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MINERALOGY OF LOWER CRETACEOUS COALS FROM THE MOOSE RIVER BASIN, ONTARIO, AND MONKMAN, BRITISH COLUMBIA

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ABSTRACT

Lignite and bituminous coal were sampled, predominantly from drillholes, in the Moose River Basin (northern Ontario) and Monkman (North East Coal Block, British Columbia), respectively. Quartz, kaolinite, and subsidiary mixed-layer clays, siderite, gypsum, pyrite, gibbsite and illite are present in the Moose River Basin lignites. The Monkman coals contain a more diverse assemblage: quartz, kaolinite, ankerite, illite, calcite, siderite, pyrite, plagioclase feldspar, mica, galena and barite. The detrital minerals, *i.e.*, quartz, feldspar and certain clays, occur predominantly in mineral-rich partings, durain and, to a lesser extent, finely distributed throughout the vitrinite macerals. The early authigenic minerals, *i.e.*, kaolinite, some illite, pyrite, quartz, and certain carbonates, are commonly associated with fusinite. The distribution of late-stage authigenic or "cleat" minerals, such as ankerite or pyrite, bears no relationship to maceral or lithotype content of the coal. Many of the common minerals have a variety of modes of occurrence. For example, pyrite in the Moose River Basin replaced organic structures, infilled pore spaces, coated organic surfaces, and infilled later stage cracks. The history of mineral formation in the coals is complex and seems to be controlled primarily by source-rock lithology, degree of weathering, nature of the coal-forming environment, hydrology, conditions of burial, and degree of coalification.

Keywords: Lower Cretaceous, lignite, bituminous coal, detrital minerals, authigenic minerals, Ontario, British Columbia.

SOMMAIRE

Des séquences de lignite et de charbon bitumineux ont été échantillonnées, principalement à partir de forages, dans le bassin de la rivière Moose (nord de l'Ontario), ainsi qu'à Monkman (terrain houiller du Nord-Est, Colombie-Britannique). Quartz, kaolinite et argiles interstratifiées accessoires, sidérite, gypse, pyrite, gibbsite et illite sont présents dans les lignites du bassin de la rivière Moose. Les charbons de Monkman contiennent un assemblage plus diversifié: quartz, kaolinite, ankérite, illite, calcite, sidérite, pyrite, plagioclase, mica, galène et baryte. Les minéraux détritiques, c'est-à-dire quartz, feldspath et certaines argiles, sont localisés surtout le long de plans de séparation et dans le durain; à un degré moindre, ils sont finement dispersés parmi les macéraux de la vitrinite. Les minéraux authigéniques précoces (kaolinite, une partie de l'illite, pyrite, quartz et certains carbonates) sont couramment associés à la fusinite. La distribution des minéraux authigéniques et de ceux qui définissent le clivage, tels que l'ankérite et la pyrite, ne dépend pas du contenu de macéraux et des lithotypes du charbon. Certains minéraux communs ont plusieurs origines. Par exemple, dans le bassin de la rivière Moose, la pyrite a remplacé des structures organiques, rempli les pores, recouvert la surface de matériaux organiques, et rempli des fissures d'origine tardive. La formation des minéraux dans les charbons est complexe, et semble être régie par la lithologie des roches hôtes, l'intensité du lessivage, le milieu de formation du charbon, l'hydrologie du milieu, la profondeur de l'enfouissement, et le degré de carbonisation.

(Traduit par la Rédaction)

Mots-clés: Crétacé inférieur, lignite, charbon bitumineux, minéraux détritiques, minéraux authigènes, Ontario, Colombie-Britannique.

INTRODUCTION

Coal, although primarily organic in composition, contains a significant quantity of inorganic matter that may be present as minerals and trace elements. The minerals most commonly found in coals are clay minerals, quartz, carbonates (such as calcite, ankerite and siderite), sulfides (including pyrite and marcasite) and, to a lesser extent, phosphates, silicates (such as feldspars), sulfates and salts (Mackowsky 1982, Gluskoter 1977). In addition, a rapidly increasing number of accessory minerals has recently been identified in coal; for example, Finkelman (1980) listed over 125 minerals, which include a wide variety of silicates, sulfides, carbonates, oxides and rare-earth-bearing minerals. Some of the common and accessory phases present problems in the utilization of coal. Many of these problems may be addressed by understanding the associations, modes of occurrence and origins of minerals in coal.

Studies of the mineral matter in Canadian coals (Williams & Ross 1979, Goodarzi *et al.* 1985) have concentrated on specific aspects of coal mineralogy and are generally restricted to identification of the mineral phases. In this study, we examine the minerals present in Cretaceous coals from the Moose River Basin in northern Ontario and the Peace River Basin in northeastern British Columbia, their mode of occurrence, and history of formation. The major- and trace-element chemistry of these coals has been discussed by Van der Flier-Keller & Fyfe (1987).

The generally accepted classification of minerals in coal differentiates between authigenic and detrital phases. On the basis of timing of mineral formation, authigenic phases can be further subdivided (Davis *et al.* 1984) into minerals formed during sedimentation of the peat, after deposition or by diagenetic alteration of pre-existing minerals, and epigenetically such as cleat infills.

Minerals formed in each of these groups may be distinguished using characteristics related to conditions and timing of formation. These include: nature of associated minerals and macerals, mode of occurrence of the mineral, its geochemistry, textural characteristics such as rounding and crystal form, and 'paragenetic' associations. For example, the detrital minerals, which are generally rounded to subangular, occur either associated in mineral-rich bands with intermixed macerals, which in some cases are broken and rounded, or isolated within the organic matter. Syngenetic authigenic minerals, formed at an early stage in the coalification process, exhibit crystal faces, are intimately intergrown with other syngenetic minerals, and generally occur in cell cavities (lumens) within the organic material. Epigenetic minerals occur in distinct fractures, cleats, or on slickenside surfaces in the coal. These minerals may exhibit crystal faces, and their occurrence generally bears no relationship to the inherent structure in the coal.

Location and General Geology

The Moose River Basin deposit is located in the James Bay Lowlands, Cochrane District, of northern Ontario between 51° and 51° 30′N and 82° and 83° W (Fig. 1). The basin is fault-bounded to the south and consists of a gently dipping succession of strata ranging from Devonian to Cretaceous in age. The coal-bearing succession is Middle to Late Albian in age (Norris 1982) and consists of largely unconsolidated kaolinitic gravels and sands, silt, clay and lignite, deposited in alluvial channel and floodplain settings respectively (Try *et al.* 1984). The succession is thickest in the northeast and southeast of the basin, where accumulation occurred in structural lows adjacent to Precambrian highs.

The Monkman coal deposit is located toward the south of the Peace River or North East Coal Block, in northeastern British Columbia (Fig. 1). The area is structurally complex, and the coal-bearing Gates Formation is folded and thrust-faulted. This formation is of early Albian age (Stott 1982) and consists of 270 meters of cyclically interbedded bituminous coal, claystone, siltstone, sandstone and lesser conglomerate. The coal is generally underlain and overlain by carbonaceous claystone, with coarser clastics occurring towards the base of each cycle. Up to 12 seams are present, and are thickest and most extensive at the base of the section, and thinner and more numerous toward the top. The sediments were deposited in floodplain or interdistributary, and channel settings, in an alluvial or upper-delta plain environment (Carmichael 1983, Van der Flier 1985).

Field and laboratory methods

Analyses were carried out on 79 coal and sediment samples from the Moose River Basin. The samples were derived predominantly from two drillholes and the recently exposed channel banks of the Adam Creek dam outflow, located in the southeast of the basin. Additional samples were collected from the Onakawana test-pit site in the northeast of the basin. In the Monkman area, 40 coal and sediment samples taken from seven drillholes located in the most northerly proposed pit site (the Honeymoon pit) were analyzed. In both areas all the coal seams were extensively sampled, and sediments were collected throughout the sequences. The samples were transported to the laboratory in sealed plastic bags.

Whole-sample mineralogy was determined using a Philips Norelco or Rigaku X-ray diffractometer. Samples were air-dried and crushed using a mortar and pestle, and subsequently analyzed as dry cavity-mounts. Qualitative mineral abundances were determined from the X-ray spectra. In order to determine the location of the minerals in the coal and their association with the organic components, reflected-light microscopy and scanning electron microscopy (SEM) coupled with energy-dispersion X-ray analysis (EDX) were used. An ISI DS-130 SEM, run at 30 kV and 25 mm working distance, utilized the wide range of magnifications available. The EDX analyzer (PGT system III), which is capable of detecting all elements with an atomic number of 11 and greater at concentrations above 100 ppm, was used primarily to list component elements in mineral grains. Relative peak-heights were used to estimate the relative amounts of the elements present, thus allowing mineral grains to be identified. The results were substantiated in a number of test cases by optical microscopy or microprobe analysis. In addition to analyzing isolated grains or locations, element windows were run over larger areas to establish relative distributions of various elements. In this way elements associated with and homogenously distributed in the organic matter were identified.

SEM samples were prepared from thin sections, grain mounts, polished blocks, and broken sample

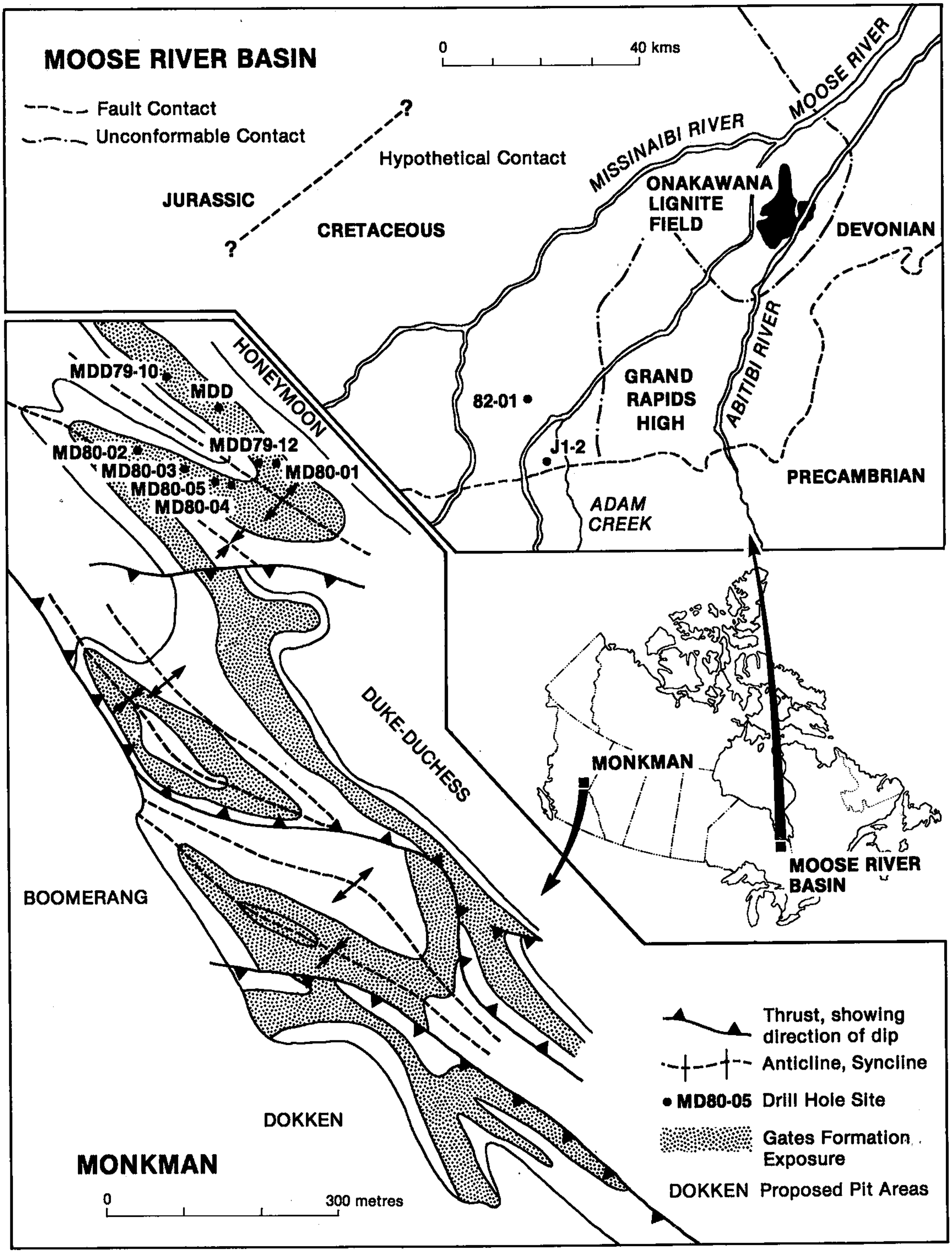

FIG. 1. Location and general geology of the Moose River Basin and Monkman coal deposits (maps modified from Van der Flier 1985, and Schiller *et al.* 1983, respectively).

TABLE 1. ABUNDANCE AND MODE OF OCCURRENCE OF MINERALS IN THE MOOSE RIVER BASIN LIGNITE

	Abundance	Suggested Mode(s) of Occurrence
Quartz	P - ND	detrital infilling cell hollows
Kaolinite	P - ND	detrital authigenic (syngenetic)
Illite	T - ND	detrital
Mica	ND (T)	detrital
Mixed-layer clay	T - ND	detrital
Pyrite	T - ND	infilling cell hollows replacing cell walls infilling cracks
Siderite	ND (T)	
Gypsum	ND (T)	recent weathering of pyrite
Gibbsite	ND (T)	authigenic, coating quartz grain surface

P : Major component, T : Trace component, ND : Not detected, () : Mineral present at this level of abundance in only one sample.

TABLE 2. ABUNDANCE AND MODE(S) OF OCCURRENCE OF MINERALS IN THE MONKMAN COAL

	Abundance	Suggested Mode(s) of Occurrence
Quartz	P - T (ND)	detrital infilling cell hollows
Kaolinite	T - ND	infilling cell hollows authigenic/associated with inertodetrinite
Illite	T - ND	detrital infilling cell hollows
Mica	ND (T)	detrital?
Mixed-layer clay	T - ND	
Pyrite	T - ND	framboids coalescing euhedral crystals infilling cell hollows infilling microscopic shrinkage cracks in macerals
Siderite	T - ND	
Ankerite	T - ND	infilling cell hollows cleat infillings
Calcite	T - ND	infilling cell hollows
Feldspar	T - ND	detrital
Galena	T - ND	associated with pyrite
Barite	T - ND	
Sphalerite	ND (T)	infilling cell hollows associated with calcite and phosphorus authigenic crystals in coal and associated sediments

Symbols: As in Table 1.

fragments. These were fixed to aluminum-stud sample holders using silver paint, and gold- or carbon-coated prior to analysis. Surface analyses of 2 lignite and 4 bituminous coal samples were run using X-ray photoelectron spectroscopy (ESCA).

Results

The results of XRD analysis of the Moose River Basin and Monkman coal samples are summarized in Tables 1 and 2, respectively.

Moose River Basin

The Moose River Basin lignites are generally clean; isolated samples show no traces of mineral matter. Approximately 80% of the samples contain quartz and kaolinite as major or trace components scattered throughout the organic fraction. Quantities vary depending on the detrital input (proximity to a major channel with splays), and the amount of chemical precipitation. The lignites can be differentiated from adjacent sediments in that the accessory clays are restricted to trace amounts of mixed-layer clays with no (or trace) illite. Kaolinite varies from absent to a major component and occurs in the clastic horizons in the lignite as well as associated with the organic material. Gypsum and pyrite occur in less than half of the samples analyzed. High values of the Al:Si ratio, on the order of 8:1, were determined by ESCA in some lignite samples, indicating the possible presence of gibbsite. There is no definite relationship between stratigraphic level of the samples and their mineral content.

Quartz and kaolinite are the major constituents in the majority of the associated sediment samples. Trace amounts of illite and some undifferentiated mixed-layer clays are also present. Trace occurrences of K-feldspar, hematite, gypsum, dolomite, ilmenite, calcite and galena were recorded in 50% of the samples. Siderite, pyrite and goethite were observed as major components in 8% of the samples. Millerite was detected in one sample, AC-10-82. The iron sulfide in isolated samples is in the form of marcasite, and gypsum is commonly associated with both marcasite and pyrite. Traces of gibbsite were detected by XRD in only one sample (AC-18-82).

Monkman

In the Monkman coal samples, quartz, kaolinite and ankerite are the most common and most abundant minerals. Illite, calcite, siderite, pyrite and plagioclase feldspar are also common and occur as trace constituents in 70% to 25% of the samples. Mica was detected in only one sample, 1296, as a trace constituent. Other minerals identified in the coals are galena (trace constituent in approximately 10% of the samples) and barite (trace constituent in approximately 20% of the samples). In the clay-rich horizons in the Monkman coals, zircon also is found. A relationship between stratigraphic level and mineral distribution is exhibited only by pyrite and siderite. In certain drillholes (*e.g.*, MDD 80-01) siderite occurs only in the upper seams (B3 and B5), whereas pyrite is restricted to the lowest seam (B1).

In the sediments associated with the Monkman coals, quartz is present in most samples as a major constituent. Illite is a common minor to trace phase. Two types have been identified, namely mica and a less-well-ordered illite phase. The illite, which occurs

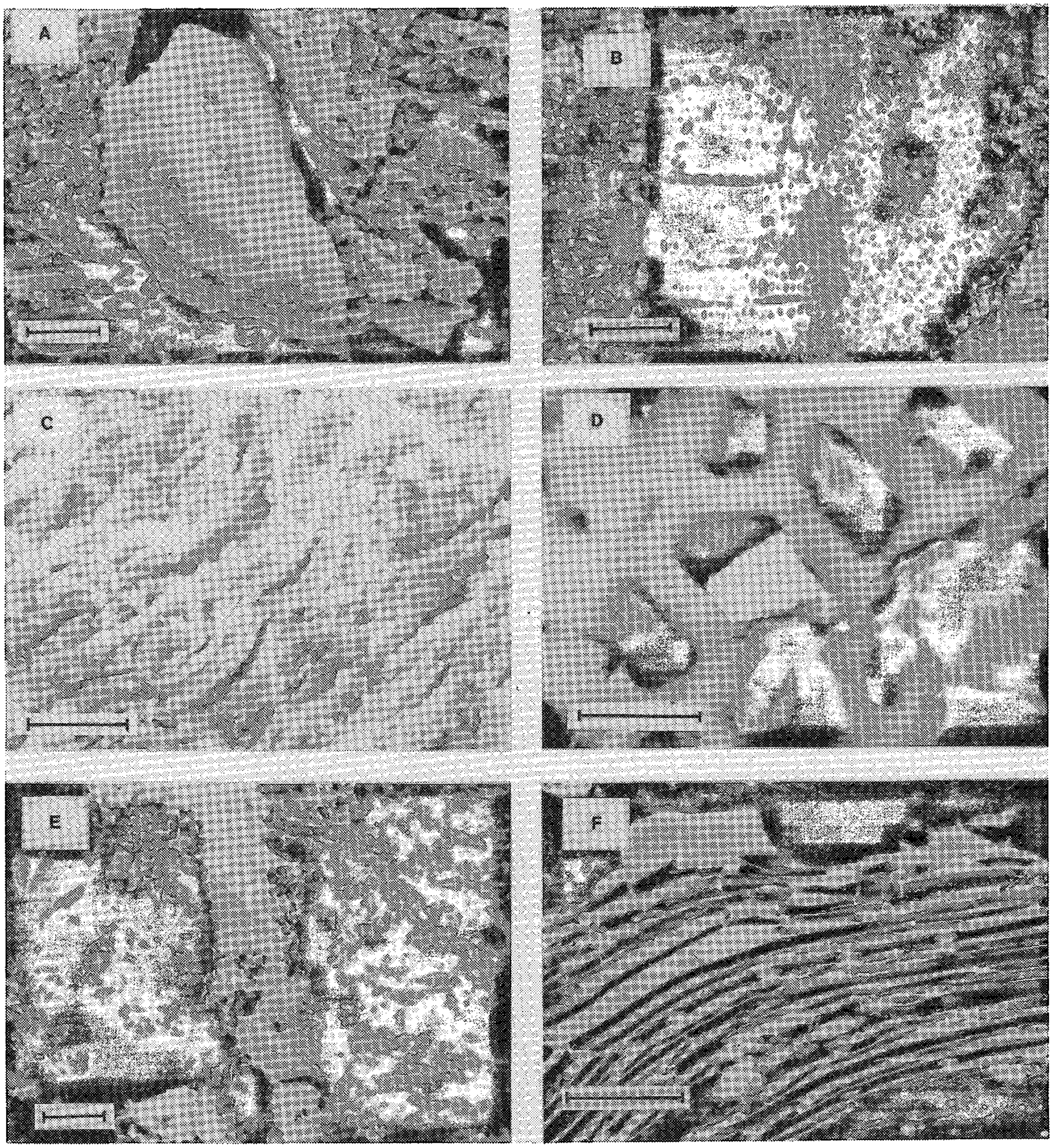

FIG. 2. A. SEM micrograph of a detrital quartz grain in Moose River Basin lignite (scale bar 40 μm). B. Photomicrograph of quartz (grey) infill of cell porosity in fusinite, Moose River Basin (scale bar 2.0 mm). C. SEM micrograph showing total replacement of organic matter by pyrite, Moose River Basin lignite (scale bar 40 μm). D. SEM micrograph showing a pyrite crystal that fills a cell lumen, Moose River Basin lignite (scale bar 20 μm). E. SEM micrograph showing pyrite infill of a crack, Moose River Basin lignite (scale bar 40 μm). F. SEM micrograph showing illite (light grey) and pyrite (bright) infilling of cell lumens in fusinite, Monkman (scale bar 40 μm). Figures 2C, D and E from Brown *et al.* (1986).

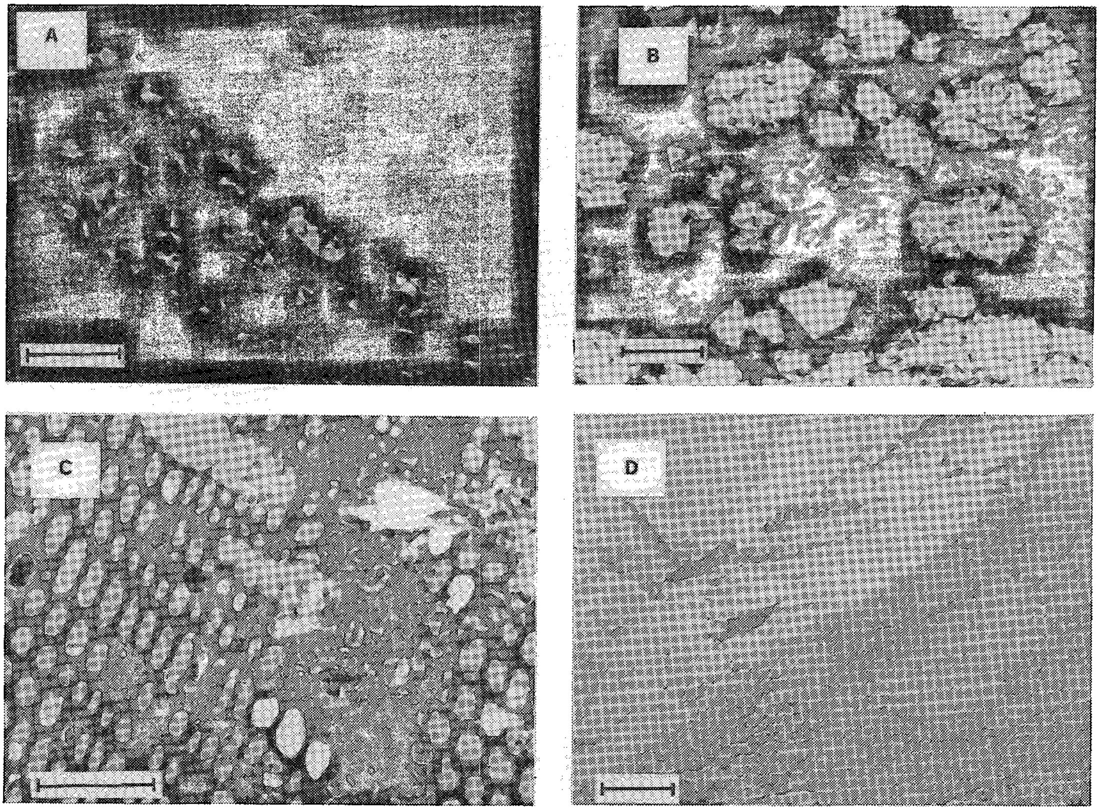

FIG. 3. A. SEM micrograph of a kaolinite-rich mineral band in vitrinite, Monkman (scale bar 80 μm). B. Photomicrograph showing single and coalesced euhedral pyrite crystals in fusinite, Monkman (scale bar 0.5 mm). C. SEM micrograph of fusinite showing ankerite (grey) and pyrite (bright) infilling of cell lumens, Monkman (scale bar 40 μm). D. SEM micrograph showing epigenetic ankerite as crack filling, Monkman (scale bar 80 μm).

in most samples, is likely the 1*Md* variety, which is the most common illite polymorph (Levinson 1955, Velde & Hower 1963). The mica was found in approximately 25% of the sediment samples as a minor or trace constituent. Kaolinite ranges from a trace constituent to absent in some samples. Mixed-layer clays were detected by XRD as a trace component in approximately 62% of the samples. Ankerite, siderite, pyrite, calcite, plagioclase feldspar and galena occur either as major constituents (*e.g.*, ankerite in S3-6) or as minor components in up to 90% of the samples.

MODES OF OCCURRENCE AND ORIGIN OF MINERALS IN THE COAL

Summaries of the mineral occurrences in the Moose River Basin and Monkman coals, as determined using SEM-EDX and optical microscopy, are given in Tables 1 and 2, respectively.

Moose River Basin

Several different modes of occurrence were noted for all of the common minerals. For example, in the Moose River Basin lignites, quartz occurs predominantly as detrital grains (Fig. 2A), but in an isolated sample of laminated fusinitic coal and sandstone (AC-12-82), cell infillings of quartz were observed (Fig. 2B). The detrital quartz is commonly associated with clay minerals (kaolinite and mica), normally in mineral-rich bands in the coal, but these minerals are also found isolated in the organic material.

Mica generally occurs associated with the detrital quartz, whereas the illite and kaolinite may be poorly formed and more commonly are intimately associated with the organic material. Kaolinite, which is the most common clay mineral in the Moose River Basin lignites, occurs associated with detrital quartz in clastic horizons and is also associated with the organic matter.

In the pyrite-rich lignite or wood samples, pyrite may replace the whole wood structure (Fig. 2C), infill the pore spaces (Fig. 2D), or occur as crystal coatings on organic surfaces or in cracks (Fig. 2E). Sulfides are also present as nodules, *e.g.*, in AC-10-82. Gypsum and pyrite are commonly associated, indicating oxidation of the pyrite.

Monkman

Minerals in the Monkman coal have a wide range of occurrences. Quartz is present both as detrital rounded grains in the mineral-rich areas and as cell fillings. Similar modes of occurrence are noted for the clay minerals. Figure 2F shows authigenic illite as a cell filling, and Figure 3A provides an example of kaolinite associated with inertodetrinite. The most common modes of occurrence of pyrite are as coalescing euhedral crystals (Fig. 3B) and as framboids. These are both commonly associated with the inertinite macerals and coaly claystones; however, crystals (in the same sample) are larger when associated with organic matter. Pyrite, precipitated in cell lumens (Fig. 3C) and microfissures caused by shrinkage in the macerals, was also observed. The carbonates infill fusinite cell lumens (Fig. 3C) and diagenetic cracks (Fig. 3D).

MACERAL-MINERAL ASSOCIATIONS

Moose River Basin

In the Moose River Basin the soily lignite contains the majority of the mineral matter. The associated organic material is commonly comminuted, which indicates the important influence of flowing water on its formation. The woody (xylite) and fusinitic (fusain) materials are generally very clean but contain isolated detrital quartz grains and clay minerals. Cell walls are in rare cases altered to pyrite, and pyrite also occasionally infills cell lumens.

Monkman

In the Monkman coals, apart from the mineral-rich bands and lenses that are occasionally associated with the coal, fusinite contains the highest proportion of mineral matter. Partings in the clean coals also contain a significant amount of mineral matter; however, these bands are relatively uncommon. Vitrinite contains few mineral particles and they are in general detrital as opposed to the authigenic type found in fusinite.

Minerals found in the fusinites occur mostly as infillings of cell hollows. Illite, quartz and pyrite are the most common, whereas ankerite and kaolinite are less common. Sphalerite was found in S14-1 (sandy coal) as infillings of some cell lumens, associated with a phosphorus-rich phase and calcite. In S2-5 (sandy coal) galena is associated with pyrite, where it occurs as overgrowths on illite cell fills and in the maceral in general. Illite and silica, and calcite to a lesser extent, are the primary authigenic minerals that infill the cell hollows in most of the fusinites examined; pyrite is observed as overgrowths on these phases (*e.g.*, Fig. 3C).

Vitrinite is clean compared to fusinite and contains rare isolated mineral grains scattered throughout the maceral. Occasional concentration of the minerals in bands parallel to the bedding of the coal, for example in S1-4 (Fig. 3A), may indicate deposition of a greater concentration of minerals at that time, or the breakup and compression of a band of vitrinite (precursor), concentrating the small amounts of authigenic and detrital mineral matter present. The minerals occasionally appear to be broken pore-fillings, as their shapes match those found in crushed fusinite grains. These bands were not observed to be continuous. Minerals found in the vitrinite are dominantly kaolinite and silica; however, occasional pyrite, illite, feldspar, and mica grains were also observed. The minerals are typically smaller than in the fusinites and are rounded to irregular in shape. Minerals present in the vitrinite, therefore, probably include both detrital and authigenic phases.

Compared to the abundant authigenic and detrital mineral matter in the macerals of the Monkman coals, the Moose River Basin lignite is very clean. In particular, very little authigenic mineral matter (with the exception of pyrite and some kaolinite, and quartz and calcite in AC-12-82) was observed intimately associated with the lignite. Thus the porosity in the lignites is high and the pores largely unfilled, compared to the Monkman coals.

MODES AND TIMING OF MINERAL FORMATION

Figures 4 and 5 classify and illustrate the proposed relative timing of mineral formation in the Moose River Basin and Monkman coals (and associated sediments).

Moose River Basin

The detrital minerals introduced into the basin include quartz, K-feldspar, muscovite, and a number of heavy minerals (Hamblin 1982). Carbonate fragments are common where bedrock was exposed above the level of the basin. Feldspar in the gravels is partly altered to kaolinite, which is also common as poorly formed crystals in the lignite. The occurrence of some kaolinite associated with quartz in clastic horizons in the lignite may indicate a detrital origin for this material; however, the kaolinite is more likely to have formed *in situ* by alteration of detrital feldspar. Other syngenetic minerals include illite (which may have formed through the alteration of detrital muscovite), gibbsite, siderite, pyrite and geothite. Siderite occurs predominantly as nodules

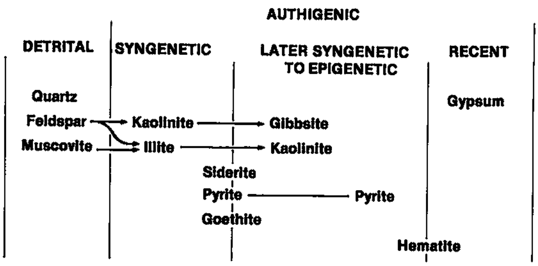

FIG. 4. Mineral genesis in the Moose River Basin, Mattagami Formation.

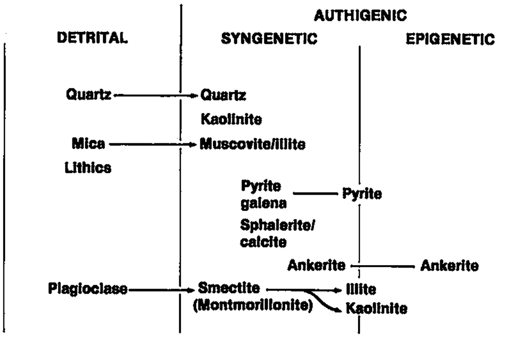

FIG. 5. Mineral genesis in the Monkman samples, Gates Formation.

in the clay, whereas pyrite is more common in the gravels and coals. The relative timing of formation of the syngenetic minerals is difficult to establish, as many of the minerals are restricted to certain types of sediment. Kaolinite and illite may have formed synchronously from degradation products of the feldspar and muscovite, respectively, with the drier and more acidic conditions in the coals favoring the crystallization of kaolinite, whereas both illite and kaolinite may have crystallized in the clays and claystones. Authigenic silica occurs in the cell lumens of a finely laminated fusinitic sandstone (AC-12-82); however, this appears to be an isolated situation, with the silica possibly derived from pressure solution of the quartz sand grains. The most important diagenetic mineral, pyrite, occurs most commonly in crack fillings and as an alteration or pseudomorph of organic matter. Gypsum is a product of the recent weathering of pyrite.

Monkman

In the Monkman samples, the dominant detrital minerals are quartz, muscovite, zircon, plagioclase feldspar and some illite. Carbonates, kaolinite, illite, barite, some quartz, and the sulfides are considered to be authigenic. The earliest syngenetic mineral to form in the coal may be kaolinite, as broken fragments of kaolinite cell fillings are intimately associated with an inertodetrinite maceral. Illite formed at an early stage (syngenetic) in the coals, infilling cell lumens. In a number of samples the illite in the macerals is overgrown by pyrite. In other samples, where the relationship with illite is not observed, pyrite nodules associated with the organic material are oriented parallel to the bedding planes, which indicates either an early syngenetic origin or preferential flow of groundwater along these horizons. The carbonates generally represent the latest stage of mineralization in the Monkman samples; however, as in the case of pyrite, carbonate minerals may have formed syngenetically, *i.e.*, infilling cell pores, in addition to overgrowing the matrix and crystallizing in late-stage cracks and on slickenside surfaces. Ankerite is the most common carbonate phase.

MAIN FACTORS DETERMINING OCCURRENCE AND FORMATION OF MINERALS, AND MINERAL-MACERAL RELATIONSHIPS

The accumulation of plant material and its maturation to form coal involves a continually changing set of geochemical and physical conditions. The changing conditions strongly influence the nature of the inorganic matter associated with the coal and in many cases result in mineral suites that reflect conditions at various stages in the accumulation and coalification processes.

Certain factors dominate mineral genesis during the main stages of coal formation (Fig. 6). The detrital minerals in coal are controlled by the lithological nature of the source area, its climatic regime, and the extent to which weathering has taken place. The predominantly granitic source area for the Mattagami Formation gave rise to detrital minerals such as quartz, K-feldspar and mica, whereas the occurrence of abundant lithic fragments and a larger range of detrital minerals in the Gates Formation resulted from sedimentary, igneous, and metamorphic source rocks. In addition, the abundance of quartz and kaolinite, and the appearance of gibbsite in the Moose River Basin lignite indicate a highly weathered environment, whereas a less weathered setting is implied by the preservation of a greater range of detrital and syngenetic minerals in the Monkman coals.

Syngenetic minerals (authigenically formed during early stages of coalification) reflect the nature of the depositional environment (*i.e.*, alluvial, deltaic, back-barrier or lacustrine), and its physical, hydrological and geochemical characteristics. The syngenetic minerals in both the Moose River Basin and Monkman coals reflect the freshwater alluvial or upper delta-plain depositional environments proposed for the deposits. Hence pyrite is less common than in marine-influenced coals, and the syngenetic clay minerals consist of kaolinite and illite rather than illite, smectite, and lesser kaolinite. The latter group would be more typical of back-barrier or lower delta plain coals (Cecil *et al.* 1981, Styan & Bustin 1983). In particular, the pH and EH of the peat are important controls on both mineral and maceral contents (Cecil *et al.* 1981). Although no strict relationship has been identified in coals between macerals and the minerals which are associated with them (Davis *et al.* 1984), the nature of the original organic matter (plant type) and subsequent conditions of maceral formation are known to give rise to certain minerals and mineral–maceral associations in some coals (Finkelman 1980, Cecil *et al.* 1981, Chandra & Taylor 1982). The strong association in the Monkman coal between fusinite and early-formed authigenic minerals may be due either to the higher porosity of fusinite [5–50 nm compared with 2–20 nm in vitrinite (Harris *et al.* 1981)] or to the oxidizing conditions required for its formation (or both).

Diagenetic minerals (formed in cleats and crack fills) are controlled by factors such as the composition and flow rates of groundwater, temperature and pressure of burial, permeability, and time. In the case of the Moose River Basin sequence, proximity to surface during ice retreat must have caused a major cold-leaching or accelerated weathering event (a process that would be accelerated by release of rebound stress), which resulted in a relatively clean coal with few authigenic (both syngenetic and epigenetic) minerals.

The main mineralogical differences between the two coals are mineral diversity, nature of the clay minerals, and proportions of detrital *versus* authigenic phases. The Monkman coals contain a more diverse mineral assemblage than the lignites. The wider range of detrital minerals is related to greater diversity of source rocks, and also to the degree of weathering in both the source area and basin of deposition. The presence of gibbsite, with quartz and kaolinite as the major mineral phases in the Moose River Basin lignite, indicates an intensely weathered situation, whereas the survival of plagioclase feldspar, for example, in the Monkman coals shows that in this area weathering was less intense.

The most abundant clay mineral in the Moose River Basin is kaolinite. In the Monkman coal both illite and kaolinite are common. This may be related to the extent of weathering, source materials (*e.g.*, the greater abundance of detrital mica in the Monkman sediments) and/or differences in wetness and acidity in the coal-forming environment (related to proximity to channels, precursor vegetation types, hydrology, *etc.*).

The relative lack of authigenic (*e.g.*, pore filling and epigenetic) minerals in the Moose River Basin lignite compared with the Monkman coal may be explained by a) the intense leaching event caused by ice retreat which affected the Moose River Basin lignite, and b) the higher rank of the Monkman coal (which in turn is related to overburden thickness during coalification, and structural setting). In particular, the occurrence of minerals infilling cleats in the Monkman coal may be related to the abundance of these structures in higher rank coals compared with the lower rank lignites.

CONCLUSION

The minerals present in the Moose River Basin lignites are limited to quartz, kaolinite, and lesser mixed-layer clays, siderite, illite, gypsum, pyrite and gibbsite. The Monkman coals contain a more diverse assemblage which includes quartz, kaolinite, ankerite, illite, calcite, siderite, pyrite, plagioclase feldspar, mica, galena and barite.

The highest proportions of mineral matter are contained in rock partings and in the durain and fusain lithotypes. The majority of the detrital minerals is located in the former, and the early authigenic minerals occur associated with fusinite and other inertinite macerals. The distribution of cleat minerals exhibits little relationship to maceral or lithotype content.

Quartz and the clay minerals are the dominant

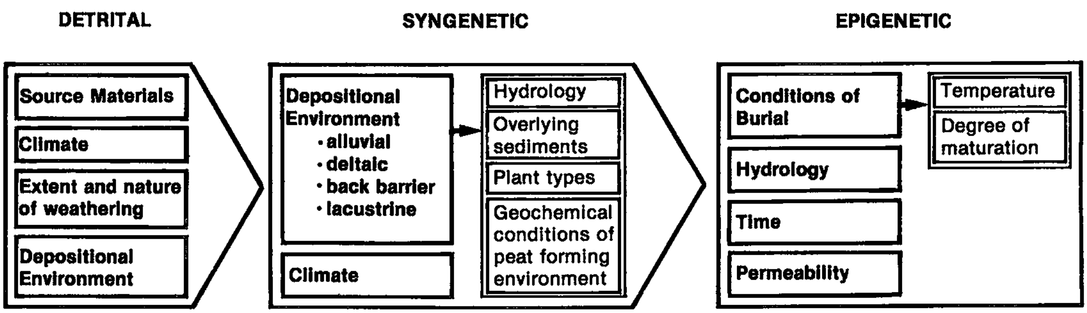

FIG. 6. Factors which influence the mineral matter of coals.

detrital minerals in both deposits. Authigenic kaolinite and illite also occur. Other common authigenic minerals are pyrite and the carbonates, formed both at early and later stages in the coalification process. In both deposits, many of the common minerals have a variety of modes of occurrence, indicating that these minerals may have formed or been incorporated into the coal at several stages during the history of coal formation.

The sequence of mineral formation in both coal deposits is therefore complex; differences in mineral content and characteristics are related primarily to source lithologies, degree of weathering, nature of the coal-forming environment, and post-depositional effects such as conditions of burial, degree of coalification, and groundwater-flow characteristics.

The environmental impact of coal burning is associated with the occurrence and habit of certain minerals and trace elements. The minerals which are of most importance are the sulfides. The Moose River Basin lignite is low in both ash and S, and much of the pyrite is present in habits which are readily removed during washing. Finer grained pyrite and crystals intimately associated with the organic matter, for example pore fillings, are more difficult to remove. Similarly, pore-filling pyrite in the Monkman coal is difficult to remove by conventional cleaning techniques, but the framboids, crack infills, and other coarse pyrite phases can be cleaned readily.

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