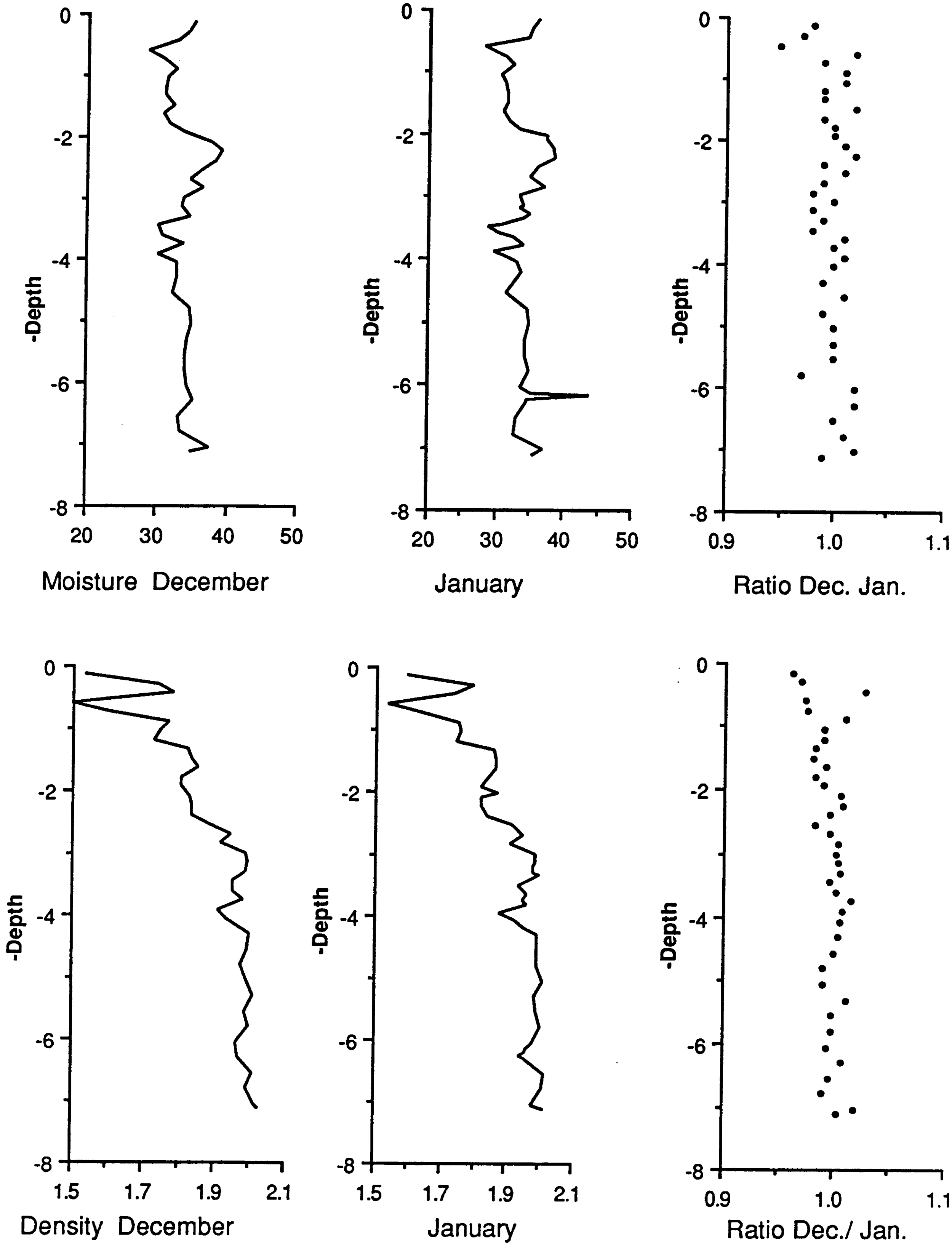

Figure 2. Site 3, comparison of December, 1988 and January 1989 data from neutron probe for volume percent moisture and wet density to demonstrate data reproducibility.

during the same visit and a similar high reading obtained. The absence from the December reading is because that exact depth was not sampled.

The December and January readings within each data type from each site show a strong reproducibility. Both the moisture ratios and the density ratios are generally within 0.1 of 1 (figure 1, 2, and table 1).

Table 1. Ratio of the December, 1988 to January 1989 moisture and density data for Site 1 and Site 3. The ratio is always close to one showing probe readings are reproducible.

	Mean	Standard Deviation	Minimum	Maximum
Site 1 Moisture	1.01	0.016	0.96	1.05
Site 1 Density	1.00	0.011	0.97	1.02
Site 3 Moisture	0.99	0.013	0.97	1.02
SIte 3 Density	0.99	0.009	0.98	1.02

Both the moisture and density data from the neutron probe was compared to that obtained from the samples. The correspondence between the two different types of data was relatively poor compared to similarity between the December and January probe readings. There was however, a consistent relationship between the readings which is best illustrated by the ratio of the neutron probe reading (average of the December and January readings) to the sample data from the closest corresponding depth (figure 3, table 2). The moisture readings from the probe are generally higher than those from the samples. The probe density are generally less than those from the samples.

DISCUSSION

This project has demonstrated that the tight fitting tubing necessary to use the neutron probe can be set to 10 m. Both the moisture (volume %) and wet density readings are reproducible over a period of at least 25 days.

The relatively poor correspondence between the probe and sample data is in part the result of the probe reading not covering the entire interval represented by the sample. The detection of the "spike" in the January moisture data from Site 3 illustrates this point. This spike was not detected during the December measurements because the probe was not positioned at the same depth as during the January reading.

The neutron probe offers the advantages of being able to take a larger number of readings within a single test hole and to be able to return to the same site later to repeat these readings. This probe may be useful for long term monitoring of the moisture conditions within a mine site. The changes in moisture content and density could be related to changes in the sediment conditions with time such as the change in

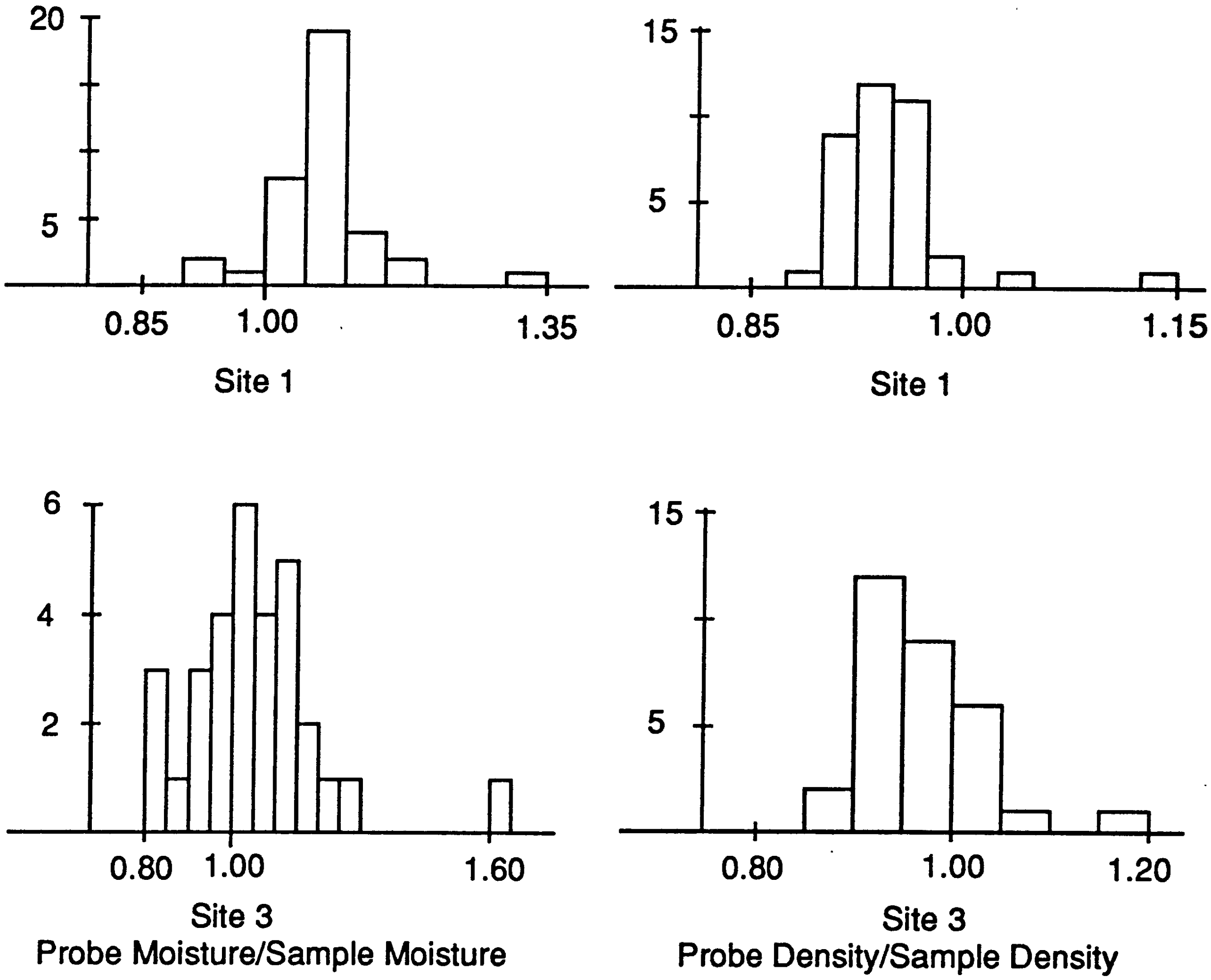

Figure 3. Ratios of probe to sample data. Probe data is average of the December and January readings.

water table resulting from mining.

SURFACE GEOPHYSICS

The Surface Geophysical Coal Research Project (1984-1986) demonstrated a number of useful applications of surface geophysical methods to prairie coal exploration and development (Green and others, 1988). The study also showed that geophysical data could be used to selectively position drill holes and provide a basis for the interpolation of subsurface conditions between drill holes. The relative cost between surface geophysics and drilling favoured consideration of using geophysical methods for exploration as target depth and/or area to be investigated increased.

A similar industry/government sponsored program has since been instituted to investigate the feasible use of surface geophysical techniques in more geologically complex foothills areas. Preliminary field results from the program are quite encouraging.

Table 2. Ratio of the probe data, averaged for December and January readings compared to the corresponding data from the samples.

	Mean	Standard Deviation	Range	Min.	Max.
Moisture					
Site 1 Probe					
(average Dec. & Jan.)	31.07	1.03	4.63	28.4	33.03
Site 1 Sample	28.90	1.50	8.74	24.6	33.61
Site 3 Probe					
(average)	34.01	2.71	14.9	29.0	43.9
SIte 3 Sample	32.51	4.04	20.3	22.7	43.1
Density					
Site 1 Probe					
(average Dec. & Jan.)	2.02	0.032	0.14	1.93	2.07
Site 1 Sample	2.15	0.092	0.57	1.72	2.29
Site 3 Probe					
(average)	1.93	0.072	0.28	1.73	2.02
SIte 3 Sample	1.99	0.100	0.44	1.71	2.15

The success of surface geophysical exploration requires that target strata exhibit discernible contrast in one or more physical properties in comparison to the properties of surrounding materials. The occurrence of such contrasts in the case of coal is amply illustrated by the suite of downhole geophysical logs (figure 4) from a typical prairie coal deposit. The electrical resistivity and bulk density contrasts for the coal are particularly distinctive at this location, as well as at most other areas for which data is available.

Two surface geophysical methods that to this date have been used most extensively for coal mapping purposes are direct current soundings and profiling, and reflection seismic profiling. Direct current methods exploit the electrical resistivity contrast of coal, while reflection seismic profiling relies on the acoustic impedance contrast, where acoustic impedance is the product of seismic compression wave velocity and bulk density.

Figure 5 shows recent current profile data from the Genesee Mine area. The data includes measurements of apparent resistivity to four different depths of exploration within the upper 30 metres of the subsurface. The data exhibits an increase in apparent resistivity with increasing depth of exploration, due to the presence of the coal seams. Between stations 230 and 310, the apparent resistivity is reduced and quite uniform, indicating the absence of all three seams at this location. Subcrops of the coal seams to either side of the washout are interpreted to occur at locations characterized by sudden changes in apparent resistivity levels. Drill holes were located on the basis of the direct current profile data. The washout was not part of the geologic model for

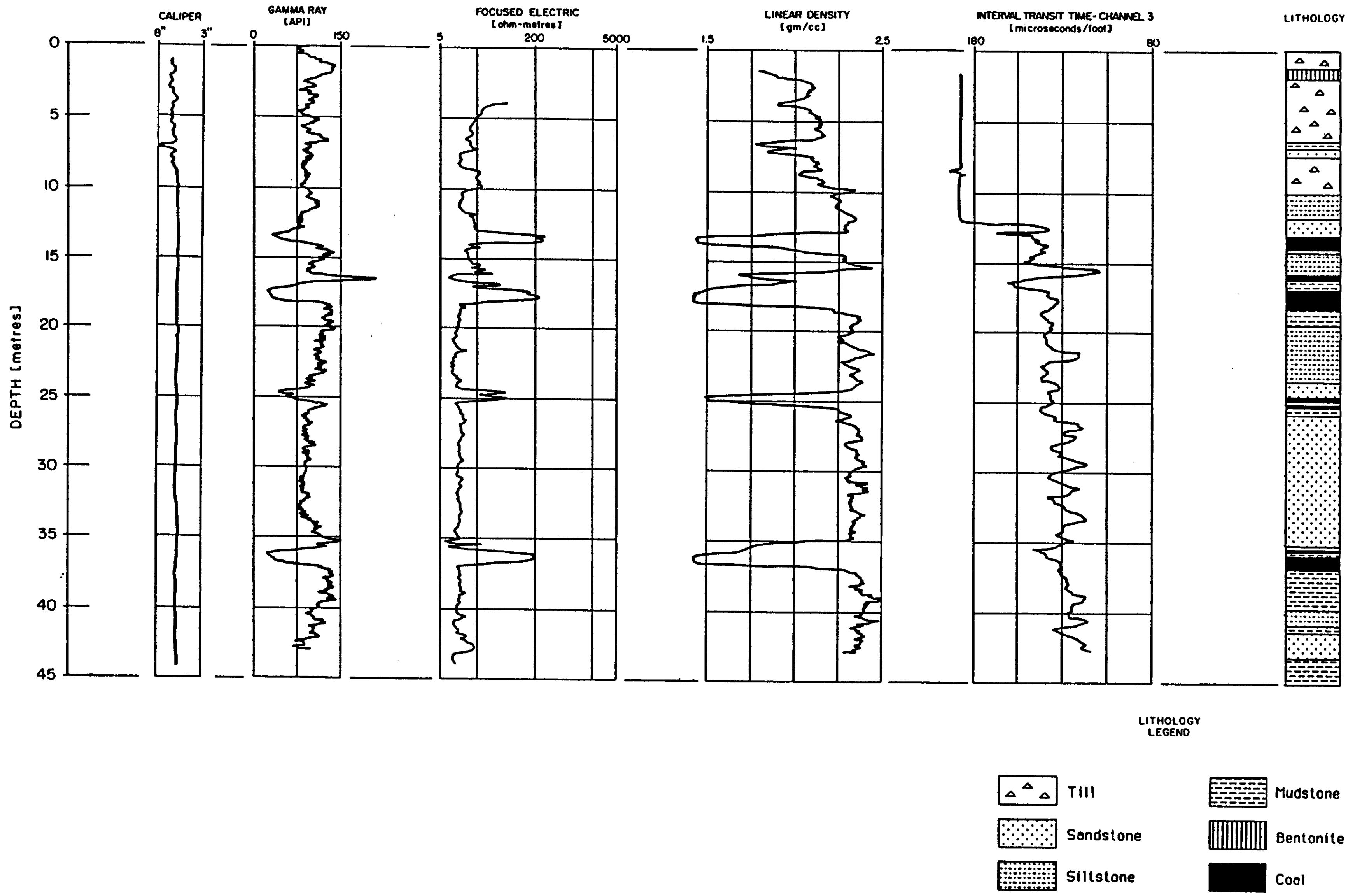

Figure 4. Typical suite of downhole geophysical logs (from Green et al. 1988).

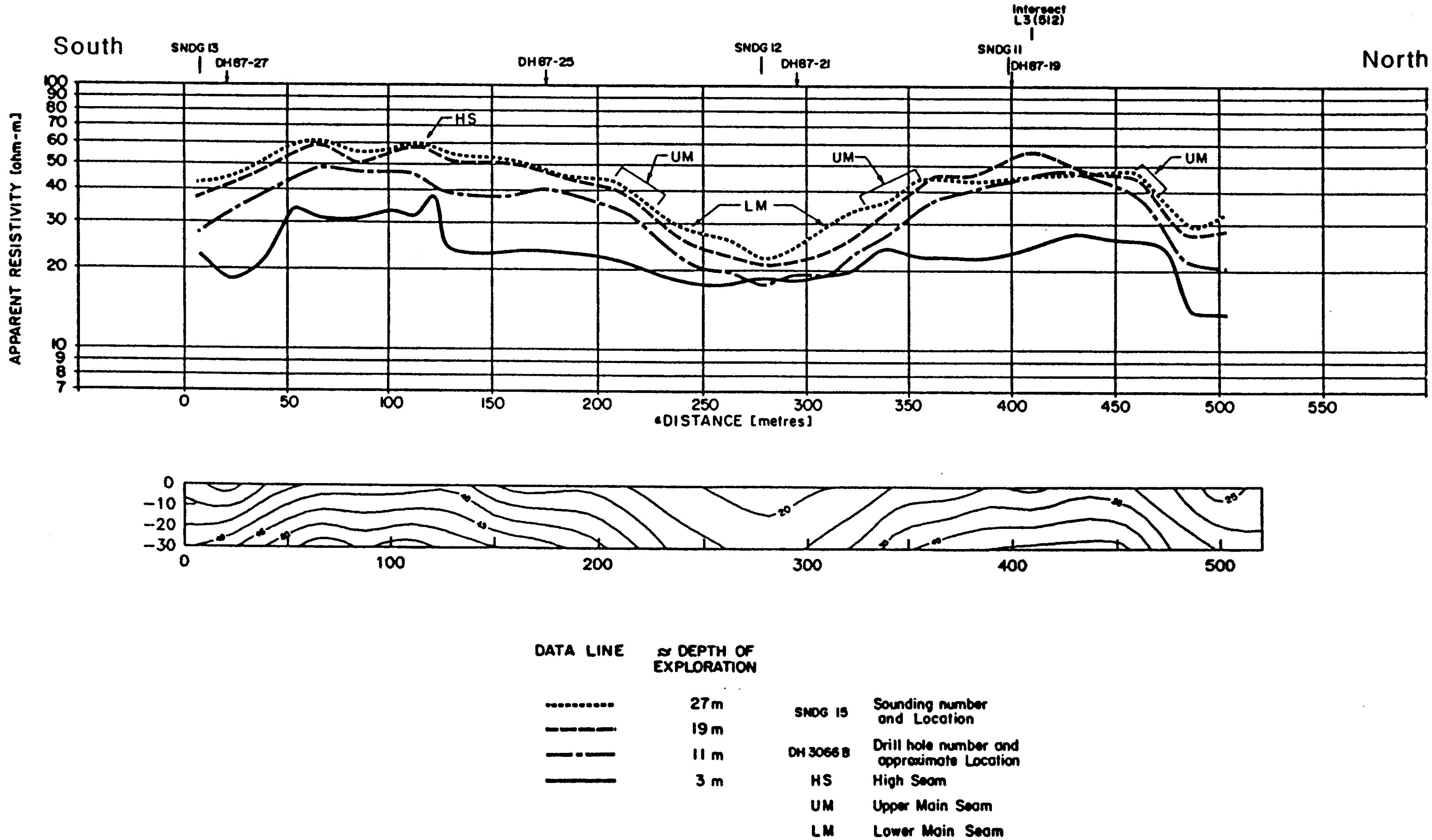

Figure 5. Direct current profile data (Genesee Mine area, Alberta) courtesy of Fording Coal Limited.

the area prior to the direct current survey.

The technique used to obtain direct current data has undergone a number of changes since initial tests of the method were performed for the surface Geophysical Coal Research Project. Data acquisition arrays now used are symmetrical with respect to current injection and potential measurement probes. The symmetry of the array allows data to be directly compared to direct current soundings data. It also increases the rate at which terrain can be covered in addition to providing data to an increased number of depths of exploration.

Figure 6 shows a portion of a reflection seismic profile from the Red Deer area of Alberta. Target strata are the lower Ardley coal seams buried by up to 200 m of overburden. These seams appear as the continuous reflecting horizon at about two way travel times of 200 milliseconds. The geologic model for the area predicts gently and uniformly dipping coal seams. The data in the vicinity of station 873 indicates that the depth to coal may vary substantially over short distances. No drilling has been undertaken to confirm this result.

The reflection seismic profiling method to delineate coal seams has undergone many changes since the first trials in 1983. The most significant improvement has been in data recording. A recording system having dynamic range and data storage capabilities that are large even in comparison to typical oil industry systems is now used on a routine basis for coal exploration and mine planning.

ACKNOWLEDGEMENTS

The authors wish to thank TransAlta Utilities Corporation and the Alberta Office of Coal Mine Research and Technology for their support.

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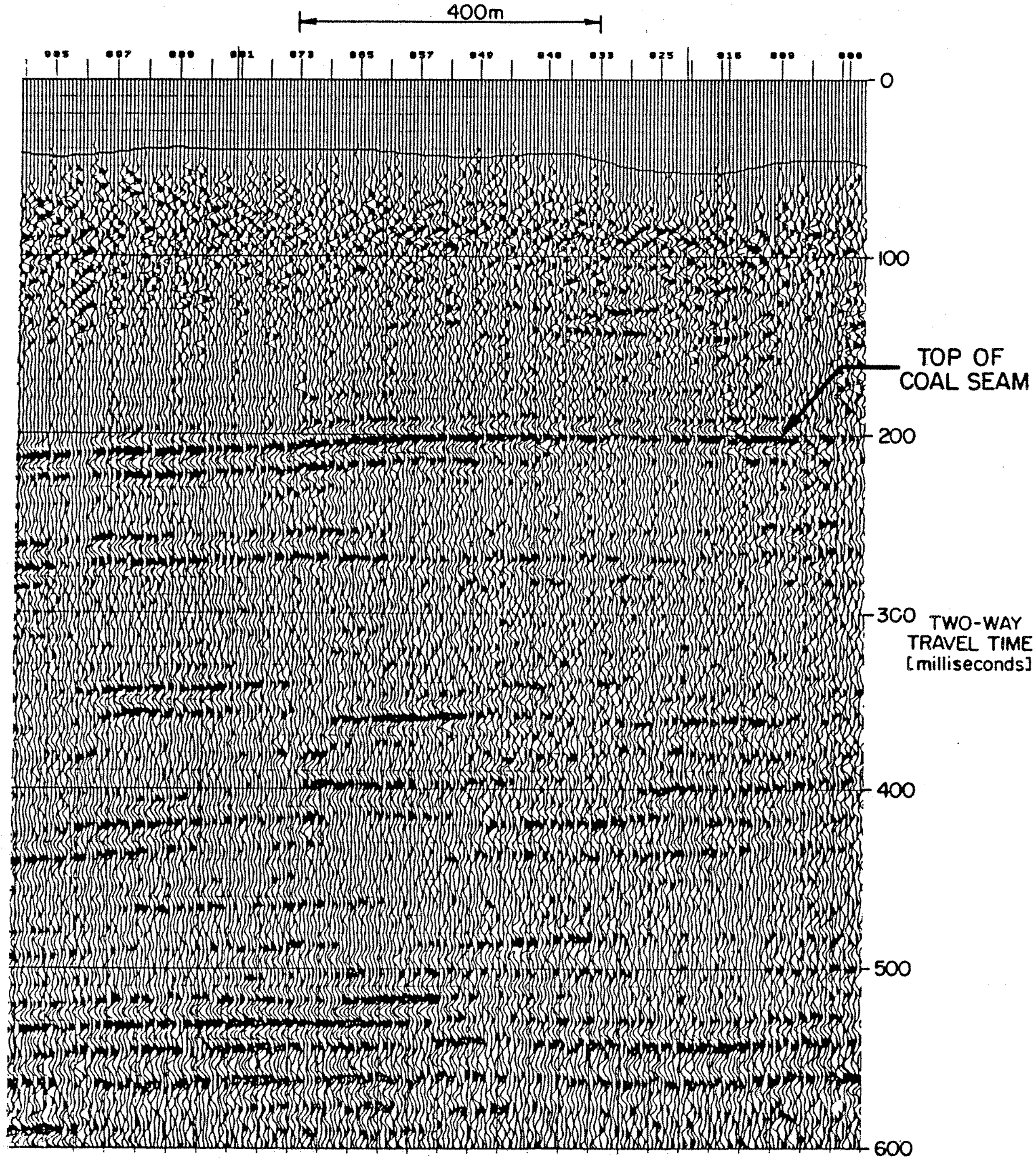

Figure 6. Reflection seismic profile (Red Deer area, Alberta) courtesy of TransAlta Utilities Corporation.

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THE PETROLOGY, MINERALOGY AND ELEMENTAL CONCENTRATIONS IN THE ESTEVAN COAL SEAM, BIENFAIT MINE, ESTEVAN, SASKATCHEWAN.

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A 5 metre thick section of lignite from the Estevan seam, Bienfait mine, southern Saskatchewan was analysed for petrographic mineral and elemental composition.

Huminite macerals are dominant (73%), with minor inertinite (11%) and liptinite (6.5%). Maceral assemblages and the banding of lithotypes indicate a shallow forest moor depositional environment.

Mineral matter content is 9.5%. Optical microscopy, SEM-EDX and XRD indicate the roof and floor rock are dominated by quartz, minor clays, feldspar and mica. The parting is kaolinite, with minor quartz. Coal mineralogy is dominated by carbonates, quartz, with minor clays and sulphates.

Most elements are inorganically bound to mineral matter. Organically-bound elements include B, Cl, Na, Sr. The elements Br, Ca,Co, Fe, Mo, W, U, show intermediate affinity. Statistical analyses correlate organically-bound elements to C, N, H, and huminite macerals, Mineral assemblages inferred for inorganically-bound elements are substantiated by observed mineralogy.

Some sulphate and carbonate may have been created during low temperature ashing for XRD, by organically bound elements (S, C) combining with ion-exchangeable cations (Ca, Na). The lignite is similar in composition to other lignites, except for high concentrations of Na, Ba, B, and Ca. These elements were likely introduced from groundwater carrying Na from surrounding bentonites, and from brines carrying elements from underlying formations abundant in Ca, Ba (Bearpaw Shales?) or the dissolution of deep, underlying Devonian Prairie evaporites.

COAL-MINING GEOLOGY OF THE COMOX AND EXTENSION FORMATIONS (UPPER CRETACEOUS) OF VANCOUVER ISLAND

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ABSTRACT

Recent detailed geological mapping and petrographic studies of coals from the Comox and Nanaimo Coalfields have yielded new insight into the complex coal-mining geology of the Santonian Comox Formation (at Comox) and the Campanian Extension Formation (at Nanaimo). Coal thickness, coal quality and mining conditions are strongly controlled by depositional environments.

The Comox No.1 and No.2 peats accumulated along the shores of coastal lagoons which were sheltered by barrier islands. Storms occasionally swept over the barriers, forming numerous thin dirt bands within the peats. Tidal inlets locally breached the barriers, feeding tidal deltas which formed clastic wedges within the lagoons. Resultant coal bed splits are readily traceable by drilling due to gradual thickening of the dirt bands which cause the splits. The coals are typically high in sulphur (2.2 to 5%) and have poor washability for sulphur, due to the fine-grained nature of the pyrite which constitutes the bulk of the sulphur.

The Comox No.4 peat accumulated in irregular alluvial plain backswamps between stream levees and steep-sided basement hills. Stream channels were stable, and splits in the No.4 coal are accordingly rare, while washouts marking avulsed stream channels are narrow. The No.4 coal grades laterally into stony coal and coaly dirt adjacent to basement hills. Rider coals and rooted zones above the No.4 coal locally cause roof instability. The coal is moderate in sulphur (0.9 to 1.6%) and variable in ash.

The Wellington peat (in the Extension Formation) accumulated in extensive coastal plain swamps, crossed by meandering streams. Stream channels migrated readily, producing wide belts of splits and washouts. Splits thicken rapidly, making their margins hard to map by drilling. The Wellington coal is low in sulphur (0.4 to 1.2%), but high in ash (up to 23%).

Marine-influenced coals such as the No.1 and No.2 are laterally persistent. Limits to workable deposits can be traced by widely-spaced drilling (one hole per 60 to 100 hectares). Nonmarine coals such as the No.4 and Wellington are less persistent. Drilling at any practicable spacing cannot disclose all floor rolls, channels and washouts. To roughly define the limits of workable deposits requires closely-spaced drilling (one hole per 10 to 20 hectares). Mining of these nonmarine coals requires geological input to compensate for the inadequacy of drilling as a means of predicting geological hazards in advance of mining.

UNDERGROUND GEOLOGICAL MAPPING OF A WORKING COLLIERY: AN EXAMPLE FROM VANCOUVER ISLAND

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ABSTRACT

Geological mapping of coal beds is often hampered by lack of outcrops. An inexpensive solution is detailed mapping in active or abandoned mine workings, projecting geological trends into areas of non-exposure. This paper is a case study of the Wellington coal bed in the Nanaimo Coalfield.

Clastic dikes, faults and folds in the roof, and stone rolls in the floor were mapped. Coal bed sections were measured on a 20 metre grid, to establish the internal stratigraphy of the coal. Maps were drawn showing minor roof and floor structures, roof-to-floor interval, net thickness of dirt bands, percentage of coal by thickness, and thickness and lithology of a major split-forming dirt band.

By overlaying these maps, relationships became clear between sedimentological and structural features of the coal bed. Gross thickness of the coal bed is controlled by topography of the floor, while splitting of the coal bed is related to a major fault which crosses the mine. Semilogarithic plots of parting thickness versus distance across the mine show how splitting accelerates once a critical minimum parting thickness has been attained, and provide a warning of impending splits. The limit of mineability due to splitting can be predicted 50 to 70 metres in advance, which gives sufficient warning to arrange a replacement face for continued coal production.

Sedimentological studies of this nature may not be possible in Rocky Mountain coals, whose internal fabric is largely tectonic. Detailed sedimentological mapping is more likely to be successful in the less-deformed coals of the Outer Foothills and Plains.

The cost of detailed sedimentological mapping is low. For a small one-unit room-and-pillar mine, one day's mapping per month, backed up by one day's office work, will suffice to keep up with mining. This level of geological attention costs only about 5 cents per mined tonne of coal.

CURRENT COAL GEOSCIENCE RESEARCH AT THE NOVA SCOTIA DEPARTMENT OF MINES AND ENERGY

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Nova Scotia's coal resources are situated on Cape Breton Island and the northern mainland. Economic coal deposits occur in the Pennsylvanian (late Carboniferous) Riversdale, Cumberland and Pictou Groups, all of continental origin, which were deposited in basins which formed mainly in response to strike-slip movement along major fault systems.

The Nova Scotia Department of Mines and Energy Coal Section conducts study of the Province's coalfields in order to obtain a better understanding of their geology and resource potential. The work carried out is multi-disciplinary and is often done in conjunction with other government agencies and industry with the results prepared as reports on various aspects of the Province's coalfields and as coalfield maps. This work aids the Province by promoting exploration and development of the resource and by ensuring its proper management and it provides the information base needed by industry interested in coal exploration.

Recent and current geoscience research at the Nova Scotia Department of Mines and Energy Coal Section includes: coalfield mapping, sedimentology and stratigraphy projects, seismic surveys, coal, peat, and oil shale resource evaluation projects, computerization of Nova Scotia coal geology data, studies on coal formation in relation to basin development, and studies on coalfield paleogeography and its effects on coal quality and mineability.

TRIPOD 3.0, A MICROCOMPUTER PROGRAM FOR COAL GEOLOGISTS

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The interactive program TRIPOD runs on IBM-compatible microcomputers. Structural, stratigraphic and positional data from drillholes and outcrops are displayed and analysed in ways that make the program extremely useful to coal geologists working in deformed terranes on both feasibility and development projects.

A database can be constructed either by using the keyboard to enter data into forms on the monitor or by reformatting existing data. Drillhole data include deviation, intersection and dip-metre readings. Outcrop data include coordinates, the exposed stratigraphic horizon, the structural unit and the orientations of up to ten kinds of planar and linear structure.

The user controls the program by operating a series of menus. Some menus control data selection which is carried out using criteria such as geographic position, stratigraphic horizon, structural unit and structural type. Other menus control the way the selected data will be displayed or analysed. Orientations can be used, for example, to prepare contoured pi diagrams and rose diagrams and to calculate orientation parameters such as fold axes and means. Data can be displayed on maps. They can also be used to establish domains in which folding can be considered cylindrical, and to construct cross-section plots showing drillhole and outcrop data projected parallel to fold axes onto planes of any orientation and position. Data can be rotated before being processed which enables, for example, composite plots from areas with several cylindrically folded domains to be produced. Each structural unit can be projected parallel to its own fold axis. The coordinates of points where a horizon is exposed or intersected can be retrieved and used as input to a contouring package.

The program is user-friendly and its operation can be learned in a day by people with little computing experience. It facilitates rapid and accurate collection and storage of data by interchangeable, easily supervized and inexperienced personnel. The program can be run in the field using portable lap-tops. Output can be generated on a variety of monitors, plotters and printers in a matter of minutes and in the hands of field personnel in time for feed-back to occur. The program saves the geologist from much tedious, time-consuming work and enables the use of sophisticated procedures that are difficult if not impossible to carry out graphically.

GLACIALLY THRUST BEDROCK: STYLES AND RAMIFICATIONS FOR COAL MINING

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Glaciotectonic deformation, of both the bedrock and drift, has been recognized in many areas of the Canadian plains. The two major products of this deformation are (1) the individual thrust mass, which may form a hill, and (2) rubble; a series of smaller thrust masses, usually forming hills, distributed downglacier from the source depression. Good three dimensional data exists for the former but are more limited for the latter. Common to both are: distinct deformation sites surrounded by undeformed sediment, large scale deformation downglacier of major changes in bedrock stratigraphy, low bedrock permeability and comparatively high bedding plane and joint permeability, disruption of the existing stratigraphy, and within each deformed mass high lateral and vertical material variability in sediment type.

The individual thrust masses contrast with rubble in that each is: a single thrust mass, composed essentially of local sediment, situated immediately downglacier of a depression, equal in volume to the depression (volume of rubble is less than depression), and the depth of the associated depression is generally more than for rubble terrain. The structure is characterized by: large scale folding and/or faulting, small scale crushing with or without compaction, a basal shear zone that disappears downglacier, upglacier dipping shear planes and, subvertical shear surfaces below basal zone.

Ramifications for both coal exploration and mining include: (i) access: glaciotectonic terrain, particularly rubble terrain, is typically rugged making access more difficult (some thrust hills are 200 m high). (ii) Core recovery: glacial deformation involving crushing without compaction can result in sediment that is comparatively loose and difficult to contain within a core barrel. (iii) Disruption of the stratigraphy: typified by removal or repetition of marker beds and/or coal. (iv) High sediment variably: typified by a lack of horizontal continuity of any sediment type and a resulting high variability in pedogenic and geotechnical soil types. (v) Highwall stability: deformed sediment is weaker than non deformed and shear planes both at base and within the thrust mass may dip into the pit depending on pit orientation. (vi) Drainage: pathways present in the undeformed sediment will be disrupted and sealed during deformation.

A PETROGRAPHIC INVESTIGATION OF THE VESTA COAL, ALBERTA PLAINS

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The Vesta Mine is an open-pit mine located within the Battle River coalfield. The coal occurs in the Horseshoe Canyon Formation, which constitutes the lower part of the Upper Cretaceous-Tertiary Edmonton Group. There are in excess of 1000 megatonnes of subbituminous coal present in the coalfield and the coal is being used for electric power generation.

Petrographic analysis of two sections of seam 3 indicates that the coal is low in mineral matter content, except for the upper part of section 1. In addition, the coal is rich in huminite, humocollinite and humotelinite being the dominant macerals. Humodetrinite is present in low to moderate amounts 2-20% (mmf) and is more abundant in section 1.

Liptinite consists mainly of sporinite with minor cutinite, resinite and liptodetrinite.

There is a considerable amount of inertinite (5-40%,mmf) present in the coal. Section 2 has higher inertinite than section 1, with the exception of an inertinite-rich interval in the latter section.

The high content of huminite points to a relatively reducing depositional environment. However, the high inertinite content of some intervals points to subaerial exposure of the peat surface, oxidation and/or fire.

Reflectance, measured on eu-ulminite B ranges from 0.39 to 0.52% Ro. This, along with proximate analysis data indicate that the coal is of subbituminous C-A rank.

Total sulfur is, generally, less than 0.6% and boron values range from 150 to 270 ppm. The high boron values indicate that the peat interacted with brackish waters, which may have invaded the normally fluvio-deltaic coal-forming environment during a marine transgression.

The Vesta Mine coal is petrologically similar to coal from the Drumheller area. However, the latter has a boron content of 70-120 ppm, indicating influence by semi-brackish waters.

DETERMINING COAL QUALITY PARAMETERS FROM DOWNHOLE GEOPHYSICAL LOGS

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The possibility of determining various coal quality parameters from conventional downhole geophysical logs has been of interest for several decades. There have been numerous publications on the topic, but none of the methods are in common use except in regional studies, because they have not been demonstrated to provide the high degree of accuracy and reliability that is required for mine planning and operations. This poster reviews the methods and their possible applications.

There are two basic approaches to evaluating coal quality parameters from conventional geophysical logs. The first involves empirically determining a relationship between a given coal quality parameter and the response of one of the logging tools. The second involves modelling the coal seam as a combination of pure coal, water, and mineral matter, and solving for those phases by using combinations of logs.

For all of the methods, the relationships are site-specific and if a high degree of accuracy is required, the constants for the equations must be carefully determined using local data. Difficulties include data handling problems, identification of bad data, the fundamental differences between in-situ geophysical measurements and laboratory analyses, and the quality and calibration of the geophysical logs.

VITRINITE REFLECTANCE BEYOND $\overline{R}$MAX AND $\overline{R}$M

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Vitrinite reflectance measurement values are dependent upon the orientation of the section being examined relative to the three principal reflectance axes and the values of these axes. The reflectance indicating surface (RIS) is an ellipsoidal model of the vitrinite reflectance measurements possible from a coal sample. RIS is analogous to the indicatrix used in optical petrology. Description of the RIS is the objective of vitrinite reflectance measurements. It has been shown that RIS shapes in the Canadian Cordillera range from uniaxial (-) through biaxial to uniaxial (+). The common measure, $\overline{R}$MAX (mean maximum reflectance), is valid only for uniaxial (-) RIS. In light of the full range of RIS shapes its use has now been recognized as being obsolete. Mean random reflectance ($\overline{R}$M) measurements provide a value which is related to the volume of the RIS but does not uniquely describe the RIS.

The reflectance crossplot procedure facilitates the determination of the three principal reflectance axes of the RIS from a standard particulate sample. Absolute reflectance axes values and descriptive measures derived from these values uniquely describe the RIS. The crossplot technique requires the collection of R'MIN (apparent minimum) in addition to the traditionally collected R'MAX (apparent maximum) reflectance for each measured vitrinite particle.

Increased reliance on each measurement in this new technique requires data quality control procedures. New microscope hardware and computer software have been developed to routinely assess the quality of the reflectance readings. Computer controlled stage rotation is used to collect reflectance values at discreet angular increments during analysis of a single vitrinite particle. The resultant reflectance ellipse (RIS cross-section) is fitted with a best fit ellipse using an eigen vector technique. R'MAX orientation and a goodness-of-fit measure are obtained for each particle measured by this technique. To be accepted as a valid measurement the standard deviation of the raw data residuals from the best-fit ellipse must be less than .05%. The preliminary cutoff value has been selected on the basis of visual inspection.

Traditional vitrinite reflectance measures, RMAX and RM, do not uniquely describe the reflectance characteristics of a coal. The reflectance crossplot procedure uniquely describes the RIS shape of a coal and requires little additional measurement effort. New analysis methods provide confidence intervals for each measured coal particle.

RISK QUALIFIED MAPS OF COAL QUALITY DATA.

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The poster presents the application of probability kriging to the analysis of selected coal quality parameters. Probability kriging is a mapping technique that allows for the compilation of maps of the local probability density distributions (PDF) for the studied variables. Using PDFs one may compile maps of quantiles or confidence intervals for a given variable. This new mapping technique is particularly useful in studying variables characterized by highly skewed distributions such as the total sulphur content in coal. The poster presents the algorithm for the probability kriging, basic products obtained from the kriging process and derivative products such as α and β probability maps. Probability kriging technique is also compared to the traditional mapping approaches such as an inverse distance to power method or trend surfaces.

THE ALBERTA GEOLOGICAL SURVEY COAL DATABASE

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A database of coal-related information is being developed at the Alberta Geological Survey. The coal database's prime function is to support the coal-related information requirements of the Alberta Geological Survey's Coal Geology Group as well as industry and government. It will also provide a centralized collection of coal data in a consistent format, regardless of the source of the data, while simultaneously archiving costly-to-obtain data.

The following broad data categories can be stored within the coal database: location information, geological picks, lithological descriptions, sample type, coal quality information, structural geology attributes, and sample storage information. Currently, the coal database contains data from the Alberta Geological Survey (AGS) and data from the Energy Resources Conservation Board (ERCB) coal hole file. Data from the AGS consists of geology picks from three coal-bearing units of the Alberta plains to a maximum depth of 400 m. These units are the Ardley coal zone, the Horseshoe Canyon Formation, and the Belly River Group (5,125 holes with 10,000 formation picks, 24,976 coal seam picks). Coal quality data is available for 205 holes. The majority of the coal-related information in the database is from the ERCB's coal hole file. The ERCB's data spans the foothills/mountains and plains coals (49,216 holes, 2,938 with coal quality information (proximate or ultimate analyses) as of March 1988).

The coal database is a relational database, implemented in Ingres database software on a VAX computer. One attraction of the relational data model is that it gives users the freedom to query the database with their current questions rather than being locked into fixed queries. For example, one person may request data related by company, another can request data related by date of sampling and log types. The coal database runs on both mainframe and micro-computers which allows portions of the database to be transferred into a user's office microcomputer.

This illustrates how the coal database can serve as an exploration, research, and information tool for the 1990's. The result of database queries, being an electronic medium, can be sent from office to office on the same day it is collected; the database speeds gathering data for a project's initiation; and the database forms a foundation to the true spatial databases and map analysis systems (i.e. geographic information systems) which will be a dominant geoscience tool in the 1990's.

THE USE OF TEMPERATURE LOGS IN COAL SEAM MAPPING

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New generation ultra high sensitivity temperature logging techniques can be used to obtain lithologic information in boreholes at logging speeds in excess of 6m/min shortly after drilling, before equilibrium temperatures have been attained between the borehole fluid and formation (transient temperature measurements). Both transient and equilibrium temperature measurements were carried out in fairly shallow holes at the Highvale Coal Mine, Alberta and were found to be useful in mapping coal seams. Permeable sandstone zones were easily detected on the transient temperature profiles obtained immediately after drilling. The high precision and high spatial resolution equilibrium temperature gradient data were used to determine accurately the depths and thicknesses of the coal seams and were successfully used in hole-to-hole correlation of coal seams between holes separated by up to 2.5 kilometres. The temperature gradient logs were also successfully used in discriminating the high electrical resistivity coal seams from the high electrical resistivity sandstone: the sandstone being characterized by low temperature gradients (thermal resistivity) whereas the coal seams are characterized by high temperature gradients. Ten to fifteen days were required after drilling for the borehole to come to equilibrium temperatures in order to obtain precise, reproducible equilibrium temperature measurements.

APPLICATION OF STATE-OF-THE-ART BOREHOLE GEOPHYSICAL TECHNIQUES TO COAL MINING PROBLEMS, HIGHVALE COAL MINE

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Borehole geophysics has been extensively used in coal exploration to provide valuable information for delineating and evaluating coal beds. Borehole geophysics may also be used for determining hydrogeological and geotechnical properties of the rocks above and below the coal. This information is important in planning coal mining operations. The Geological Survey of Canada conducted a number of borehole geophysical measurements with the state-of-the-art GSC R&D logging system, at the Highvale Coal Mine, Alberta during the summer of 1988. The parameters logged included:-

1) natural gamma ray spectral logs - total count, K, U, and Th;
2) spectral gamma gamma logs - density and spectral ratio;
3) induced polarization;
4) resistivity logs - single point resistance, lateral, symmetrical lateral, normal, micronormal resistivity;
5) self potential;
6) magnetic susceptibility and
7) temperature and temperature gradient logs.

Particularly useful logs were: natural gamma ray spectral logs for characterizing bentonitic layers; symmetrical lateral resistivity logs for resolving thin beds; temperature logs for mapping and hole-to-hole correlation of coal seams as well as detecting permeable zones using transient temperature profiles. The electrical resistivity, spectral gamma gamma, and natural gamma ray spectral logs may also be used in coal quality evaluation. Examples will be presented showing interpretations of these logs and their use in the determinations of geotechnical, hydrogeological and other parameters related to coal mining.

A GEOSCIENCE INFORMATION SYSTEM (GSIS) FOR ALBERTA COAL

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Management of information related to coal resources involves complex operations on tabular databases and mapping systems. Traditionally, Database Management Systems (DBMS) and Mapping Systems were two distinct software packages. Tasks often involved complex transfers of files between systems. Geographic Information Systems (GIS) allow for functional graphics and analysis integration within one package and using one database platform.

The system created during this study operates under the shell of pcARC/INFO. A menu system was created within the shell to allow for standard queries by geologists having no special training in computing systems. In addition to the above capabilities, the Coal Groups GeoScience Information System (GSIS) provides a graphic query window for the Alberta Geological Surveys coal database created in the INGRES relational database system residing on a VAX 780.

The GSIS system is designed on four levels of detail:

1. Level One - provincial scale maps (1:1 000 000) include general data on coal information for the province of Alberta;
2. Level Two - 1:250 000 scale maps include above information plus information on coal disposition, oil wells and mine permits;
3. Level Three - selected subareas of Level Two include oil well names and mine permits, in addition to the information available on Level Two are the 400 m development buffer zones for oil wells;
4. Level Four scale maps (1:5000) include information on coal quality, overburden and stratigraphy for the mine areas and also detailed contour maps of coal seam thickness.

On all levels, selected information may be linked (related) to the ARC coal database by a index key item. The system has the capability of producing high-quality color or black and white maps (at any scale) and or reports from any combination of available data, allowing for a hard copy record. It will also produce new maps from existing information, and allows for the interactive composition of custom thematic maps related to the display of geological information.

COAL QUALITY - INSIGHTS FOR THE COAL GEOLOGIST

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As coal geologists it is our goal to fully understand the utilization potential of a particular coal. This understanding starts by using many cheap and simple analyses of samples collected during exploration and development and continues with the use of a few elaborate and expensive tests on production coal samples. Often we tend to neglect the earlier data preferring to put more emphasis on the more sophisticated and limited data base collected from production samples. This paper presents ideas that may help coal geologists extract more information from exploration data.

Five general areas of an exploration coal quality data base will be investigated for their potential to provide additional insight into the coal's overall character.

1. Volatile Matter (VM) vs Ash. This data can provide information about rank, coal petrography, variation in coal petrography, ash chemistry and oxidation.

2. FSI vs Ash. This data can provide information about petrography and can be used to distinguish between high organic inert samples and oxidized samples.

3. Raw and Float Paired Data. Very often analyses are performed on a raw or head sample then on the same sample floated at a single S.G. This paired data can be presented in many different forms which help in understanding the way the coal is likely to perform in a wash plant.

4. Coal density is a simple concept but a difficult physical property to measure. A procedure is presented which is in part empirical and in part theoretical; this procedure is of use in reserve calculations.

5. Saleable metallurgical coal is about 10% mineral matter. The influence that this mineral matter has on metallurgical coal quality properties has probably been underestimated in the past. It may be possible to calculate an approximate mineral composition from an analysis of the oxides in the coal ash.

STABLE ISOTOPE, IRIDIUM AND PALYNOLOGICAL VARIATIONS OF ORGANIC MATTER FROM TWO WESTERN CANADIAN LOCATIONS SPANNING THE CRETACEOUS-TERTIARY BOUNDARY

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Anomalous iridium concentration has been correlated with a floral extinction event, Lerbekmo *et al.* (1987) in two Western Canadian locations, Red Deer Valley (SE1/4 sec. 11, T. 34, R. 22 w4 Mer.; GSC Locality Nos. C-119651 through 69) and Frenchman River Valley (sec. 31, T. 4, R. 18 w3 Mer.; GSC Locality Nos. C-135392 through 99). The anomalous iridium is presumed to have been emplaced as fallout created during some catastrophic event, either a volcanic eruption or an asteroid-cometary impact. Such catastrophic changes in the environment may also be recorded in the carbon and hydrogen isotope ratios of contemporaneous vegetation. In both locations the iridium "spike" occurs within or at the base of a coal seam. The two sites were sampled in 2 cm intervals for carbon and hydrogen isotope analysis. Carbon isotopic composition of the coal was uniform for sample intervals containing only a nominal iridium concentration; -24.25 ± 0.06‰ (Red Deer Valley), -23.73 ± 0.15‰ (Frenchman River Valley). Hydrogen isotopic composition of these same samples showed a greater variation, -169 ± 5.0‰ (Red Deer Valley), -168 ± 9.9‰ (Frenchman River Valley). Coal samples enriched in iridium exhibit 0.8 to 0.9‰ enrichment in $\delta^{13}C$ and a 12 to 14‰ enrichment in δD at both locations. No correlation of $\delta^{13}C$, δD or iridium concentration with ash content was observed for coal sampled in the Frenchman River Valley location. No correlation of $\delta^{13}C$ or δD with ash content is observed in Red Deer Valley coals either, but a strong correlation (R=0.96) is observed between wt% ash and iridium concentration. This correlation may indicate a reworking of sediments at Red Deer Valley through erosion and redeposition of iridium-enriched ash from the surrounding terrain. In both locations major floral variations determined by palynological profiles, appear to be represented by a shift in measured $\delta^{13}C$. Elemental ratios (H/C, C/N, C/S, O/C) were measured for Red Deer Valley coal samples. Ratios showed little variation over the entire suite. Coal samples enriched in iridium show a slight increase in C/N ratio and smaller S/Ash ratio. The co-variations in isotopic ratios of coal samples may represent a sympathetic response of the local flora to a climatic or environmental change.

Reference:

Lerbekmo, J.F., Sweet, A.R. and St.Louis, R.M., 1987. The relationship between the iridium anomaly and palynological floral events at three Cretaceous-Tertiary boundary localities in western Canada. Geological Society of America Bulletin, v.99, p.325-330.

LOGGING WHILE DRILLING (LWD)

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The LWD technologies concentrates on the increased ability of identifying the ground properties as the drilling process takes place. This immediate capability of identifying the underground conditions increases significantly the possibilities of using engineering procedures to increase the rate of success of the specific boreholes. Significant cost reduction related to rig, crew immobilization will occur as logging is dome parallel to the drilling process. Increased income for the drilling industry will be, buy itself an incentive for modernization of the rigs with the LWD products. The LWD modernization of the drilling rigs will produce significant increased possibilities of the investigation capabilities of better identification of in situ ground properties e.g. thin bed resolution, identification of ground properties not affected by the invasion of process related to specific drilling fluids, etc.

The actual stage of development of the LWD instruments refers to the construction of the first engineering prototype. The unit was tested for calibration purposes on an API reference borehole in Fort Worth, Texas, 1986.

The Retom LWD Logging System is an advanced, modular geophysical logging device designed for use in the geotechnical, civil and mining engineering fields. The system combines extremely hardy, but very sensitive gamma rays, resistivity (dual single point) and temperature sensors reporting to an 8 bit downhole computer to monitor accurately lithologic changes in a borehole as it is drilled (DDAU). Physically, the 2 sensor/computer modules are fitted to a custom modified mandrel mounted directly above the bit. This arrangement allows the sensors to analyse the host rock directly upon penetration. The data gathered therefore is more accurate as it is not affected by the filtrate invasion and washout effect suffered by conventional wireline logging equipment. The Retom LWD system also eliminates the need for costly and time consuming wireline logging in most cases allowing the operator greater rig efficiency and a commensurate economic saving. The system, unlike MWD systems built for oil and gas sectors, is designed to be economical and easy to operate and could host up to six logging sensors which are under different stages of development.