COMPOSITION AND FACIES VARIATIONS IN MID-CRETACEOUS GATES FORMATION COALS, NORTHEASTERN BRITISH COLUMBIA: IMPLICATIONS FOR INTERPRETATION OF PALEO-WETLAND ENVIRONMENTS AND ASSESSMENT OF COALBED METHANE CHARACTERISTICS

by

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ABSTRACT

A field and laboratory based study of medium volatile bituminous coals of the mid-Albian Gates Formation in northeastern British Columbia, Canada, was undertaken to determine the nature, controls and implications of coal compositional variation. Differences in lithotype composition reflect microscopic compositional variation. From bright to dull coals, there is a progressive decrease in vitrinite and increase in inertinite. Liptinite is negligible (<1%). Composition and texture affect the methane and carbon dioxide gas adsorption characteristics of the coal. On a mineral-matter-free basis, the amount of methane adsorbed generally increases with vitrinite enrichment. Carbon dioxide surface area generally decreases with increased mineral matter and increases with increased vitrinite content. The increase in adsorption of both methane and carbon dioxide with increased vitrinite concentration is attributable to differences in the pore size distribution of vitrinite (microporous) and inertinite (meso- to macroporous). Methane adsorption isotherms and surface area data indicate that the maceral compositional variations are at least as significant as coal rank in determining coalbed methane characteristics.

Compositional differences between lithotypes reflect differences in vegetation, accumulation rate and degree of plant decomposition. Lateral and vertical variation in lithotype composition was controlled by groundwater fluctuations and proximity to active fluvial systems. The coals formed on broad, low relief coastal plains, but were rarely subject to marine inundation as sulphur content is consistently low. The vegetation of the Gates mires is interpreted to have grown in environments ranging from low nutrient, taxodiaceous stillwater swamps with little or no fluvial influence, to eutrophic, higher energy taxodiaceous alluvial swamps subject to frequent flooding, to marsh environments. The Gates peats were deposited east of the rising Canadian Cordillera. This leeward position resulted in drier conditions than the humid climate normally associated with peat formation. Inertinite formed as a result of fires during periodic drought, and was concentrated by preferential destruction of vitrinite precursors at the peat accumulation stage. Image analysis and point-count petrographic data show that inertinite percentage on average is quite high, and may vary cyclically within seams. Cyclic variation in composition within some of the seams is attributed to climatic variations, subsidence rates or both.

Scrub savanna wetlands were one of the most common environments. Scrub savanna peats gave rise to low ash yield, inertinite rich coals. Gates Formation wetlands were maintained by periodic disturbance, and the stratigraphy of the coals reflects short and long term changes in sedimentological, tectonic and climatic conditions. In ombrotrophic settings, fire was fundamental to nutrient cycling and maintenance of hydric conditions, whereas periodic flooding was important in alluvial settings. Constant (or near constant) subsidence associated with deposition in a foreland basin allowed for preservation of the Gates Formation peats in an area which, due to climatic conditions, might not normally give rise to significant peat deposits.

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PREFACE

STATEMENT OF AUTHORSHIP

Chapter 2 was published in the International Journal of Coal Geology, Volume 18, 1991, pages 87-124, with the title *Lithotype (maceral) composition and variation as correlated with paleowetland environments, Gates Formation, northeastern British Columbia, Canada.* The paper is my original work; only editorial and supervisory assistance was provided by my co-authors: R.M. Bustin and W.D. Kalkreuth.

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Chapter 3 has been accepted for publication (with minor revisions) in the American Association of Petroleum Geologists Bulletin with the title: *Coalbed methane characteristics of Gates Formation coals, northeastern British Columbia: Effect of maceral composition.* The paper represents my original work, with editorial and supervisory assistance provided by my co-author, R. Marc Bustin.

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CHAPTER 1

INTRODUCTION: THE NATURE OF THE PROBLEM

1.1 STATEMENT OF THE PROBLEM

Compositional variation in coal seams is believed to result from differences in the conditions present in the original peat forming wetlands. However, the controls on compositional variation are not completely known. This thesis investigates the nature of compositional variation in coal seams, with specific application to the coals of the Albian Gates Formation in northeastern British Columbia. In northeastern British Columbia, both thick laterally extensive, and thinner, regionally limited coal seams crop out in the structurally and stratigraphically complex Rocky Mountain Foothills belt. The petrography of the coals is distinct, being more enriched in inertinite macerals (Kalkreuth and Leckie, 1989) than the coals present in Cretaceous and Tertiary strata to the south in the United States (data in Meissner, 1984). The following questions concerning the coals of the Gates Formation are addressed within the thesis:

(1) On what scale is compositional variation expressed?

(2) What factors control compositional variation?

(3) What are some of the implications of compositional variation in terms of utilization of coal as a resource, and in terms of understanding the types of wetland environments which gave rise to the Gates coal seams.

In order to address these questions, a combined field and laboratory study of samples representing eight coal seams from the Gates Formation, collected from mine exposures, was undertaken. The first priority was to document the variation on both a megascopic and microscopic scale. Following the documentation of the compositional characteristics, the main factors controlling the variation seen were interpreted. The final phase of the study was to investigate the implications of compositional variation.

1.2 INTRODUCTORY REMARKS: COAL COMPOSITIONAL HETEROGENEITY

The rather humble external appearance of coal belies its complex nature. Coal is composed of a heterogeneous mixture of organic materials known as macerals, and inorganic material known as minerals. Compositional heterogeneity is expressed at a number of scales (Figure 1-1) from the elemental level to the seam level. At the elemental level, coal is composed primarily of carbon, oxygen, hydrogen, nitrogen and sulphur. These elements, and a variety of other elements, are organized into more complex organic compounds which form the basic building blocks of the microscopically recognizable component of coal: macerals. Three maceral groups are found within coal, each with a common basic chemistry, as expressed as a ratio of either oxygen or hydrogen to carbon: liptinite (high H/C ratio), inertinite (high O/C ratio) and vitrinite (chemical composition intermediate between the two other maceral groups). Vitrinite is volumetrically the most important maceral group in many coals, and most research which has documented the change in chemical and physical properties of coal with increasing maturation has focused on the vitrinite maceral group. However, not all coals are vitrinite rich and, as discussed in this thesis, coal properties differ with respect to differences in composition.

As illustrated in Figure 1-1, at approximately the same level of organization as macerals, though not necessarily the same physical size, is the phyteral level. Phyterals are recognizable plant parts or organs. In some cases, these organs correspond to a particular maceral, e.g., cutinite is derived from a plant cuticle. Other phyterals, such as a root, consist of a variety of macerals, including structured vitrinite and resinite in the xylem, and usually suberinite in the bark. Research which addresses the phyteral composition of a deposit is sparse, and primarily confined to peat and low rank coal studies. The level of cell preservation varies with respect to depositional conditions and with rank, making identification of phyterals difficult, and impossible in many cases. Phyteral identification is usually a supplementary type of analysis.

Researchers have recognized that macerals tend to occur in particular associations with one another. These associations of macerals at the microscopic level are known as microlithotypes. By definition, microlithotypes must be at least 50 microns in thickness in perpendicular section, or cover a 50 X 50 micron area (Stach, 1982). The procedure for microlithotype analysis is tedious, and the method is not often used. At the

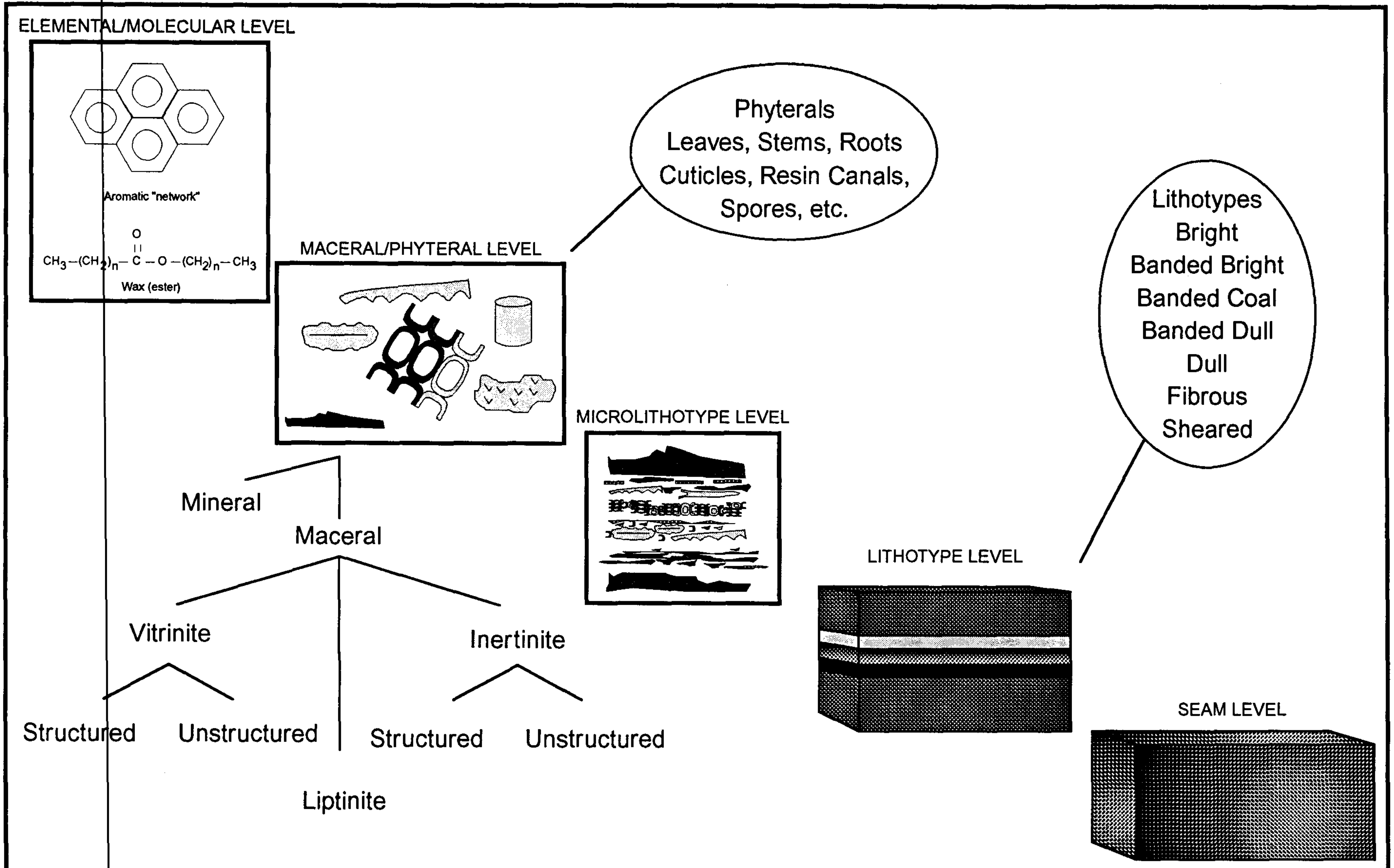

Figure 1-1 Schematic illustration of levels of coal heterogenity from the elemental/molecular level (examples of common plant polymers shown) to the seam level. Each successive level is to certain extent constructed from pieces of the previous level. Concept adapted from a photogaphic slide devised by W. Spackman. Wax chemical compound drawing from Barnes et al. (1990).

megascopic level, coal is differentiated on the basis of the relative proportion of bright and dull bands into lithotypes. Coal seams are usually composed of alternating bands of lithotypes.

1.3 ENVIRONMENT: THE PRIMARY CONTROL OF COAL COMPOSITION

The composition and texture of the peat and its resultant coal deposit are a function of vegetation type, water depth (ground water table height), decomposition rate and accumulation rate of the original wetland (Ting, 1989). All of these factors reflect climatic conditions (particularly temperature and precipitation). Peats which form in consistently wet, though not subaqueous, conditions will be enriched in vitrinite (given exclusion of clastics), with variable amounts of liptinite and fungal derived inertinite. Periodic interruptions in precipitation supply allow for a drawdown of the wetland water table. As a result, the peat is exposed to destruction by detrivores or lightning-induced wildfires, and becomes enriched in fire-derived inertinite at the expense of the vitrinite.

For a number of years there has been a lively debate in the coal petrologic literature concerning which, if any, modern wetland environments are good analogs of ancient peat-forming ecosystems (summarized in McCabe, 1984, 1987, 1991; Cameron et al., 1989; Teichmuller, 1989). Peats form where there is an excess of plant productivity over decompositional processes, a situation usually associated with wet, low-lying, poorly drained areas adjacent to water bodies (river, lake, ocean) and/or in high rainfall areas. In order to form an appreciable low ash yield coal deposit, the peat forming area must also be protected from clastic influx for extended periods. Modern peats form in a variety of settings due to favourable climatic and geomorphological conditions. In order to preserve the peat deposit from oxidation and/or erosion, constant subsidence or periodic subsidence (such that over time the subsidence could be considered constant) is necessary. High subsidence rates are associated with tectonically active areas such as fault-bounded (e.g., rift), fore-arc and foreland depositional settings (McCabe, 1991). Few modern peat deposits are likely to give rise to significant coal accumulations due to their tectonic setting (Cameron et al, 1989).

1.4 STRUCTURE OF THESIS

This thesis is organized into four papers, each of which discusses aspects of the three questions put forth above. Chapter 2 approaches the problem from a megascopic perspective. The primary objectives of the chapter are to: 1) determine whether or not similarity in megascopic appearance reflects similarity in microscopic composition and; 2) determine the general characteristics of the peat-forming wetlands of the Gates Formation in terms of petrography and vegetation.

Chapter 3 investigates the implications of compositional variation from the perspective of gas adsorption characteristics. Published research (summarized in Rightmire, 1984; Choate et al., 1986) had suggested that the key variables controlling methane adsorption in coals are rank and ash yield. The primary objective of the research was to determine whether or not maceral composition is also a controlling factor.

Chapters 4 and 5 investigate the implications of compositional variation from an environmental perspective. A combination of standard point-count petrography and image analysis petrography is used in chapter 4 to interpret aspects of the paleoclimate, including the impact of paleowildfire on the peat-forming wetlands. In chapter 5, petrography is used to interpret the types and varieties of wetlands which formed the peats. In addition, the effect of disturbance events (fire, flooding) on wetlands is interpreted from the pattern of compositional variation.

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CHAPTER 2

LITHOTYPE (MACERAL) COMPOSITION AND VARIATION AS CORRELATED WITH PALEO-WETLAND ENVIRONMENTS, GATES FORMATION, NORTHEASTERN BRITISH COLUMBIA, CANADA

2.1 ABSTRACT

Lithotype samples collected from mid-Albian Gates Formation coal seams in northeastern British Columbia, were analysed in order to gain a better understanding of coal facies variation. The coals formed on broad, low relief coastal plains. Compositional boundaries between lithotypes are gradational. From bright to dull coals, there is a progressive decrease in vitrinite and increase in inertinite. Liptinite is negligible (<1%); the dull appearance of some of the lithotypes is due to inertinite content and, to a lesser extent, degraded vitrinite. The lithotypes represent a broad spectrum of depositional environments from forest swamps to dry, herbaceous and/or shrubby marshes. Compositional differences between lithotypes are due to vegetational characteristics as well as differences in the rate of accumulation and decomposition of plant communities. Lateral and vertical variation in lithotype composition was probably controlled primarily by groundwater levels (due to sea level variations and climatic conditions?) and proximity to active fluvial systems. Forest swamps were dominated by coniferous trees with a significant component of ferns as herbs or low trees. Angiosperms and cycads contributed to the vegetation in the form of shrubs. Angiosperms were probably also present as herbs in marginal areas.

2.2 INTRODUCTION AND OBJECTIVES

Coal facies, represented at the megascopic scale by lithotypes, are compositionally and texturally distinct units within coal seams. By mapping the distribution of coal facies, geologists may be able to reconstruct a three dimensional model of ancient wetland environments. The model may be used to assess the variation in seam composition within a mine, enabling prediction of coal quality variations.

To date, the majority of published research on coal facies has dealt with Carboniferous (*e.g.* Hacquebard and Donaldson, 1969), Permian (*e.g.* Smyth, 1984; Marchioni, 1980; Diessel, 1986), or Tertiary (Teichmuller 1962, 1982) coal deposits. Teichmuller (1989) provides a comprehensive review of these studies.

Paleodepositional environment reconstructions have drawn heavily on the ideas put forth by studies of modern wetland settings (*e.g.* Spackman, et al., 1966; Cohen, 1968, 1984; Cohen et al., 1987, 1989; Styan and Bustin 1983a, b). Little has been published concerning the wetland environments of Mesozoic, and in particular, Lower Cretaceous coals.

A combined field and laboratory investigation of selected coal seams of the mid-Albian Gates Formation in the Rocky Mountain Foothills of northeastern British Columbia (Fig. 2-1) was undertaken in order to: 1) determine the petrographic composition of coal lithotypes; 2) document lateral and stratigraphic variation in lithotype and maceral composition; 3) interpret the original peat-forming environments and; 4) interpret the sedimentological factors controlling lithotype and maceral distribution (coal sedimentology). Previous investigations of the coals have been regional in scope (Kalkreuth and Leckie, 1989), and have involved definition of bulk compositional characteristics. This investigation focuses on both in-seam and between-seam variations.

2.3 GEOLOGIC SETTING OF STUDY AREA

2.3.1 Regional geology

The study area is located in the Rocky Mountain Foothills of northeastern British Columbia, in the vicinity of Tumbler Ridge (Fig. 2-1). Lower Cretaceous strata in the area comprise a series of transgressive-regressive clastic wedges deposited in response to periodic uplift of the Canadian Cordillera (Stott, 1968, 1982; Smith et al., 1984). During the late Cretaceous - early Tertiary the strata were folded into northwest trending chevron and box folds and cut by numerous thrust faults (Thompson, 1981; Kilby and Johnston, 1988). Coal seams are finely sheared in places, rendering determination of primary lithotypes difficult. To the east, in the Plains region, correlative strata are relatively undeformed and dip gently to the west. The Moosebar (marine) and Gates Formations and their subsurface (Plains) equivalents, the Wilrich, Falher and Notikewin Members of the Spirit River Formation (Fig. 2-2), form a third order transgressive-regressive depositional cycle (Leckie, 1986a). Seven fourth order cycles (Falher G, F, D, C, B, A and the Notikewin Member) are superimposed on the third

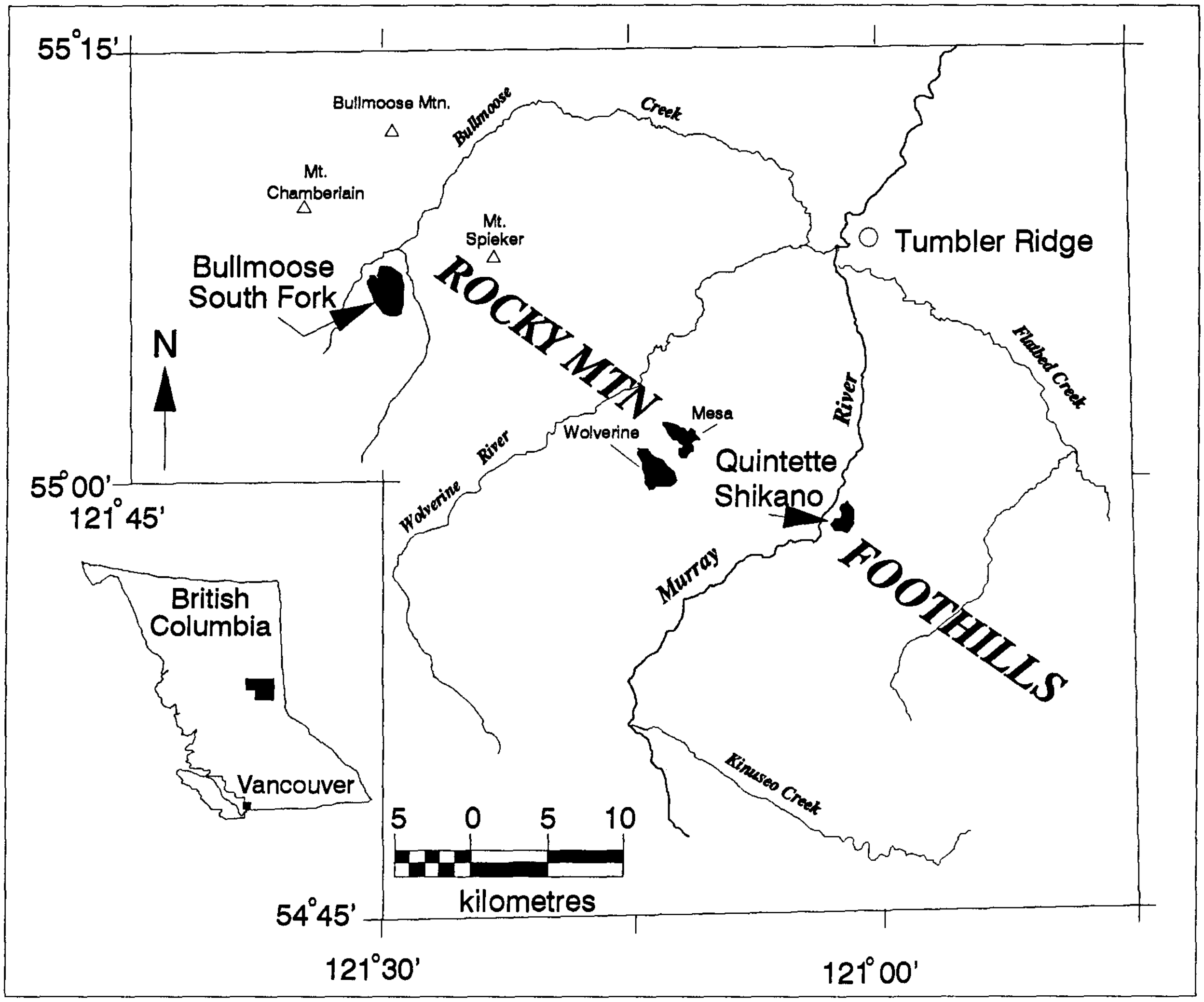


Figure 2-1. Location map of study area. Shaded areas indicate location of coal mines. Named areas are referenced in the text. Modified from Matheson (1986).

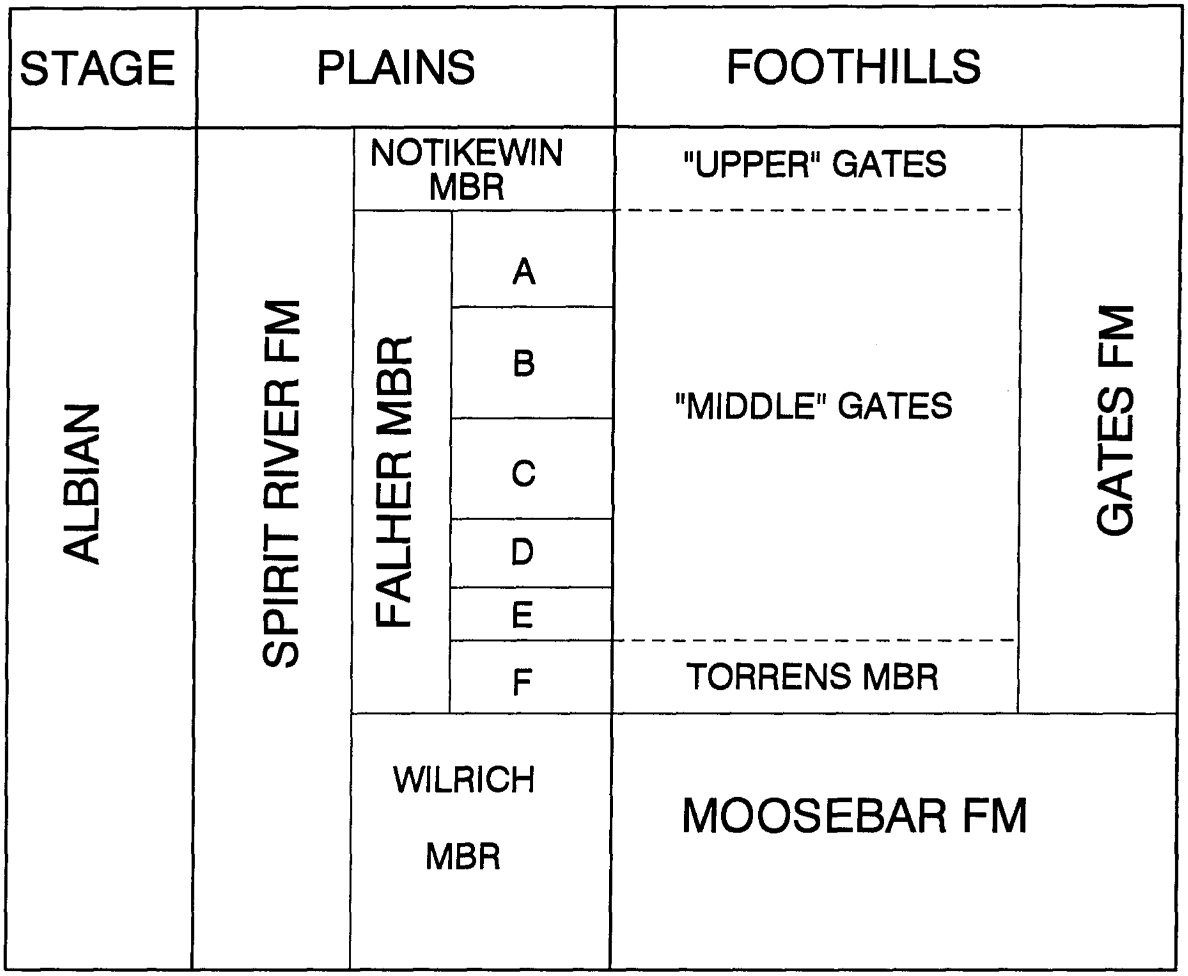


Figure 2-2. Stratigraphic chart of a portion of the Lower Cretaceous of northeastern British Columbia. Modified from Leckie (1986a) and Carmichael (1988).

order cycle (Leckie, 1986a). Within each cycle, sediments coarsen upward from offshore shales to, in most locations, beach deposits capped by coals and other nonmarine sediments.

Informally, the Gates is commonly divided into the Torrens member, the middle Gates and the upper Gates (Fig. 2-2). The Gates may be further subdivided (Leckie, 1986a) by using the informal subsurface stratigraphic nomenclature (Falher A - F, Notikewin; Fig. 2-2) for the individual third order cycles within the Gates Formation. Coals of economic thickness occur only in the middle Gates, which includes strata from the base of the nonmarine section of the Falher F to the top of the Falher A cycle (Fig. 2-2). The northern limit of economic coal deposits in the Gates Formation is in the vicinity of the Bullmoose mine leases; to the north, Gates Formation sediments thin and are primarily marine (Stott, 1982; Leckie and Walker, 1982).

2.3.2 Local geology

Coal samples used in this study were collected from the Bullmoose mine (South Fork deposit) and the Shikano area of Quintette (Fig. 2-1). Detailed sedimentological studies of Gates Formation strata in the area were done by Leckie (1983) and Carmichael (1983). The six seams of economic thickness present at Bullmoose (Drozd, 1985; Fig. 2-3) are designated, from oldest to youngest, A1, A2, B, C, D and E. The reflectance (R_0max) varies from 1.14% in the A seam to 1.02% in the E seam (Kalkreuth and Leckie, 1989). The A seam directly overlies the Torrens member whereas the E seam occurs a few metres below the middle Gates - upper Gates contact.

Nine coal seams are recognized in the Quintette area (Rance, 1985; Fig. 2-3); from youngest to oldest, the seams are referred to as A, B, C, D, E, F, G/I, J and K. Seams A, B and C occur in the upper Gates (Notikewin) and are not mined. The reflectance (R_0max) varies from 1.20% - 1.26% (Kalkreuth and Leckie, 1989). Samples used in this study were collected from the D seam in the Shikano area. The D seam occurs at the top of the middle Gates member, directly underlying marine deposits of the basal upper Gates, and is not correlative with the Bullmoose D seam.

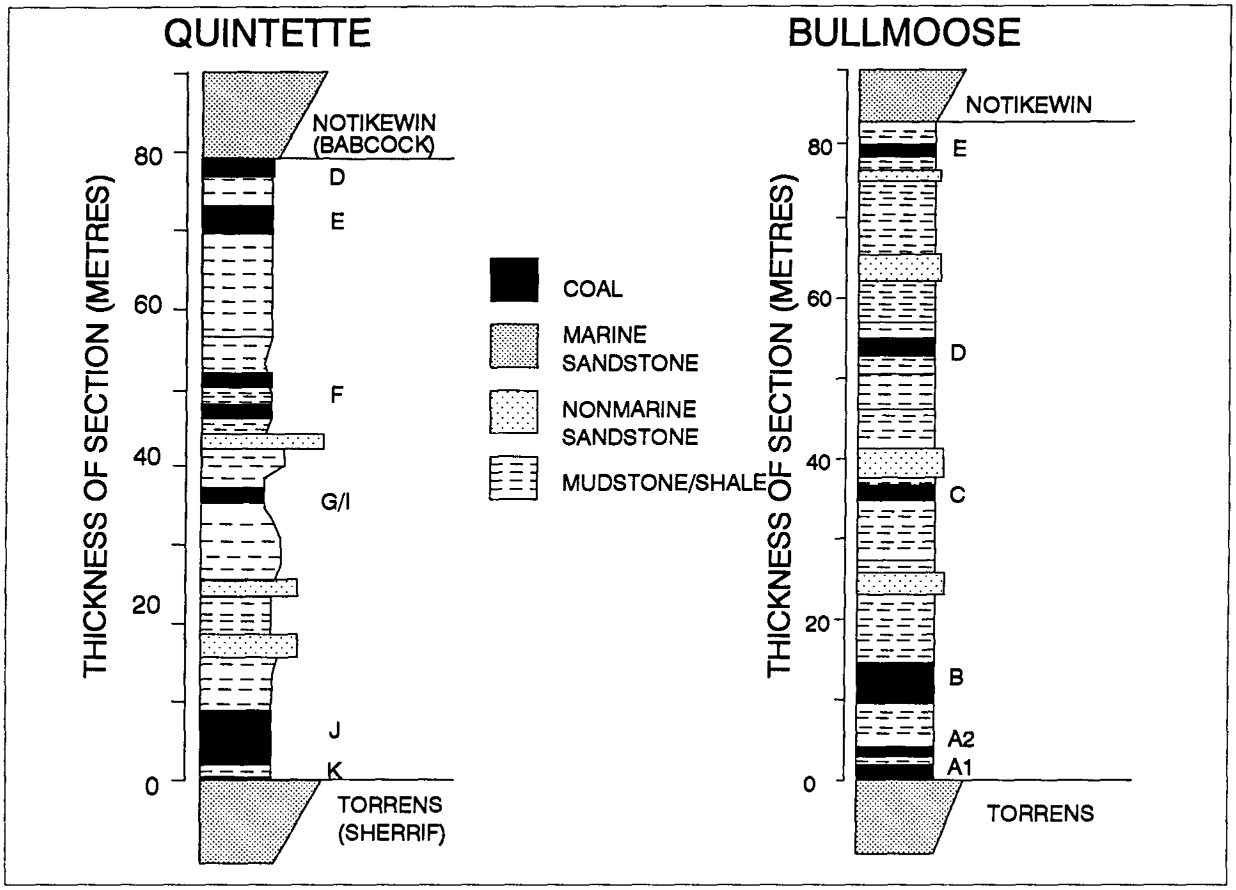


Figure 2-3. Generalized stratigraphic columns, Bullmoose and Quintette areas showing relative position of coal zones. Note that the seam designations are different for each mine. Bullmoose stratigraphy modified from Drozd (1985). Quintette stratigraphy modified from Rance (1985) and Kalkreuth and Leckie (1989).

2.3.3 Depositional Environment

Gates Formation coal accumulated in a strandplain setting (Kalkreuth and Leckie, 1989; Fig. 2-4). The coastline consisted of a series of high energy, wave-dominated arcuate or cuspate deltas resulting from northward-flowing rivers, with a major depocentre existing in the Bullmoose Mountain - Mt. Spieker area (Leckie, 1983). Coals directly overlie beach deposits and occur within flood plain deposits (Leckie 1986a). The paleoshoreline of the Gates cycles was oriented west-northwest and located just north of the Bullmoose mine area throughout much of Gates time (Leckie, 1986a). The transgressive limit of the Falher D and C cycles was in the Bullmoose - Mt. Spieker area whereas the marine sediments of the Falher B and A cycles do not outcrop in the study area.

In the Bullmoose area, the A1, A2 and B seams developed in nonmarine environments atop the first cycle (Torrens/Falher F), and the C, D and E seams developed atop the second cycle (Falher D). The Falher D cycle shoreface/beach sands and gravels at Bullmoose Mtn. and Mt. Chamberlain (Fig. 2-1) are not present four kilometres to the south in the South Fork pit area (Leckie, 1983, 1986b). With the exception of the A1 seam, all coals directly overlie nonmarine sediments. The upper Gates member (Notikewin), is the only marine unit in the Southfork area. The base of the upper Gates member lies stratigraphically a few metres above the E seam.

The Shikano D seam was deposited in a nonmarine coastal plain setting (Carmichael, 1988). The coastal wetlands of the D seam were progressively drowned as a result of encroachment by the Notikewin sea (Fig. 2-5), culminating in the deposition of estuarine marine shelf sediments (Carmichael, 1988). As will be discussed below, the marine encroachment is recorded in the petrographic profile of the seam.

2.4 MACERAL-BASED COAL FACIES INTERPRETATION

Peat deposits form in depositional environments where the accumulation rate of vegetal material approximately equals the subsidence rate and predominantly wet conditions are maintained. Compositional variations within the resultant coal deposit, expressed as coal facies variations, are therefore essentially a function of vegetation type, water depth (ground water table height), level of decomposition and rate of accumulation (Ting, 1989). These parameters can be approximated from a coal facies diagram (Diessel, 1986), which is a cross-plot

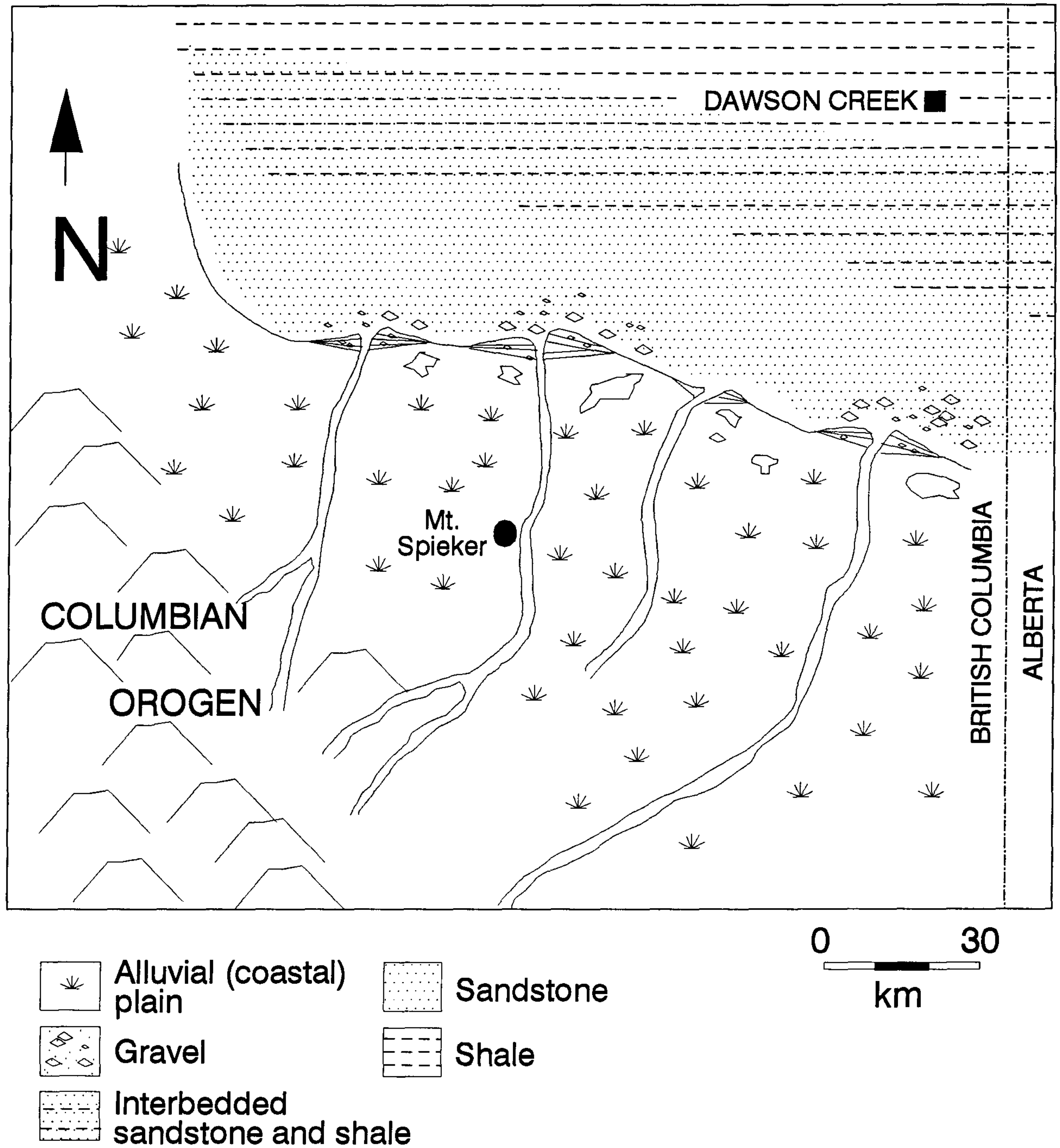


Figure 2-4. Idealized reconstruction of depositional setting of the Gates Formation during maximum regression. Modified from Leckie (1986a).

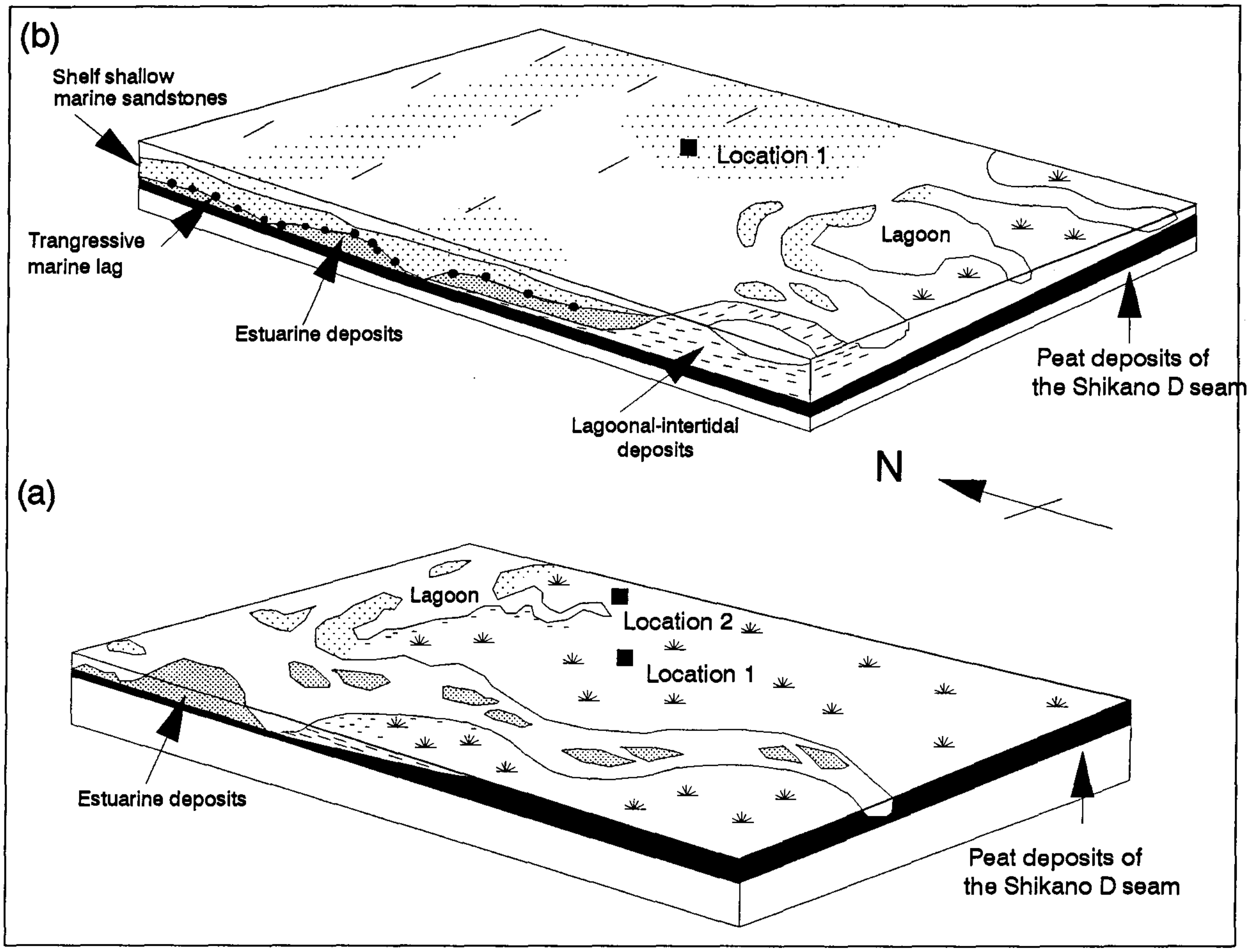


Figure 2-5. Idealized reconstruction of the progressive drowning of the Shikano D seam by a marine transgression. The peats were initially deposited in nonmarine conditions (4a - location 1). As transgression progressed, the environment became estuarine (such as 4a - location 2) and eventually fully marine conditions (4b - location 1). Modified from Carmichael (1988).

(Fig. 2-6) of two petrographic indices, the gelification index and the tissue preservation index. The tissue preservation index (TPI) is essentially a measure of the predominance of material with remnant cellular structure over that without cellular structure. Diessel's original TPI formula was modified here to include the percentage of pseudovitrinite and vitrodetrinite which occur in significant quantity in some of the Gates Formation coals. Pseudovitrinite typically contains remnant cellular structure, so the percentage of pseudovitrinite was added to the numerator whereas vitrodetrinite, which contains no cellular structure, was added to the denominator. For the purpose of this study the TPI is defined as:

$$TPI = \frac{\text{telinite + telocollinite + pseudovitrinite + semifusinite + fusinite}}{\text{vitrodetrinite + desmocollinite + inertodetrinite}}.$$

Higher TPI values indicate the presence of more well preserved plant tissues, and is interpreted to reflect an increase in the percentage of arboreal vegetation (lignified tissues). However, the TPI can also be high due to concentrations of semifusinite and fusinite, which owe their origin to decomposition by rapid oxidation (burning).

The formation of vitrinite is favoured when a peat is persistently wet and oxygen levels are low. Thus, the predominance of vitrinite and other gelified material (macrinite) suggest the presence of a high water table with limited availability of oxygen. The gelification index (GI) provides a measure of the persistence of wet conditions and is defined as proposed by Diessel (1986) as:

$$GI = \frac{\text{vitrinite + macrinite}}{\text{total inertinite}}.$$

An alternate way to view the GI is as an inverted oxidation index. A decrease in the GI indicates an increase in oxidation. Level of decomposition is approximated by a combination of the TPI and the GI. A combination of high (>1) TPI and GI indicates low levels of aerobic decomposition. High levels of anaerobic decomposition (loss of cell structure, without the production of abundant inertinite) or limited aerobic decomposition, is implied by a high GI and low TPI. The rate of accumulation can also be inferred from these two indices. When organic matter accumulates rapidly, oxidation levels are kept to a minimum, resulting in a high GI and, in most cases, a high TPI.

Diessel (1986) defined fields within the facies diagram which correspond to the hydrologic, decomposition and vegetation characteristics of common wetland environments. In this study, the hydrologic

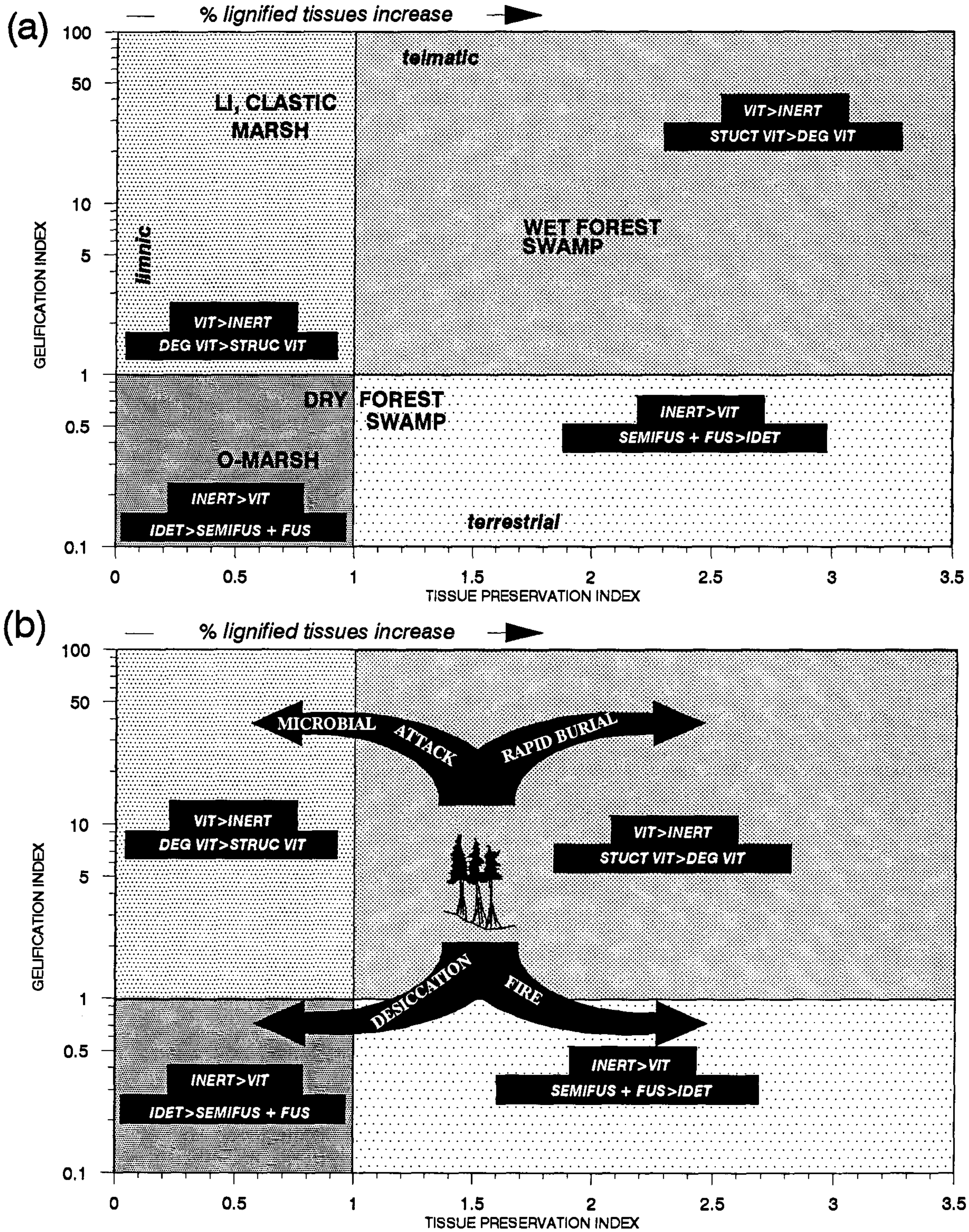


Figure 2-6. (a) Generic facies diagram (modified from Diessel, 1986) as used in this study showing wetland environment fields and bulk maceral composition. (b) Diessel facies diagram of four possible degradation pathways possible for a wet forest swamp which would result in maceral compositions similar to other wetland environments. See text for further explanation. LI=limited influx; O-MARSH =open marsh; VIT =vitrinite; INERT =inertinite; SEMIFUS =semifusinite; FUS = fusinite; IDET = inertodetrinite; STRUC = structured; DEG = degraded.

regime is divided on the basis of water level into (Fig. 2-7): 1) terrestrial - above water level, dry conditions; 2) telmatic - between high and low water; and 3) limnic - subaqueous. Vegetation type corresponds to marsh (primarily herbaceous vegetation) or swamp (primarily arboreal vegetation).

Following North American custom, the term marsh covers all peat-forming regions which are predominantly herbaceous. All marsh peats, with their low lignin:cellulose ratio, will be characterized by variable GI's, but low (<1) TPI's (Fig. 2-6a). Studies of modern peats in the Fraser Delta (Styan and Bustin, 1983a, b;) have shown that herbaceous peats may give rise to several types of coal. Under freshwater conditions, with rapid burial and little oxidation, a desmocollinite- or vitrodetrinite-rich peat with lesser telinite and liptinite and minor inertinite form. In brackish water conditions, more alkaline conditions promote fungal and bacterial activity such that an even more degraded (less structured vitrinite precursor material) peat is formed. These *limited influx marshes* are characterized by high GI's, but like all of the marsh peats, low TPI's. If the peat is oxidized and desiccated by a drop in the water table, or frequently flooded with oxygenated water, the percentage of inertinite, particularly inertodetrinite, macrinite, sclerotinite and degradofusinite, will increase; this *open marsh* (Fig. 2-6a) has a low GI. If a marsh environment is open to clastic influx, but is rapidly buried, a situation transitional with carbonaceous mudstones will occur. These *clastic marsh* (Fig. 2-6a) peats may or may not have inertinite, but will be enriched in vitrodetrinite and mineral matter. Thus, the GI's will be quite variable, but the mineral content will be high.

Diessel (1986) differentiated between wet and dry forest swamps. Both environments initially have an overall higher lignin:cellulose ratio than the marsh environments and consequently, TPI's are normally higher (Fig. 2-6a). The GI and TPI vary with respect to the height of the groundwater table. *Wet forest swamps* are characterized by the predominance of structured over unstructured vitrinite, and vitrinite over inertinite. *Dry forest swamps* have a consistently lower water table which allows for the concentration of inertinite through preferential destruction of humic material. The boundary between the two environments is gradational.

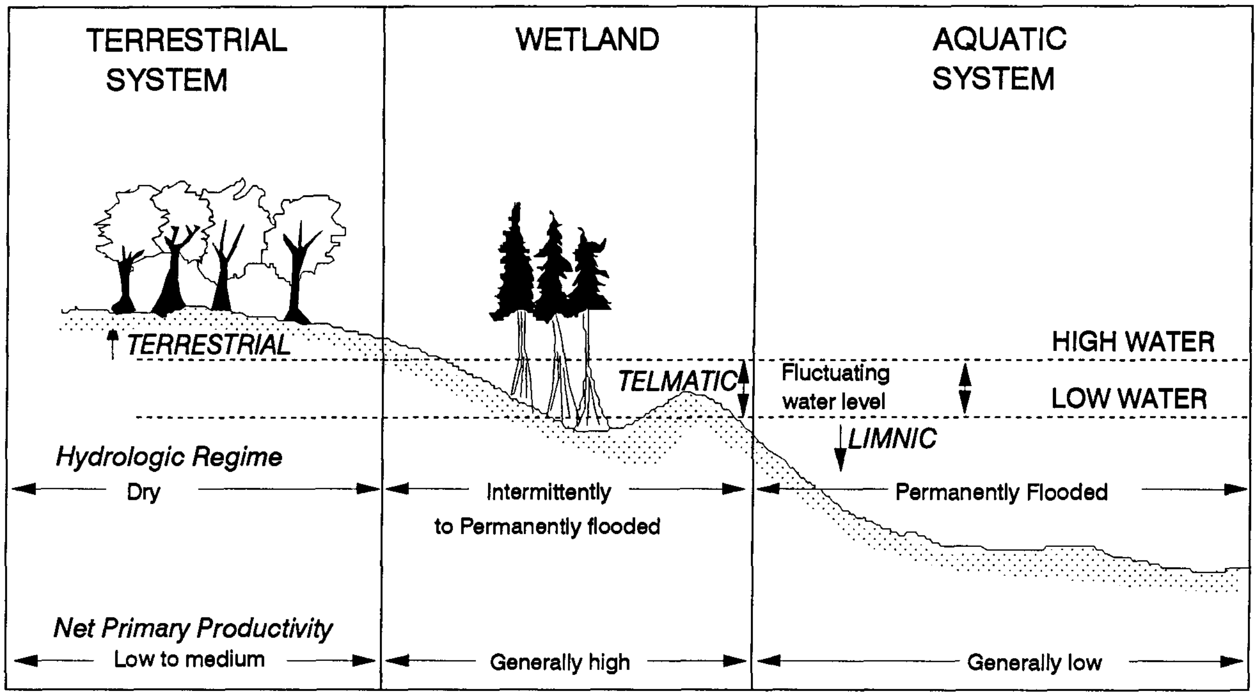


Figure 2-7. Classification of hydrologic regime by water depth. Modified from Mitsch and Gosselink (1986).

2.5 METHODS

2.5.1. Section correlation and sample collection

All coal sections were described according to a modified Australian lithotype classification scheme (Table 2-1) using a minimum lithotype thickness of one centimetre. Like the Permian coals studied by Marchioni (1980) and Diessel (1965), Gates formation coals are for the most part finely banded and would be almost exclusively classified as clarain in the Stopes-Heerlen (ICCP) system. Use of the modified Australian system allowed for further subdivision, and thus, facilitated the interpretation of wetland depositional environments. A comparison of the two classification schemes is found in Marchioni (1980) and included within Table 2-1. In order to determine wetland environment zones (Shikano D) and facilitate section correlation, the lithotypes were subsequently regrouped using a minimum thickness of five centimetres. Exceptions were made for the occurrence of fibrous coal and mudstone; the unique environmental significance of each of these lithologies would be lost if combined with another lithotype. One section of the Shikano D seam was described and a representative sample of the lithotype at each stratigraphic interval was collected. In order to assess lateral and vertical variation in seam stratigraphy in the Bullmoose mine area, at least four sections of each of five seams (A1, B, C, D and E) were described and correlated as discussed above. Wherever possible, samples were collected of each of the seven lithotypes.

2.5.2 Maceral point count analysis

A total of 110 representative lithotype samples were prepared and polished according to standard procedures to yield 2.54 cm petrographic pellets. Three hundred points were counted (mineral matter free) using the established maceral classification scheme for bituminous coals (Bustin et al., 1985). Mineral matter was counted separately.

Table 2-1 Lithotype classification scheme. Modified from Diessel, 1965 and Marchioni, 1980.

Stopes-Heerlen (ICCP) Classification	Nomenclature used in this study	Description
vitrain	bright coal	subvitreous to vitreous lustre, conchoidal fracture, less than 10% dull laminae
clarain	banded bright coal	predominately bright coal, with 10-40% dull laminae
clarain	banded coal	interbedded dull and bright coal in approximately equal proportions
clarain	banded dull coal	predominately dull coal with 10 - 40% bright laminae
durain	dull coal	matte lustre, uneven fracture, less than 10% bright coal laminae, hard
fusain	fibrous coal	satin lustre, very friable, sooty to touch
no equivalent	sheared coal	variable lustre, disturbed bedding, numerous slip/slickenside surfaces, very brittle

2.6 RESULTS

2.6.1 Field Observations:

The banded lithotypes predominate in all seams studied. Two types of both banded dull and dull coal exist: mineral-rich and a mineral-poor varieties. Bright coal and fibrous coal are lenticular, which may reflect their origin from individual logs and stems. However, fibrous coal occurring in accumulations of 1 centimetre or greater is rare. The thickest lens of fibrous coal found is 2.5 cm thick. Banded bright coal often contains abundant thin lenses and laminae of fibrous coal.

In the Bullmoose area, banded dull and banded coal are the most common lithotypes in the A1, B and C seams. Banded bright and banded coal are more common in D and E seams. Mudstone partings are rare, thin and lenticular where present in A1, B and E seams, whereas they tend to be thicker and more laterally extensive in C and D seams.

2.6.2 Section description and correlation

Cross sections of the Bullmoose B and D seams are illustrated in Fig. 2-8. The two seams differ in lithotype composition and stratigraphy, reflecting differences in depositional conditions within their original wetland environments. Within the B seam (Fig. 2-8a), banded dull coal is the only lithotype which can be consistently correlated; other lithotypes are more restricted in areal distribution. In all of the sections examined the basal part of the seam is sheared, although the thickness of the sheared interval varies. Within sections 87B, B2 and B1 there is a general increase in the percentage of the duller lithotypes from the base to the top of the seam. The trend is not as well developed in B3. There is also a decrease in the duller coal lithotypes from north to south, and from east to west. No significant mudstone interbeds are present.

The Bullmoose D seam (Fig. 2-8b) consists mainly of banded bright coal, sheared coal and carbonaceous mudstone interbeds. Individual units within the D seam are more laterally continuous than within the B seam. A sheared zone averaging about 50 cm thick occurs approximately 0.5 m above the base of the seam. Within the

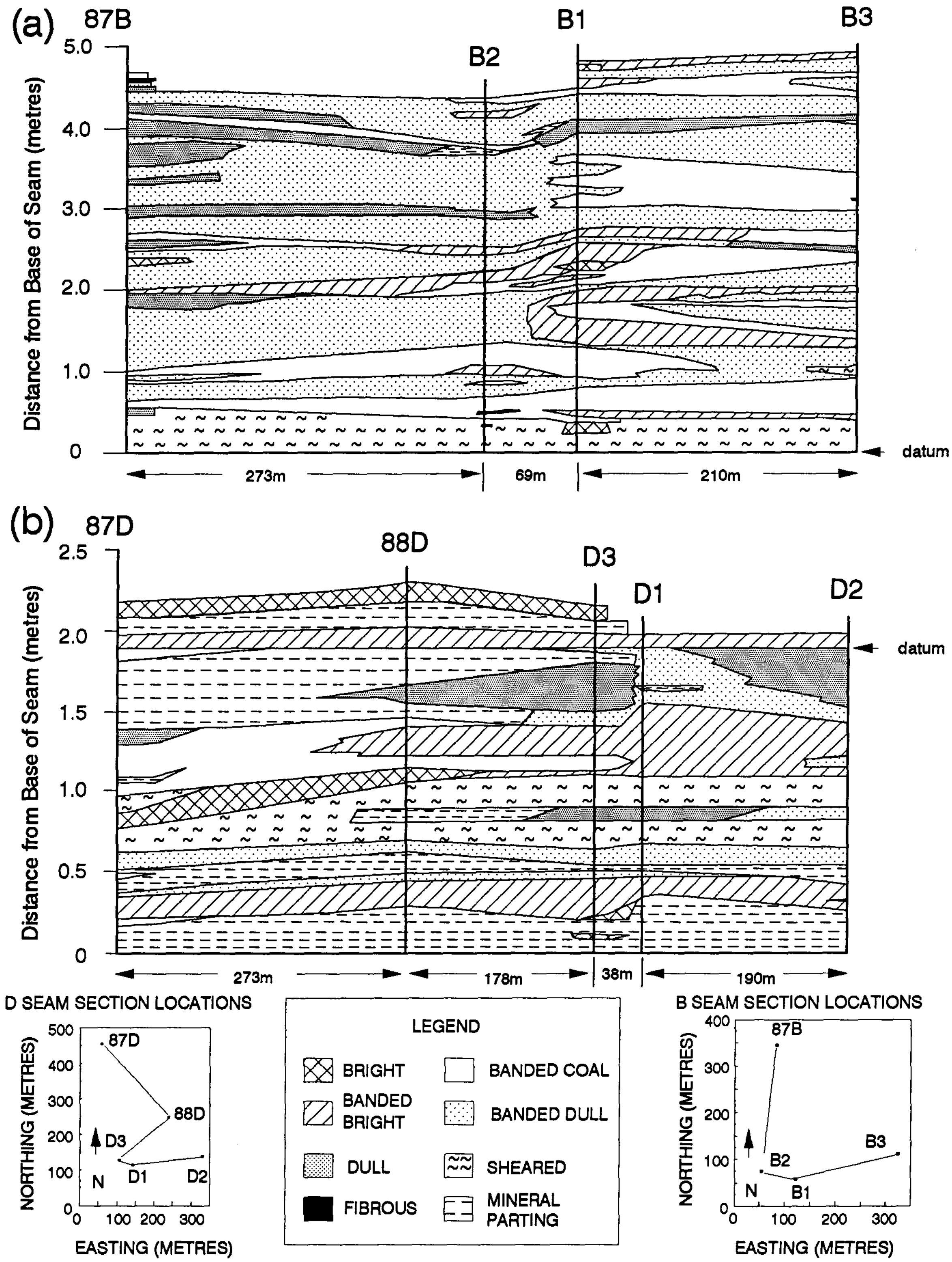


Figure 2-8. (a) Section correlation for Bullmoose B seam. Datum for correlation is the floor of the seam. (b) Section correlation of Bullmoose D seam. Location of seam base problematic in some locations. Datum for correlation is the base of a banded bright layer occurring across the section line, near the top of the seam. Inset maps show relative section locations.

unsheared zones of D seam there is a cyclic repetition of lithotypes. Banded bright coal is replaced by carbonaceous mudstone and dull coal, followed by banded bright or bright coal. From north to south carbonaceous mudstones tend to grade into dull and banded dull coal.

A section profile of the Shikano D seam is illustrated in Figure 2-9. The basal third of the seam consists primarily of interbedded banded and banded bright with occasional banded dull layers. The upper two-thirds of the seam contains a higher proportion of the duller lithotypes.

2.6.3 Maceral point count analyses

The results of maceral point count analyses of lithotype samples from all seams are reported in Tables 2-2 and 2-3, and illustrated in Fig. 2-10. There is a marked decrease in vitrinite with a concomitant increase in inertinite from bright to progressively duller lithotypes as illustrated in the photomicrographs of each lithotype (Fig. 2-11). The compositional variation in large part reflects a decrease in the percentage of pseudovitrinite. On average, in all lithotypes except sheared coal, semifusinite is the most abundant inertinite maceral. Micrinite and macrinite are nowhere abundant. There is very little liptinite recognizable in any of the lithotypes (1% or less). The fibrous (fusain) coals, although quite rare, are composed primarily of inertinite (both semifusinite and fusinite). The composition of the clastic partings is variable; inertodetrinite is the most abundant inertinite maceral. Sheared coals are compositionally distinct, with high vitrinite and mineral matter contents.

Conventional ternary composition diagrams for coals depict vitrinite, liptinite and inertinite on the apices. However, because of the lack of liptinite, little information is gained with this plot for the Gates Formation coals. The three "end member" components of the Gates Formation coals are structured vitrinite (telinite + telocollinite + pseudovitrinite), degraded vitrinite (vitrodetrinite + desmocollinite) and inertinite (Fig. 2-12). The percentage of inertinite and degraded vitrinite increases, and structured vitrinite decreases from the bright to dull lithotypes.

The three fibrous lenses sampled group together in the inertinite-rich corner of the ternary plot (Fig. 2-12) with structured vitrinite more abundant than unstructured vitrinite. On average, the vitrinite in clastic partings is evenly split between structured and unstructured, and inertinite is subordinate. The bulk of the unstructured

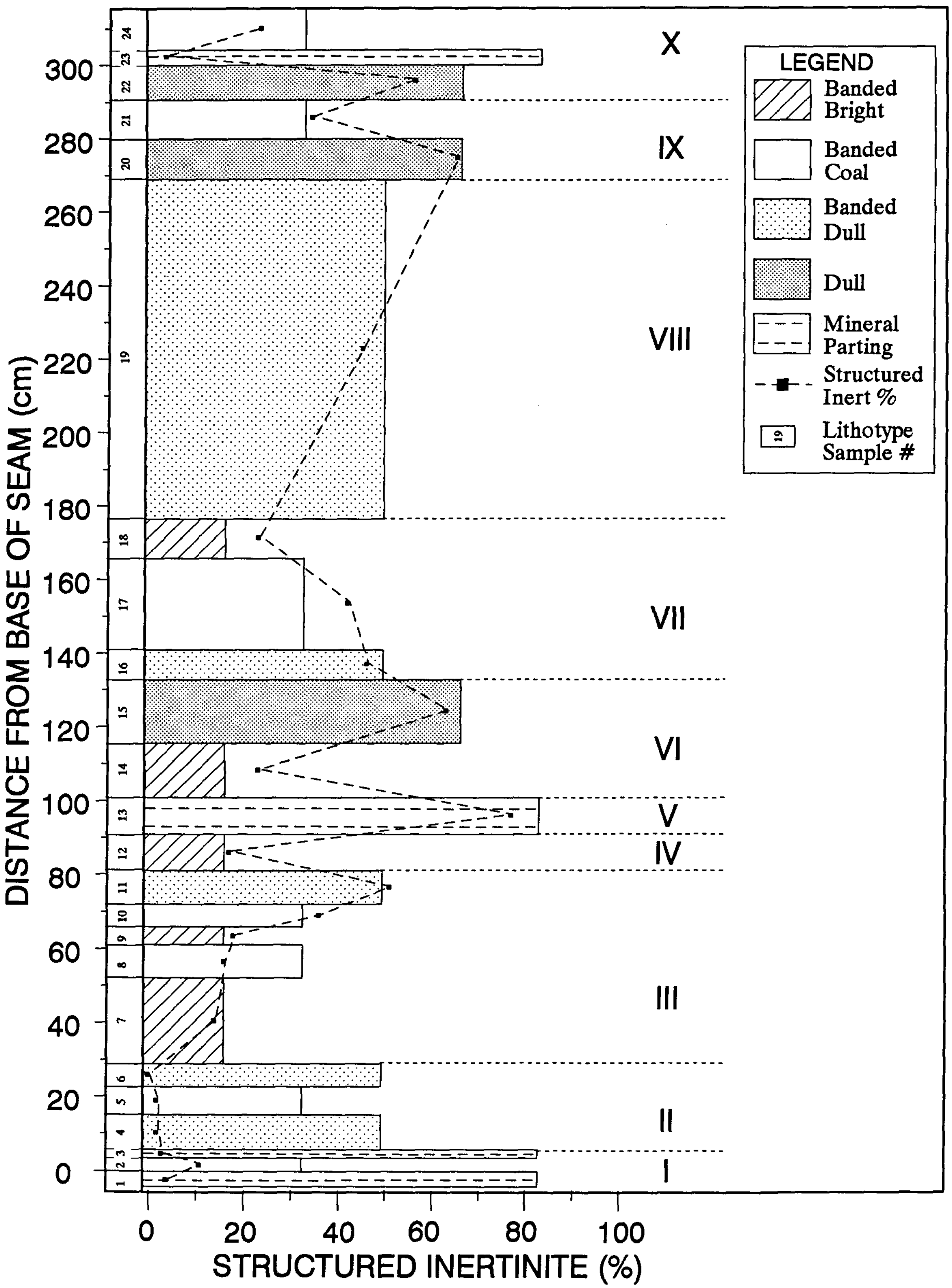


Figure 2-9. Lithotype profile and variation in percentage of structured inertinite (semifusinite + fusinite) of Shikano D seam. Roman numerals are zones explained in the text.

Table 2-2. Maceral composition by lithotype, volume %, average and standard deviation, mineral matter free basis, as determined by point counting (all seams).

MACERAL		BRIGHT (20)	BANDED BRIGHT (17)	BANDED COAL (20)	BANDED DULL (22)	DULL (11)	FIBROUS (3)	SHEARED (8)	MINERAL PARTING (8)
TELOCOLLINITE	AVG	6	11	9	7	4	5	10	16
	SDEV	6	8	9	7	5	2	5	15
TELINITE	AVG	18	17	14	10	9	11	11	6
	SDEV	16	9	6	5	8	6	9	5
PSEUDOVITRINITE	AVG	46	23	13	5	2	9	21	14
	SDEV	25	13	9	5	2	8	11	20
DESMOCOLLINITE	AVG	17	22	25	20	16	13	28	4
	SDEV	16	10	11	12	9	6	15	4
VITRODETRINITE	AVG	1	7	8	12	8	0	21	28
	SDEV	2	12	12	16	18	0	14	21
TOTAL VITRINITE	AVG	88	79	69	54	39	38	91	68
	SDEV	9	12	16	21	24	16	4	34
SEMIFUSINITE	AVG	4	9	13	20	25	29	2	5
	SDEV	5	6	8	12	12	9	2	5
FUSINITE	AVG	3	6	9	8	18	28	3	5
	SDEV	3	6	6	7	18	9	2	8
INERTODETRINITE	AVG	3	5	7	17	17	4	3	22
	SDEV	3	4	5	11	17	1	1	26
TOTAL INERTINITE	AVG	10	20	30	45	60	61	8	32
	SDEV	9	11	16	21	23	17	4	35
SPORINITE	AVG	1	0	1	1	1	1	0	0
	SDEV	1	1	1	1	1	1	0	0
TOTAL LIPTINITE	AVG	1	0	1	1	1	1	1	0
	SDEV	1	1	1	1	1	1	1	0

AVG = AVERAGE; SDEV = STANDARD DEVIATION; (**) = NUMBER SAMPLES ANALYSED

Table 2-3. Maceral composition by lithotype, volume %, average and standard deviation mineral matter containing basis, as determined by point counting (all seams).

		BRIGHT (20)	BANDED BRIGHT (17)	BANDED COAL (20)	BANDED DULL (22)	DULL (11)	FIBROUS (3)	SHEARED (8)	MINERAL PARTING (8)
TELOCOLLINITE	AVG	6	10	8	5	3	5	8	7
	SDEV	6	6	8	5	3	3	3	8
TELINITE	AVG	18	16	13	9	8	10	8	3
	SDEV	15	8	6	5	8	6	7	3
PSEUDO-VITRINITE	AVG	46	22	13	5	1	8	17	10
	SDEV	25	13	8	4	1	8	12	18
DESMO COLLINITE	AVG	17	21	24	19	15	13	22	5
	SDEV	16	10	11	12	9	6	17	8
VITRODETRINITE	AVG	1	6	7	9	5	0	13	14
	SDEV	2	10	10	11	9	0	8	12
TOTAL VITRINITE	AVG	87	75	65	46	33	37	68	38
	SDEV	9	11	12	15	15	16	19	30
SEMIFUSINITE	AVG	4	9	12	18	23	29	2	3
	SDEV	5	7	8	11	12	10	2	2
FUSINITE	AVG	3	6	9	8	16	28	3	2
	SDEV	3	6	6	6	15	10	2	3
INERTO-DETRINITE	AVG	3	5	7	15	16	4	2	10
	SDEV	3	4	4	9	16	1	1	14
TOTAL INERTINITE	AVG	10	20	29	42	56	61	7	15
	SDEV	9	11	16	19	22	17	4	17
SPORINITE	AVG	1	0	1	1	1	1	0	0
	SDEV	1	1	1	0	1	1	0	0
TOTAL LIPTINITE	AVG	1	1	1	1	1	1	0	0
	SDEV	1	1	1	0	1	1	1	0
PYRITE	AVG	0	0	0	0	1	0	0	0
	SDEV	0	0	1	0	2	0	0	0
QUARTZ	AVG	0	3	4	8	5	0	21	36
	SDEV	1	4	5	11	13	0	21	26
CLAY	AVG	0	1	0	3	1	0	3	9
	SDEV	0	3	1	4	2	0	3	12
CARBONATE	AVG	0	0	0	1	3	1	1	2
	SDEV	0	1	1	1	5	1	1	3
TOTAL MINERAL	AVG	1	4	5	11	10	1	25	47
	SDEV	2	6	6	13	14	1	22	24

AVG = AVERAGE; SDEV = STANDARD DEVIATION; (**) = NUMBER SAMPLES ANALYSED

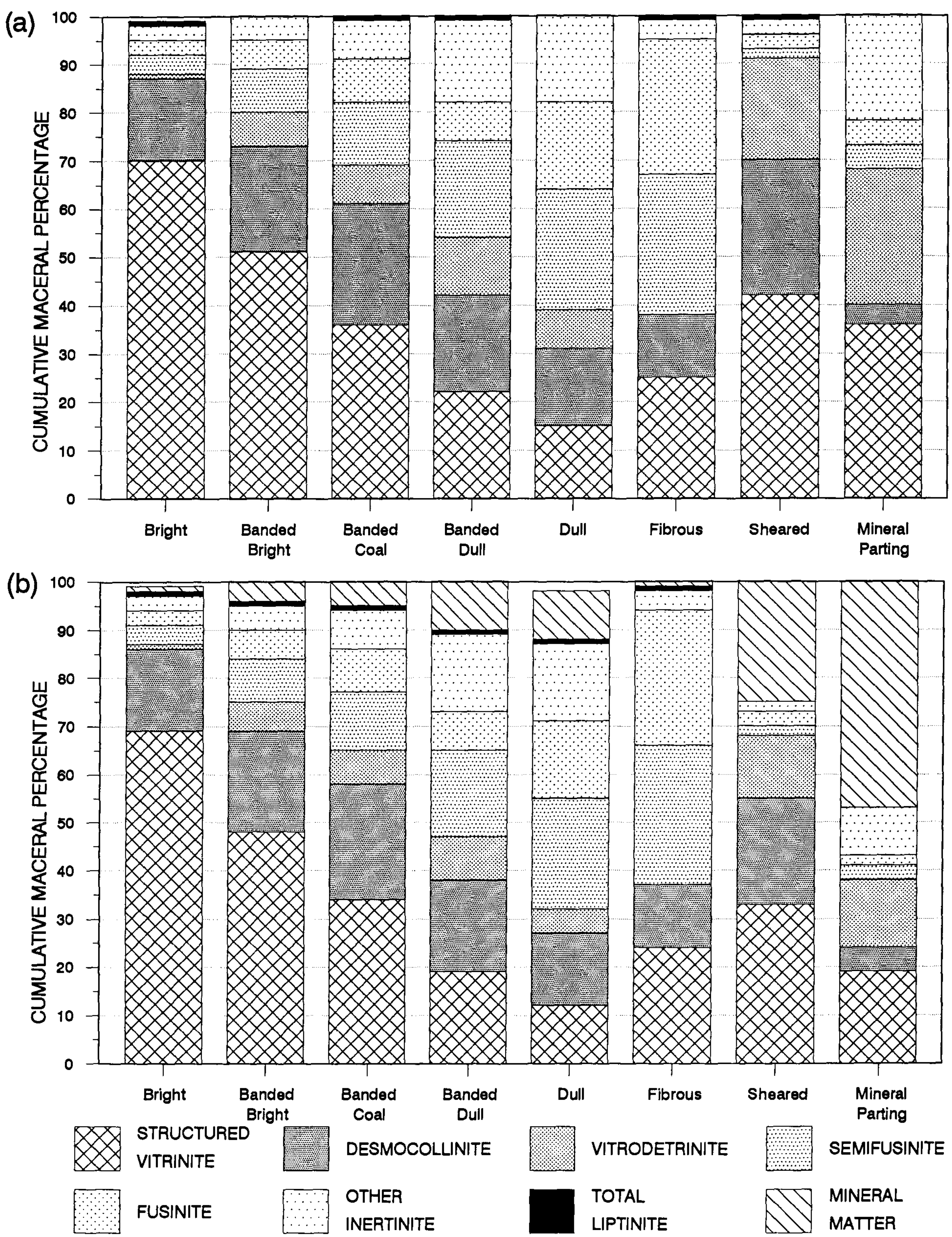


Figure 2-10. Average maceral composition of Gates Formation lithotypes and mineral partings on a (a) mineral matter-free basis and (b) raw coal basis (all seams). Structured vitrinite=telinite + telocollinite + pseudovitrinite.

vitrinite is vitrodetrinite. However there are two clusters: 1) vitrinite-rich (either structured or unstructured); and 2) inertinite-rich, with inertodetrinite >50%. Within sheared coals, the vitrinite composition is variable, and is either predominantly structured or unstructured.

2.7 DISCUSSION

2.7.1 Petrographic composition of lithotypes

With the exception of an unusual amount of pseudovitrinite in the brighter lithotypes (Fig. 2-11a), the macerals present in the Gates Formation coals are typical of humic bituminous coals, being mainly telocollinite, desmocollinite, semifusinite and fusinite. The origin of pseudovitrinite has been attributed to primary oxidation (Benedict et al., 1968), early/peat-stage oxidation (gel desiccation and shrinkage; Hagemann and Wolf, 1989), post-coalification oxidation (Kaegi, 1985) and overmaturation of formerly asphaltene-rich vitrinites (Teichmuller, 1989). None of these proposed origins provides a satisfactory explanation for the pseudovitrinite in Gates Formation coals. The occurrence of pseudovitrinite in inertinite-rich coals is used as support for an early (primary or peat-stage) oxidation origin. The Gates Formation coals are inertinite-rich, however, the pseudovitrinite is concentrated in the brighter, vitrinite-rich lithotypes. If pseudovitrinite formed via maturation or post-coalification thermal oxidation processes, it should be more randomly distributed. However it is possible that bright coals, which tend to be brittle and fracture more readily than duller coals, may be more permeable, and thus more susceptible to oxidation by the flow of oxygen-containing gas or liquid. More research, as well as a search for pseudovitrinite precursors in modern peats, is necessary in order to understand the origin of this problematic maceral.

One aspect of the petrography of Gates coals which deserves further investigation is the paucity of liptinite. Liptinite is often difficult to distinguish in medium volatile bituminous or higher rank coals. However, where liptinite is observed in the Gates coals, it is quite distinct from vitrinite (Fig. 2-11c). Plant anatomical and physiological characteristics, such as spore/pollen exine thickness, spore/pollen production, cuticle thickness and wax and resin production, vary significantly between plant families and between plant species. In a study of the

Figure 2-11

Photomicrographs of lithotypes showing enrichment of inertinite from bright to dull coals. Scale same for all photomicrographs, as in (h). Pseudovitrinite=PV; telocollinite (TC); desmocollinite (DC); sporinite (SP); semifusinite (SF); fusinite (FUS); inertodetrinite (ID).

(a) Bright - note pseudovitrinite has slightly higher reflectance than telocollinite and contains slitted structures.

(b) Banded bright - primarily telocollinite but often contains scattered laminae of inertinite.

(c) Banded coal - note difference in reflectance between desmocollinite and sporinite.

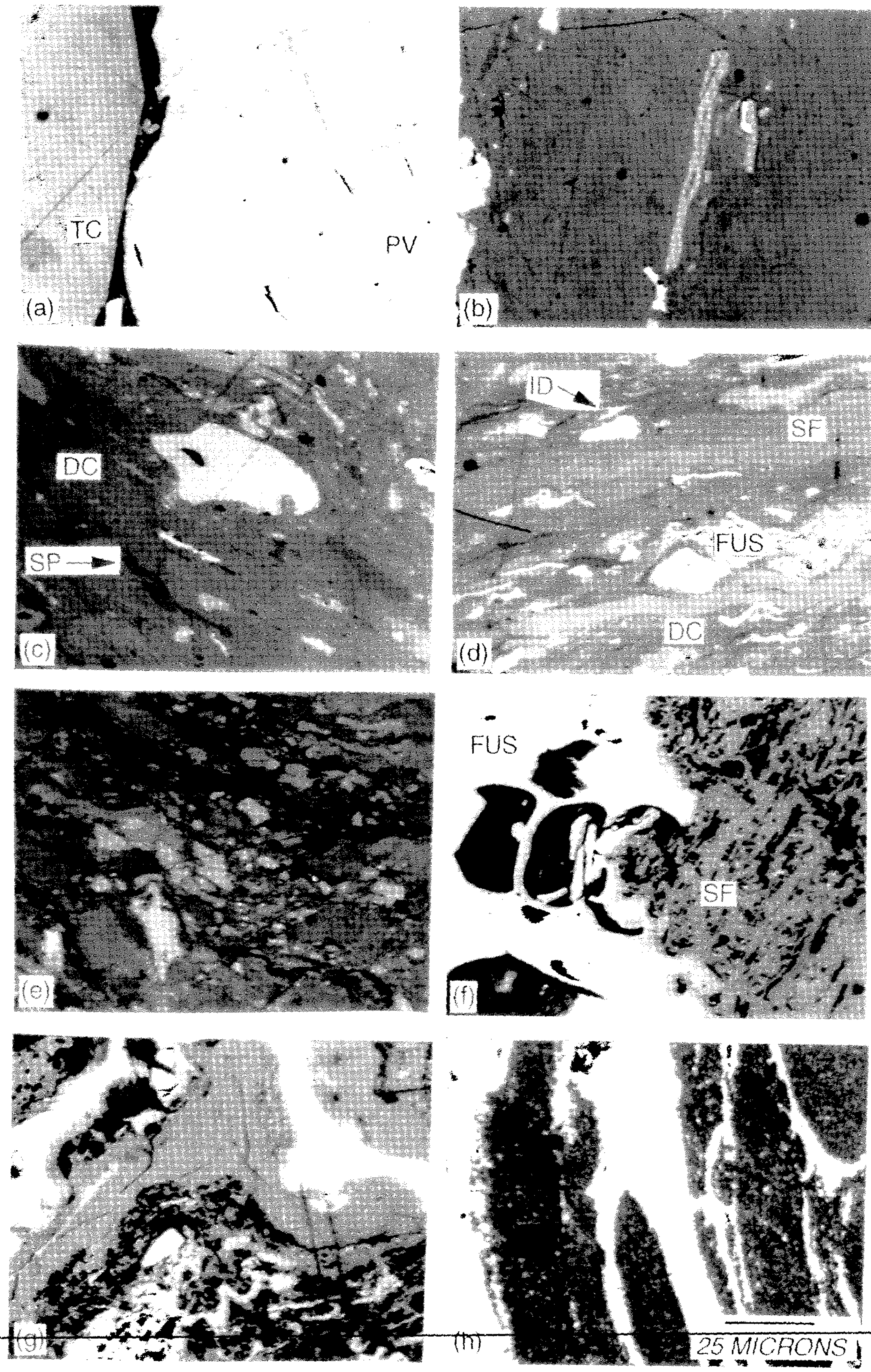
(d) Banded dull - semifusinite, fusinite and inertodetrinite in matrix of desmocollinite.

(e) Dull - Field of view shows abundant inertodetrinite in desmocollinite matrix.

(f) Fibrous - Fusinite and semifusinite are most common macerals.

(g) Sheared coal - note high concentration of mineral matter with shreds of vitrodetrinite, inertodetrinite and telocollinite.

(h) Clastic parting - note remnant cellular outline in vitrinite.


TC
PV
(a)
(b)
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SP
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FUS
DC
(d)
(e)
FUS
SF
(f)
(g)
(h)
25 MICRONS

Kootenai Formation flora (Early Cretaceous, Montana), Lapasha and Miller (1984) reported that *Elatides curvifola* and *Athrotaxites berryi* have thin cuticles whereas some of the *Elatocladus* sp. have thick cuticles. These genera are quite common in the Gates Formation (Leckie, 1983; this study). It may be that the plants occupying the peat-forming wetlands had thin, rather than thick walled cuticles and consequently, the cuticles are not well preserved. Although liptinite macerals tend to be quite resistant to decay, they are susceptible to oxidation and microbial attack if not buried immediately (removed from the aerobic zone). In both freshwater and brackish environments, spores and pollen are readily attacked by chytrid fungi (Scagel et al., 1982; G. Rouse, pers. comm.). The pH of the environment exerts a controlling influence over microbial activity. Although peat-forming environments tend to be acidic, groundwaters in the peats may be closer to neutral or slightly alkaline if the wetland is open to freshwater influx. For example, the pH of modern southern (United States) deep water cypress (taxodiaceous) swamps varies from 3.5 - 5.0 in cypress domes (primarily rainwater-fed) to 6-7 in alluvial swamps (open to river flooding; Mitsch and Gosselik, 1986). More research concerning the vegetation of the wetland environments is necessary. However, it seems reasonable to propose that the low liptinite concentrations are due to a combination of enhanced activity by microbes in more neutral waters of fresh water wetlands and the characteristics of the vegetation.

The substantial compositional overlap that occurs between the lithotypes (Figs. 2-12, 2-10) is not surprising in that the five "main" lithotypes (bright, banded bright, banded coal, banded dull and dull) are visibly differentiated by the relative percentage of the two end member components, *i.e.*, bright and dull bands, with the divisions somewhat arbitrarily defined. Do the two megascopically differentiated end members correspond to particular maceral compositions? Another way to phrase this question is: what makes a coal bright or dull? Based on the maceral analyses of Gates Formation coals, as well as most humic bituminous coals, brightness is attributable to vitrinite, particularly structured vitrinite. In most coals, dullness has been attributed to either liptinite or inertinite content (Teichmuller, 1989). Visible liptinite cannot be the cause of the dullness in the Gates coals (liptinite concentrations <2%). Petrographic data collected for this study indicate that the dull component of the Gates Formation coals is due primarily to inertinite content and to a lesser extent, unstructured vitrinite and mineral matter. From the brighter to duller lithotypes, the grain size of the vitrinite changes from coarse

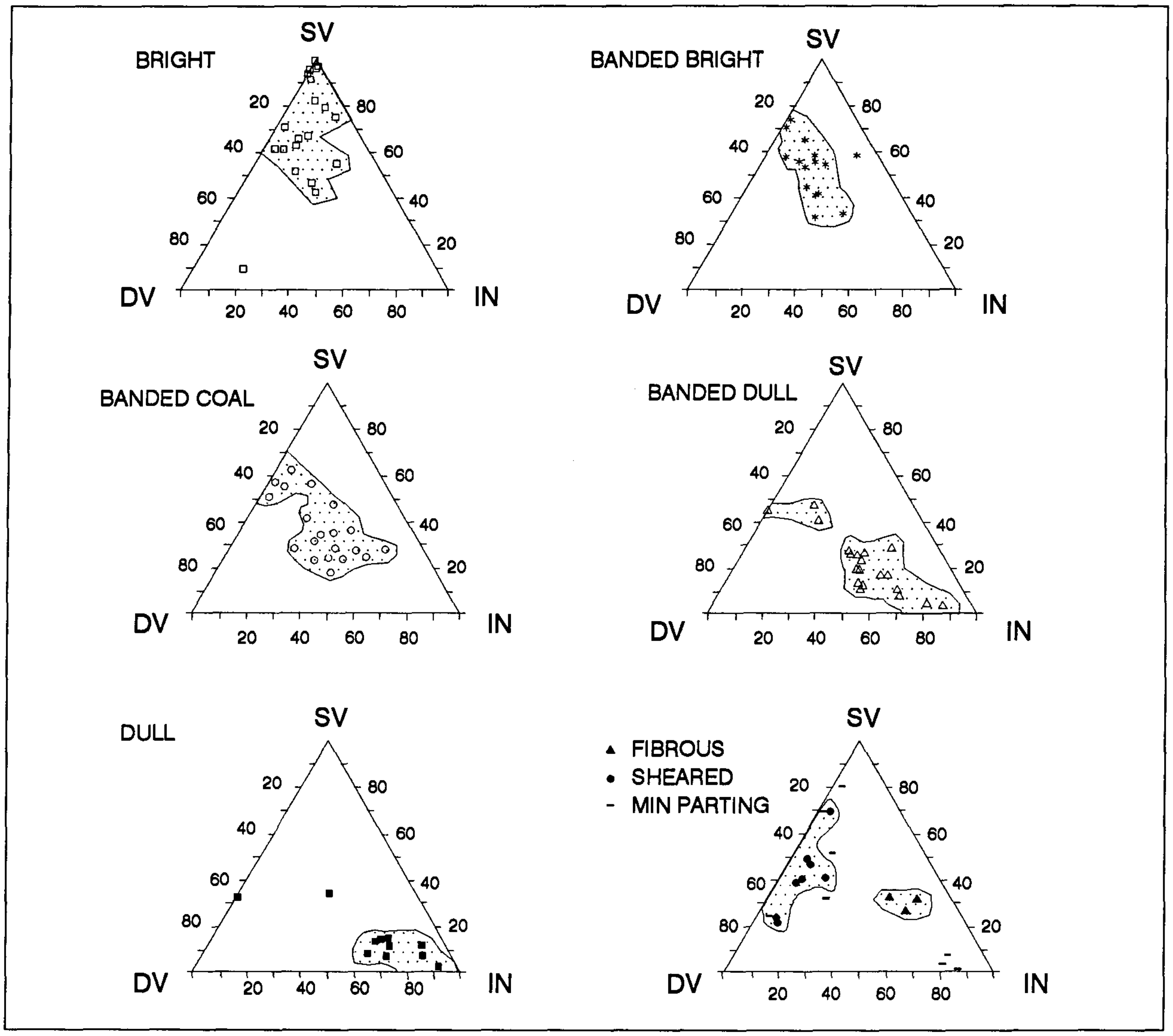


Figure 2-12. Ternary composition diagrams by lithotype, mineral matter free basis. SV = structured vitrinite; DV = degraded vitrinite; IN= total inertinite. Stippled areas show major groupings of points. See text for further explanation;

fragments of structured vitrinite (intact plant tissues) which have large reflective surfaces, to fine pieces of vitrodetrinite and desmocollinite (degraded or chemically altered bits and pieces of plant tissues) which have small reflective surfaces. The smaller reflective surfaces disperse light more readily, creating a dull appearance. Additionally, petrographic analysis results indicate an average increase in mineral matter from bright to dull coal (Fig. 2-10).

2.7.2 Wetland Vegetation

One of the most difficult problems in interpretation of pre-Late Cretaceous or pre-Tertiary wetland environments lies in visualization of a world without grasses, sedges and floating angiosperm aquatics, plants which occupy important marginal and successional environments in modern temperate wetlands (Collinson and Scott, 1987). Between Aptian and Cenomanian time, major changes in vegetation occurred with the expansion of angiosperms from open/disturbed sites (as successional weedy herbs or shrubs) into forest tree environments. The vegetation changed from one dominated by conifers (araucarian and taxodiaceous) and cycads (as shrubs) to one dominated by conifers and angiosperms (Crane, 1987). ***Herbaceous*** vegetation during the Aptian to Cenomanian was composed of ferns, gnetalean plants, lycopods and angiosperms, with the percentage of angiosperms increasing from Aptian to Cenomanian time.

The Gates Formation was deposited during the Albian, a poorly understood time in terms of paleobotany; previous studies of western North American Cretaceous plant communities have bracketed this time period. The wetland vegetation of the Aptian Kootenai Formation (Montana) was dominated by taxodiaceous conifers with an understory of tree ferns or herbaceous ferns (Lapasha and Miller, 1984) . By Upper Cretaceous time, during deposition of the Blackhawk Formation (Book Cliffs, Utah), arboreal angiosperms were co-dominants with the conifers in swamps (the *Sequoia cuneata - Rhamnites eminens* association), in addition to occupying floating aquatic and marginal sites (Parker, 1976). According to Balsey and Parker (1983) the environments were similar to the Okefenokee *Taxodium* swamps, but with *Araucaria* dominant in paralic settings and *Sequoia* dominant in more landward settings.

Megafossils identified in roof and floor rocks of Gates Formation coal seams during this study, some of which are illustrated in Figure 2-13, and in an earlier study by Leckie (1983), include conifers (*Elatocladus* sp., *Elatides* sp., *Cyparissidium* sp., *Athrotaxites berryi*, *Sequoia* sp.,), pteridosperms (*Sagenopteris williamsii*), cycadophytes (*Pterophyllum* sp., *Ptilophyllum* sp., *Pseudocycas* sp., *Nilssonia* sp.), ferns (*Cladophlebis* sp., *Coniopteris* sp., *Klukia canadensis, Sphenopteris* sp.) and ginkgophytes (*Ginkgoites pluripartitus, G. digitatus*). Although no megafossil remains of angiosperms have been found in the study area, their presence in the wetland is evident from scalariform perforation plate and vessel pitting structures preserved in telinite (Fig. 2-14) and fusinite from several samples taken from the Bullmoose B seam. However, the dominant form of vegetation was probably coniferous as indicated by the abundance of uniseriate ray and large bordered pit structures (Fig. 2-14) commonly seen in fusinite and semifusinite. Which conifers actually dominated in the wetlands requires future research. Fossil foliage and structures seen in fusinitized wood indicate the dominant vegetation was from the Taxodiaceae, Cupressaceae, Pinaceae or Araucariaceae, or a combination of the four families. Cycadophytes are often considered "upland" flora (Tidwell et al., 1976). However, in view of the abundance and excellent preservation of their fossil remains in fine-grained sediments of the Bullmoose area (Fig. 2-13), it is postulated that they were also found in the peat-forming wetlands.

The peat-forming wetland of the Gates coals was a wide, low relief, poorly drained coastal plain (Fig. 2-4). In view of the age of the coal, and based on the megafossil and phyteral evidence, the wetland environments most likely contained taxodiaceous conifers as the dominant tree (swamp) type, with cycads, tree ferns and perhaps angiosperms as understory or open area shrubs. Ferns, angiosperms and herbaceous lycopods (?) occupied marshy or marginal environments. Several wetland types were present: herbaceous marshes, open marshes with or without shrubs, and forest swamps, with or without standing water. These conclusions are preliminary; more sample collection is necessary before any firm conclusions are possible.

Figure 2-13.

Examples of some of the more common plant fossils in the middle Gates Formation, Bullmoose mine area. Coin scale = 1.9 cm.

(a) Floor rock, A1 seam, with scattered plant impressions. Ni = *Nilssonia* sp., Pt =*Ptilophyllum* sp.

(b) Enlargement of (a) showing *Sagenopteris williamsii* (Sg), *Coniopteris* sp. (Co), *Ptilophyllum* sp. (Pt).

(c) *Pseudocycas sp.*;

(d) Enlargement of (a) showing unidentified conifer branch;

(e) Enlargement of (a) showing *Elatides curvifola* (El);

(f) *Athrotaxites berryii.*

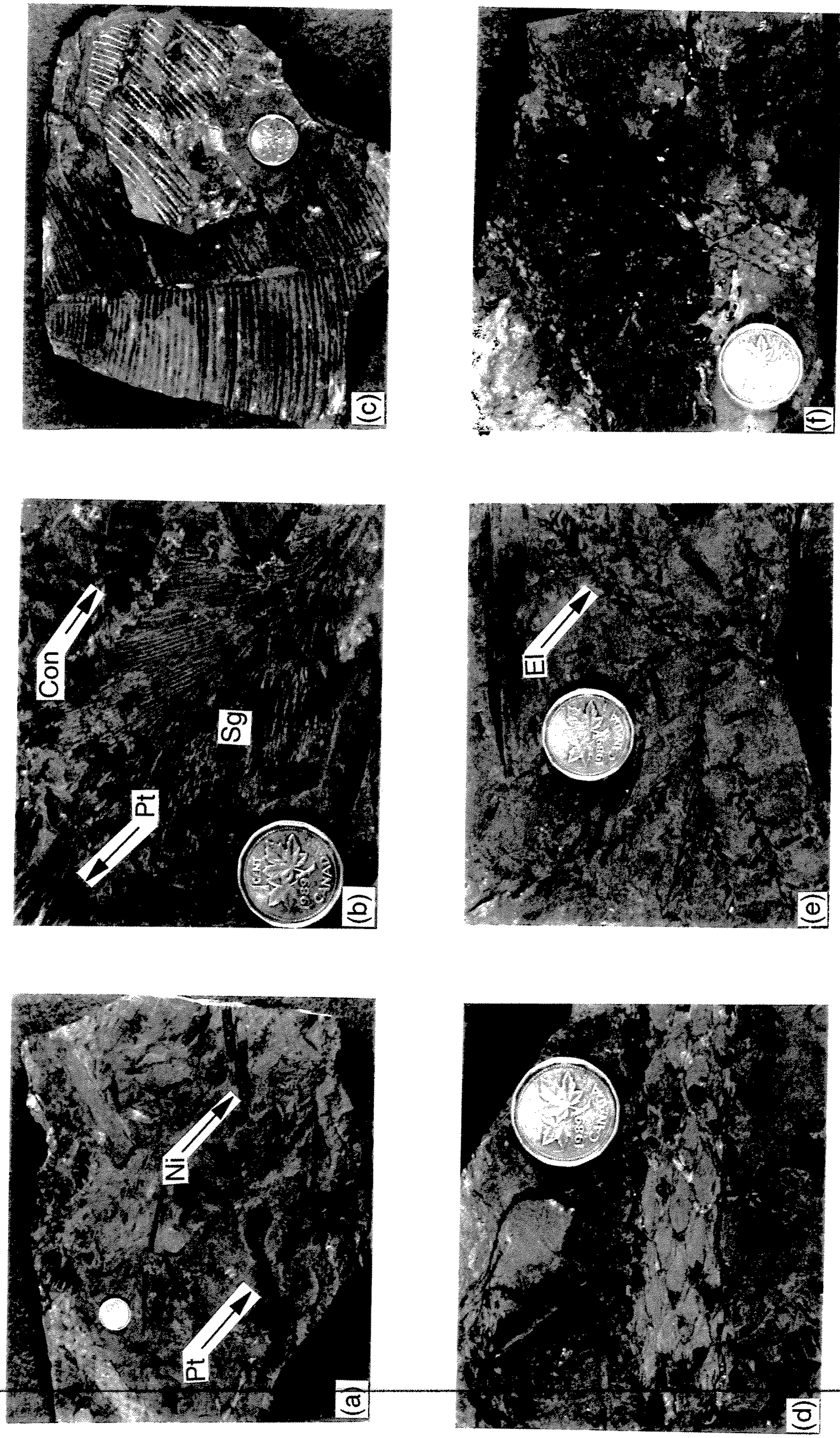

(a)
Pt
Ni
(b)
Pt
Sg
Con
(c)
(d)
(e)
El
(f)

Figure 2-14.

Phyteral evidence of plant types within the Gates peat-forming wetlands. Scale same for all photomicrographs as in (e).

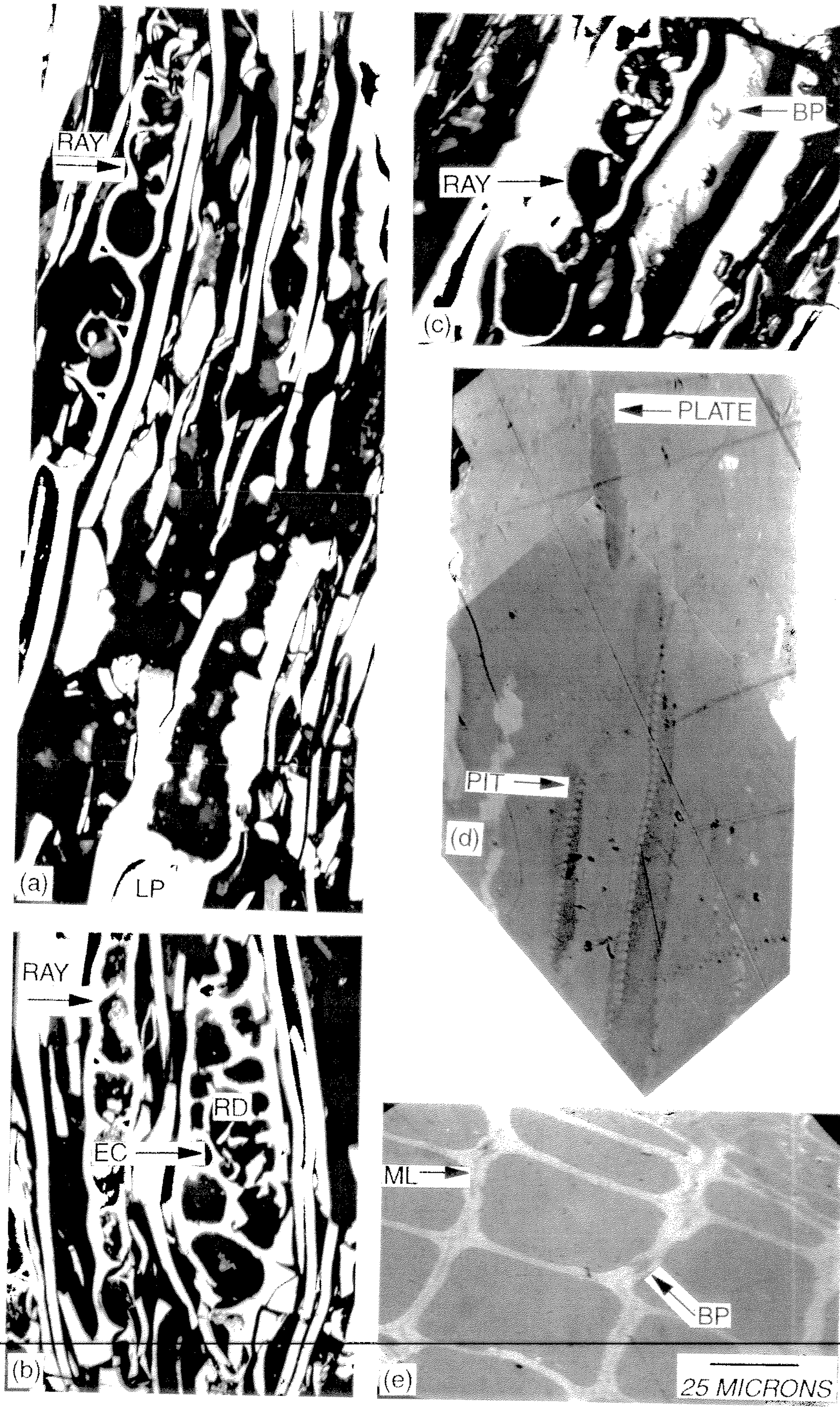
(a) Fusinitized coniferous wood with uniseriate rays, tangential section. Note longitudinal parenchyma (LP) cells with former phenolic (?) waste product.

(b) Fusinitized coniferous wood with uniseriate rays, tangential section. RD = resin duct; EC = epithelial cell.

(c) Fusinitized coniferous wood, tangential section. Note large bordered pits (BP).

(d) Angiosperm wood vessel structures preserved in telinite, including scalariform pitting and remnant scalariform perforation plate.

(e) Coniferous wood, cross section, telinite. Note excellent preservation of bordered pits (BP) and middle lamella (ML).


RAY
LP
(a)
RAY
RD
EC
(b)
BP
RAY
(c)
PLATE
PIT
(d)
ML
BP
25 MICRONS
(e)

2.8 COAL FACIES REPRESENTED BY GATES FORMATION LITHOTYPES

2.8.1 Environment interpretation based on maceral composition

The Diessel coal facies diagrams facilitate interpretion of the characteristics of the original peat-forming wetland based on assumptions (previously discussed) concerning the origin of the lignin and cellulose derived macerals. However, it must be kept in perspective that compositional differences between lithotypes may arise as a result of differences in wetland communities, or may represent different decompositional states of a single plant community (Ting, 1989). For example (Fig. 2-6b), a wet forest swamp may give rise to peats with four different petrographic compositions if depositional conditions change during the lifetime of the swamp: 1) telinite rich (high TPI, low GI) if buried rapidly enough to avoid extensive microbial attack; 2) desmocollinite rich (high GI, low TPI) if buried such that microbial decay destroys cellular structure, but does not completely degrade the humic material to CO_2 and H_2O; 3) semifusinite and fusinite rich, if subjected to fire; and 4) inertodetrinite-rich (low TPI, GI) if frequently subjected to fires, and relatively dry conditions prevail allowing desiccation and the preferential destruction of humic material.

The results of the maceral analyses were used to calculate GI and TPI of each lithotype sample. Coal facies diagrams for Gates Formation lithotypes are illustrated in Fig. 2-15. As may be inferred from the compositional overlap seen in Fig. 2-10, there are no strictly defined lithotype fields. The trend of inertinite enrichment from bright to dull is reflected in a progressive decrease in the GI, and to a lesser extent, the TPI.

For the most part, the bright and banded bright lithotypes (Fig. 2-15a) plot in the wet forest swamp field of Diessel (1986). Three bright lithotype samples have very high (>90) TPI values, and an undefined (infinite) GI due to lack of inertinite. These samples are believed to represent individual logs, rather than an entire plant community. Gates Formation banded bright and bright lithotypes are interpreted to have formed in wet areas dominated by plants with lignified tissues which were not exposed to extensive oxidation. However, occasional fires may have swept the wetlands, as evidenced by the scattered fibrous lenses and laminae noted in outcrop. Banded coals (Fig. 2-15b) also plot in the wet forest field, but have lower GI, indicating drier conditions. The shift toward drier conditions is interpreted to represent the presence of a persistently lower water table, allowing for

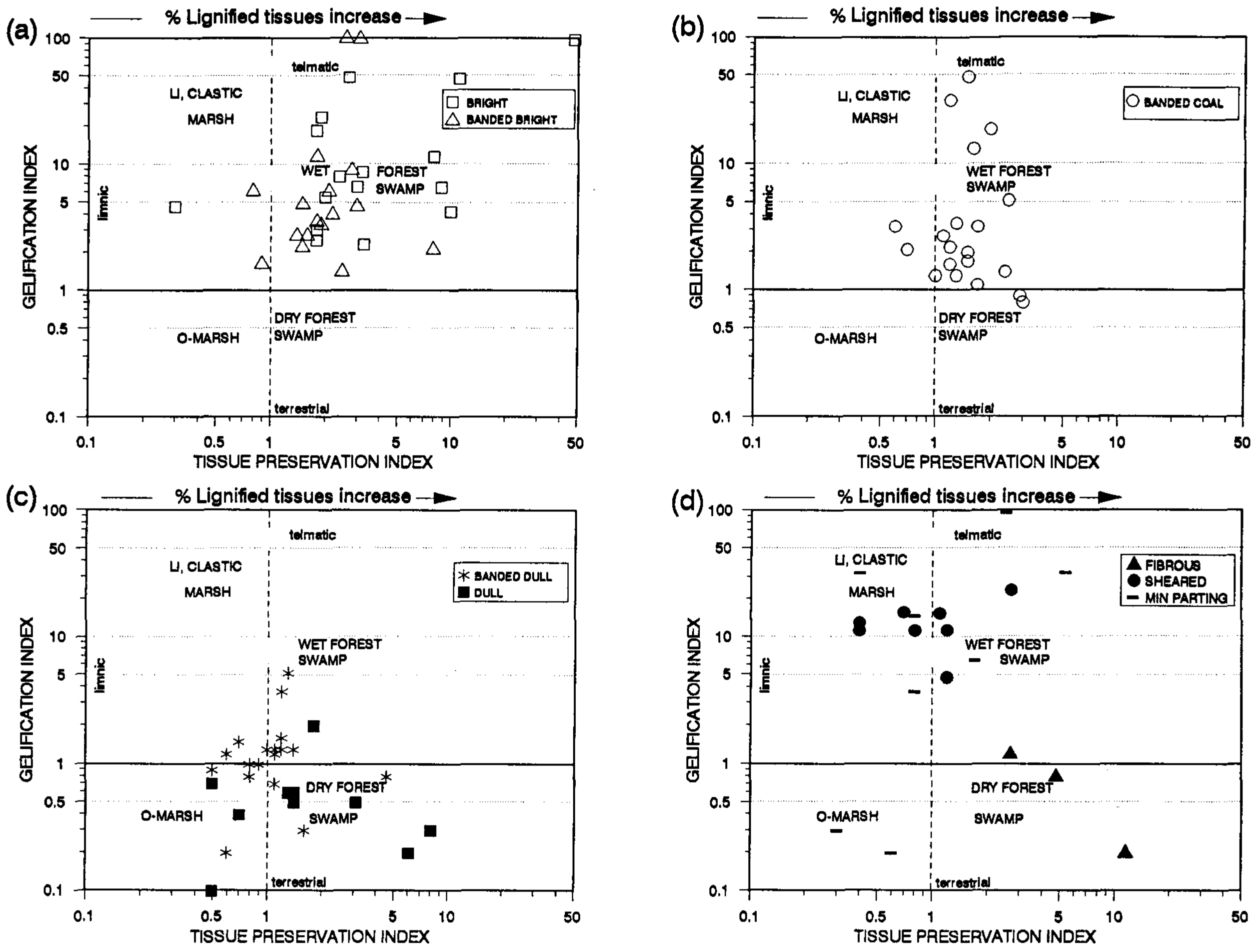


Figure 2-15. Coal facies diagrams for Gates Formation lithotypes (modified from Diessel, 1986). Gelification and tissue preservation indices defined in methods section. See text for explanation.

more intense oxidation at the surface (increase in inertinite). Alternatively, banded coals may represent marginal environments between swamps and marshes, or an increased percentage of shrub vegetation (lower initial lignin: cellulose ratio).

Banded dull coals (Fig. 2-15c) have low GI's, and TPI values of less than 2. Dull coals tend to have very low GI (<1) and variable TPI. Several different wetland environments could have produced the duller lithotypes. The low GI's imply overall drier depositional conditions (the dry forest swamp of Diessel, 1986) and/or a fluctuating water table resulting from periods of drought. The petrography of some of the banded dull coals is similar to the *Taxodium* peat described by Cohen (1973) from the Okefenokee swamp-marsh complex (Georgia). *Taxodium* peat has a high proportion of twig and leaf litter, a framework to matrix ratio of 50/50 and often contains abundant charcoal. The cypress stands commonly occur in several centimetres to a metre of water, but are periodically subjected to periods of drought, allowing oxidation of the peat. During the drought periods, fires are common. According to Cohen's study, these communities will tend to give rise to laminated coal lithotypes, particularly duroclarain (banded dull). Thus, what might be considered a wet forest swamp, follows the desiccation pathway shown in Fig. 2-6b. In consideration of the phyteral and megafossil evidence discussed previously, it is interpreted that the majority of the banded dull and dull coals in the Gates Formation formed in taxodiaceous wetlands. Compositional differences between these lithotype samples are attributable to differences in depositional conditions within the plant community.

The lower GI's and TPI's of the duller lithotypes may also be due to a change in vegetation type from arboreal to shrub and herbaceous vegetation, depending on the accumulation rate and exposure to oxygen. Two banded dull coals and one dull coal have undefined GI's (contain inertinite < 1%), and therefore do not plot on the facies diagram. All three of the samples are mineral-rich, with low TPI's and enriched in vitrodetrinite. Although the samples do not plot on the diagram, the maceral content corresponds to that described for the clastic marsh. Banded dull and dull coals with TPI and GI values significantly less than one are believed to have formed in the open marsh setting (Fig. 2-15c).

The three fibrous coal lenses examined had high TPI's, with variable, though relatively low, GI's (Fig. 2-15d). The origin of fibrous coal has been the subject of speculation for some time. However, the bulk of evidence points to an origin from wildfires (Scott, 1989). The pristine cell structure preserved in the fusinite of the Gates Formation coals along with the association with semifusinite and structured vitrinite supports the wildfire hypothesis. The presence of numerous lenses and laminae of fibrous coals indicates that fires were common in the wetland and/or adjacent environments. However, the rarity of thick accumulations suggests that the fires were of a surficial (crown or surface; Davis, 1959) nature, rather than ground fires. Several of the banded dull and dull coal samples also have high TPI's (Fig. 2-15c) caused by the presence of semifusinite and fusinite, rather than structured vitrinite. These lithotypes are also believed to represent fire episodes in the wetland.

Several possibilities exist for the origin and depositional environments of the roof and floor rocks and clastic partings examined (Fig. 2-10, Fig 2-15d). Five of the eight samples (Fig. 2-15d) have low TPI's but variable GI's. Samples with low GI's are enriched in inertodetrinite, suggesting an allochthonous source for the organic matter. These strata were probably deposited in marginal (stream side or lake side) areas subject to clastic influx. Alternatively, they represent splays (flooding events) into a previously closed peat-forming wetland.

Clastic partings or roof/floor rock samples with higher (>1) GI's are interpreted to have formed either in a low energy pond/lake or in marshes. Organic accumulation rates were high enough to induce partial anoxia, thus preventing complete decomposition of organic material, but clastic influx was high enough to prevent coal formation. This type of environment is similar to that in which canneloid coal forms. Many canneloid coals contain a high proportion of vitrinite (desmocollinite and vitrodetrinite), along with inertodetrinite and fine grained mineral matter. However, the Gates Formation coals are practically devoid of liptinite. Vitrinite-rich carbonaceous mudstones may also form in a clastic marsh environment where organic accumulation rates do not keep up with the rate of clastic influx. leaving a mudrock with fragments of tissue (vitrodetrinite), degraded vitrinite (desmocollinite) and/or inertodetrinite. Three clastic samples fall within the wet forest swamp category. In the three samples, the structured vitrinite is contained within a mud matrix. These partings represent either: an overbank splay/flood deposit in which fragments of twigs, leaves, branches, etc. are rapidly buried (preventing degradation); or the rooted rocks of a roof or floor.

Sheared coals (Fig. 2-15d) owe their origin to post-depositional tectonic disturbance. No facies assignment can be made with certainty. Six of the eight sheared coal samples plot in a cluster in an area of the diagram which lies between clastic marsh and wet-forest swamp, whereas the remaining two plot in the wet forest field proper. The coal may be sheared due to high mineral matter contents (Fig. 2-10); the presence of clay in particular tends to facilitate movement during deformation. It may be that the high mineral matter content found in coals, particularly those formed in the clastic marsh environment, promotes shearing.

2.8.2 Bullmoose B and D seams

The general characteristics and lithotype trends in the Bullmoose B and D seams were described in an earlier section. The two seams represent two different types of depositional systems. The B seam developed within a broad, low relief coastal plain protected from clastic input. However, degradation levels were relatively high, as evidenced by the predominance of the duller lithotypes. The dull and banded dull coals analysed from the B seam have relatively high TPI's, but variable GI (all are less than 2). Differences in lithotype stratigraphy are primarily the result of fluctuations in ground water level, rather than differences in plant communities.

The Bullmoose D seam is characterized by a cyclic repetition of lithotypes. The cyclic repetition is interpreted to represent fluctuations in wetland type due to repeated influx of clastic material from adjacent fluvial channels. The banded dull coal and two of the three mudstones analysed have low TPI, and variable GI. These lithotypes are interpreted to have formed in marshy areas marginal to fluvial environments. The D seam developed as a result of cyclic burial and re-establishment of wet forest conditions.

2.8.3. Facies analysis of Shikano D seam

A facies profile of the Shikano D seam is shown in Fig. 2-16. The D seam formed in a broad coastal plain wetland (Fig. 2-4). The wetland environment established itself on a muddy substrate (Fig. 2-9, zone I; Fig. 2-16, 1-3), marginal to a low energy stream. A clastic marsh developed (zone II, 4-6), as indicated by enrichment in vitrodetrinite and mineral matter coupled with low inertinite. Vegetation was composed of mixed herbs and

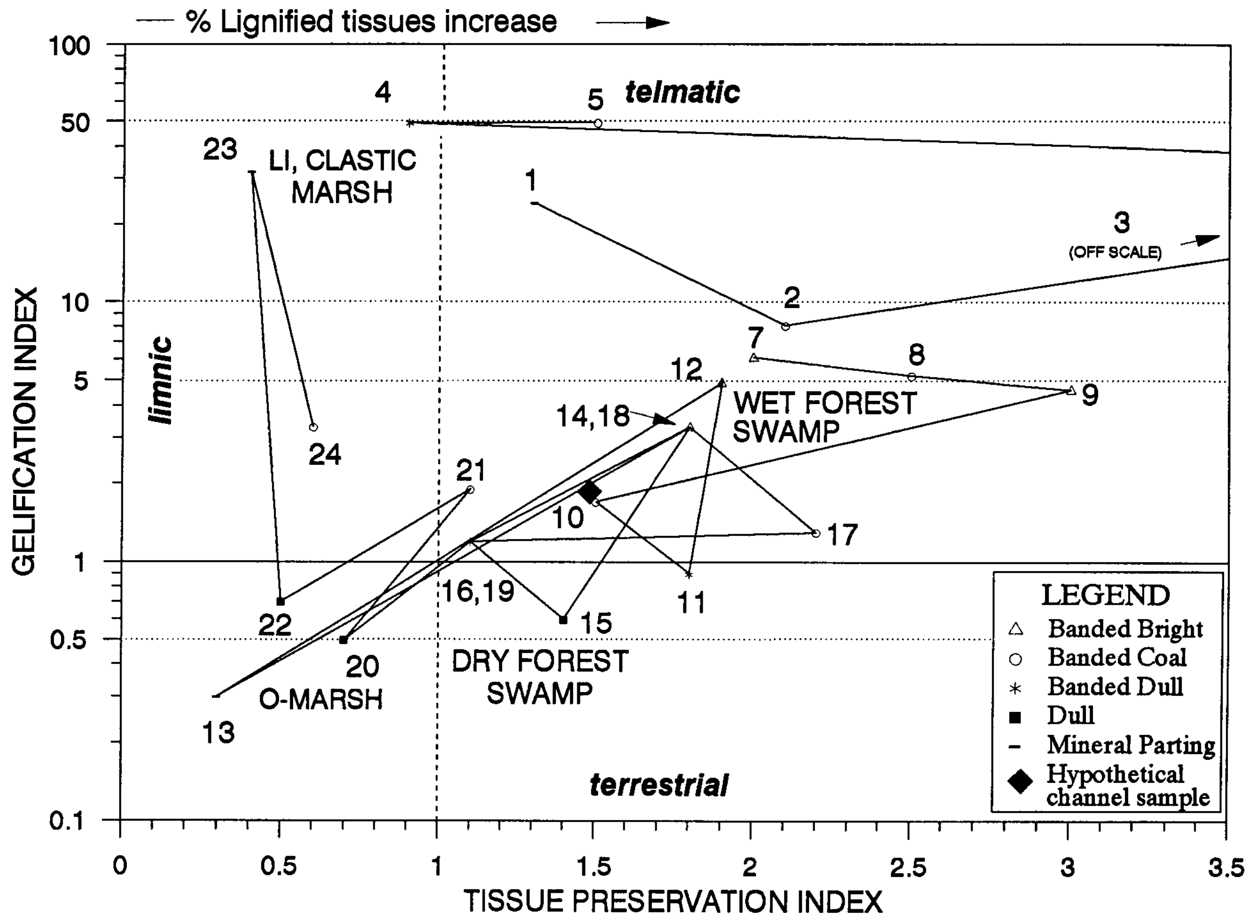


Figure 2-16. Coal facies diagram depicting the change in wetland environments during the deposition of the Shikano D seam. Numbers correspond to lithotype samples depicted in Fig. 8. Note location of hypothetical channel sample (weighted compositional average of all samples).

shrubs, as indicated by the variable TPI. The majority of seam development (zones III-IX) is interpreted to have taken place in forest swamps. Lithotype variations were primarily due to fluctuations in ground water level. Zone III (7-11) represents a gradual drying cycle. Inertinite increases gradually as ground water level drops, culminating in the banded dull section at the top of the cycle. The wet forest re-establishes itself in zone IV (12), only to be destroyed by a fire or drowned as a result of a crevasse splay in zone V (13). Zone VI (14-15) represents another drying out cycle. A gradual rise in ground water table is recorded by zone VII (16-18), which changes from a banded dull coal (or even the dull coal at the top of zone VI), to a banded bright coal. A long period of relatively dry, or periodically dry conditions follows (zone VIII, 19). Zone VIII probably represents the *Taxodium* type swamp described above. The dull layer at the top of the cycle (base of zone IX) records the destruction of this community and the establishment of the open shrub marsh. Ground water levels again rise (Zone IX, 20-21) and a wet shrub mire developed. This elevation of the groundwater table is interpreted to represent a regional rise in sea level. Zone X records a change to estuarine conditions, as indicated by the presence of abundant pyrite in sample 22 (a dull coal). All three lithotypes in the zone X are mineral rich. The zone is interpreted to be a muddy salt marsh environment. Directly overlying the D seam are transgressive marine deposits (Fig. 2-4; Carmichael, 1988).

2.8.4 Use of channel samples for interpretation of environment

The TPI - GI facies diagram was developed using channel samples (Diessel, 1986). In this study, the TPI-GI facies diagram has been used to interpret the results of lithotype samples - samples which represent individual facies, and hence, depositional environments at particular locations within the seam. The composition of a hypothetical coal channel sample of the Shikano D seam is plotted on the facies diagram (Fig. 2-16). Care must be taken if one is attempting to assess wetland environments using a channel sample. It might be argued that a channel sample represents an "average" environment, or that which predominated during seam development. However, an "average" environment does not exist. If a marsh and a tree swamp are averaged, does a shrub mire result? Use of channel samples to interpret (wetland) depositional environments ignores the complexity of the natural system and should be avoided.

2.9 SUMMARY AND CONCLUSIONS

Compositional boundaries between bright, banded bright, banded coal, banded dull and dull coal are gradational in the mid-Albian Gates Formation coals in northeastern British Columbia. From bright to dull coal, there is an increase in the percentage of inertinite, with a concomitant decrease in vitrinite. The dullness of the coals is primarily due to inertinite, not liptinite (liptinite concentrations are negligible in these coals). A minor component of the dull appearance may be due to high concentrations of unstructured vitrinite and/or mineral matter. Fibrous coals are composed primarily of inertinite; the pristine cell structure preserved and its association with structured vitrinite suggests an origin from wildfire.

The coals formed on broad, low relief coastal plains. The wetlands were dominated by coniferous trees, with a significant component of ferns as herbs or low trees. However, angiosperms and cycads contributed to the vegetation in the form of shrubs, and in the case of angiosperms, marginal herbs. Differences in lithotype stratigraphy are due to variations in ground water level as well as differences between wetland types. Peats formed in areas protected from clastic influx (Bullmoose B seam) are generally duller, with rather uniform stratigraphy. Coals developed in less protected areas (Bullmoose D seam) have more variable stratigraphy, and a higher component of the brighter lithotypes. The lithotypes represent a continuous spectrum of depositional environments from predominantly forest swamps (both wet and dry) to dry, herbaceous and/or shrubby marshes. Bright and banded bright coals formed in wet swamp forests. Banded dull and dull coals represent a number of environments including drier phases of *Taxodium*-type deep water swamps, dry forest swamps, open marshes and clastic marshes.

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CHAPTER 3

COALBED METHANE CHARACTERISTICS OF GATES FORMATION COALS, NORTHEASTERN BRITISH COLUMBIA: EFFECT OF MACERAL COMPOSITION

3.1 ABSTRACT

The majority of research reported on methane adsorption characteristics of coal seams has focused on vitrinite-rich coals. However, western Canadian coals are more inertinite-rich than those of the western United States and are shown to differ in gas adsorption characteristics. The influence of maceral composition upon gas adsorption characteristics of medium-volatile coal samples from the mid-Cretaceous Gates Formation of northeastern British Columbia was investigated. Lithotype (coal facies) samples were analyzed for surface area, maceral and mineral composition and methane adsorption, as well as standard coal analyses (proximate, low temperature ash and equilibrium moisture). The vitrinite content of the samples analyzed ranges from 18 to 95% (volume %, mineral matter-free); the ash yield varies from 4.4 - 33.7% (weight %). Both maceral composition and mineral matter content have an important influence on adsorption characteristics as indicated by carbon dioxide surface areas and methane adsorption isotherms. On a mineral-matter-free basis, the amount of methane adsorbed generally increases with vitrinite enrichment. Maceral texture also influences adsorption characteristics; methane adsorption increases with increased structured vitrinite on both mineral matter-free and raw-coal bases. The lowest methane adsorption occurs in the sample with the highest inertinite content. Carbon dioxide surface areas of the lithotypes range from 58 - 124 m^2/g on a raw-coal basis, and 66 - 132 m^2/g on a mineral matter-free basis. Surface area generally decreases with increased mineral matter content, and increases with increased vitrinite content. The increase in adsorption of both methane and carbon dioxide with increased vitrinite concentration is interpreted as being due to differences in the pore size distribution of vitrinite and inertinite: vitrinite is predominantly microporous whereas inertinite is meso- to macroporous. The monolayer volumes of carbon dioxide (as calculated from the Dubinin-Radushkevich equation) are higher than those of methane (as determined from the Langmuir equation), but are correlated. The methane adsorption isotherms and surface area

data indicate that the maceral compositional variations in coal are at least as significant as coal rank in determining the potential volume of adsorbed methane and thus coalbed methane potential of a deposit.

3.2 INTRODUCTION AND RESEARCH OBJECTIVES

Coals are derived from the thermal and biogeochemical alteration of terrestrial plant accumulations. The resultant deposit is a heterogeneous mixture of organic (maceral) and inorganic (mineral) substances. As the organic deposit is buried and subjected to increased pressure and temperature, the physical and chemical structure of the individual macerals, and the coal as a whole, changes. The nature and extent of the changes to each maceral group are only partially understood. Despite the incomplete understanding, it is known that, at a given rank, the composition of the coal controls its utilization properties, as amply demonstrated by the variation in coking qualities of coals of different compositions (Shapiro et al, 1961; Shapiro and Gray, 1964; Benedict et al., 1968).

One effect of the maturation process is the generation of large quantities of thermogenic methane beginning in the high-volatile bituminous range (Meissner, 1984; Rightmire, 1984), and continuing through anthracite rank. The large internal surface area of coal (Gan et al., 1972; Thomas and Damberger, 1976), provides an extensive surface for adsorption. Recently there has been a great deal of interest in coal as a natural gas source and reservoir (e.g., Rightmire, 1984; Choate et al., 1986; Ayers and Kelso, 1989; Moore et al., 1991). Researchers identify rank, pressure, hydraulic gradients, degree of deformation (fracturing) and the amount of mineral matter as important parameters for assessing a particular coal as a methane resource (Kim, 1977; Meissner, 1984; Ayers and Kelso, 1989). Currently over 28 million cubic metres of natural gas are produced from some 500 wells in the Unitied States (Kuuskraa et al., 1992). However, there has been no systematic study which has investigated the effect of variable petrographic (aside from mineral matter) composition on methane adsorption. This fact is not surprising, in that much of the published work on coalbed methane is focused on the almost exclusively vitrinite-rich Cretaceous coals of the western interior of the United States (Meissner, 1984; Choate et al., 1986).

The abundant coal reserves of Jurassic and Cretaceous strata of the Western Canada Sedimentary Basin (WCSB) are also believed to be source and reservoir for major methane accumulations (Wyman, 1984; Dawson et al., 1991). These coals differ markedly in composition from the Cretaceous coals of the United States. Jurassic and Cretaceous coals of the WCSB are enriched in inertinite relative to vitrinite and contain low quantities of liptinite (Kalkreuth and Leckie, 1989; Lamberson et al., 1991). The chemical and physical properties of vitrinite and inertinite differ markedly from one another, giving rise to distinct source and reservoir characteristics in the western Canadian coals. The objective of our ongoing research is to characterize, and eventually quantify, the effect of maceral and mineral compositional variability on the methane adsorption characteristics of western Canadian coals and thus coalbed methane potential. Inertinite-rich coals are also found in basins in other parts of the world, most notably Permian coals in Australia (Hunt, 1989; Smyth, 1989) and India (Navale and Saxena, 1989). In this paper, the results of a study of the adsorptive behavior of a suite of isorank coal samples of variable composition from the WCSB is reported, and the implications for understanding the controls on methane retention in seams is explored. Prior to discussing the results of this study, a brief review of information concerning coal composition and structure is provided as a basis for the conclusions.

3.3 STUDY AREA

The coals utilized for this study were collected from mine exposures of the Lower Cretaceous Gates Formation located in northeastern British Columbia (Fig. 3-1). In the Gates Formation, the majority of the coal reserves are present within the middle member (Carmichael, 1988). The middle Gates is stratigraphically equivalent to the Falher Member of the Spirit River Formation (Fig. 3-2), a unit known to have generated and retained large reserves of coalbed methane in the Deep Basin of Alberta and British Columbia (Wyman, 1984). Coals in the Bullmoose mine area range in reflectance (Romax) from 1.02% - 1.14% (Kalkreuth and Leckie, 1989), which corresponds to a coal rank range of high-volatile A - medium-volatile bituminous.

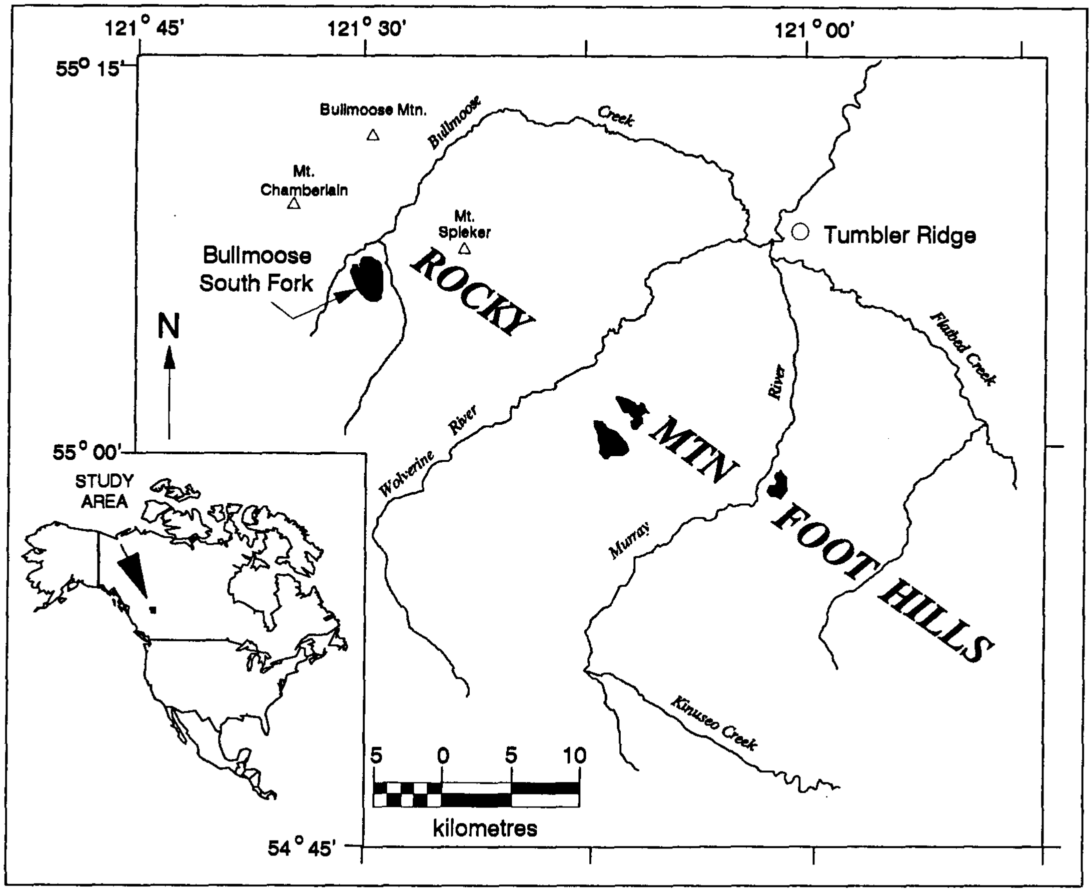

Figure 3-1. Location map showing the study area and sampling site of Bullmoose mine. black areas indicate major coal deposits of the Gates Formation. Map modified from Matheson (1986) and Lamberson et al. (1991).

STAGE	PLAINS			FOOTHILLS	
ALBIAN	SPIRIT RIVER FM	NOTIKEWIN MBR		GATES FM	"UPPER" GATES
		FALHER MBR	A		"MIDDLE" GATES
			B		
			C		
			D		
			E		
			F		TORRENS MBR
		WILRICH MBR		MOOSEBAR FM	

Figure 3-2. Stratigraphic chart of portion of Lower Cretaceous strata of northeastern British Columbia. Stratigraphic nomenclature modified from Leckie (1986), and Carmichael (1988).

3.4 COAL COMPOSITION AND STRUCTURE

3.4.1 Coal Composition

Maturation can be viewed as a process which takes the randomly oriented, extremely heterogeneous mixture of organic and inorganic compounds at the peat stage, and slowly alters them towards the highly ordered and oriented aromatic structure of graphite. All coals, including those of bituminous rank, are composed of three basic maceral groups: liptinite, vitrinite and inertinite. Liptinite, the hydrogen-rich maceral group, is virtually absent from the Gates Formation coals (Kalkreuth and Leckie, 1989; Lamberson et al., 1991), so this discussion will confine itself to the other two maceral groups. Vitrinite is derived from the lignin- and cellulose-rich tissues of plants. Sufficient differences exist in the optical, chemical and structural characteristics of vitrinite of different ranks that two separate petrographic nomenclature systems are used for low (less than bituminous rank), and for higher rank coals. Vitrinite in bituminous and higher rank coals commonly is differentiated, on the basis of retention of cellular structure, into structured (including telinite, telocollinite and pseudovitrinite) and unstructured/degraded (including desmocollinite and vitrodetrinite) varieties. The most abundant inertinite macerals (semifusinite, fusinite and inertodetrinite) are also derived from lignic and cellulosic tissues. However, the plant material undergoes a pyrolysis or partial combustion stage prior to burial, normally as a result of fire. Virtually all of the inertinite in the Gates Formation coals is interpreted to be fire-derived (Lamberson et al., 1991). The burning process drives the volatile material from the plant tissues, and consequently inertinite is composed of a higher weight-percent carbon and a lower weight-percent volatile matter than vitrinite. The differentiation of the two maceral groups is not always clear, and transitional material is commonly found. As might be expected from the chemical differences, the surface properties of the inertinite and vitrinite differ. Within the bituminous coal rank range, vitrinite-rich coals are more hydrophobic than inertinite-rich coals (Arnold and Aplan, 1989; Holuszko, 1991).

3.4.2 Coal Structure: Porosity Differences

One key parameter vital to understanding methane adsorption and diffusion from reservoirs is the nature of the porosity and pore size distribution in coals. Both of these parameters vary with rank (commonly expressed as weight percent carbon, % C), as shown in a study of vitrinite-rich coals by Gan et al. (1972). Porosity, as interpreted from a combination of helium and mercury density determinations, is initially high in low rank coals (maximum of 23%), decreases to a minimum (4%) at approximately 81% C (high-volatile bituminous), remains relatively constant until about 89% C (low-volatile bituminous) and increases abruptly (up to 10%) as the rank approaches 91% C (anthracite). Three pore size classes were defined by Gan et al. (1972): macropores, with pore diameters > 30 nm; transitional or mesopores, with pore diameters falling between 1.2 - 30 nm; and micropores, with pore diameter < 1.2 nm. The pore size distribution in coals varies with rank such that lignite (< 75% C) pores are primarily in the macropore range, high-volatile B and C bituminous coal pores (75 - 84% C) fall within the macropore and mesopore range and higher rank coal pores are dominantly microporous (Gan et al., 1972; Mahajan and Walker, 1978). It should be noted that pore size classes are now defined somewhat differently (MSTPQU, 1972). Micropores are pores with pore diameters less than 2 nm. Mesopores fall within the range 2 - 50 nm. Macropore diameters exceed 50 nm.

The coals studied by Gan et al. (1972) were chosen for their high vitrinite content, so the results reflect more on the structural changes of vitrinite with rank, rather than on the coal as a whole. Harris and Yust (1976; 1979) concluded from the data of Gan et al. (1972), that there is a relationship between vitrinite content and microporosity. They studied samples of high-volatile bituminous coals using transmission electron microscopy and small-angle x-ray scattering methods. These methods revealed that, at least within the high-volatile bituminous coal range, the porosity of vitrinite is a mixture of micropores (<2 nm) and pores at the lower end of the mesopore range (2 - 20 nm), whereas porosity in inertinite falls within a broad range of mesopores (5 - 50 nm).

Because the porosity in the higher-rank coals is predominantly of a microporous nature, adsorption is not thought to occur by simple area filling, but instead volume filling of the micropores (Mahajan and Walker, 1978; Marsh, 1987). The standard equation for determining surface areas, the BET (Brunauer et al., 1938), is not considered valid for use with microporous coals, rather the Dubinin-Radushkevich and Dubinin-Astakov methods, which involve the determination of monolayer capacity (micropore volume) are recommended (Mahajan and Walker, 1978; Marsh, 1987; Mahajan, 1991). The monolayer capacity is value then converted to an equivalent surface area by multiplying by the cross sectional area of the adsorbate molecule. Surface area analyses of coals are normally performed using carbon dioxide as the adsorbate at 298°C, using the lower pressure, linear end of the adsorption isotherm. Two recent reviews of gas adsorption in coals detail the reasons for using the equations, as well as the necessity for using carbon dioxide as the adsorbate (Marsh, 1987; Mahajan, 1991).

Surface areas (raw-coal basis) of coals vary with rank in a fashion similar to pore size distribution (Gan et al., 1972). Surface areas of low rank coals (<75% C) are high (225 - 359 m^2/gram), lower in the 75% C - 85% C range (high-volatile bituminous, 96 - 228 m^2/gram) and increase again through the medium-volatile and anthracite ranks (197 - 426 m^2/gram). However, considerable scatter exists in the data; as much as 80 m^2/gram within coals of the same carbon content (Gan et al., 1972). Surface area has also been shown to be related to maceral content. In the only published study to date which attempted to link maceral content and gas adsorption characteristics, Thomas and Damberger (1976) showed that the surface area of the coal increased with increasing vitrinite content. The chemical, surface property, surface area and pore size distribution differences between vitrinite and inertinite together suggest that compositional variation in coals is a critical variable in understanding differences in methane adsorption of different coals.

3.4.3 Gates Formation Coal Facies

The composition of a coal is essentially determined by differences in hydrologic conditions and vegetation in the original peat-forming wetland together with subsequent diagenesis. Stratigraphic (vertical) and lateral variations in environmental conditions within the original peat-forming wetland are expressed on the megascopic scale as variations in the relative concentration and sequence of bright and dull layers. Coal geologists term these distinct, recognizable layers lithotypes, which are considered to reflect coal facies. A number of classification schemes have been developed to facilitate lithotype field description. In this study, a modified Australian classification (Diessel, 1965) system was utilized (Table 3-1) which consists of differentiating lithotypes based on the relative percentage of bright and dull bands.

In the Gates Formation (Lamberson et al., 1991), variations in lithotype stratigraphy reflect variations in wetland environments ranging from herbaceous or shrubby marshes to Okefenokee-type conifer swamps

Table 3-1 Lithotype classification scheme used in this study. Modified from Diessel (1965), Marchioni (1980) and Lamberson et al. (1991).

Stopes-Heerlen (ICCP) Classification	Nomenclature used in this study	Description
vitrain	bright coal	subvitreous to vitreous lustre, conchoidal fracture, less than 10% dull laminae
clarain	banded bright coal	predominately bright coal, with 10-40% dull laminae
clarain	banded coal	interbedded dull and bright coal in approximately equal proportions
clarain	banded dull coal	predominately dull coal with 10 - 40% bright laminae
durain	dull coal	matte lustre, uneven fracture, less than 10% bright coal laminae, hard
fusain	fibrous	satin lustre, very friable, sooty to touch
no equivalent	sheared	variable lustre, disturbed bedding, numerous slip/slickenside surfaces, very brittle

(Lamberson et al., 1991). The brighter lithotypes consist primarily of vitrinite, particularly structured vitrinite. From the brighter to the duller lithotypes, there is progressive increase in inertinite and in some coals, mineral matter and degraded vitrinite. This "dulling" reflects changes in vegetation (from woody to herbaceous) and/or changes in rate of accumulation and decomposition of vegetal material (Lamberson et al., 1991). Fibrous coals are a special case, in that they are believed to form as a result of a fire (or a series of fires) within the original wetland, and as such reflect the destruction of a particular plant community.

Although it would perhaps be ideal to analyze pure maceral separates to determine their "true" gas adsorption properties, macerals are extremely difficult to isolate from one another. Indeed, questions exist as to whether or not the chemical and physical properties of the macerals are altered by current separation techniques (Bustin et al., 1993). The natural associations of macerals (and minerals) in lithotypes provide a method by which the effects of compositional variation on gas adsorption characteristics can be studied. This method of analysis requires many samples in order to quantify or statistically validate relationships. However, the general relationships may be seen by study of a suite of the lithotype samples.

3.5 METHODS

Eight lithotype samples were collected from Bullmoose mine (Fig. 3-1). Each was analyzed for petrography (maceral and mineral), proximate analysis, low-temperature ash, mineralogy (x-ray diffraction), sulphur, equilibrium moisture, carbon dioxide adsorption and methane adsorption. Seven of the eight samples are from the Bullmoose C seam. The other sample is from the A1 seam, located approximately 50 metres stratigraphically below the C seam. Prior to performing the methane adsorption isotherm analysis, all coals were crushed, wet sieved through a 250 μm screen, and brought to equilibrium moisture according to ASTM standard D1412-89.

Volumetric adsorption techniques were used to assess the monolayer capacity and surface area of the samples. Methane adsorption isotherms were performed using a high pressure adsorption technique similar to that of Mavor et al. (1990), at 22°C, with the coal at equilibrium moisture. The volume of methane adsorbed onto the coal for seven successively higher pressure points was determined utilizing pressures ranging from approximately 1 MPa - 15 MPa. A plot of P vs. V is termed an adsorption isotherm. Each data set was fitted to the Langmuir equation (Mavor et al., 1990):

$$\frac{P}{V} = \frac{P}{V_m} + \frac{1}{aV_m}$$

where P = pressure, V = volume of methane adsorbed, V_m = monolayer volume, a = constant.

According to the Langmuir adsorption theory, a plot of P vs. P/V yields a straight line; the reciprocal of the slope of the line fitted to the points corresponds to the methane monolayer volume. As is standard practice, the isotherm data were calculated to an ash-free basis and replotted.

The sample used for isotherm analysis (approximately 300 gram sample) was split for the remaining analyses. Carbon dioxide surface area analyses were performed at The University of British Columbia using a Micromeritics ASAP 2000M low pressure volumetric gas adsorption apparatus at 25°C. Each test was performed at least 2 times in order to check reproducibility of the data. Each 0.2 - 0.3 gram coal sample was first degassed at 70°C overnight to remove residual gas and moisture. Following free space determination with helium, each sample was evacuated and a series of leak tests performed. Once the leak test was passed, each sample was cooled to 25°C. Carbon dioxide was then bled into the sample chamber at a fixed rate; the tests were run at relative CO_2 pressures varying between approximately 0.0006 - 0.0100. Monolayer capacities were determined from the Dubinin-Radushkevich equation (Sato, 1981; Lowell and Shields, 1984; Marsh, 1991):

$$\log V = \log V_0 - S\,[\log (\frac{P}{P_0})]^2$$

where V_0= total micropore volume, V = volume filled at P/P_0, S = constant, P = pressure, P_0 = saturation vapaour pressure

Surface areas were calculated using a value of 17 x 10^{-20}m^2 for the cross sectional area of the carbon dioxide molecule.

Proximate, sulphur and maceral analyses were performed by standard techniques (Montgomery, 1978; Bustin et al., 1985). Maceral analyses are based on a 300 point count (mineral matter-free, minerals counted separately) on a polished, 2.54 cm crushed particle pellet. Low temperature ashing (LTA) of the coal samples was performed using the oxygen plasma technique described in Suhr and Gong (1983). X-ray diffraction (XRD) of the low temperature ash residue was used to qualitatively assess the mineral composition of each sample. Random reflectance (R_o) of two vitrinite samples from the C seam, and the sample from the A1 seam was measured with a Kontron IBAS image analysis system attached to a Zeiss universal research microscope utilizing a procedure modified from Pratt (1989). Mean random reflectance of telocollinite is based on the analysis of 50 points.

3.6 RESULTS

3.6.1 Standard Industrial Analyses and Rank

Proximate, sulphur, ash yield (for methane adsorption test samples) and equilibrium moisture data are presented in Table 3-2. All the coals are low in sulphur, varying between 0.2 - 0.8 weight %. The weight - percent volatile matter is variable, ranging between 17.4 - 30.5%, dry mineral matter-free (dmmf). The high value corresponding to the fibrous coal sample, LTC-5, is not believed to be representative, due to a high carbonate content. Volatile matter determination involves heating the coal in rigidly controlled conditions up to 950°C, and measuring the weight loss. The weight loss is interpreted as the amount of volatile material originally present in the coal. Carbonates thermally decompose at a temperatures lower than the 950°C maximum temperature of the volatile matter test (Montgomery, 1978), resulting in a weight loss of 44% of the original carbonate concentration. This weight loss due to breakdown of carbonates is recorded as part of the volatiles, causing a higher value to be reported. The LTC-5 value is ignored in further comparisons.

Random reflectance values for LTC-1, LTC-15 and LTA1-6 are 0.97, 0.96 and 1.03%, respectively, which spans the high-volatile A – medium-volatile bituminous rank boundary determined by Cameron (1991) for western Canadian coals. This result is in agreement with Kalkreuth and Leckie (1989). ASTM coal rank classification for higher rank coals is based on fixed carbon percentage on a dry mineral matter-free basis (dmmf)

Table 3-2. Results of proximate, sulphur and equilibrium analyses on several different bases.

Sample	Proximate Analysis: Ash Yield (w%)	Moisture (w%, AR)	Volatile Matter (w%, daf)	Fixed Carbon (w%, daf)	Volatile Matter (w%, dmf)	Fixed Carbon (w%, dmf)	Total Sulphur (w%)	Equ. Mois. (w%)	Ash Yield Ads. Test (w%)
LTC-1	8.0	1.1	28.6	71.4	28.0	72.1	0.7	2.1	9.2
LTC-7	6.8	1.0	24.6	75.4	24.0	76.0	0.7	1.7	7.0
LTC-15	9.6	0.7	26.7	73.3	25.9	74.1	0.8	1.7	10.3
LTA1-6	3.6	0.9	24.0	76.0	23.7	76.3	0.4	2.0	4.4
LTC-11	20.5	0.9	23.2	76.8	21.5	78.5	0.4	1.6	17.1
LTC-14	17.6	0.7	22.8	77.3	21.3	78.8	0.5	1.4	17.0
LTC-9	33.8	0.8	20.9	79.1	17.4	82.6	0.3	1.5	33.7
LTC-5	22.2	0.5	32.2	67.8	30.5	69.5	0.2	1.4	20.7

w% = weight percent *daf = dry, ash free* *dmf = dry, mineral matter free (ASTM)*
AR = As received *Ads. = adsorption* *Equ. Mois. = equilibrium moisture*

where high rank coals are those with fixed carbon > 69% dmmf. Excluding LTC-5, the fixed carbon values range from 83 - 72% dmmf, which indicates the coals range in rank from medium-volatile bituminous to low-volatile bituminous. This result illustrates one of the problems associated with extending the rank parameters derived for vitrinite-rich coals in the United States to the more inertinite-rich coals of western Canada. As illustrated in Figure 3-3, there is a direct correlation between the volatile matter and vitrinite content. The inertinite suppresses the relative volatile matter values, indicating a higher rank than actually exists.

3.6.2 Sample Composition

The relative percentage of each maceral was calculated on a volume percent, mineral matter-free basis; these percentages were recalculated by the Parr formula to included mineral matter content (volume %, raw-coal). Compositional data (both bases) are presented in Figure 3-4, and listed in Table 3-3. The coals analyzed are essentially a three component system consisting of vitrinite, inertinite and mineral matter. Vitrinite contents of the samples range from 18 - 95% by volume, mineral matter-free (mmf); the remainder of the coal is essentially inertinite, as liptinite is very low (varying from 0 - 3% mmf). On a raw-coal basis, vitrinite content varies from 15 - 90% mmf, inertinite varies from 3 - 71%, and mineral matter varies from 2 - 22%. In general, the samples with a lower ash yield (LTC-1, LTC-15, LTC-7 and LTA1-6) are enriched in the structured vitrinite varieties (pseudovitrinite, vitrinite and telocollinite) with variable amounts of desmocollinite and inertinite. The higher ash yield samples (LTC-9, 11 and 14) are higher in inertinite (particularly inertodetrinite) and the more attrital form of vitrinite, (i.e., vitrodetrinite; Fig. 3-4). Table 3-3 also shows ratios of structured maceral varieties to degraded (unstructured) maceral varieties. With the exception of LTC-5, a decrease in total vitrinite content accompanies a decrease in structured vitrinite. With the exception of LTC-1, which is effectively inertinite-free and LTC-5, an increase in inertinite content marks a decrease in structured inertinite. This decrease reflects the nature of the original depositional environment and vegetation type. The brighter coal varieties probably formed in wetlands dominated by more resistant, woody material (swamps). The duller lithotypes probably formed in wetlands subject to frequent fire and/or composed of a more herbaceous vegetation, which degrades more easily.

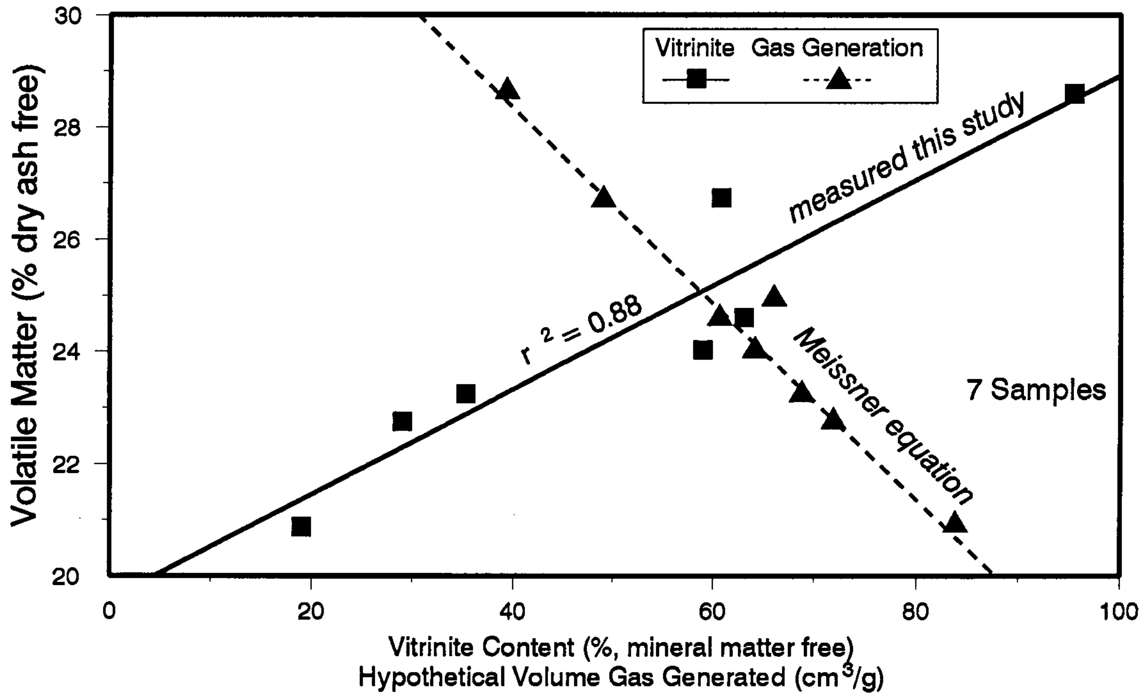

Figure 3-3. Relationship between vitrinite content and volatile matter, and volatile matter and hypothetical volume of gas generated by the coal through maturation using the equation of Meissner (1984). Please see text for further discussion.

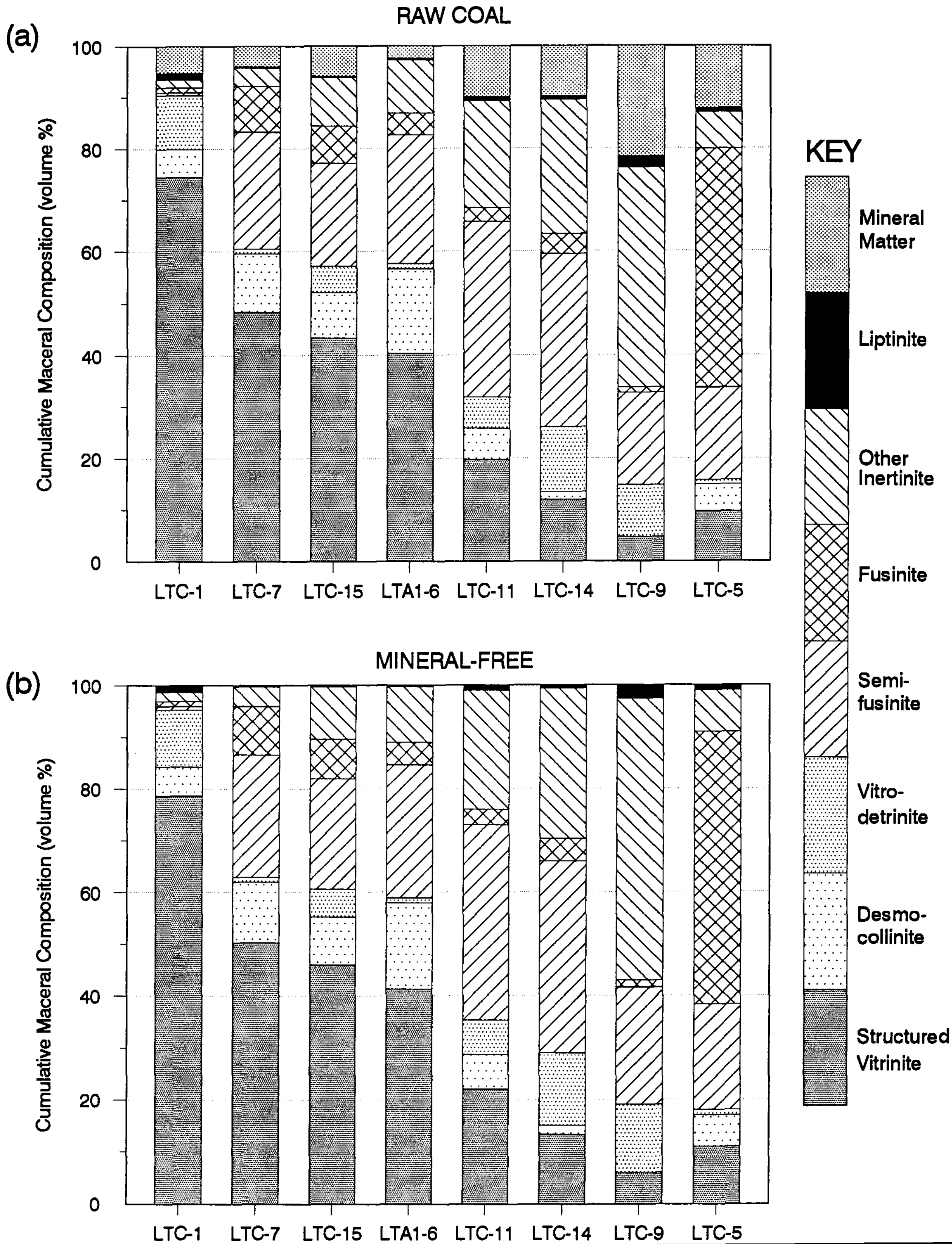

Figure 3-4. Maceral and mineral composition of samples on a (a) mineral free and (b) raw coal basis.

Table 3-3 Maceral and mineral composition of samples analysed on a mineral-free and raw coal basis. Raw coal values calculated using Parr mineral formula.

	Maceral	LTC-1	LTC-7	LTC-15	LTA1-6	LTC-11	LTC-14	LTC-9	LTC-5
Volume %, Mineral-Free	Structured Vitrinite	79	50	46	41	22	13	6	11
	Desmocollinite	6	12	9	17	7	2	0	6
	Vitrodetrinite	11	1	5	1	7	14	13	1
	Semifusinite	1	24	21	26	38	37	23	20
	Fusinite	1	9	8	4	3	4	1	53
	Other Inertinite	2	4	10	11	23	29	54	8
	Total Liptinite	1	0	0	0	1	1	3	1
	Total Vitrinite	95	63	61	59	35	29	19	18
	Total Inertinite	3	37	39	41	64	70	78	81
	Struc:Deg Vitrinite [1]	5	4	3	2	2	1	1	2
	Struc:Deg Inertinite [2]	1	9	3	3	2	11	0	9
Volume %, Raw Coal	Structured Vitrinite	75	48	43	40	20	12	5	10
	Desmocollinite	5	11	9	16	6	2	0	5
	Vitrodetrinite	10	1	5	1	6	13	10	1
	Semifusinite	1	23	20	25	34	33	18	18
	Fusinite	1	9	7	4	3	4	1	46
	Other Inertinite	2	4	9	10	21	26	43	7
	Total Liptinite	1	0	0	0	1	1	2	1
	Total Vitrinite	90	61	57	58	32	26	15	16
	Total Inertinite	3	35	37	40	57	63	61	71
	Ash Yield (vol.%)	5	4	6	2	10	10	22	12

1 Structured Vitrinite: Degraded Vitrinite

2 Structured Inertinite : Degraded Inertinite

Herbaceous wetlands (marshes) are more subject to clastic inundation, and often contain a higher mineral matter content.

LTC-5, the fibrous (fusain) coal, is markedly different from the other samples. This lithotype is not a volumetrically significant part of any of the seams, but it does represent a unique compositional end member (Lamberson et al. 1991). It is composed of 81% by volume (mineral matter-free) inertinite, the bulk of which is structured inertinite. The majority of the vitrinite present is also structured. Thin section examination of the sample reveals it to be predominantly composed of charred and semi-charred wood with carbonate filling fracture and cellular spaces and lesser amounts (approximately 7%) of the admixtures of vitrinite and inertinite that is typical of banded bituminous coals.

The fibrous coal sample also contrasts with the remaining samples in terms of its mineralogy, as indicated by the results of the LTA and XRD analyses (Table 3-4). LTC-5 is essentially monomineralic, with dolomite present as pore and fracture fillings. Other examples of fibrous coal examined from the Gates Formation are characterized by the presence of carbonate in cell fillings and fractures as well (chapter 4). The other monomineralic sample was LTA-6, a banded coal which has a low ash yield (3.6%) consisting predominantly of quartz. The remaining samples contain dominantly quartz and kaolinite, with dolomite and ferroan dolomite occurring in minor proportions (Table 3-4). Quartz (silica) occurs as primary detrital grains or secondary replacements. Kaolinite (or related clay) occurs either as primary detrital grains or concretions in the coal matrix, whereas the carbonate grains occur as concretions, cell fillings and fracture fillings.

3.6.3 Gas Adsorption

Methane adsorption isotherms are illustrated in Figure 3-5 on a moist, raw-coal (Fig. 3-5a) and ash-corrected basis (Fig. 3-5b). The primary effect of the ash correction is to shift the curves upward on the graphs, without a significant shift between the curves. Methane monolayer capacity, as determined by the Langmuir equation, is listed in Table 3-5. Mean carbon dioxide surface areas of the samples vary from 57.6 m^2/g to 123.9 m^2/g (Table 3-5); monolayer (micropore) capacities range from 12.6 cm^3/g to 27.1 cm^3/g (raw-coal basis). These values have an experimental error of approximately ± 10%. The raw-coal values for monolayer capacity of

Table 3-4 Results of low-temperature ash and qualitative mineralogical analysis using x-ray diffraction.

Sample	Lithotype	Low-temp. ash yield (weight %)	Quartz	Kaolinite	Dolomite	Ferroan Dolomite
LTC-1	Bright	7.20	major	major	-	minor
LTC-7	Banded bright	7.51	major	major	-	minor
LTC-15	Banded coal	11.28	major	major	minor	-
LTA1-6	Banded dull	2.83	dominant	minor	-	minor
LTC-11	Banded dull	18.57	major	major	-	minor
LTC-14	Dull	19.15	major	minor	minor	-
LTC-9	Dull	37.59	major	minor	-	-
LTC-5	Fibrous	33.43	minor	-	dominant	-

Note: detection limit of XRD technique is approximately 5%.

Dominant: essentially the only mineral present.

Major: strong peaks present (15-40%?).

Minor: Weak peaks, but detectable (5-15%?).

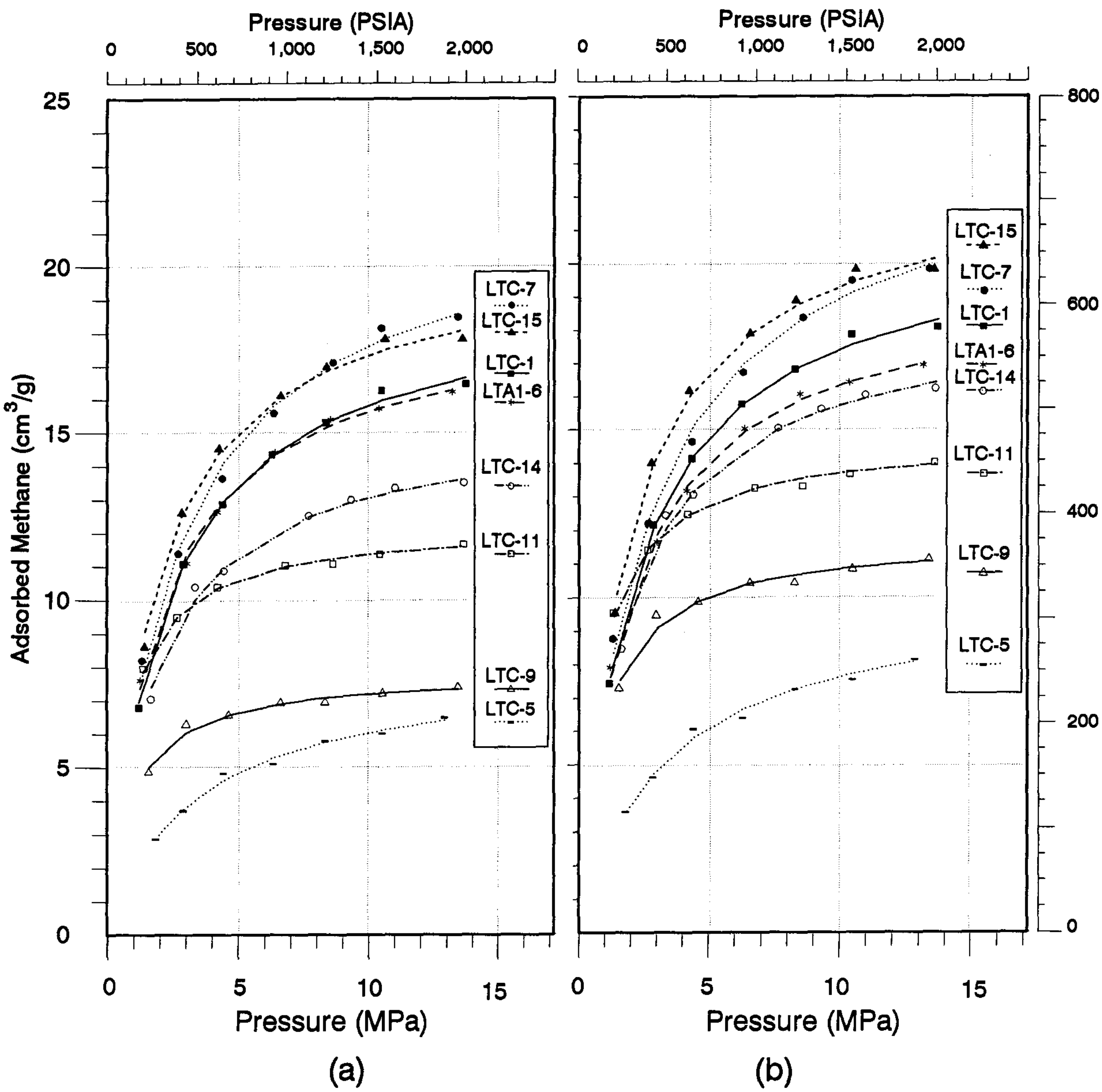

Figure 3-5. Methane adsorption isotherms on a (a) raw coal and (b) ash free basis. Analyses performed at 22°C and under equilibrium moisture.

Table 3-5. Summary of methane monolayer capacity, carbon dioxide monolayer capacity and surface area of samples, raw-coal, ash-free and mineral-free (Parr-correction) bases.

	Monolayer Volume (cm^3/g)						Surface Area (m^2/g)		
	Methane			Carbon Dioxide			Carbon Dioxide		
Sample	Raw Coal	Ash-Free[1]	Min-Free[2]	Raw Coal	Ash-Free[1]	Min-Free[2]	Raw Coal	Ash-Free[1]	Mineral-Free[2]
LTC-1	19.3	21.3	20.4	25.7 (5)[3]	28.3	27.1	117.7	129.6	124.2
LTC-7	22.0	23.7	22.9	26.5 (2)	28.6	27.7	121.2	130.4	126.3
LTC-15	20.5	22.9	21.8	21.1 (2)	30.2	28.8	123.9	138.0	131.6
LTA1-6	18.7	19.5	19.1	24.5 (2)	25.7	25.1	112.1	117.2	114.9
LTC-11	12.3	14.8	13.6	21.3 (4)	25.7	23.6	97.1	117.2	107.9
LTC-14	15.5	18.6	17.2	21.2 (2)	25.6	23.6	96.9	116.8	107.6
LTC-9	7.9	11.8	10.0	16.0 (2)	24.2	20.5	72.6	109.5	92.7
LTC-5	8.1	10.2	9.2	12.6 (5)	15.9	14.4	57.6	72.6	65.6

1 Corrected using ash yield, weight %

2 Min-Free = Mineral-Free, Corrected using ash yield, volume % - Parr Formula

3 Number of times analysis was performed, value represents average

methane and carbon dioxide and carbon dioxide surface area were recalculated using the Parr mineral formula to a volume percent, mineral matter-free basis (Table 3-5).

The adsorption of methane and carbon dioxide is correlated with vitrinite content (Fig. 3-6) on both a mineral matter-free and raw-coal basis. The best correlations are found using a logarithmic regression, although the linear correlations are not too different from the logarithmic regression (Fig. 3-6). With the limited data points we have in hand, it is uncertain as to what the fundamental (physical) basis for the logarithmic fit is, except perhaps that many geologic relationships tend to be logarithmic. More analyses are needed to clarify this relationship.

3.7 DISCUSSION

3.7.1 Controls on Gas Adsorption

The primary focus of this investigation is to determine the relationship between coal composition and methane adsorption characteristics. In order to allow for comparison between the Gates coal isotherms (Fig. 3-5) with other published data, the isotherms are constructed on what is termed an "ash-free" basis. However, we have chosen to use a volumetric, rather than a weight-based correction for mineral matter for the remaining comparisons (since we are trying to ascertain *volumes* of gas adsorbed as a function of a particular volume percentage of maceral and/or mineral matter). The validity of making volume and weight corrections is arguable, as the calculation assumes that the mineral matter has no surface area open to gas adsorption. There is some basis for this assumption, as Gan et al. (1972), noted that the finely dispersed mineral surfaces in coals are probably inaccessible to the gas, particularly carbon dioxide at the utilized pressures. It is well known that there is an inverse relationship between ash yield and methane adsorption (Meissner, 1984; Choate et al., 1986; Ayers and Kelso, 1989), as the adsorption of gas is primarily thought to be on the organic fraction (Gan et al., 1972), with little or no contribution by the mineral matter. Our results agree with previously published results. An increase in mineral matter causes a decrease in methane and carbon dioxide monolayer capacity (and by extension, carbon dioxide surface area).

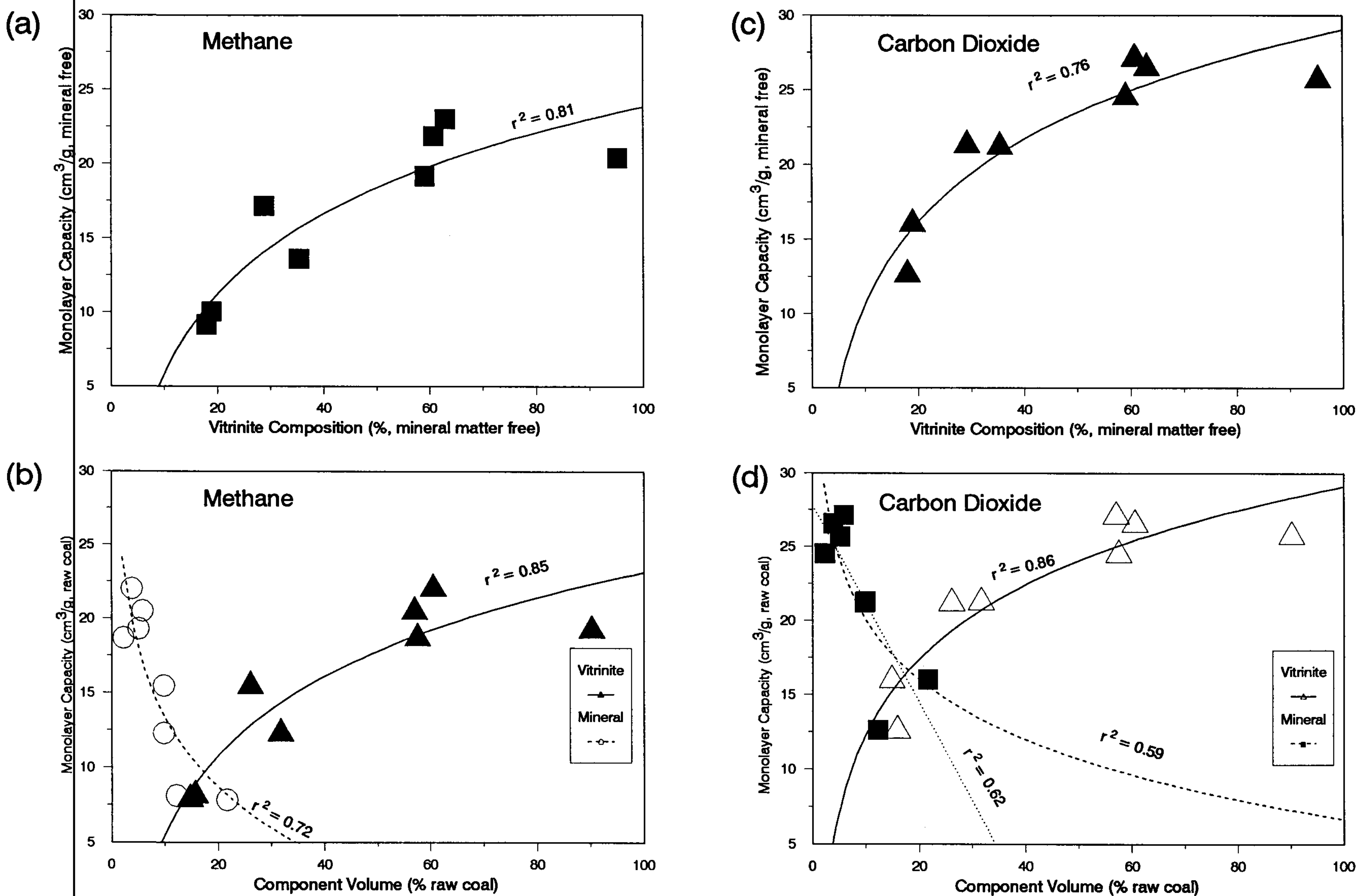

Figure 3-6. Relationship between coal composition and monolayer capacity of methane (a, b) and carbon dioxide (c, d) on mineral-free (a, c) and raw-coal (b,d) bases. Mineral free monolayer capacity calculated using the Parr Formula.

The importance of vitrinite content (independent of the mineral matter) on monolayer capacity of methane and carbon dioxide is conspicuous (Fig. 3-6a, 3-6b). The most likely cause is a difference in pore size distribution between the two macerals. As shown by Harris and Yust (1976, 1979), vitrinite is predominantly microporous, whereas inertinite, although more porous overall, is mainly mesoporous to macroporous. Assuming spherical pores, the surface area to volume ratio of a substance is inversely proportional to the pore radius. Given the same porosity, a microporous substance has a higher surface area than a mesoporous or macroporous substance. Because vitrinite is microporous, it is likely that the surface areas of vitrinite-rich material are higher than inertinite-rich material, even if the porosity of inertinite is a bit higher. The lowest surface area and methane adsorption capacity is found in the sample with the highest inertinite content. However, the relationship is not a simple one. The highest surface areas and methane adsorption are not found in the sample with the highest vitrinite content sample, but rather in samples with a mixture of vitrinite and inertinite. Why this occurs is not certain. The two highest surface area samples, LTC-7 and LTC-15, both contain abundant semifusinite, which is a transitional material between structured vitrinite and fusinite. Semifusinite material forms by partial burning/charring. This process can take place by combustion or pyrolysis. Perhaps pyrolysis enhances the microporosity in the transitional material.

The monolayer capacities determined by the high pressure methane adsorption test are consistently lower than those obtained from the carbon dioxide low pressure isotherms (raw-coal basis, and mineral matter-free basis, Fig. 3-7). The methane and carbon dioxide monolayer capacities apparently have an exponential relationship, with a correlation coefficient of 0.95 and 0.93 on a mineral matter-free and raw-coal basis, respectively. Sato (1981) also noted a relationship between the two monolayer capacities for sub-bituminous and bituminous coals of the San Juan Basin of the United States. He concluded that the difference between the two was most likely due to the molecular functionality of the two molecules. Carbon dioxide is quadrapolar, and may adsorb in a more tightly packed arrangement than the non-polar methane molecule. Methane may be more restricted to selective sites on the surface. Further research is needed to fully understand the relationship between methane and carbon dioxide adsorption behaviors, as well as the physical basis for the relationship.

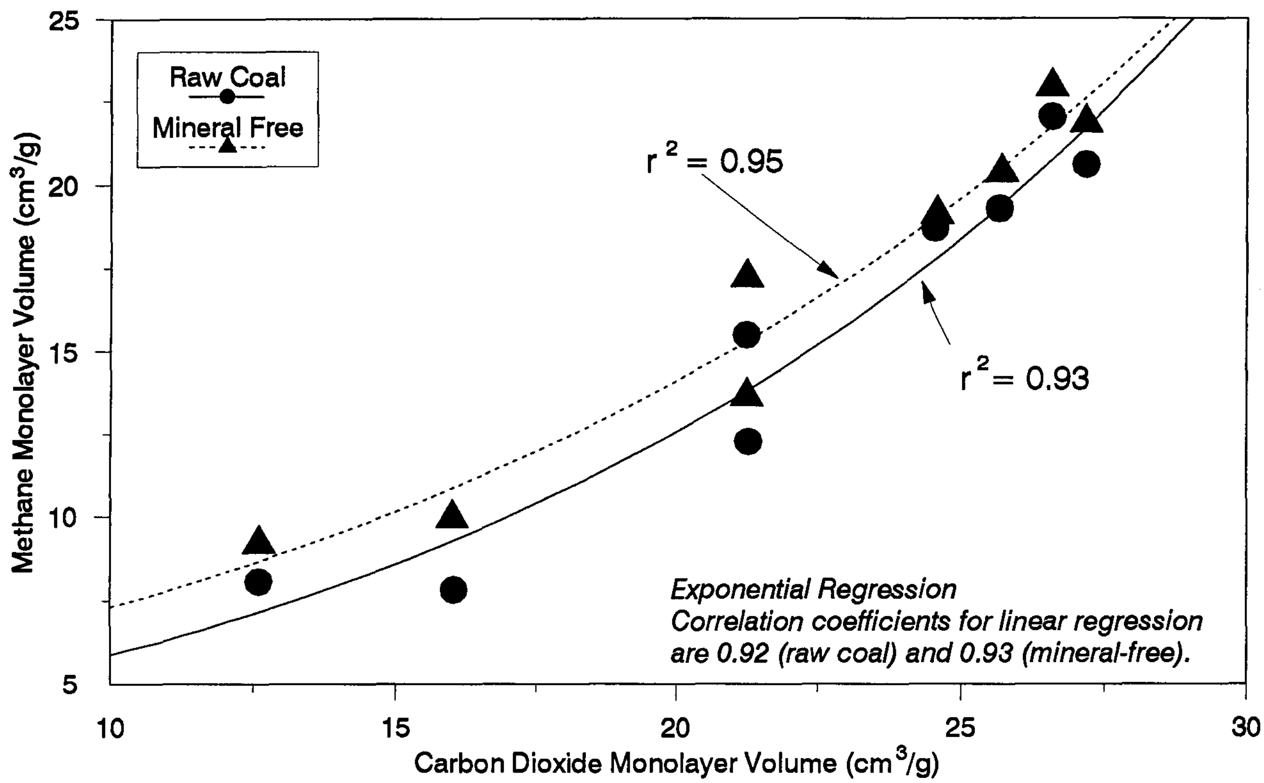

Figure 3-7. Correlation between carbon dioxide and methane monolayer capacities of the coal sample on a raw-coal and mineral-free basis.

3.7.2 *Methane Generation*

The inertinite content of many western coals has a direct effect on the volatile matter, as discussed above, and illustrated in Figure 3-3. Vitrinite-rich coals contain more primary volatile matter than inertinite-rich coals. Meissner (1984), evaluated the predominantly vitrinite-rich coals of Cretaceous and Tertiary units within the Rocky Mountain area of the United States and derived an equation for the total amount of methane (V_{CH4}) generated by a coal based on the percentage of volatile matter (VM), on an ash-free basis:

$$V_{CH4} = -325.6 \log(\frac{VM}{37.8}).$$

The assumption of this equation is that methane generation commences at 37.8% VM. Because most coals generate more gas than they are capable of retaining, this estimate may only be of academic value, unless the study is designed to assess how much gas has migrated to other reservoirs. Applying the Meissner equation to calculate the amount of gas generated from an inertinite-rich western Canadian coal would result in an erroneous (higher) quantity of gas generated. Ultimately, the equation assumes that the lower the volatile matter the greater the amount of generated methane. This assumption makes no sense when applied to inertinite-rich coals because vitrinite contains more material capable of generating gas than does inertinite. A volumetric correction which accounts for the reduction in volatile matter by inertinite, and the reduction in gas generated by the amount of mineral matter, is needed. An analysis similar to Meissner's (1984) evaluation of a number of U.S. Rocky Mountain coals is needed for Canadian coals. Our ongoing research is aimed at deriving such an equation. This type of correction would probably be needed for assessing coalbed methane potential of the inertinite-rich Permian coals of Australia (Hunt, 1989; Smyth, 1989) and India (Navale and Saxena, 1989) as well.

3.8 CONCLUSIONS: IMPLICATIONS OF COAL MACERAL VARIATION ON PREDICTING COALBED METHANE GENERATION AND RETENTION

The adsorptive capacity of a coal has been traditionally attributed to be a function of pressure (burial depth), coal rank, ash yield and moisture content (Ruppel et al., 1972; Joubert et al., 1973; Kim, 1977; Rightmire, 1984; Wyman, 1984; Choate et al., 1986). The data presented herein clearly indicate that surface area and adsorptive capacity of a coal is also a function of the maceral composition. Indeed, the variation that is seen within a single coal deposit as a result of maceral composition differences is just as large as that found in previous studies between coals of different rank, as illustrated in Figure 3-8. As a result, a coal which has a lower rank, but is enriched in vitrinite can have a higher methane adsorption capacity than a coal which is enriched in inertinite, but is of higher rank. This observation has important implications for coalbed methane exploration. In the selection of samples for analysis, whether it be for adsorption or desorption, one must ensure that the sample is representative of the reservoir of concern. A thorough investigation into the nature of the stratigraphic and lateral facies variations must be undertaken as part of a routine exploration program in order to correctly assess the coalbed methane potential of a deposit.

Figure 3-8 also provides information which allows another preliminary conclusion to be drawn: despite the enrichment in inertinite, the coals are still capable of adsorbing large quantities of methane. It is only where the vitrinite content drops below approximately 40 – 50% (Fig. 3-6) that the adsorption isotherms differ significantly from the "average" behaviour of bituminous coals. Within the Deep Basin Gas Field (northeastern British Columbia–west central Alberta, Fig. 3-1), the thickest coal zone present is the Fourth Coal (Wyman, 1984). The outcrop equivalent of the Fourth Coal interval is the zone which contains the Bullmoose A1, A2 and B seams. The most common lithotypes within those seams (chapter 2, 5) are banded dull coal and banded coal, analogous in this study to samples LTA1-6, LTC-15 and LTC-11. The sample with the poorest adsorption characteristics, LTC-5, is a rare lithotype in all of the Gates seams studied. If the samples analyzed for this study are representative of other thick laterally extensive seams, such as the Fourth coal interval, large reserves of coalbed methane are most likely present in the Western Canada Sedimentary Basin. A basin - wide assessment of the variation in maceral composition of the coals of the WCSB is needed to verify this conclusion.

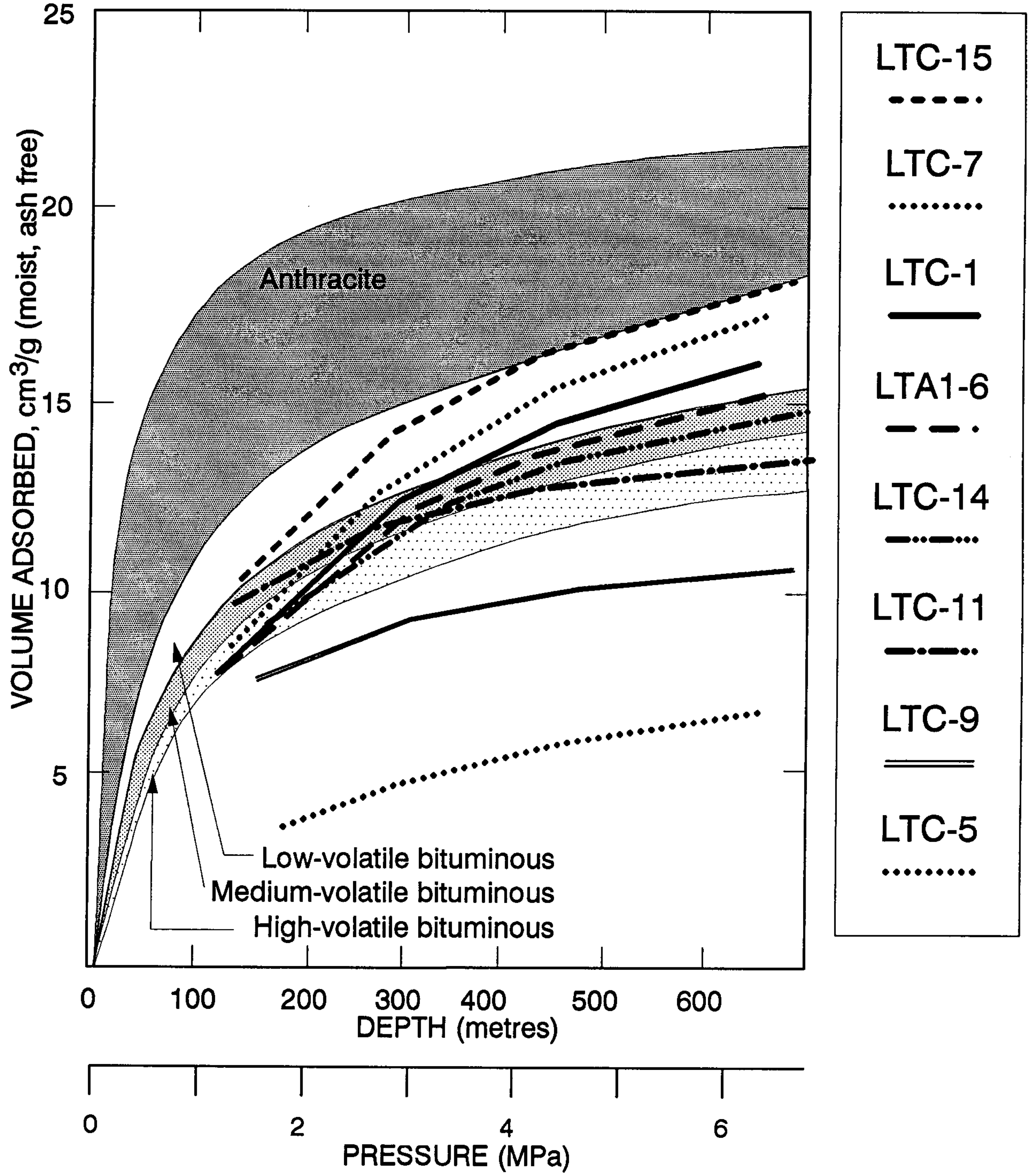

Figure 3-8. Comparison of a portion of the methane adsorption isotherms of Gates Formation coal samples with published isotherms of coals of different ranks. Rank boundaries after Kim (1977).

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CHAPTER 4

THE FORMATION OF INERTINITE RICH PEATS IN THE MID-CRETACEOUS GATES FORMATION: IMPLICATIONS FOR THE INTERPRETATION OF MID-ALBIAN HISTORY OF PALEOWILDFIRE

4.1 ABSTRACT

Image analysis and manual petrographic data are used to interpret the amount, source and variation of inertinite in coal seams of the mid Cretaceous Gates Formation (Rocky Mountain Foothills, northeastern British Columbia). Inertinite on average is quite high (between 40 — 60%, and higher in sone zones), and within seams may vary cyclically. The inertinite is almost exclusively fire-derived. In modern wetland peats the formation of inertinite rich horizons is primarily a function of climate; inertinite is common where rainfall is seasonally distributed, rather than ever-wet. The enrichment in fire-derived inertinite in the Gates coals suggests that the original peat-forming wetlands were subject to periodic drought or drying. However, no peats forming in modern wetlands subject to periodic drought and wildfire contain inertinite in the quantity present in the Gates Formation. Inertinite enrichment in the Gates coals appears to have resulted from preferential destruction of vitrinite precursors at the peat accumulation stage, either by burning or low temperature degradation processes, rather than by formation of inertinite by low temperature oxidation or fungal attack. The position of the Gates Formation depositional setting east of the rising Canadian Cordillera is interpreted to have resulted in overall drier conditions in the region, and periodic drought in the wetland settings. Cyclic variation in inertinite (vitrinite) composition within some of the seams is primarily attributed to climatic variations, although variation in subsidence rates could also have been responsible.

4.2 INTRODUCTION

A number of coal-bearing formations deposited in the foreland basin (Western Canada Sedimentary Basin) east of the emerging Canadian Cordillera from Late Jurassic through Paleocene time contain seams enriched (>35% by volume) in fire-derived inertinite, including the Late Jurassic - Early Cretaceous Mist Mountain Formation (Bustin and Dunlop, 1992), the mid-Albian Gates Formation (Kalkreuth and Leckie, 1989; Lamberson et al., 1991; Marchioni and Kalkreuth, 1991) and the early Paleocene Ardley coal zone of the Scollard Formation (Demchuk and Strobl, 1989). Although the wildfire (pyrolitic) origin for much of the inertinitic material exclusive of sclerotinite (fungal remains) in coal seams has been well established (Harris, 1958; Cope, 1980; Cope and Chaloner, 1985; Scott, 1989; Sander and Gee, 1990; and Jones and Chaloner, 1991), the formation of inertinite rich coals is still somewhat of an enigma. Peats forming in modern wetland settings subject to periodic fires are not notably enriched in inertinite (average approximately 5% by volume; data in Cohen, 1974; Spackman et al., 1976).

Peat deposits accumulate in areas where the water table is consistently at or near the surface, plant growth is able to keep pace with subsidence, and clastic inundation is limited. According to McCabe and Parrish (1992), the location of peat-forming regions is primarily a function of tectonism and climate; in general, tectonism controls subsidence rates and preservation potential whereas climate controls organic productivity, preservation (decomposition rate) and to a large extent, the regional hydrology. The presence of thick, laterally extensive coal seams indicates the persistence of relatively wet conditions, where a net excess of rainfall over evapotranspiration occurred in a region for time scales of thousands to perhaps hundreds of thousands of years (McCabe, 1991; McCabe and Parrish, 1992).

On both long (thousands of years) and short time scales (decades or less), however, such as those represented by peat deposits, climate can change markedly. Precipitation patterns in a region may be highly variable from year to year (Shroeder and Buck, 1970) and drought (or simply an abnormally low rainfall year) may occur. Drier years allow a wetland to dry out (although it is usually only the standing biomass, surface litter and perhaps the upper peat layers), promoting wildfire. Fire events in wetland settings may be severe enough to leave behind recognizable fusain horizons in coal seams. Alternately, the inertinite may be scattered within a matrix of organic and inorganic material, lending a dull, matte appearance (durain) to the coal. Char-coalified material, once deposited, is extremely resistant to diagenetic alteration or destruction. As long as the coal seam is not eroded or subjected to extreme thermal metamorphism, inertinitic material, particularly fusain layers, become a permanent record of paleo-wildfire. Peat deposits are arguably the best records of relatively continuous (uninterrupted) sedimentation in a terrestrial setting over long time scales. By analyzing a vertical compositional profile of a seam, a qualitative wetland fire history can be interpreted.

The process by which inertinite-rich coals are formed and the paleoclimatic implications of the presence of inertinite rich coals within one of the western Canadian sequences, the middle Albian Gates Formation (northeastern British Columbia, Canada), are explored within this paper. The objectives of my research are to document the amount and variety of inertinite in the Gates Formation coals, and interpret the cause of inertinite enrichment with respect to the paleodepositional and paleogeographic setting during Gates deposition. Previous research on modern wetland fire frequency/history, and the relationship between fossil charcoal occurrence and interpreted paleoclimate is briefly reviewed. A combined procedure utilizing image analysis of block samples and conventional petrography of sub-samples of coal seams was used to construct high resolution profiles of inertinite compositional variation. It is suggested that this method may provide a relatively efficient method of gathering petrographic data for understanding fire frequency in the stratigraphic record. This chapter concentrates on the bulk changes in composition within seams; detailed environment of these seams is interpreted in chapter 5.

4.2.1 Fire frequency in Modern Wetland Settings

The importance of fire in modern ecosystems has been recognized by forest researchers for some time, and most modern forestry texts (e.g., Kimmins, 1987) contain at least a chapter on the subject. Fire is believed to be one of the key factors controlling the structure and functional diversity of wetlands in Florida (Ewel, 1990, Table 4-1) and the coastal plain region of the southeastern United States (Christensen, 1987). Fire is also considered to be an important agent for recycling nutrients in many different types of ecosystems (MacLean et al, 1983; Pyne, 1984), including wetland settings (Wein, 1983; Christensen, 1987).

Three types of fires are commonly recognized (Davis, 1959; Kimmins, 1987): surface, crown and ground. Surface fires cause the least damage to trees as they rapidly move through an area, destroying only surface litter, part of the herbaceous ground cover, and in peat-lined areas, some of the upper peat layers. Crown fires move through the upper story of vegetation, destroying the tops of the trees, resulting in widespread death and toppling. Ground fires are slow moving, smoldering fires which destroy the surface accumulations, as well as the uppermost soil layers. In areas underlain by peat, ground fires have the potential to do the most damage, as peat itself is a fuel. For the most part, surface fires in treed swamps do not result in destruction of a wetland, but periodically clean out the understory (Brown, 1990). This process eliminates less water-tolerant vegetation which may have colonized the area during times of lower water (Cypert, 1961, 1972; Spackman et al. 1976; Mitsch and Gosselink, 1986), allowing continued dominance of the swamp trees.

The frequency of occurrence and effect of fires are dependent upon regional climate, lightning frequency, site moisture conditions and fuel quality and quantity (Christensen, 1987). Wildfire can occur anywhere, given sufficient fuel and ignition conditions. However, fires are obviously more frequent in some areas than others due to the strong climatic influence on temperature and moisture conditions, as well as the regional topographic effects on thunderstorm development. Fires are more common in low-middle latitude, warm dry areas than in higher latitude, cool, moist areas (Wein and MacLean, 1983). The characteristics of modern North American fire regimes are reviewed in Shroeder and Buck (1970).

Data on fire frequency in wetland environments is highly variable. Perhaps the best information documented is for Florida (Table 4-1) and the "coastal plain" region of the southeastern United States (encompassing the coastal area from northern Florida to New Jersey). Frequency is strongly linked to hydroperiod, i.e., the length of time an area is flooded during the year (Ewel, 1990), water source (river, rain and/or groundwater), and site fertility (Christensen, 1987). Alluvial (river) swamps have the longest fire return intervals of 1 or less per century. Rain-fed, nutrient-limited, wetlands such as the Okefenokee swamp marsh complex (SMC) in southern Georgia - northern Florida have more frequent fire return intervals of every 20-40 years (Cypert, 1961, 1972; Christensen, 1987). Herbaceous wetlands (marshes) have the highest fire frequencies (1-2 per 10 years, as interpreted from Klukas, 1972; Christensen, 1987). The presence of the extensive saw grass

Table 4-1. Ewel's (1990) classification of Florida swamps.

Swamp Type	Average Hydroperiod [1]	Approximate Fire Frequency [2]	Organic Matter Accumulation [3]	Main Water Source
River Swamp				
whitewater floodplain forest	Short	Low	Low	River
blackwater floodplain forest	Short	Low	Low	River
spring run swamp	Short	Low	Low	Deep groundwater
Stillwater Swamps				
bay swamp	Long	Low	High	Shallow groundwater
cypress pond	Moderate	Moderate	High	Shallow groundwater
cypress savanna	Moderate	High	Low	Rain
cypress strand	Moderate	Moderate	High	Shallow groundwater
gum pond	Long	Low	High	Shallow groundwater
hydric hammock	Short	Low	Low	Deep groundwater
lake fringe swamp	Moderate	Low	High	Lake
Melaleuca swamp	Moderate	High	Low	Shallow groundwater
Mixed				
hardwood swamp	Moderate	Low	High	Shallow groundwater
Shrub Bog	Long	Moderate-High	High	Shallow groundwater

1. short= <6 months; moderate=6 to 9 months; long = > 9 months.
2. low = 1 per 100 years; moderate = 5 per 100 years; high = 1 per 10 years
3. low = <1 metre; high = >1 metre

marshes in the Florida Everglades swamp marsh complex (SMC) has been attributed to a combination of high fire frequency and the post-burn regenerative capacity of the saw grass plant (Spackman et al., 1976). In the more northerly latitudes (Wein, 1983), characterized by lower temperatures, low productivity rates and a pronounced seasonal light (insolation) and temperature variation, fire frequency in areas underlain by organic terrain is poorly documented. According to Wein (1983), most wetland fires occur only during low rainfall years and burn only shallow humus layers. He estimates a low frequency (1 per hundred years) for surficial fires, and even lower (1 per hundreds of years) for deep burning peat fires.

4.2.2 Previous Research on Paleoclimate and Fossil Charcoal

Published studies of fossil charcoal in the geological and paleobiological literature have spanned many topics and applications, including: documentation of origin (Cope and Chaloner, 1985; Scott, 1989); comparative experimental analyses of modern and ancient charred wood (Sander and Gee, 1990; Jones et al; 1991; Jones et al., 1993); paleobotany (Alvin, 1974; Alvin et al., 1981; Friis and Skarby, 1981; Harris, 1981; Herendeen, 1990); and long term global cycling of carbon and oxygen (Cope and Chaloner, 1980; Chaloner, 1989; Robinson, 1989, 1991; Jones and Chaloner, 1991). Reports on the interpretation of "long term" climatic change from fossil charcoal abundance in sediments has primarily been confined to the modern ecological literature. Tolonen (1983) provides an excellent review of research concerned with post-glacial fire history of higher latitude regions. Three methods are commonly used to interpret fire history (Tolonen, 1983): fire scars on very old trees, vegetative spreading of clonal species (e.g., *Lycopodium spp.*), and the type and amount of charcoal in peat and lake sediments. Varved lake sediments appear to more accurately represent regional fire history (Tolonen, 1983), whereas peat deposits may only reflect *in-situ* fires. However, varved sediments are rare throughout the stratigraphic record, and the differentiation of annual rhythmicity becomes more difficult with increased age of the deposit (Ripepe et al., 1991). With respect to this study, it is important to note that varved sediments are not as common as coal seams in Cretaceous strata of the Western Canada Sedimentary Basin..

The relationship between fire frequency and the climate of northern Minnesota (USA) for the last 750 years was interpreted by Clark (1990). The frequency of occurrence of fire scars on red pine (*Pinus resinosa*) and the amount of charcoal in varved sediments of three small lakes located within a 1 km^2 area of mixed conifer-hardwood old growth forest were determined. Clark concluded that fires occurred throughout the measured time interval, but were more frequent during warm/dry intervals than during cool/moist intervals.

Palynological and paleobotanical data have been used to interpret long term climatic changes in Carboniferous (Phillips and Peppers, 1984; Phillips et al., 1985; Donaldson et al., 1985) and Permian (Geera-Sommer et al., 1991) strata. However research concerned with interpreting fire history or fire effects within (geologically) ancient wetland environments is a developing field. A recent paper by Arens (1991) describes fire succession within clastic sediments deposited in a floodplain setting of the Joggins Section (Middle Pennsylvanian), Cumberland Basin, western Nova Scotia. Palynological analyses of the strata immediately below and above an interpreted fire horizon in clastic sediments revealed a major decrease, then increase in the lycophyte composition, coincident with an increase and decrease in the gymnosperm (pteridosperms and cordaiteans) component. Arens (1990) interpreted this trend to indicate differences in ecological niches of the components within the floodplain community. A study which links fire history with detailed compositional changes within Carboniferous coal seams, however, has not been published to date.

Jerzykiewicz (1992) analyzed the distribution of coals and caliche bearing clastics in the Campanian to Paleocene strata of the Rocky Mountain Foothills of Alberta in order to interpret regional climate. He concluded that there was a gradation from humid conditions (represented by coals) in the north to semiarid conditions (represented by caliche-bearing sediments) in the south throughout the time period, although the boundaries of the zones shifted through time. Unfortunately, no discussion of the coal composition was undertaken. Two columnar sections detailing petrography, palynology and sulphur variation of one of the coals from the Paleocene strata within the Ardley coal zone (Highvale #2, central Alberta) are presented in Demchuk and Strobl (1989). This seam shows vertical and lateral variation in inertinite content, with a general trend in inertinite enrichment from the base to the top of the seam. Demchuk and Strobl (1989) interpreted the enrichment in terms of an increase in oxidation/oxidizing conditions toward the top of the seam, but do not specifically address the importance of paleowildfire in the original mires. A more recent paper on the Ardley Zone coals (Demchuk, in press) does discuss the general origin of the inertinite in terms of paleowildfires; no paleoclimatic interpretation is discussed.

Hence, the research reported here represents the first detailed (2 mm scale resolution) compositional analysis of Cretaceous coal seams utilizing an image analysis system. Vegetational changes coincident with fire events have not been interpreted for Cretaceous coals and represents a future research area.

4.3 LOCATION AND GEOLOGIC SETTING OF STUDY AREA

The coals examined for this study were collected from Gates Formation exposures in the Bullmoose mine, located in the vicinity of the town of Tumbler Ridge, British Columbia (Figure 4-1). The Moosebar and Gates Formations, and the more deeply buried correlative strata of the Western Canada Sedimentary Basin (WCSB) to the east were deposited in a foreland basin setting which developed in advance (and eastward) of the emerging Canadian Cordillera (Cant, 1989). The coal-bearing Gates Formation and the underlying Moosebar Formation (Figure 4-1) comprise an unconformity-bound, time-transgressive sedimentary package (third-order sequence of Leckie, 1986a) which coarsens upward from marine shales (Moosebar Formation strata) to nearshore marine sands and nonmarine strandplain and fluvial deposits (Gates Formation sediments). Deposition of the sequence commenced in the Early Albian; the system prograded northward from possibly as far south as the current 49^{o} N latitude to the vicinity of the Peace River (presently at $55\text{-}56^{o}$ N) by Middle Albian time (Stott, 1982, 1984; Jackson, 1984), a period of 2 - 6 million years (Caldwell, 1984; Leckie, 1986a). Northward progradation of the clastic wedge was not uniform, and at least seven smaller order coarsening upward cycles are recorded within the Moosebar-Gates interval (Leckie, 1986a).

In the study area the Gates is informally divided into three units (Figs. 4-1, 4-2), lower, middle and upper, with the bulk of the coal occurring in the middle Gates. Six coal seams are present in the middle Gates of the Bullmoose area, including, from the base upwards, the A1, A2, B, C, D and E (Fig. 4-2); the seams average in thickness 1.45 m, 1.15 m, 4.84 m, 1.8 m, 1.96 m and 1.39 m (Drozd, 1985) respectively. The top of the lower Gates consists of an upward coarsening marine shoreface sandstone sequence known locally as the Torrens member (Leckie, 1986a). The upper Gates (alternately known as the Notikewin member) is also an upward coarsening marine unit topped with nonmarine sediments containing thin coals. Sedimentological evidence

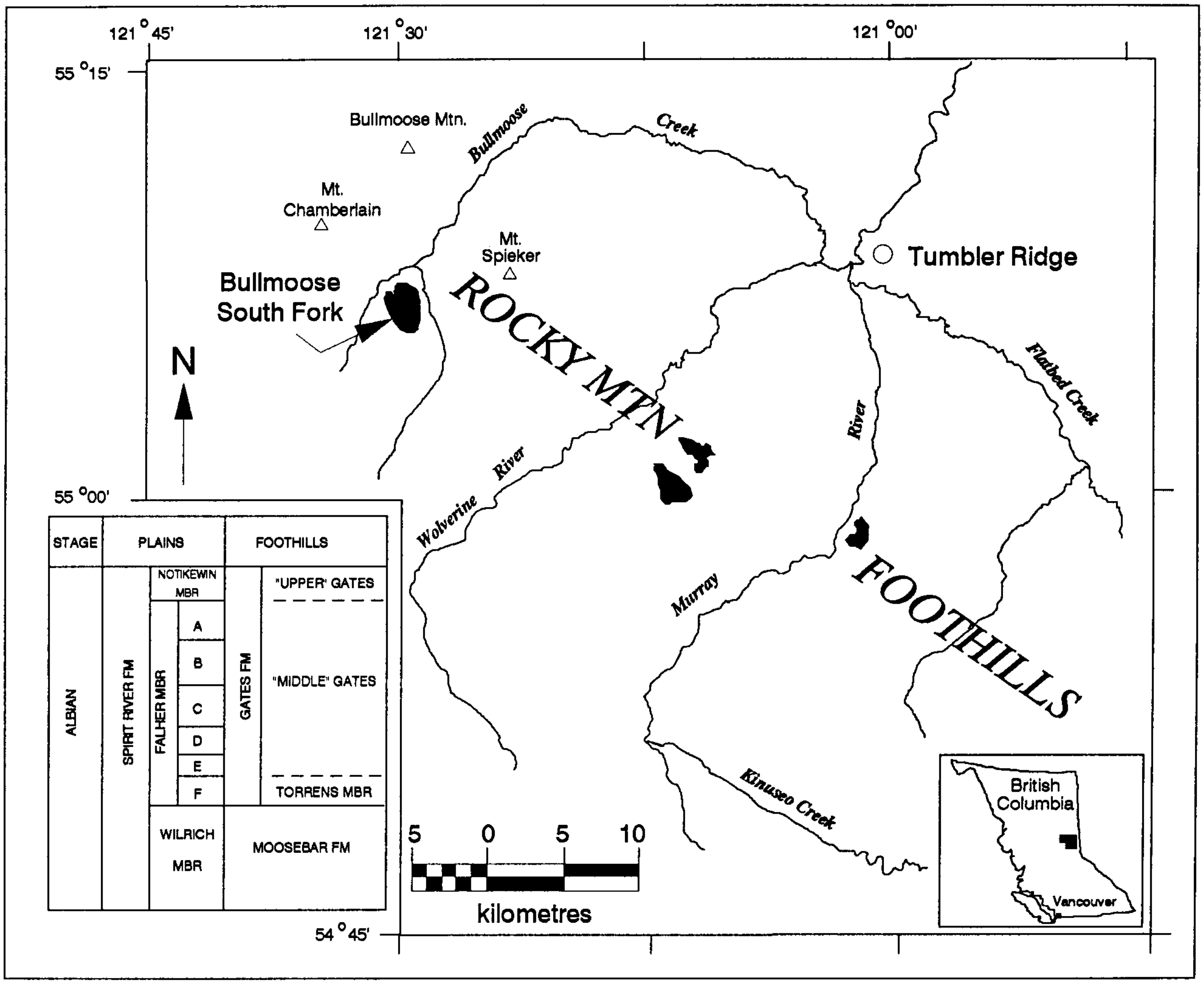

Figure 4-1. Location map of study area showing location of main areas mentioned in the text. Inset chart shows stratigraphic nomenclature of a portion of the Lower Cretaceous section in the study area and correlative strata in the plains to the east. Map modified after Matheson (1986). Stratigraphic nomenclature after Leckie (1983),

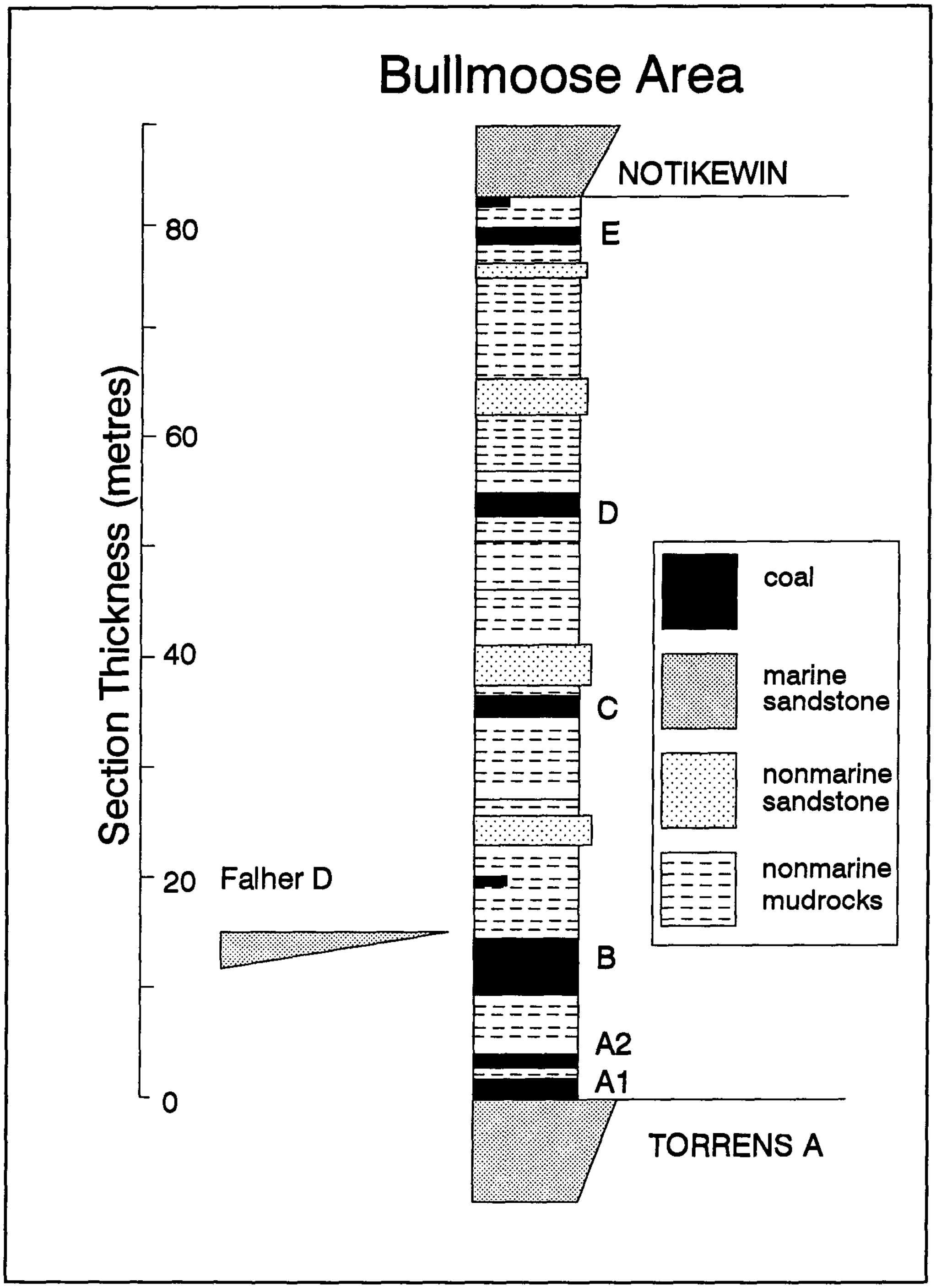

Figure 4-2. Generalised stratigraphic section of local study area showing mine nomenclature for coal seams. Falher D refers to marine shoreface sandstone which overlies and in part erodes B seam 4 kilometres north of study area (Leckie, 1986b). Mine nomenclature from Drozd (1985).

(Leckie, 1983; Kalkreuth and Leckie, 1989) indicates that the coals of the middle Gates formed in wetlands within a coastal plain setting, shoreward of a high energy, wave dominated shoreline. The proximity of the peat forming regions to the ocean has not yet been determined, and it may be that the peats formed a considerable distance inland (Kalkreuth and Leckie, 1989), in part similar to the origin interpreted by Cohen (1984) for the Okefenokee SMC. The Torrens and the Notikewin are the only identified marine units within the area sampled for this study. However, four kilometres north of the mine proper, at Bullmoose mountain, a thick marine shoreface sandstone unit (Falher D) occurs above and in part erodes the top of the B seam (Leckie, 1986b; Fig. 4-2).

The Gates Formation was deposited along the western margin of the Cretaceous interior seaway (Fig. 4-3). Plate tectonic reconstructions (Barron, 1987) place the study area in a position slightly north of its current position (Fig. 4-3), near 60 degrees north latitude. Sediments of the Gates Formation were sourced from highlands to the west and southwest (Carmichael, 1983; Leckie 1983); these sources include sedimentary (primarily Paleozoic carbonates and evaporites), metamorphic and igneous rocks of the main and front Ranges of the Rocky Mountains, as well as the Omineca Belt to the west. During the mid-Cretaceous, material was also being shed from the Omineca Belt west into the Bowser Basin, where alluvial and marginal marine sedimentation was occurring (Cookenboo, in preparation.). The height and width of the intervening mountain belt are still a matter of speculation. The quantitative model simulations of Barron and Washington (1984) and subsequent papers (Barron, 1989; Barron et al., 1989) which included a "realistic" Cretaceous geography envision the Cordilleran highland as a series of low hills, rather than a substantial barrier. In contrast, those of Zeigler et al. (1987), Parrish et al.(1982) and Patzkowsky et al. (1991) assume the mountains to be of significant height, indicating that a rain shadow effect might be expected on the eastern (leeward) flank of the range.

The juxtaposition of a major peat-forming area adjacent and in lee of (on the dry side) what may have been a rather high mountain range is puzzling (McCabe and Parrish, 1992). The highland area would have separated the coastal plain mires of the epeiric seaway from the large moisture source of the Pacific Ocean. McCabe and Parrish (1992) list several possibilities for overcoming the apparent moisture supply problem, including: (1) climatic control was less of a factor due to high subsidence rates associated with the tectonic setting (foreland basin, McCabe 1991); (2) warm convection over the interior seaway (Gyllenhaal et al., 1991) resulting in

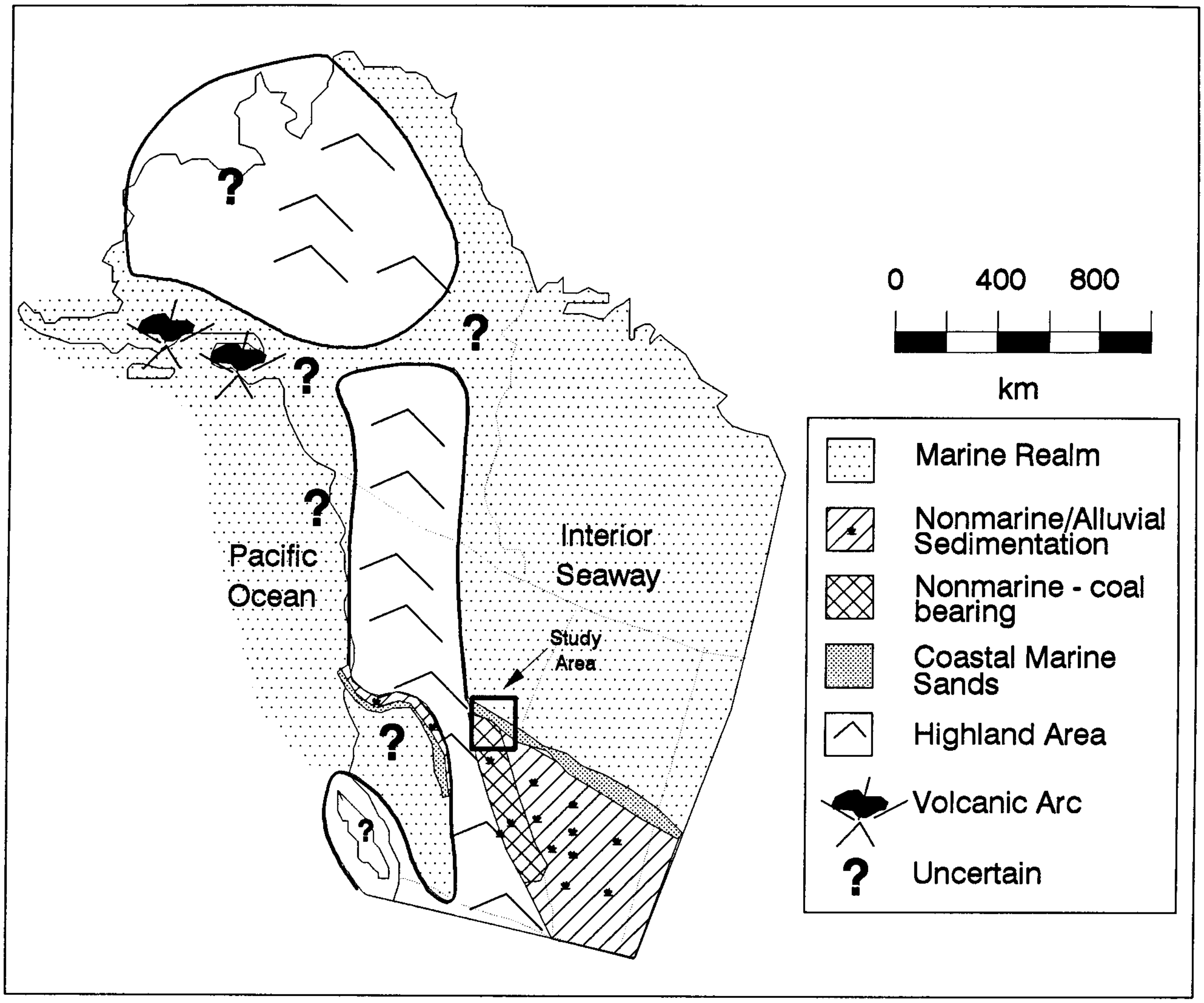

Figure 4-3. Generalized paleogeographic map in region of study area during mid-Albian time. Base map shows modern geography. Modified from Williams and Stelck (1975), Stott (1984) and Jackson (1984).

high coastal rainfall; and (3) the development of a high altitude low pressure cell over the Rocky Mountains resulting in high summer rainfall (McCabe and Parrish, 1992). Although this question is not explored fully in this paper, I believe the characteristics of the coals provide evidence which may help address the apparent discrepancy.

4.4 METHODS

A flow sheet of the procedure followed for sample analysis is presented in Figure 4-4. An attempt was made to collect oriented bench (block) samples from the Bullmoose A1, A2, B, C, D and E seams. Channel samples were collected from intervals which were too sheared or friable. The most complete sequence was obtained from the thickest seam, the B seam; aside from possible minute (millimetre-scale) gaps between samples, only 3 centimetres of vitrain from a position near the top of the seam is underrepresented by block samples. Lithotypes of each seam were described from the unprocessed coal blocks using the scheme illustrated in Table 4-2, using a minimum thickness of 1 centimetre. This allowed the comparison of field data with petrographic data. The block samples were sawn in half, and an embedded epoxy block made of half of the block. The block samples were then polished, and a number of them examined to qualitatively determine the types of phyterals present.

The other half of the block was subdivided as much as possible into the individual lithotype samples. Some layers were too thin to separate, so for practical purposes, the minimum thickness of each lithotype was 2 to 5 centimetres. A representative sample of each interval was crushed to fit through a 20 mesh (850 μm) screen and a pellet was prepared for maceral analysis, following standard procedures (Bustin et al., 1985). Caution was used in sample preparation, because the crushing process used to make the pellets fragments the brittle charcoal, resulting in a net loss of the finer material (see discussion in Bustin, 1990). A 300 point maceral analysis using standard coal petrographic nomenclature was performed on each pellet. A fragment of inertinite was counted as inertodetrinite only if it occurred within an identifiable matrix of either mineral or maceral material. Singular fragments of inertinite occurring in the epoxy matrix were assumed to be broken from fusinite or semifusinite during the crushing process, and counted as such. In total 234 pellets were examined for this study.

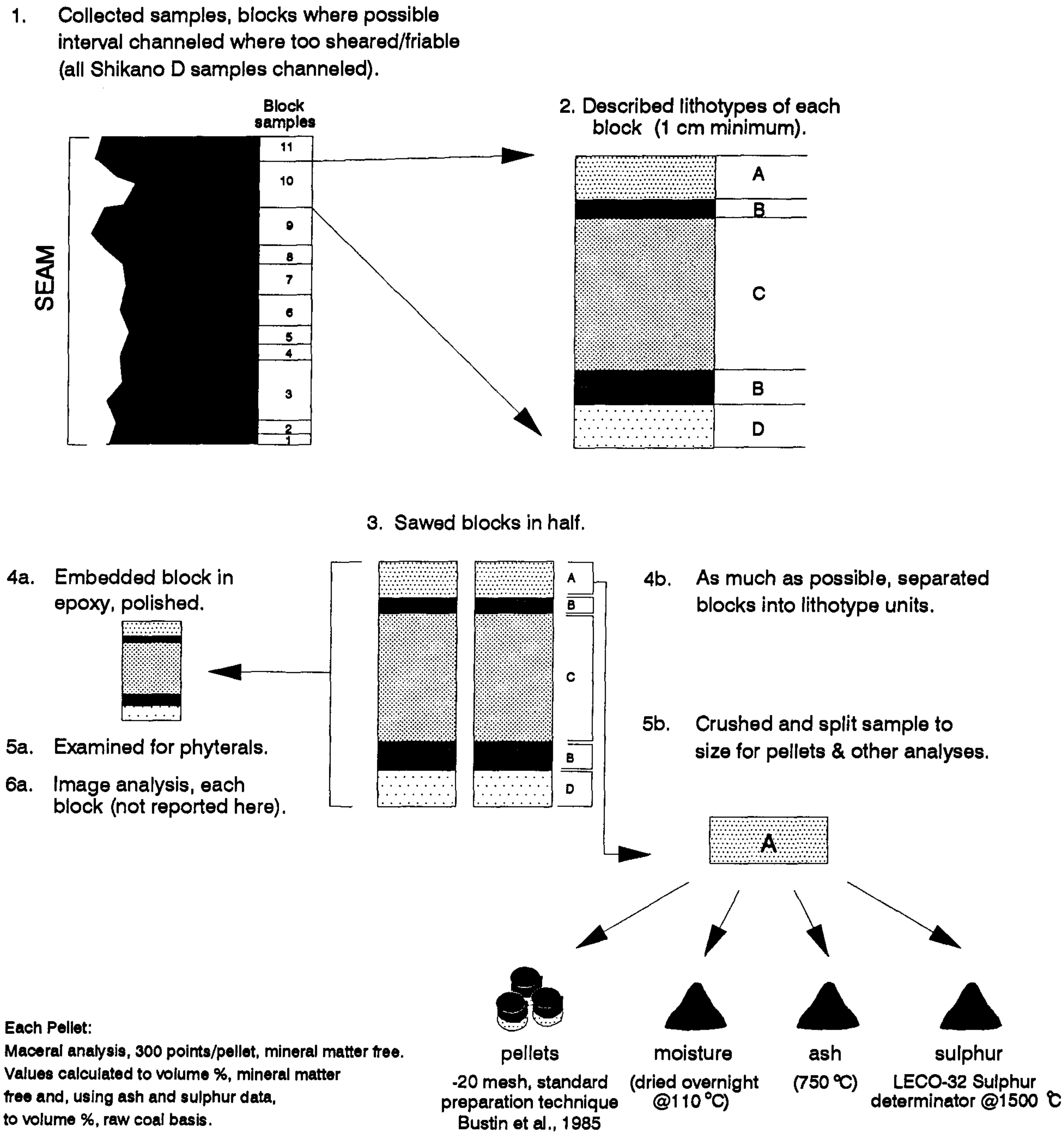

Figure 4-4. Generalized sample preparation and analysis procedure.

Table 4-2. Lithotype classification scheme used in this study. Modified after Diessel (1965).

Lithotype	Description
bright coal	subvitreous to vitreous lustre, conchoidal fracture, less than 10% dull laminae
banded bright coal	predominately bright coal, with 10-40% dull laminae
banded coal	interbedded dull and bright coal in approximately equal proportions
banded dull coal	predominately dull coal with 10 - 40% bright laminae
dull coal	matte lustre, uneven fracture, less than 10% bright coal laminae, hard
fibrous	satin lustre, very friable, sooty to touch
sheared	variable lustre, disturbed bedding, numerous slip/slickenside surfaces, very brittle

A split of each sample was ground to fit through a 60 mesh (250 μm) sieve. Ash yield and total sulphur data analysis were performed on almost every sample, unless there was insufficient coal for analysis.

Image analysis was performed using a Kontron IBAS 2 system attached to a Zeiss universal research microscope following a procedure modified from Pratt (1989). Analyses were performed using a 40X oil objective; the size of each field evaluated is 3.61×10^4 square micrometres. Images are input to the analysis system via a Dage 70 black and white television camera; the system converts the analog signal from the camera to a digitized image, scaled to grey levels of 1-255. The relative percentage of each maceral group is determined by counting the frequency of occurrence of each grey level from the reflectance histogram, a sample of which is illustrated in Figure 4-5. Upper and lower background values are determined by the operator, and the data reduction program eliminates extremely low (from epoxy, cracks, holes, etc.) or extremely high (from pyrite, etc.) reflectance values. Some of the problems associated with this procedure are discussed in the results section.

Maturation decreases from the base to the top of the middle Gates section (Kalkreuth and Leckie, 1989) necessitating the use of different reflectance thresholds for each seam. The grey level and calculated reflectance range (Pratt, 1989) for liptinite, vitrinite, low-reflecting inertinite and high-reflecting inertinite for each seam are listed in Table 4-3. The primary objective of the analysis was to determine bulk changes in maceral composition with respect to stratigraphic position. The system was programmed to follow the continuous pattern shown in Figure 4-6. The values for the horizontal part of each traverse (four fields) were averaged to yield an approximation of the average maceral composition of each 0.5 millimetre stratigraphic thickness of the block. As shown in Figure 4-7, low values caused by epoxy, cracks or scratches, result in blank fields on the output. These data were then reduced again (average 16 fields) to yield data on a 2 mm scale. Figure 4-8 illustrates the nature of the changes associated with some lithotype transitions. All the data for each seam were combined to yield a seam compositional profile. The thickness obtained by image analysis was occasionally slightly lower (millimetre-scale differences) or higher than the manual measurement, usually due to the path chosen on the block, or to sample loss during preparation. These differences were accommodated by placing blank fields in the data set at appropriate locations, or eliminating overlapping fields of adjacent blocks.

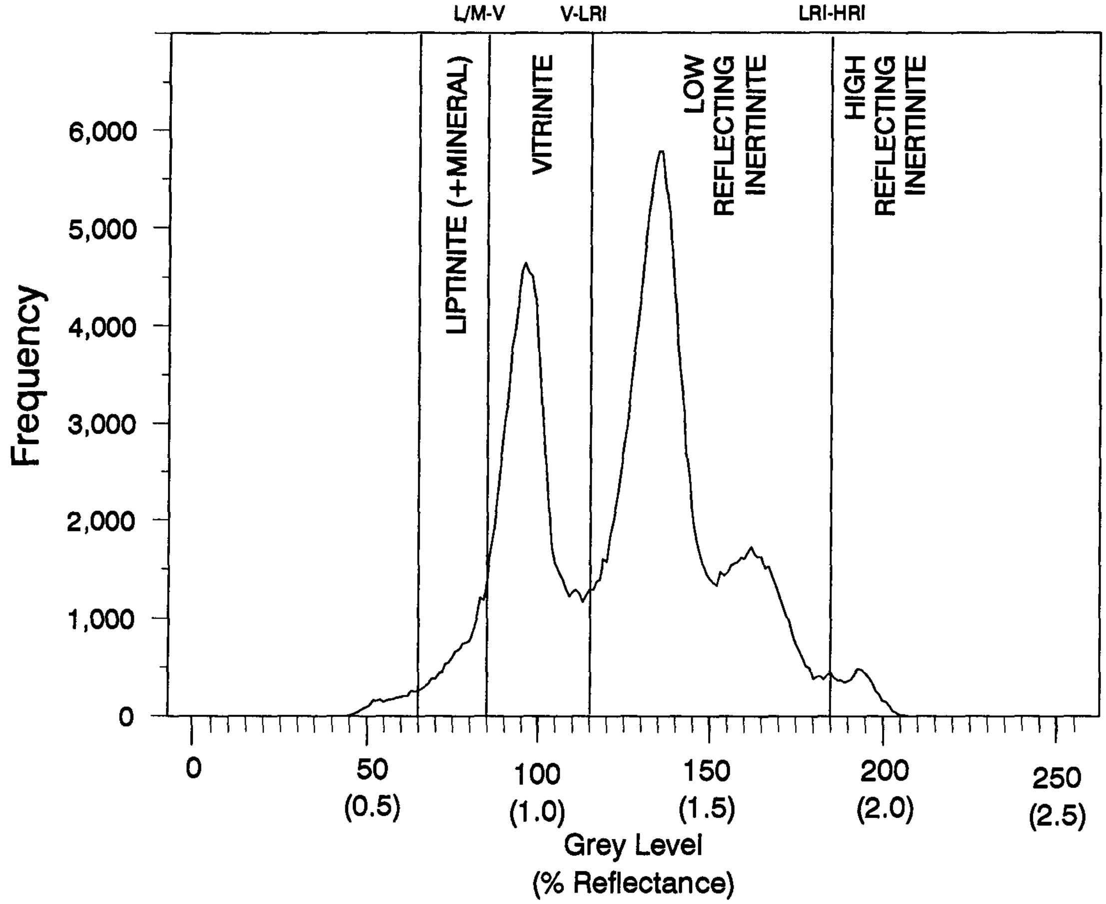

Figure 4-5. Grey level histogram of a field enriched in low-reflecting inertinite showing sample compositional threshhold locations. Abbreviations as in Table 4-3.

Table 4-3. Grey level and reflectance thresholds used, predicted maximum reflectance (in oil), and previously published refelctance values.

SEAM	GREY LEVEL THRESHOLD L/M-V	V-LRI	LRI-HRI	Midpoint (vitrinite)	REFLECTANCE (in oil) L/M-V	V-LRI	LRI-HRI	Midpoint (vitrinite)	Predicted (1) Max Ro	Ro max (2)
A1	86	130	185	108	0.88	1.37	2.00	1.12	1.23	1.26
A2	79	125	185	102	0.80	1.32	2.00	1.06	1.15	1.26
B	87	118	185	102.5	0.89	1.24	2.00	1.06	1.16	1.14
C	75	120	185	97.5	0.75	1.26	2.00	1.01	1.10	1.15
D	74	120	185	97	0.74	1.26	2.00	1.00	1.10	1.06
E - low	65	120	185	92.5	0.64	1.26	2.00	0.95	1.04	
E - mid	70	120	185	95	0.69	1.26	2.00	0.98	1.07	1.04
E - high	75	120	185	97.5	0.75	1.26	2.00	1.01	1.10	

(1) Utilizing equation of Pratt (1987) RoMAX =((grey level) -(.040))/1.055
(2) Kalkreuth and Leckie (1989)
L/M = liptinite + mineral; V=vitrinite; LRS = low reflecting inertinite; HRI = high reflecting inertinite

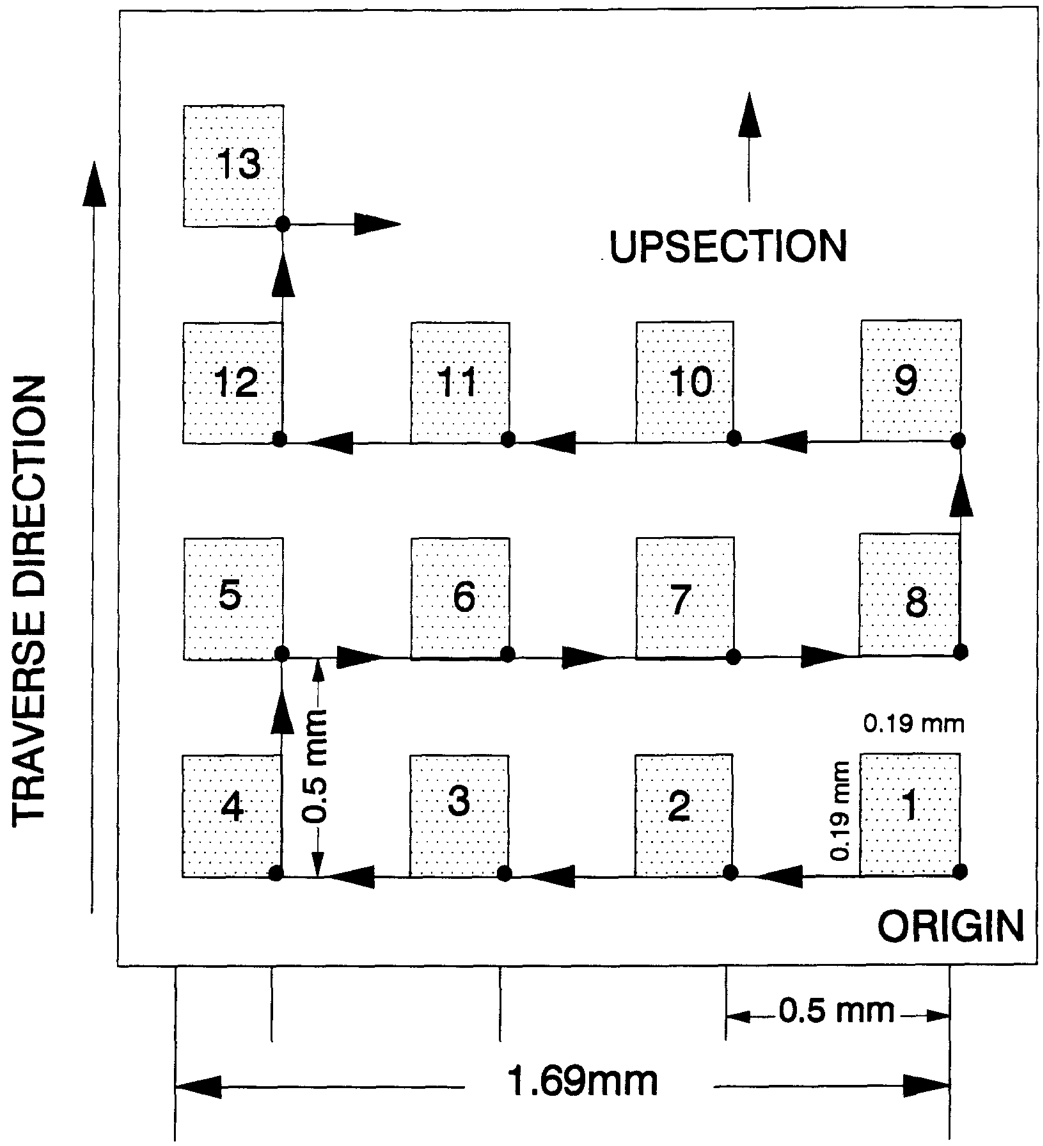

Figure 4-6. Schematic illustration (not to scale) showing path of IBAS traverse and size of fields evaluated.

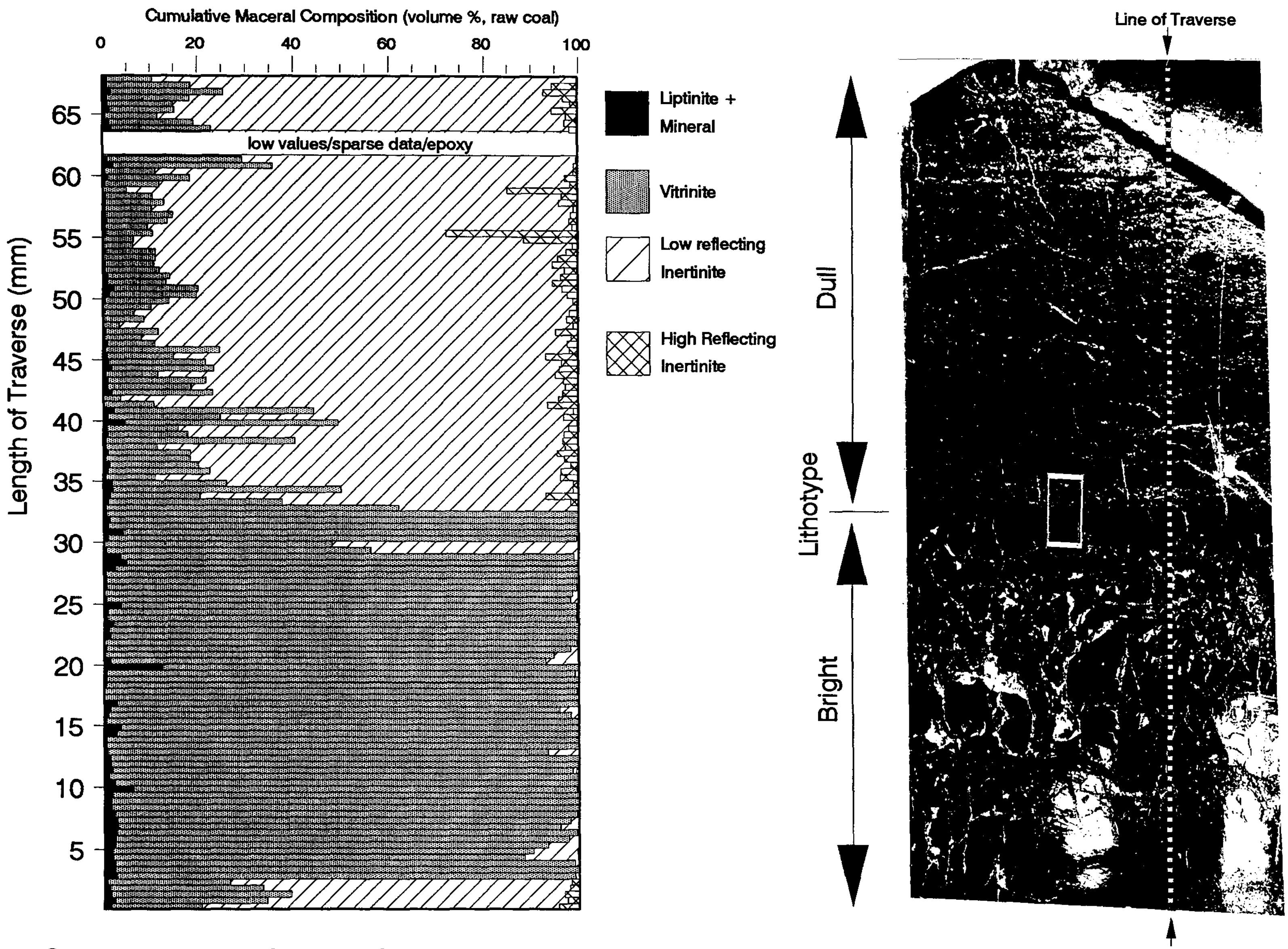

Figure 4-7. Scaled illustration of output of IBAS system, with a photograph of sample B66a. Note the abrupt change in composition from bright coal at base to dull coal at top. Inset rectangle on photo shows area of composite image in Figure 4-8. Also note low data associated with crack in block near top.

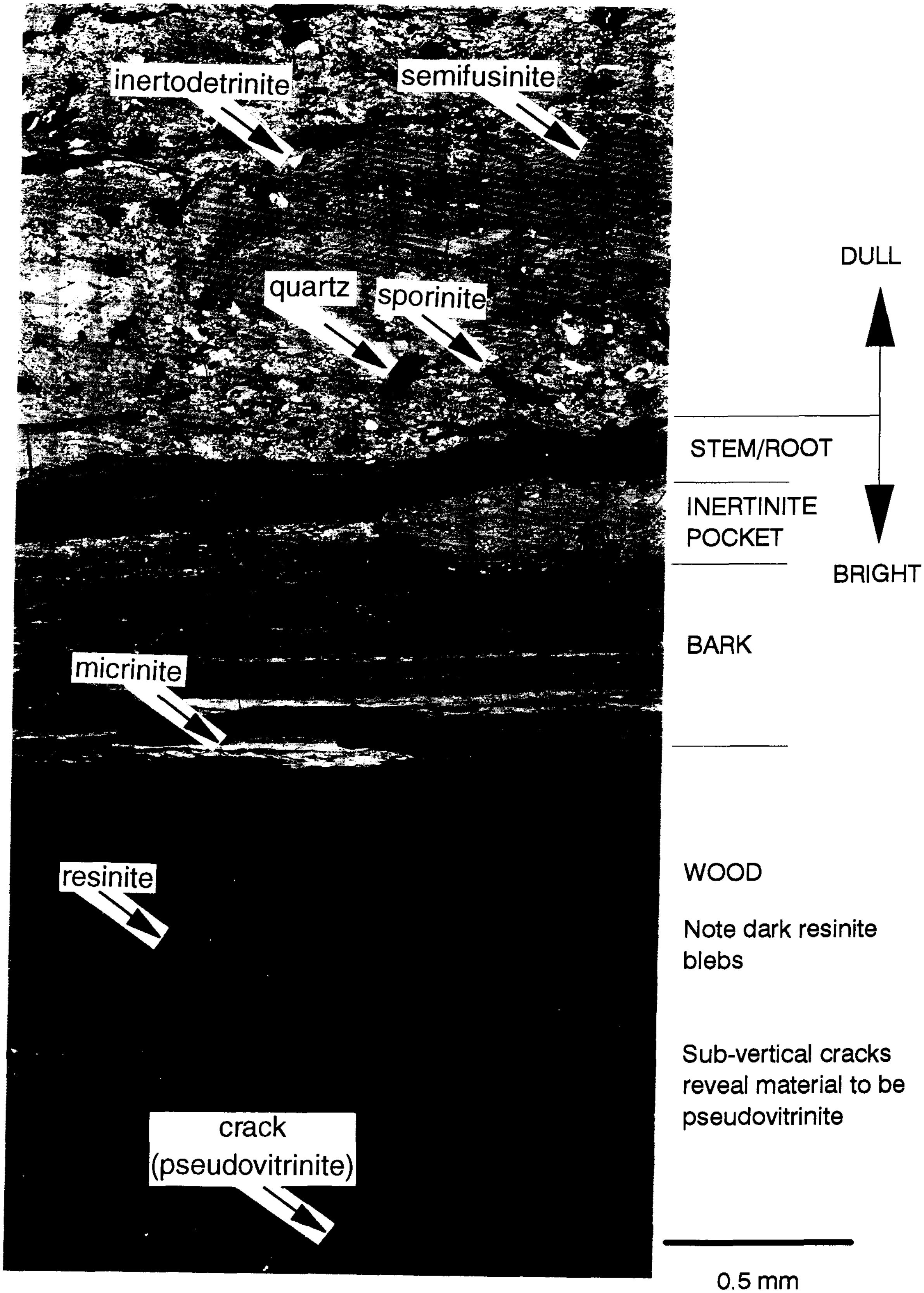

Figure 4-8. Photomosaic of area shown in Figure 4-7 generated with IBAS according to procedure of Pratt (in press). Note abrupt change from vitrinite-rich to inertinite and mineral rich composition across boundary.

4.5 RESULTS

The average maceral composition of each lithotype (Table 4-4) determined for this study are in general agreement with those of Lamberson et al. (1991) and Marchioni and Kalkreuth (1991). From brighter to duller lithotypes vitrinite decreases; inertinite and, to a lesser extent, mineral matter increases . A decrease in the ratio of structured: unstructured inertinite and structured: unstructured vitrinite also occurs from bright to dull coal. Fibrous (fusain) coals are rare, with only six occurrences in the seams studied. Fibrous coals analyzed are variable in composition (Table 4-5), but all have high ratios of structured to unstructured inertinite (average of 34:1). Total inertinite varies from 38% - 92% by volume, mineral matter free, with an average composition of 30.9% vitrinite, 68.6% inertinite, and < 1% liptinite; on average the inertinite is consists of 25.1% semifusinite, 44.5 % fusinite and 3.7% other inertinite (primarily inertodetrinite).

Lithotype, manually (point count) determined and image analysis compositional profiles are illustrated side-by-side for each seam in Figure 4-9 to 4- 14. One disadvantage of image analysis results is the inability to distinguish texture, so differentiating between vitrinite and inertinite maceral varieties is not possible. The manual petrography is grouped into the basic maceral groups to allow comparison with the image analysis results. Inertodetrinite occurs as both high and low-reflecting inertinite varieties. Compositional data averaged for selected intervals of each of the seams is given in Table 4-6.

The primary advantage of the data obtained by image analysis lies in stratigraphic resolution. The variation in composition of the seam is a finer scale than the 2-5 centimetre lithotype scale represented by the manual petrographic data. By following a vertical traverse of the seam, millimetre scale variations in composition are resolvable. This fine scale is illustrated by the composite image shown in Figure 4-8. The most significant problem with the image analysis technique lies is the determination of liptinite percentage. Edge effects around cracks, holes, scratches, mineral matter etc., produce a gradation in values that are lower than the adjacent maceral. For this reason, liptinite values obtained by image analysis are higher than those obtained by point counting and often reflect mineral matter concentration, rather than liptinite percentage (Pratt, 1988, 1989). It has previously been determined (Kalkreuth and Leckie, 1989; Lamberson et al., 1991; Marchioni and Kalkreuth,

Table 4-4. Average petrographic composition by lithotype.

	Bright	Banded Bright	Banded Coal	Banded Dull	Dull	Fibrous (Fusain)	Mineral Rich	Sheared
(number of samples)	(23)	(18)	(19)	(87)	(33)	(5)	(12)	(20)
Ash Yield (weight %)	5.5	10.4	17.1	10.6	17.6	11.4	54.5	13.3
	Volume %, Mineral Matter Free							
Total Vitrinite	84.0	76.3	66.4	43.3	30.6	24.9	60.9	89.7
structured vitrinite	70.2	50.9	42.1	23.1	16.6	14.9	32.0	54.2
degraded vitrinite	13.7	25.4	24.3	20.2	14.0	9.9	28.9	35.6
Total Inertinite	14.1	22.1	32.0	55.1	67.4	74.7	38.6	9.2
semifusinite	6.0	9.2	13.8	27.2	30.7	26.2	14.1	3.6
fusinite	5.1	6.7	8.8	11.8	10.6	44.5	7.1	2.7
inertodeterinite	2.4	6.0	9.1	15.6	25.3	3.8	17.2	2.1
other inertinite	0.6	0.2	0.3	0.5	0.8	0.2	0.2	0.8
Liptinite	2.0	1.6	1.6	1.6	2.0	0.4	0.5	1.0
Ratios:								
structured: degraded vitrinite	5.11	2.01	1.73	1.15	1.18	1.50	1.11	1.52
struct inert: inertodetrinite [1]	4.57	2.66	2.50	2.49	1.63	18.61	1.23	2.95
	Volume %, Raw Coal							
Mineral Matter	3.1	6.3	10.6	6.4	11.5	6.6	44.1	8.8
Total Vitrinite	81.4	71.5	59.4	40.5	27.1	23.2	34.0	81.9
structured vitrinite	68.1	47.7	37.6	21.6	14.7	13.9	17.9	49.4
degraded vitrinite	13.3	23.8	21.7	18.9	12.4	9.3	16.1	32.5
Total Inertinite	13.6	20.7	28.6	51.6	59.6	69.8	21.6	8.4
semifusinite	5.8	8.7	12.4	25.5	27.2	24.5	7.9	3.3
fusinite	4.9	6.3	7.9	11.0	9.3	41.6	4.0	2.4
inertodeterinite	2.3	5.6	8.1	14.6	22.4	3.5	9.6	1.9
other inertinite	0.6	0.2	0.2	0.5	0.7	0.2	0.1	0.8
Liptinite	1.9	1.5	1.4	1.5	1.8	0.4	0.3	0.9

[1] *struct inert = semifusinite + fusinite*

Table 4-5. Petrographic composition of six fibrous (fusain) samples distinguishable in Bullmoose seams. These samples represent only those thick enough to be defined as a lithotype (> 1 cm). Scattered fibrous material is found commonly in the coal seams on bedding surfaces.

			Volume %, Mineral Matter Free								
	Thickness (cm)	Ash Yield (weight %)	Structured Vitrinite	Degraded Vitrinite	Total Vitrinite	Semi-fusinite	Fusinite	Inerto-detrinite	Total Inertinite	SINERT: IDET	Total Liptinite
D27b	2	3.3	4.7	3.3	8.0	27.0	64.0	1.0	92.0	91	0.0
B25b	4	21.8	4.3	9.0	13.3	42.0	36.3	7.7	86.0	10	0.7
B72c	2	6.4	20.3	9.7	30.0	17.7	50.3	2.0	70.0	34	0.0
A2-6	2	9.3	15.3	17.3	32.7	25.0	34.7	7.0	66.7	9	0.7
B43b	1	16.3	30.0	10.3	40.3	19.3	37.3	1.3	59.0	43	0.7
E-4	4	N.D. [a]	42.0	19.3	61.3	19.3	16.3	2.3	38.0	15	0.7
	Average	11.4 [b]	19.4	11.5	30.9	25.1	44.5	3.6	68.6	34	0.4
	Standard Deviation	6.7 [b]	14.7	5.9	19.2	9.1	16.1	3.0	19.4	31	0.3

[a] *N.D. = not determined*

[b] *Average and standard deviation of 5 samples for which ash was determined.*

SINERT:IDET = semifusinite + fusinite/inertodetrinite

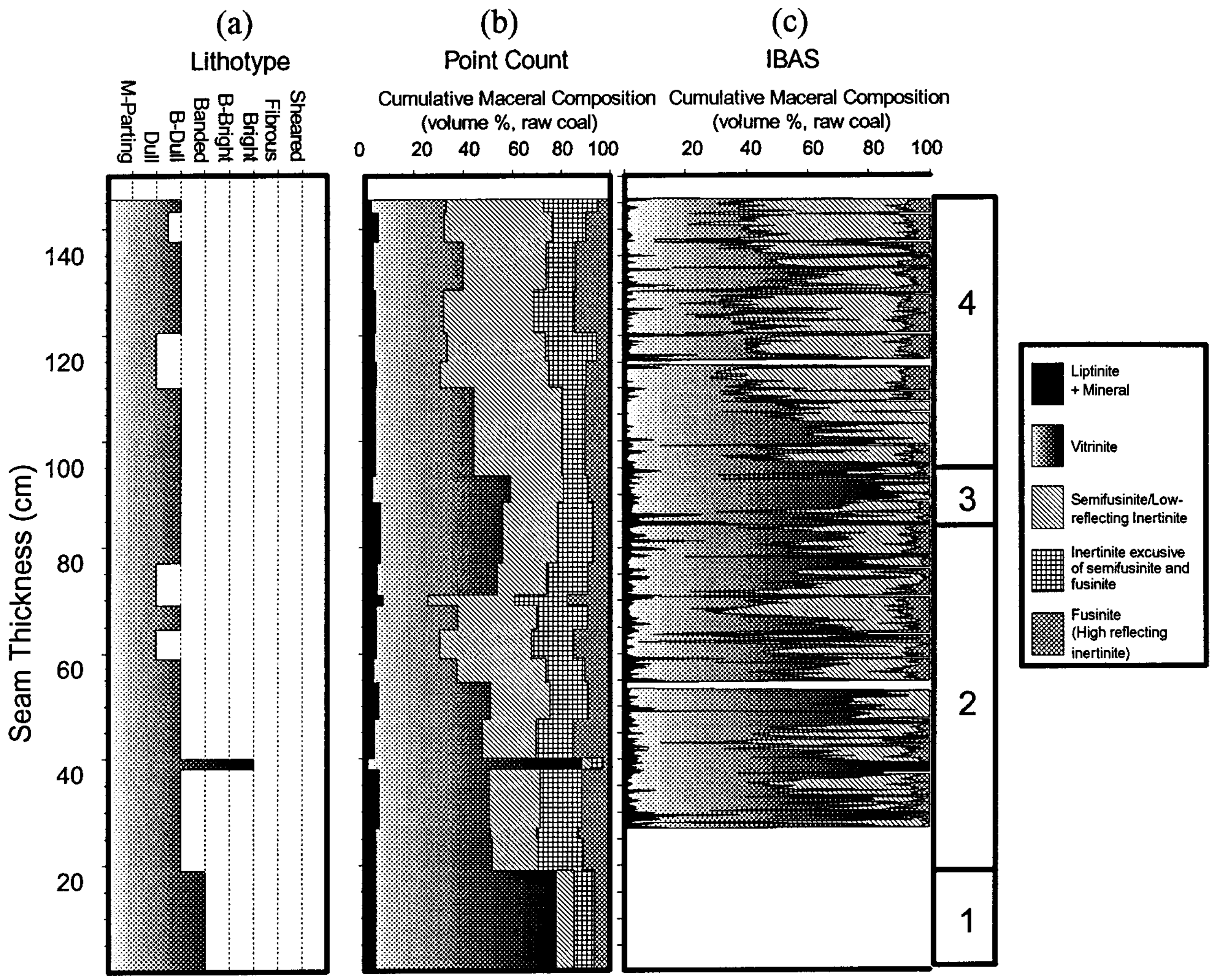

Figure 4-9. Stratigraphic profiles of the Bullmoose A1 seam. Includes (a) lithotype stratigraphy, (b) maceral analysis by point counting and (c) maceral analysis as determined by image analysis. Breaks in IBAS data indicated by blank spaces. For ease of discussion, IBAS profile has been separated into zones indicated by Arabic numerals (1, 2,3, etc.).

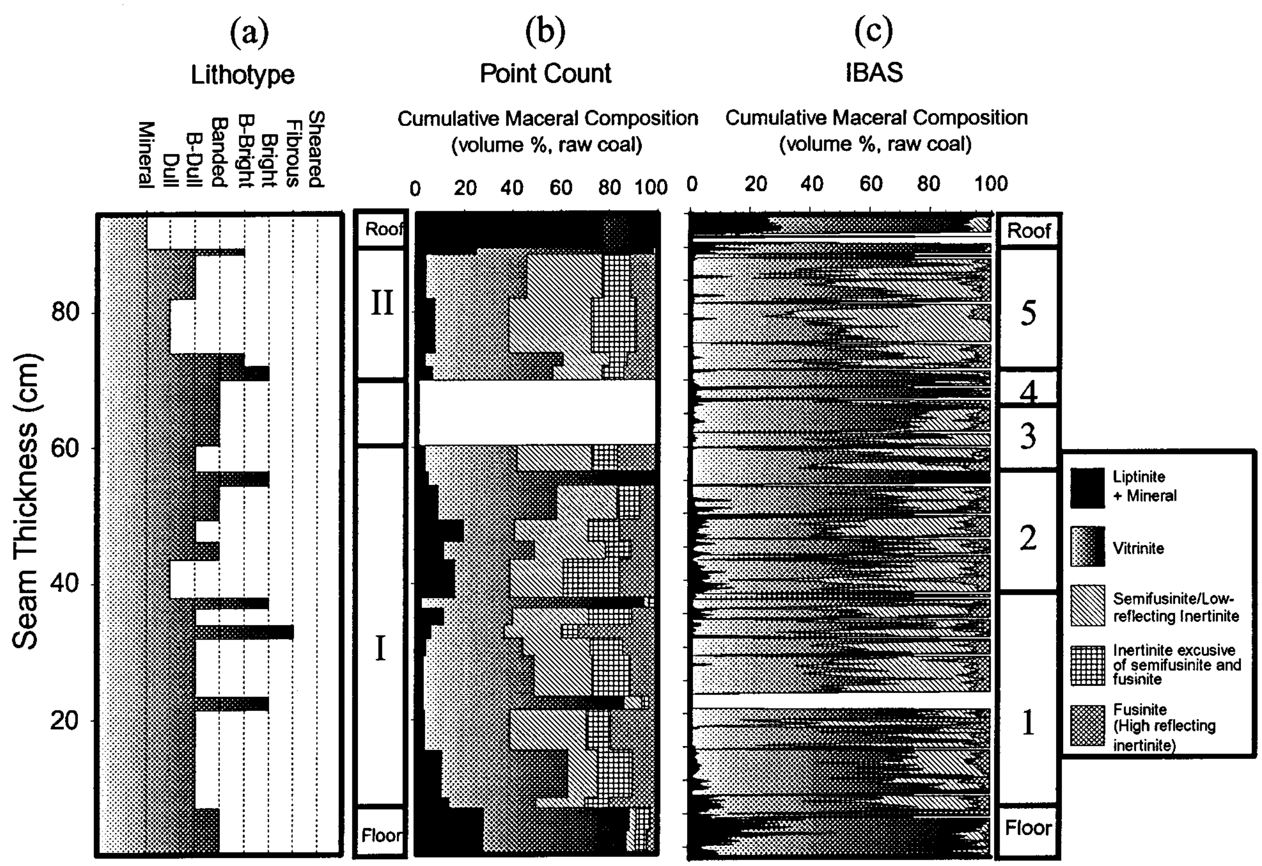

Figure 4-10. Stratigraphic profiles of the Bullmoose A2 seam. Includes (a) lithotype stratigraphy, (b) maceral analysis by point counting and (c) maceral analysis as determined by image analysis. Breaks in IBAS data indicated by blank spaces. For ease of discussion, profiles have been separated into zones. Arabic numerals (1, 2, 3, etc.) refer to point count data, whereas Roman numerals (I, II, II, etc.) refer to IBAS data.

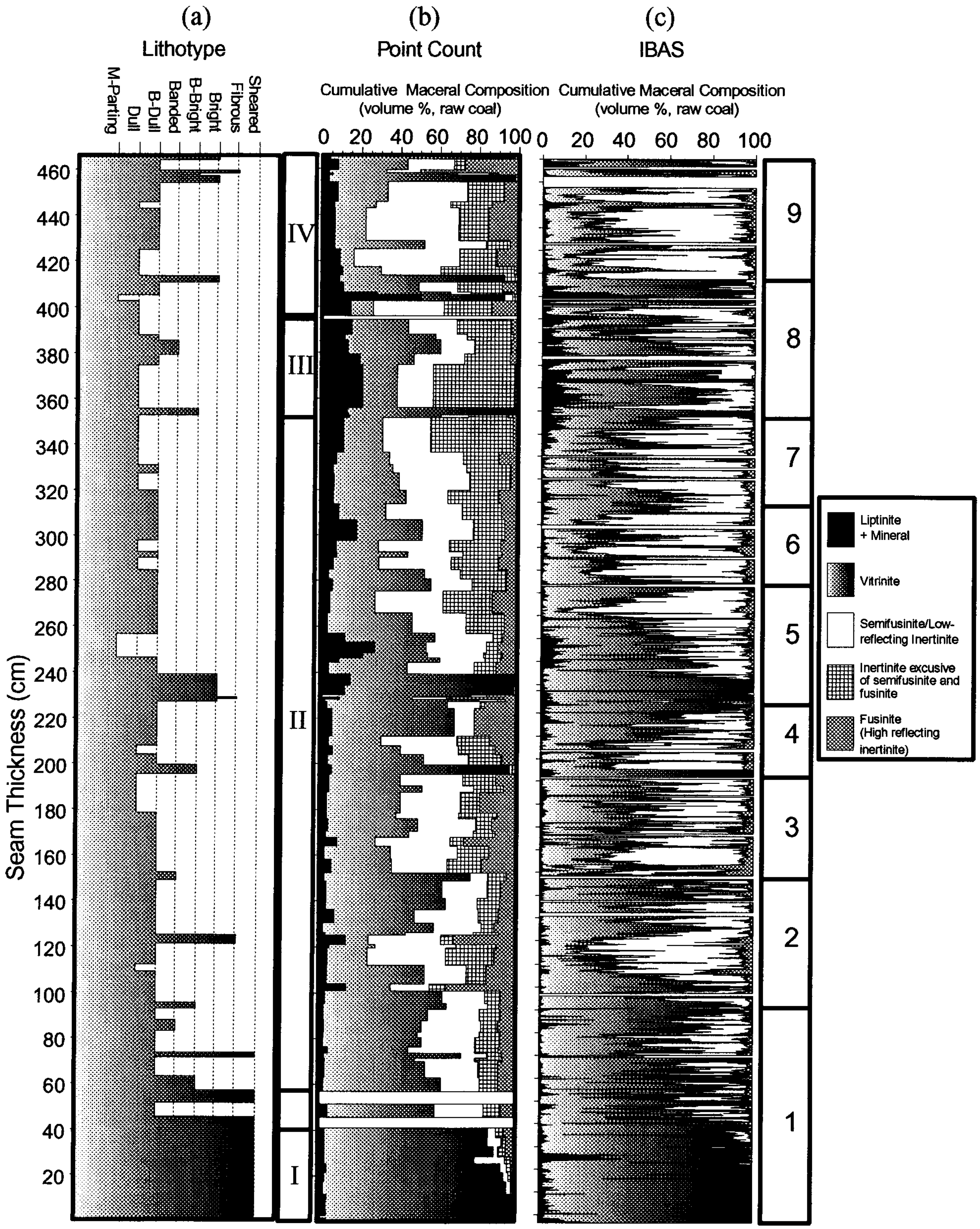

Figure 4-11. Stratigraphic profiles of the Bullmoose B seam. Includes (a) lithotype stratigraphy, (b) maceral analysis by point counting and (c) maceral analysis as determined by image analysis. Breaks in IBAS data indicated by blank spaces. For ease of discussion, profiles have been separated into zones. Roman numerals (I, II, II, etc.) refer to point count data, whereas Arabic numerals (1, 2, 3, etc.) refer to IBAS data.

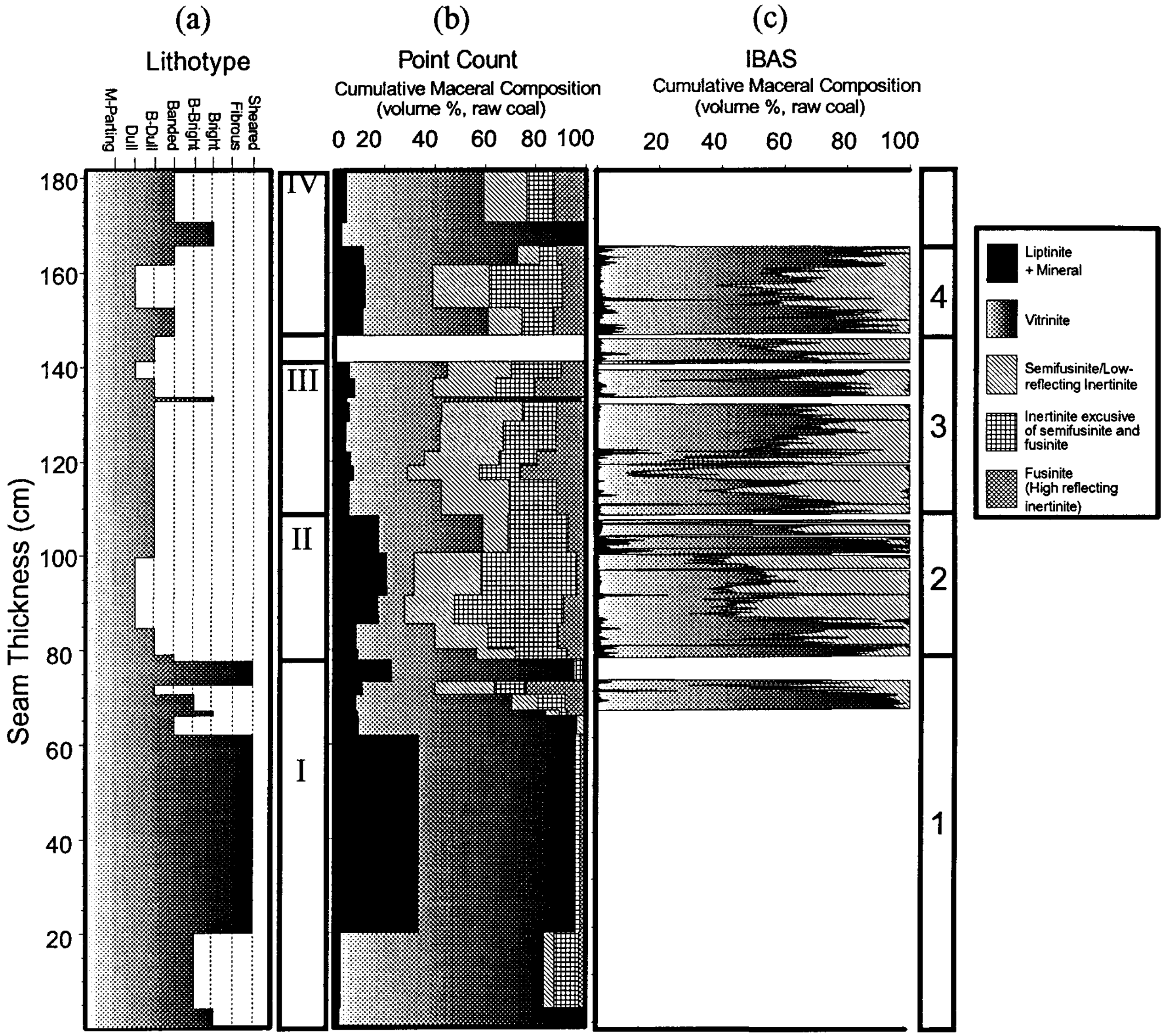

Figure 4-12. Stratigraphic profiles of the Bullmoose C seam. Includes (a) lithotype stratigraphy, (b) maceral analysis by point counting and (c) maceral analysis as determined by image analysis. Breaks in IBAS data indicated by blank spaces. For ease of discussion, profiles have been separated into zones. Roman numerals (I, II, III, etc.) refer to point count data, whereas Arabic numbers (1, 2, 3 etc.) refer to IBAS data.

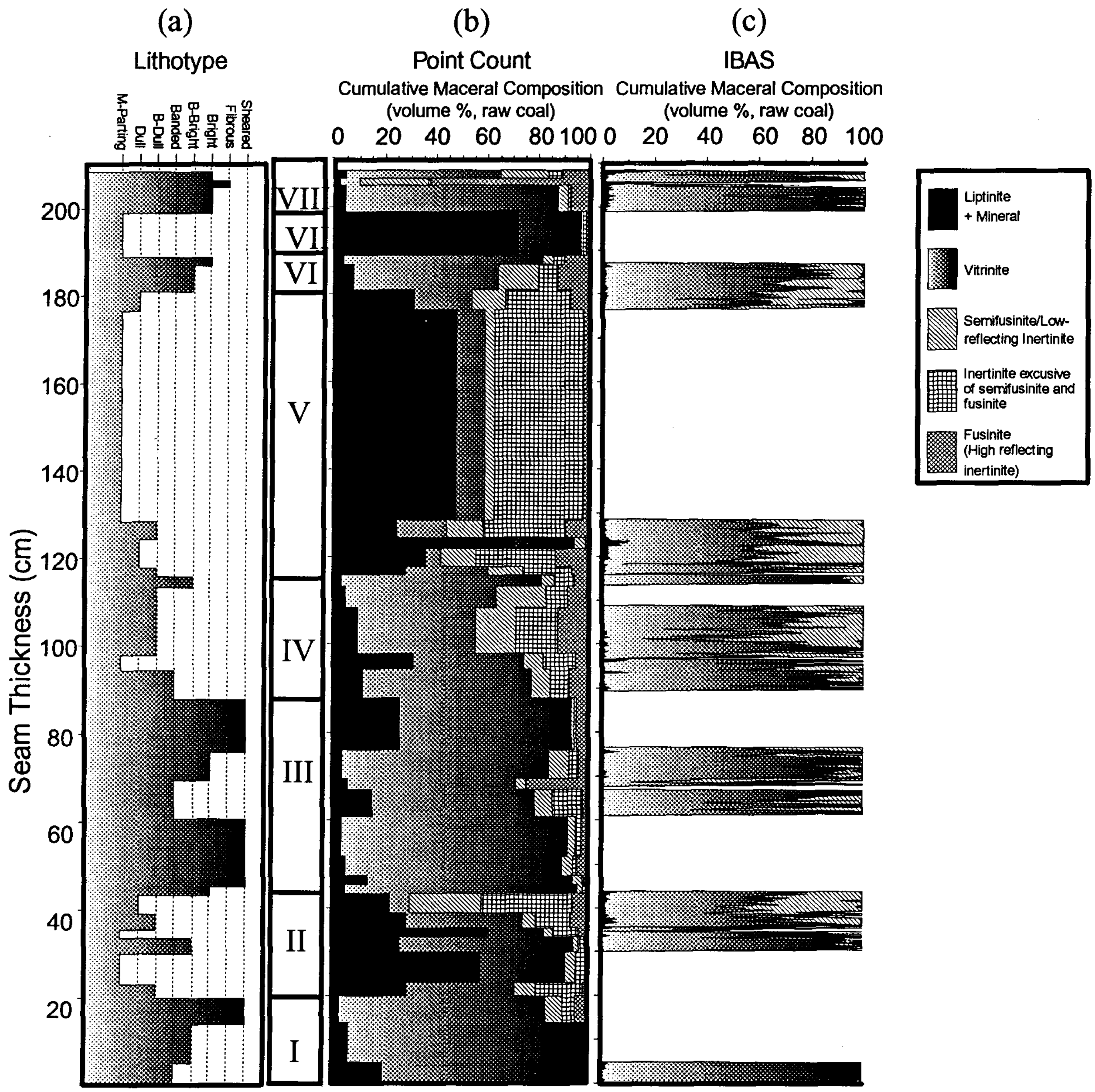

Figure 4-13. Stratigraphic profiles of the Bullmoose D seam. Includes (a) lithotype stratigraphy, (b) maceral analysis by point counting and (c) maceral analysis as determined by image analysis. Breaks in IBAS data indicated by blank spaces. For ease of discussion, profiles have been separated into zones. Roman numerals (I, II, III, etc.) refer to point count data, whereas Arabic numerals (I, II, II, etc.) refer to IBAS data.

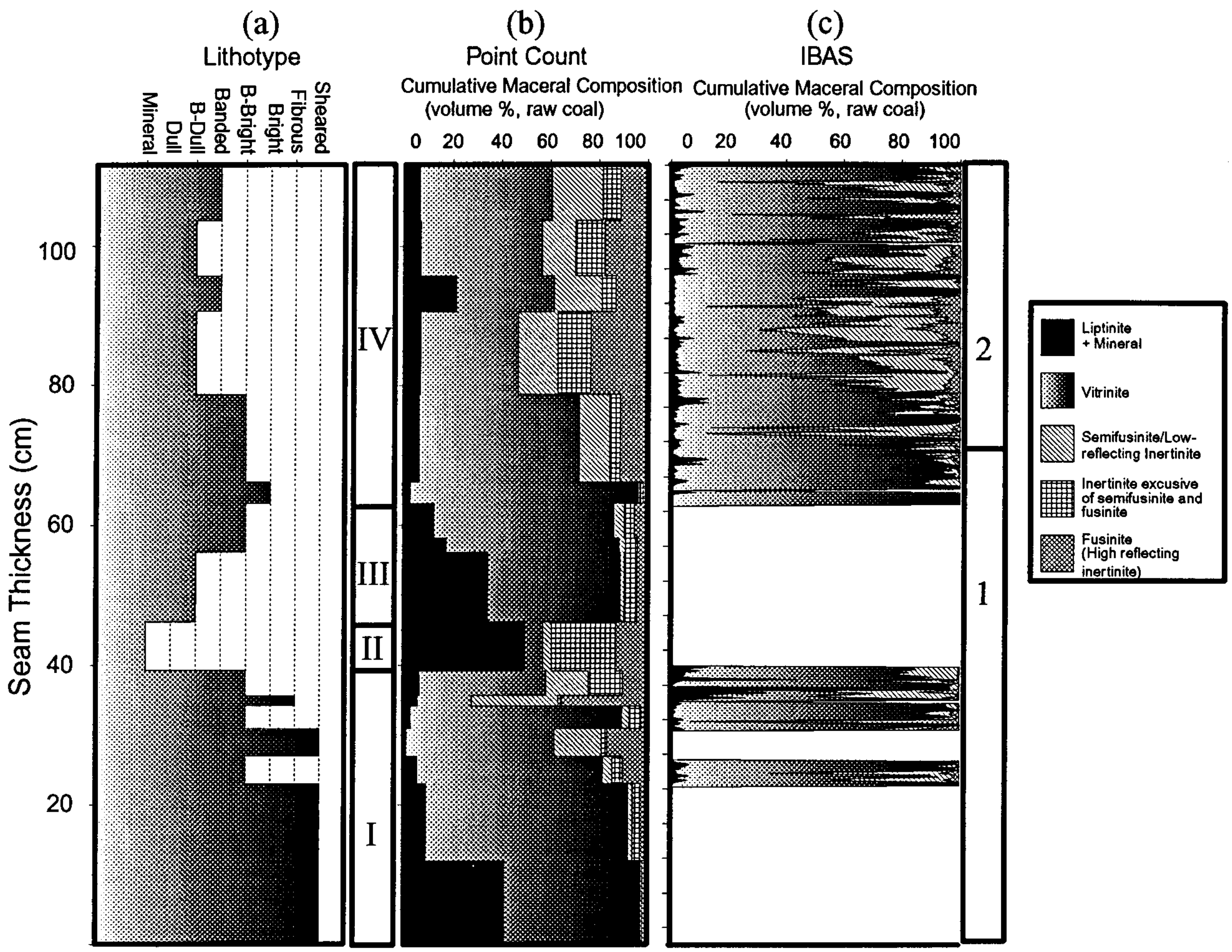

Figure 4-14. Stratigraphic profiles of the Bullmoose E seam. Includes (a) lithotype stratigraphy, (b) maceral analysis by point counting and (c) maceral analysis as determined by image analysis. Breaks in IBAS data indicated by blank spaces. For ease of discussion, profiles have been separated into zones. Roman numerals (I, II, II, etc.) refer to point count data, whereas Arabic numerals (1, 2, 3, etc.) refer to IBAS data.

Table 4-6. Petrographic composition of zones in Figures 4-9 to 4-14.

	Volume %, Raw Coal Basis									Volume %, Mineral Matter Free Basis						
	Structured Vitrinite	Degraded Vitrinite	Structured Inertinite	Inerto-detrinite	Total Vitrinite	Total Inertinite	Total Liptinite	Mineral Matter	SINERT: IDET	Structured Vitrinite	Degraded Vitrinite	Structured Inertinite	Inerto detrinite	Total Vitrinite	Total Inertinite	Total Liptinite
A1 Seam	25	19	37	14	44	51	2	3	2.7	26	19	38	14	46	53	2
A2 Floor	25	35	7	5	60	12	0	28	1.4	35	48	10	7	83	17	0
A2 I	28	17	34	11	45	45	2	8	3.1	30	18	36	12	49	49	2
A2 II	20	19	40	14	40	54	2	4	2.9	21	20	42	14	41	56	2
A2 Roof	13	17	0	0	31	0	0	69	2.0	43	56	1	0	99	1	0
B I	61	27	6	1	88	8	1	2	4.2	63	20	6	1	90	8	1
B II	25	17	37	14	42	51	2	5	2.6	26	18	39	15	44	54	2
B III	19	12	21	30	31	51	1	17 *	0.7	23	14	26	36	37	62	1
B IV	20	10	43	15	31	59	1	9	2.9	22	11	48	17	34	65	1
C I	39	30	6	4	69	10	0	21	1.3	50	37	7	5	87	12	0
C II	15	10	26	32	25	59	1	15 *	0.8	17	12	31	38	29	69	2
C III	19	17	41	17	36	58	2	5	2.4	20	18	43	17	38	61	2
C IV	32	21	25	14	53	38	1	7	1.8	35	23	27	15	57	41	2
D I	57	29	4	2	86	6	0	8	2.5	62	31	4	2	93	6	1
D II	17	18	12	13	36	26	1	38 *	0.9	28	30	20	22	58	41	1
D III	45	32	8	3	76	12	1	11	2.8	50	36	9	3	86	13	1
D IV	35	20	21	12	55	33	2	10	1.8	39	23	24	13	61	37	2
D V	6	7	10	32	13	42	0	44 *	0.3	11	13	18	57	23	76	0
D VI	44	18	25	7	62	32	2	4	3.7	46	19	26	7	64	33	2
D VII	15	9	3	1	25	4	0	72	2.2	54	33	9	4	87	13	0
D VIII	52	14	28	2	66	30	2	2	12.8	53	14	28	2	68	30	2
E I	41	26	12	4	67	16	1	16	3.4	49	30	15	4	80	19	1
E II	2	6	17	26	7	43	0	50 *	0.6	3	11	33	52	15	85	0
E III	35	27	7	5	62	12	1	25	1.4	47	36	9	7	83	16	1
E IV	33	21	30	8	54	38	3	5	3.7	34	22	31	9	57	40	3

SINERT:IDET = semifusinite + fusinite/inertodetrinite

* *High clastic mineral input, high inertinite*

1991) that the liptinite content of Gates Formation coals is negligible. Although some of the highest and lowest reflecting mineral matter is eliminated by the background values chosen, the lowest reflecting data set can be considered to be a low end approximation for mineral matter content by volume rather than liptinite concentration.

A statistical comparison of the results of image analysis with manual petrographic data was not included in this study as comparative analyses utilizing the system used here have been published previously (Pratt, 1988, 1989; 1991). A visual inspection of the results (Figs. 4-9 to 4-14), however, does reveal a very close correspondence between the two. The only real discrepancy lies in comparison of the percentage of high-reflecting inertinite and fusinite; manual results indicate a higher fusinite concentration. The process of charcoal formation produces abundant transitional reflecting material (Scott, 1989) and because of this the threshold between fusinite and semifusinite cannot be viewed as absolute. However, for practical purposes, a threshold between the two is needed; it appears that manual determination had a lower "visual" reflectance threshold than automated analysis. The presence of abundant transitional material was a particular problem in the E seam, where the use of three different threshold values was necessary (Table 4-3).

4.5.1 A1 Seam

The basal seam, A1 (Fig. 4-9a), is quite uniform in megascopic appearance, being primarily composed of banded dull and dull lithotypes and only one petrographic average was calculated. On a raw, whole coal basis, the seam is composed of 44% vitrinite, 51% inertinite, 2% liptinite and 3% mineral matter (Table 4-6). As determined from point count analysis (Fig. 4-9b) the basal zone for which there are no block samples is vitrinite rich. It can be seen from the IBAS profile that inertinite concentrations are cyclic in the basal part of the seam, reaching a low between 85-95 cm above the floor. From that interval, the inertinite concentration increases to around 60%, and remains remaining relatively stable throughout the remaining thickness.

4.5.2 A2 Seam

The A2 seam (Fig. 4-10) is more variable in lithotype stratigraphy. Both roof and floor rocks are carbonaceous mudstones with abundant bright streaks and are enriched in vitrinite (Table 4-6). The floor rock in particular contains enough bright material to be classified as a banded coal. The seam contains more bright intervals and a mineral-rich zone between 40-55 centimetres, but overall resembles the A1 seam. Inertinite and vitrinite are in approximately equal proportions in the basal part of the seam (zones 1 and 2, Fig. 4-10c), but the variation appears to be cyclic at a very fine scale, even through the more mineral rich conditions of zone 2. Above the bright layer at about 55 centimetres (zone 3), the inertinite increases to greater than 60%, then gradually decreases to less than 20% (zone 4). In zone 5, the inertinite concentration increases again to between 40 - 60 %. At a position just below the top of the seam, a thin bright layer occurs, and vitrinite again is high.

4.5.3 B Seam

The most complete stratigraphy is retained for the thickest seam, the B seam (Fig. 4-11). The variation in vitrinite/inertinite content appears to be cyclic, with 9 distinct cycles resolvable. Although the basal part of the seam is sheared (Fig. 4-11a), it does appear relatively bright (unlike the more mineral rich sheared zones found in the C and D seams) and is composed of 88 % vitrinite by volume. The remainder of the seam is composed of primarily dull and banded dull lithotypes. This dullness is attributable for the most part to the presence of inertinite, rather than mineral matter. Clastic minerals are present in quantity only in the upper approximately 1.5 metres of the seam (zone III, Figure 4-11b); mineral matter in the basal part of the seam consists of carbonate concretionary layers and fracture fillings. The IBAS data collected from zone 8 is not as complete as from the remainder of the seam; mineral matter is often associated with cracks and holes in a block, causing blank fields in the data set.

4.5.4 C Seam

Variation in inertinite content of seam C (Fig. 4-12) is difficult to interpret from the IBAS profiles due to sampling gaps. The seam is mineral rich. Dullness in the lithotypes of the C seam is primarily due to mineral content, as well as inertinite content. The basal part of the C seam, as shown in the manual petrography data (Fig. 4-12b), is vitrinite rich (87% vitrinite). Two sheared intervals occur within zone I which are both mineral and vitrinite rich. In zone II (and 2, Fig. 4-12c), the mineral rich zones are also inertinite rich, particularly inertodetrinite, suggesting an allochthonous source of inertinite. In zone 3 (Fig. 4-12c), one major cycle and several smaller cycles of low to high to low inertinite concentration are present, resembling the cycles seen in the lower, mineral poor seams. Another clastic influx occurs above this zone (zone 4, IV), with an increase in the percentage of inertodetrinite. A bright, then banded coal sequence (an overall change from low to high inertinite concentration) terminates the seam stratigraphy. The millimetre-scale stratigraphic changes are not known from this interval.

4.5.5 D Seam

Gaps in the profile of the D seam (Fig. 4-13) do not allow for a detailed description of the stratigraphy. The seam is higher in vitrinite than the lower seams, but mineral matter is also high. The basal part of the seam is particularly enriched in vitrinite, as well as mineral matter. Inertinite is associated with some of the mineral rich zones. As in seam C, if a mineral rich zone such as zone V (Fig. 4-13) is inertinite rich, inertodetrinite comprises a significant proportion (Table 4-6).

4.5.6 E Seam

The most continuous part of the E seam profiled by the IBAS is the uppermost 50 centimetres (Fig. 4-14). The E seam is a relatively low inertinite coal. The basal part of the seam is mineral and vitrinite rich, with an ~~increase in inertinite content and a marked decrease in mineral content up section to just below 40 centimetres~~ above the base (zone I). Zone II is composed of a carbonaceous mudstone, enriched in inertinite, particularly inertodetrinite. Vitrinite is high (83% mineral matter free) in zone III, which is marked by a consistent decrease in mineral matter from bottom to top. The upper part of the seam contains one cycle of increased, then decreased inertinite concentration. As can be seen in the IBAS profile (Fig. 4-11c), at a fine scale, this major cycle is composed of a number of thinner gradations from lower to higher inertinite concentrations.

4.6 DISCUSSION OF RESULTS

4.6.1 Petrographic Features Indicating Fire Influence

Within the Gates Formation coals, fusinite, semifusinite and inertodetrinite (including what Marchioni and Kalkreuth, 1991, term discrete macrinite) represent the bulk of all of the inertinite in the Gates coals. Micrinite, classically-defined macrinite and fungal-derived sclerotinite are rare. Fusinite and semifusinite represent discrete plant organs, principally stem and root wood, leaves, and bark of gymnosperms as well as the leaves and rhizomes of ferns. Rare materials which may be angiosperm wood and unidentified seeds are also found. Inertodetrinite is primarily derived from discrete pieces of crushed semifusinite and fusinite. Some of the inertodetrinite may be "fly ash" (soot). Rare amorphous material occurs which is interpreted to be pyrolyzed peat. Pyrolitic carbon was included with inertodetrinite.

Accumulations of fibrous coal (fusain) thick enough to constitute a lithotype (> 1 cm) are uncommon (Table 4-5). Aside from the megascopically identifiable fibrous layers, another type of fire horizon is interpreted to be present within the B seam. These layers, unlike the soft, sooty, black fibrous units, are very hard, weather to a brown-grey colour, and resemble mineral partings. As illustrated in the photomosaics of Figure 4-15 and 4-16, the lenses are composed almost completely of inertinite, but are calcium carbonate impregnated. A structure which is clearly a branched gymnospermous root is present in Figure 4-16, and has been pyrolyzed to fusinite. The carbonate in this layer may be in part primary. A rise in pH as a result of fire in acid soils (Christensen, 1987), along with the formation of alkali oxides (Kimmins, 1987), would facilitate the precipitation of carbonate in a burned peat horizon.

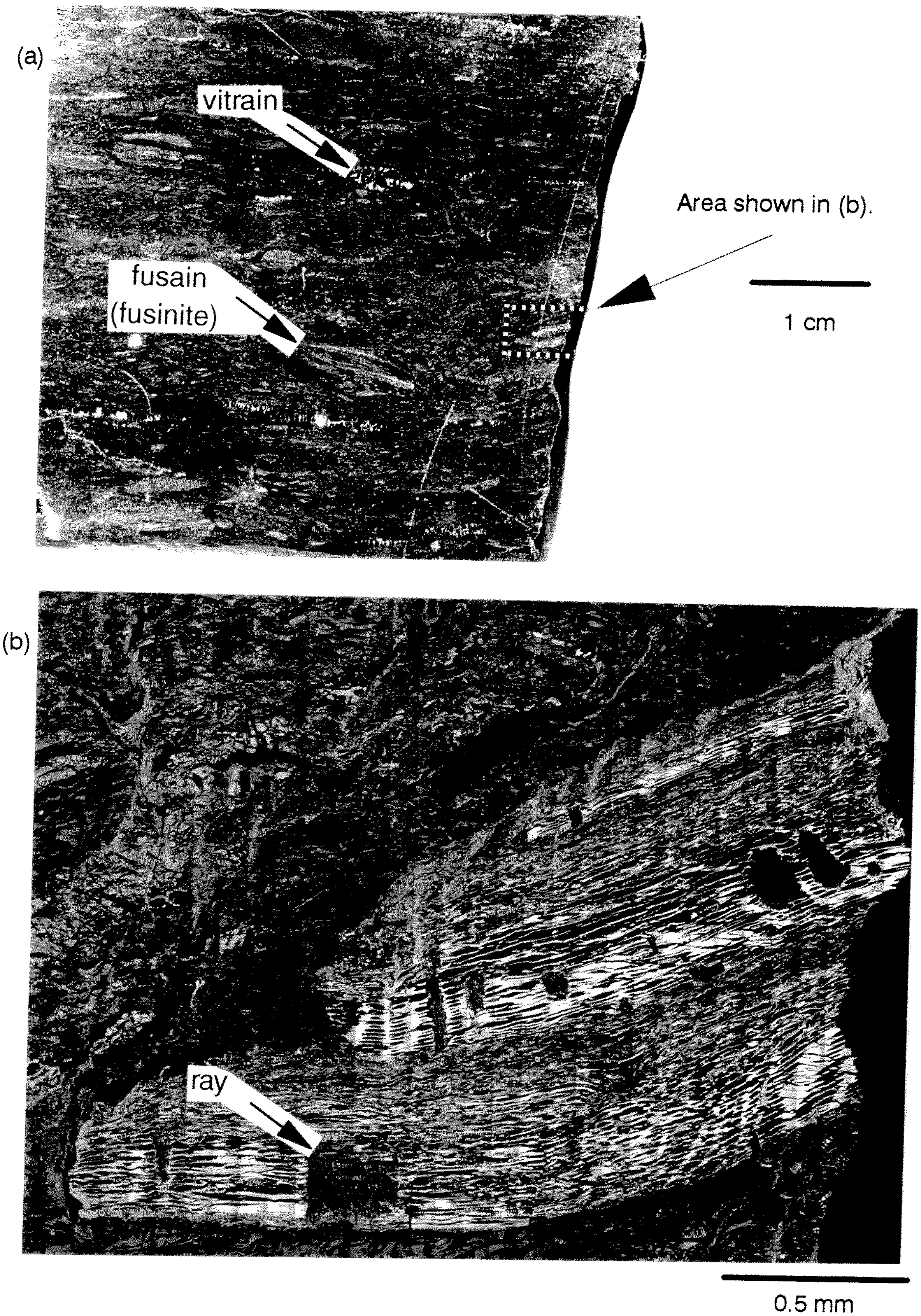

Figure 4-15. Photograph of mineral parting which is in fact a calcium carbonate-impregnated fusain layer. (b) Enlargement of (a), showing radial cut of fusinitized coniferous wood. Note fine detail preserved in ray structure.

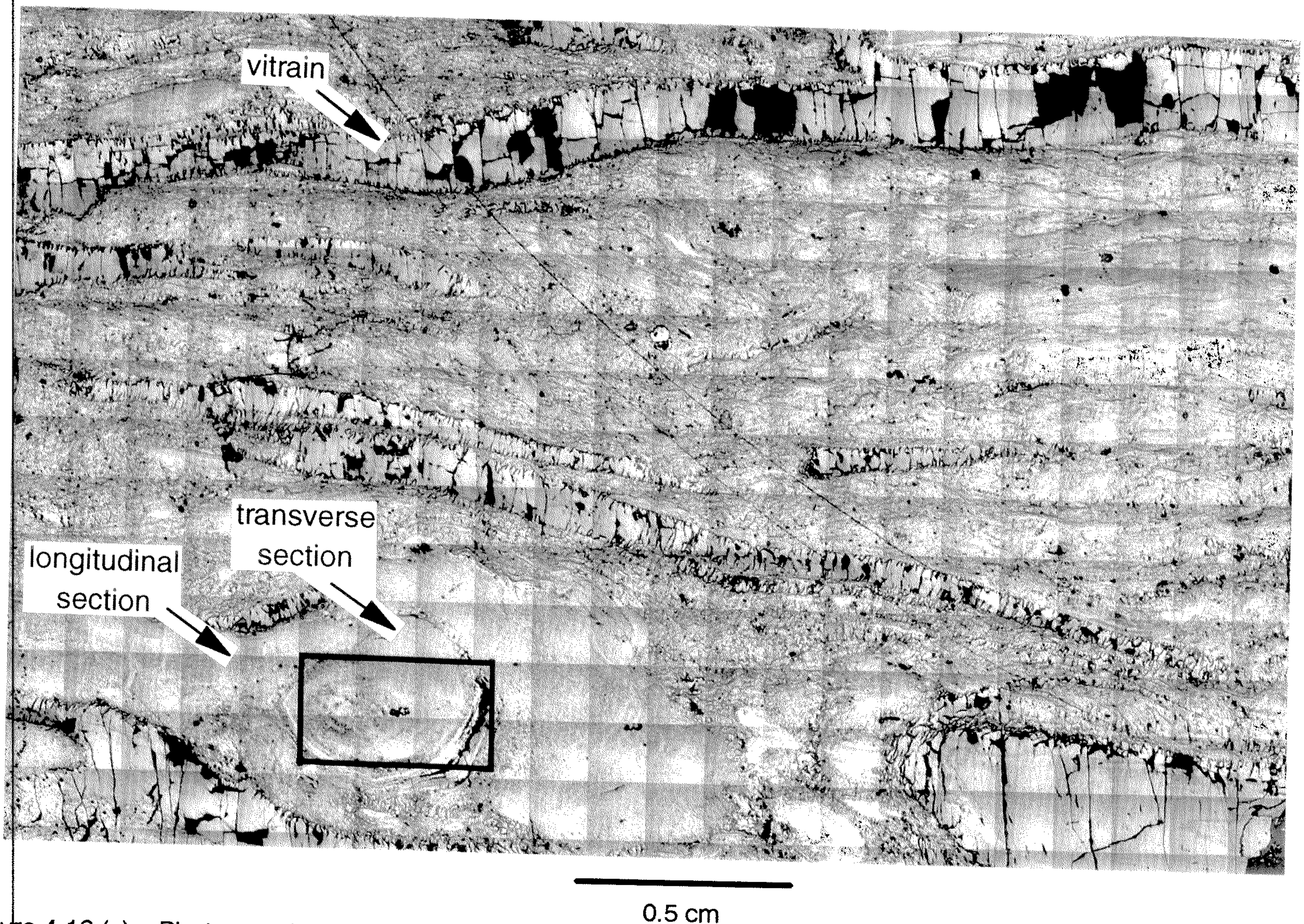

Figure 4-16 (a). Photomosaic of mineral parting which is in fact a calcium carbonate-impreganted fusain layer. Photographed with IBAS with 10X objective in air. Note characteristic vertical fracture pattern of vitrinite. Majority of block is inertinite. Large horizontal feature in bottom part of photograph is branched root. Rectangle shows area of enlargement in (b).

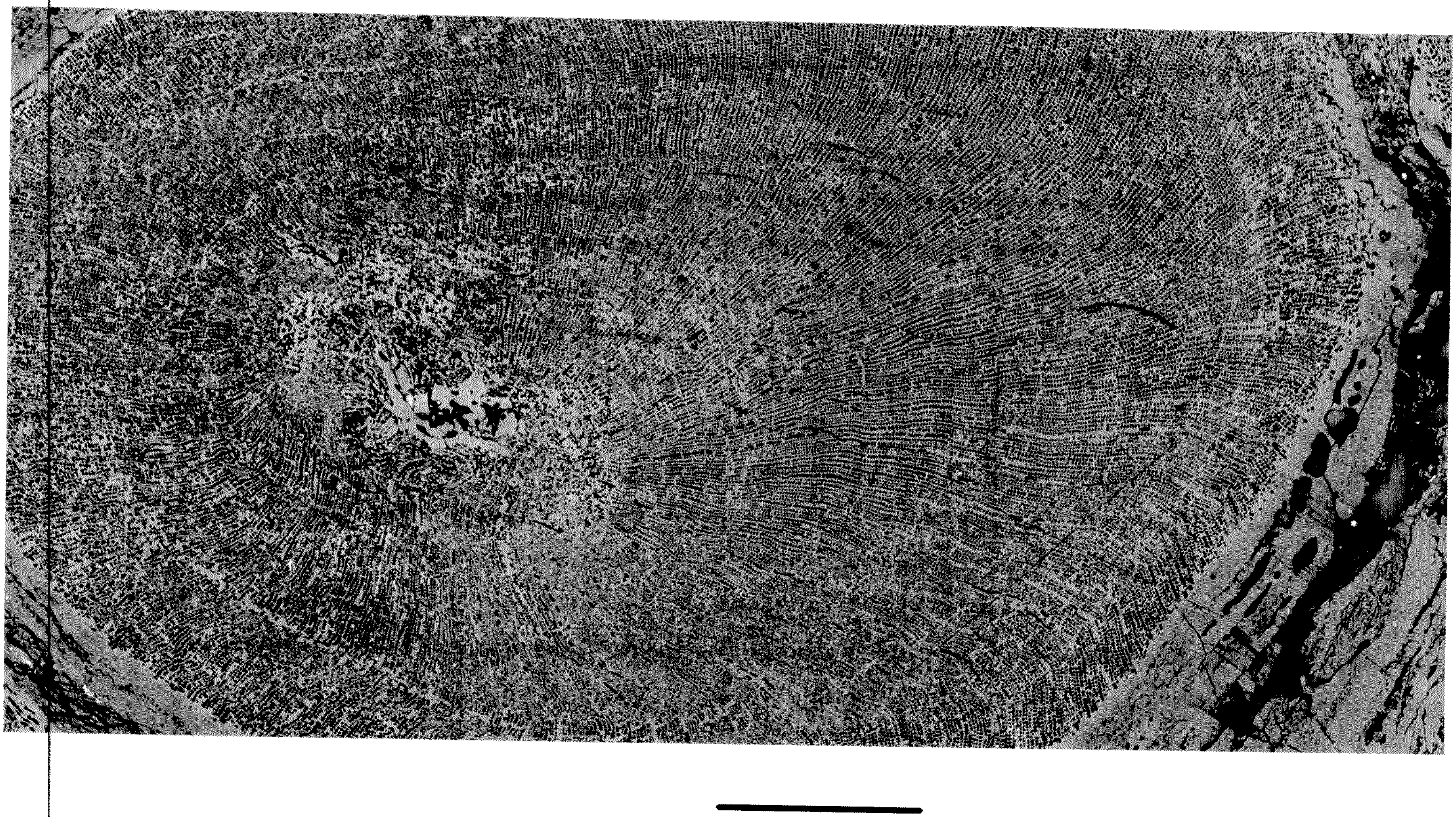

Figure 4-16 (b). Enlargement of area shown in (a). Photomosaic shows a tranverse section of gymnospermous root structure. Small cell size and lack of definition in annual ring pattern indicates root origin. Imaged with 40X objective in oil according to procedure of Pratt (in press).

The presence of material which has the well preserved texture of semifusinite, but the reflectance of vitrinite in the Gates coals provides information concerning the coalification pathway(s) of inertinite. Jones and Chaloner (1991) differentiate three distinct phases of reaction of wood to pyrolysis (Table 4-7). The first phase results in charred wood, described as material that had "...sufficient preservation-potential to resist being converted to vitrinite, but is not fully fossil charcoal, but rather is fossil charred wood" (Jones and Chaloner, 1991, p. 46-47). This material, which has a lower reflectance range of 0.4%, gives rise to semifusinite. However, the description is a little puzzling; what happens to the lignin and cellulose derived material as it is buried and subject to increasing maturation level? More specifically, what happened to that material in the Gates coals as it passed through the 0.4% reflectance level on its way to the current $R_o$max reflectance range of 1.04 - 1.26 %? Clearly it cannot remain at the 0.4% level.

The coalification pathway of the inertinite macerals is still an open question. If an initial low maturation value is preset at burial, such as 0.4%, does the material remain essentially inert until that maturation level is reached and then continue afterwards, thereby skipping the "gelification" stage of diagenesis? The transitional material present within the Gates Formation supports an affirmative answer to this question and may correspond to the lower end of Jones and Chaloner's (1991) phase 1 material; the non-charred organic matter (represented by vitrinite) eventually "caught up" to the maturation level of the semi-charred material set at the time of burial, and continued to its current maturity.

The formation of high reflectance is the most critical stage in the process of inertinite formation. The only rigourously proven method of forming highly reflecting substance from organic material (with the exception of fungal material) is by exposure to high temperatures (fire/pyrolysis, contact metamorphism). If vitrinite precursor material is left to oxidize at the surface, it will eventually be completely degraded to simple compounds (e.g., carbon dioxide and water) via a number of decomposition pathways (Stout, 1985), not altered into a highly reflecting substance. Surficial or early diagenetic alteration of the high reflectance and cell structure may mask the original fire-induced origin of material such as "degrado-fusinite". The initial reflectance is gained by charring/burning followed by a degradation stage. Weathering of the higher reflecting inertinite would lower the reflectance and result in a breakdown of the cell structure via mechanical disintegration and biochemical processes.

Table 4-7. Experimentally determined phases of charcoal formation and likely coalification products. Modified after Jones and Chaloner (1991).

Phase 1	Phase 2	Phase 3
Charred wood.	Charcoal.	Charcoal breaking up.
Experimental chars 180-220 °C.	Experimental chars 230-340 °C.	Experimental chars 340-600 °C.
Internal cell wall structure seen.	Cell walls apparently homogenised.	Cracking along site of middle lamella.
Preservation potential moderate, usually compressed.	Preservation potential excellent. Anatomical preservation of high fidelity.	Preservation potential poor. Very fragile, typically smashed to minute pieces.
Pit membranes intact.	Pit membranes usually disappeared.	Pit membranes disappeared.
Reflectance > 0.4%.	Reflectance = 0.4 - 1.2%.	Reflectance > 1.25%.
Seen in fossil record as semifusinite, or (anisotropic?) vitrinite in higher rank coals.	Seen in fossil record as fusinite and semifusinite.	Seen in fossil record as fusain, inertodetrinite.

Semi-charred material would be particularly susceptible to this process since some of the organic material is still unaltered, and hence palatable to microorganisms.

4.6.2 Fire Frequency

In order to retrodict fire frequency from compositional profiles, several parameters have to be interpreted, namely: (1) the amount of inertinitic material generated during fire events; (2) the proportion of the fire-derived inertinite preserved in the peat; (3) whether or not the inertinite is allochthonous or autochthonous and; (4) the peat (coal) accumulation rate. Unfortunately, all of these parameters are difficult to assess. With respect to (1) and (2), we know of no studies which have examined these questions. Experimental studies (Scott, 1989; Jones and Chaloner, 1991; Jones et al., 1991; Table 4-7) have focused more on determining what macerals are formed during pyrolysis, rather than the efficiency of the process.

The source of the inertinite can be interpreted by assessing the texture of the deposit and the presence/absence of allochthonous minerals. Charcoal, including ash and discrete pieces of charred wood is readily transported by air and water. Inertodetrinite, fragments of charred material, can be either autochthonous (indicating fire at that location in the past) or allochthonous (formed outside of the local area), causing ambiguity in fire frequency interpretation. The percentage of inertodetrinite produced relative to structured inertinite during a severe burn (as represented by fusain layers) appears to be relatively low (Table 4-5) in the Gates coals. Zones which have a structured inertinite to inertodetrinite ratio of less than 1, and are enriched in inertodetrinite and detrital mineral matter can usually be interpreted as being allochthonous.

The determination of fire frequency relies strongly on independent, short term time control, like the dates derived from varved units, tree rings, and radiocarbon isotope data used in assessing post-Glacial fire frequency (Tolonen, 1983). However, fine scale time resolution is not possible at this time for older rocks such as those of the Gates Formation. The best estimate possible can be made by comparison with modern peat accumulation rates for temperate, middle to high latitude regions. Determination of peat accumulation rate in modern settings is commonly accomplished by assessing the total age and thickness of the deposit, sometimes in a number of places within the mire, and calculating a numerical average. This method is obviously not wholly accurate. Peat is a fuel and if conditions are appropriate (if the upper part of the peat is dried and/or fire temperatures are extremely high) it will burn, resulting in an unconformity in the sequence and causing ambiguity in stratigraphic interpretation. Additional problems associated with determining peat accumulation rate include erosion, differential compaction of different peat types, and differences in the magnitude of compaction from the top to the base of the profile. In a sense, however, the average value takes the erosive episodes into account and represents a net accumulation rate over an extended time period, rather than a yearly accumulation rate.

Modern temperate low ash yield peats accumulate at rates of approximately 1 mm or less per year (data compiled in McCabe, 1986; 1991); accumulation rates generally decrease from this figure in higher latitude regions. Utilizing a compaction ratio of 10:1 for the transition from peat to bituminous coal, each centimetre of coal takes at least 100 years to accumulate. On average, each 2 mm interval of coal (the scale of resolution of the IBAS data in figures 9 - 14) represents 20 years of accumulation. If a wetland area is subject to surface fires throughout its history, and a fire destroys only the surface litter, not the peat itself, inertinite present within a 2 mm interval would indicate *at least* 1 fire event in 20 years. If accumulation rates were lower — for example, one centimetre per 200 years — only at least one fire per 40 years could be predicted utilising the IBAS data. Considering the abundance of inertinite in almost all levels within the coal seams of the Gates Formation, it is probable that fires took place regularly in the original mires. Thick intervals without inertinite are rare in almost every seam. Although it cannot be rigorously proven, it is reasonable to believe that fires occurred in the mires on at least 20-40 year intervals during peat formation throughout much of Gates deposition.

4.7 FORMATION OF INERTINITE RICH PEATS

Few of the peats forming in modern wetland environments hint at inertinite concentrations of 40-60 % (and more) that are found in some of the Gates Formation coal seams. The Gates Formation seams, like many Cretaceous coals (Collinson and Scott, 1987; Cross, 1991), are interpreted to have formed in taxodiaceous wetlands (Lamberson et al., 1991; chapter 5), in part similar to those found in the southeastern and southern United States.

Peats derived from arboreal vegetation in the Okefenokee SMC (*Taxodium* - type), contain an average of approximately 5% charcoal by volume (Cohen, 1973). Despite having a higher fire frequency than the treed wetlands, peats forming in the herbaceous environments of the Okefenokee SMC and the Everglades SMC are also reported to be generally low in inertinite (<5%) (Cohen, 1968; Cohen, 1973; Spackman et al., 1976). The petrography of the fire horizons themselves is not reported in Cohen's (1973; 1974) accounts of the petrography of the Okefenokee peats, but presumably these zones were more enriched in inertinite. What is responsible for the widespread occurrence of the inertinite rich coals in the Western Canada Sedimentary Basin?

I believe that a unique combination of climatic and geographic factors are responsible for the occurrence of fires in the Gates Formation wetlands, as well as the concentration of inertinite in the coals. These include: a high latitude setting with seasonal variation in light, precipitation and probably temperature; a warm, relatively dry continental interior setting; low accumulation rates due to both high fire frequency and lower productivity, and: a long term variation in precipitation through time. The lines of evidence which support this interpretation are discussed below.

4.7.1 Characteristics of modern fire-prone wetland settings

Peats (and coals) are considered climatically sensitive sediments in that their occurrence is commonly associated with high rainfall and humid conditions. Patzkowsky et al. (1991) reviewed the occurrence of peats in modern settings, concluding that it is not a high mean annual rainfall which determined the occurrence of peat, rather it is continuity of rainfall throughout the year, with at least 20 mm/month occurring in at least 6 months of the year. The majority of the peat forming locations cited have at least 20 mm/month precipitation for 12 months of the year, as well as a mean annual precipitation greater than 1m. The data set, however, was confined to areas located between 40 degrees north and south latitude. Extensive peat forming areas are present in higher latitude regions as well. High latitude peat forming areas are characterized by low productivity and accumulation rates; decomposition rates of the organic material are quite low, due to lower temperatures.

Peats forming in the ever-wet tropical regions are characterized by high mean annual rainfall and a continuity of rainfall throughout the year. Elevated rainfall and temperatures promote luxuriant plant growth; peat accumulates so rapidly that the peat-forming area domes above the surrounding environs. Tropical domed peat-forming areas seldom dry, and naturally caused lightning fires are rare events. Ongoing research indicates (S. Phillips, personal communication, 1993) that very little inertinite (with the exception of fungal material) is present in these peats.

In modern wetland settings fires appear to be most common in peat forming areas where rainfall is seasonally distributed, and subject to periodic drought. For example, 60-80% of the annual rainfall in the Florida Everglades is concentrated between May and October, with infrequent and light rain occurring during the remainder of the year (Klukas, 1972). Klukas (1972) reports that rainfall is low enough that, on average, conditions are dry enough 2 years out of 10 to present severe fire hazards throughout the area. In the Okefenokee SMC, the dry season occurs from October through November, moist conditions prevail from December through May, and the wet season is from June through September (Rykiel, 1984). However, evapotranspiration is high enough in the summer months to cause a decrease in the water table towards the end of the summer despite high rainfall (Rykiel, 1984). Drier years have occurred on approximately 20 year cycles (Cypert, 1972; Spackman et al., 1976). The ignition source for wildfire is lightning. According to Rykiel (1984) approximately 70 thunderstorms are expected every year in the Okefenokee. Lightning is also common on the southern tip of Florida, where 21-40 lightning derived wild fires per million acres occur annually.

Peats forming in ombrogenous wetlands of the Fraser River Delta region (particularly those of the ericaceous shrub-*Sphagnum* communities) southern British Columbia (approximately 49° N latitude) also contain evidence of periodic fires (Styan and Bustin, 1983a, 1983b). Unfortunately, neither fire frequency data nor quantitative inertinite concentrations are available. Fire frequency does appear to be lower than in the southeastern U.S. settings discussed, as stratigraphic profiles of the peats contained in Hebda (1977) record only 3 charcoal horizons within the last 4500-5000 years. The frequency of less severe fires may be higher; fire frequency data from the southeastern U.S. are based on historical records, rather than the occurrence of charcoal horizons. The vegetation in the Fraser River Delta peats is markedly different from the taxodiaceous wetlands mentioned above;

peat-forming plant communities are dominated by *Sphagnum* sp., *Pinus* sp. and a variety of angiosperm shrubs and herbs. The climate of the region is considered winter wet, with the highest rainfall occurring from October through March; on average the yearly minimum occurs during July (Hare and Thomas, 1974). During the summer months the Fraser River delta area can be very dry, and prolonged drought is common (Hare and Thomas, 1970). The occurrence of inertinite in these peats is notable in that local geographic factors are responsible for modifying the climate; a broad-based paleogeographic prediction for the area might indicate ever-wet conditions.

4.7.2 Interpretation of Gates Formation paleoclimate

Inertinite in the Gates Formation is fire derived, indicating that the paleogeographic and/or paleoclimatic setting must have been conducive to peat formation as well as allow for periodic drought. Published paleoclimatic studies which retrodict temperature and precipitation tend to large scale (worldwide) and are confined to certain time intervals. Hence, only general characteristics of the climate of the Gates can be interpreted from these studies.

Geologic data indicate that the Cretaceous was warmer than the present (Fig. 4-17), with a smaller equator to pole temperature gradient (Barron, 1989). Modeling studies (Barron, 1989) suggest temperatures were 6 – 12°C higher than the current global average. The magnitude of the increase varied through the Cretaceous, (although it was always warmer than Recent times). Temperatures increased from a cool early Cretaceous (Hauterivian–Barremian) to a maximum in the Aptian–Albian, and in general cooled throughout the remainder of the period (Frakes and Francis, 1990). A lower magnitude warming (relative to the Aptian–Albian episode) occurred during Coniacian–Santonian time (Frakes and Francis, 1990). No permanent ice is interpreted to have been present at either pole during the Albian (and possibly the remainder of the Cretaceous); whether or not the winter dark coincided with extended freezing temperatures is not known (Spicer and Corfield, 1992). Analysis of fossil megafloras indicates that climatic zones were shifted northward, with a complete absence of the arctic and subarctic zones (Saward, 1992; Fig. 4-18).

Paleoclimate modeling studies have been unable to reproduce year round warm (above freezing) temperatures near the poles and within continental interiors (Schneider et al., 1985; Barron, 1989). There is

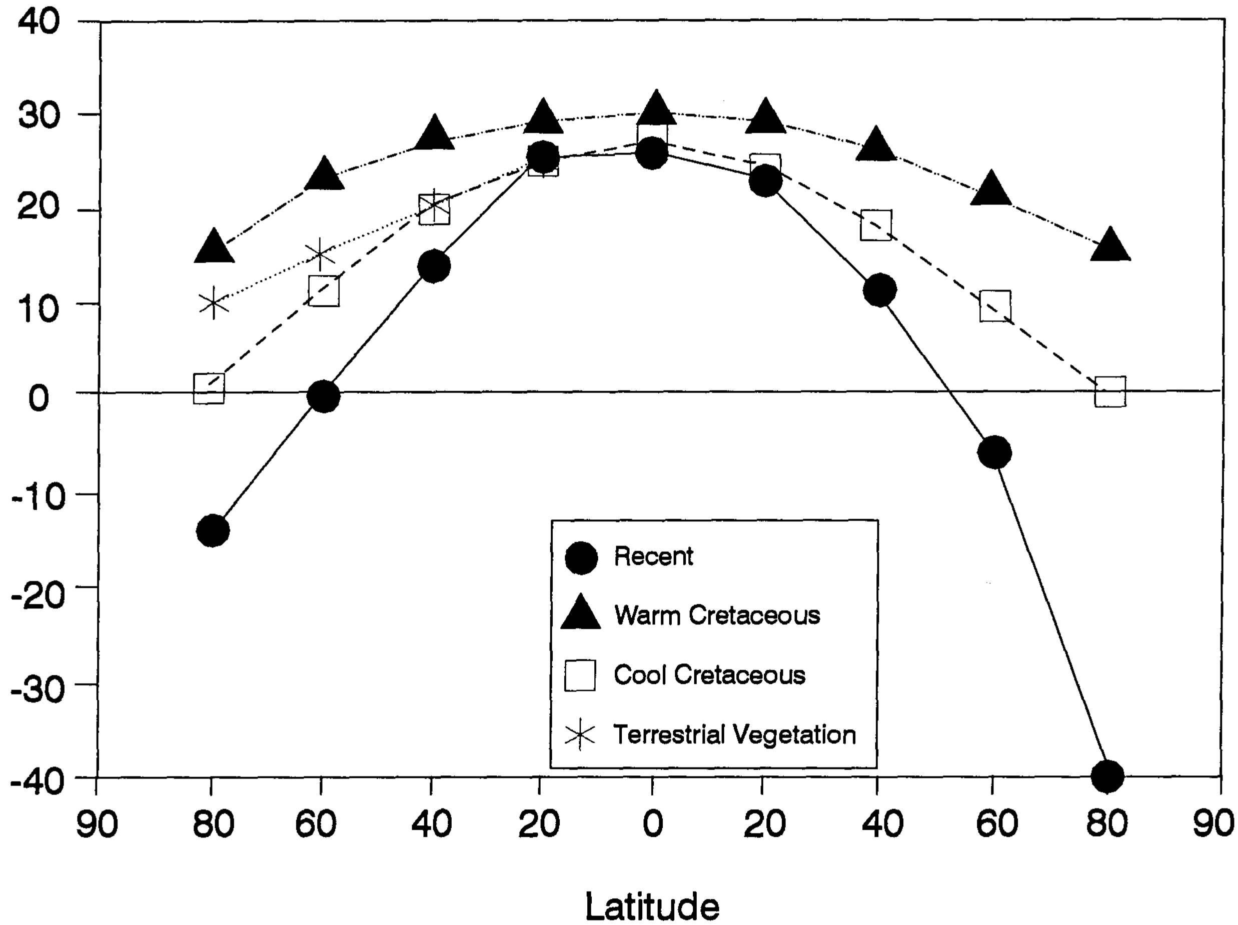

Figure 4-17. Variation in temperature with latitude of modern day and interpreted for various Cretaceous reconstructions. Warm Cretaceous data interpreted from oxygen isotope data; cool Cretaceous based on assumption that freezing temperatures in winter were reached, but not exceeded near poles. Included is Cenomanian estimate of Wolfe and Upchurch (1987) of 0.3 degrees Celsius per 1 degree of latitude. Modified after Barron (1989) and Spicer and Corfield (1992).

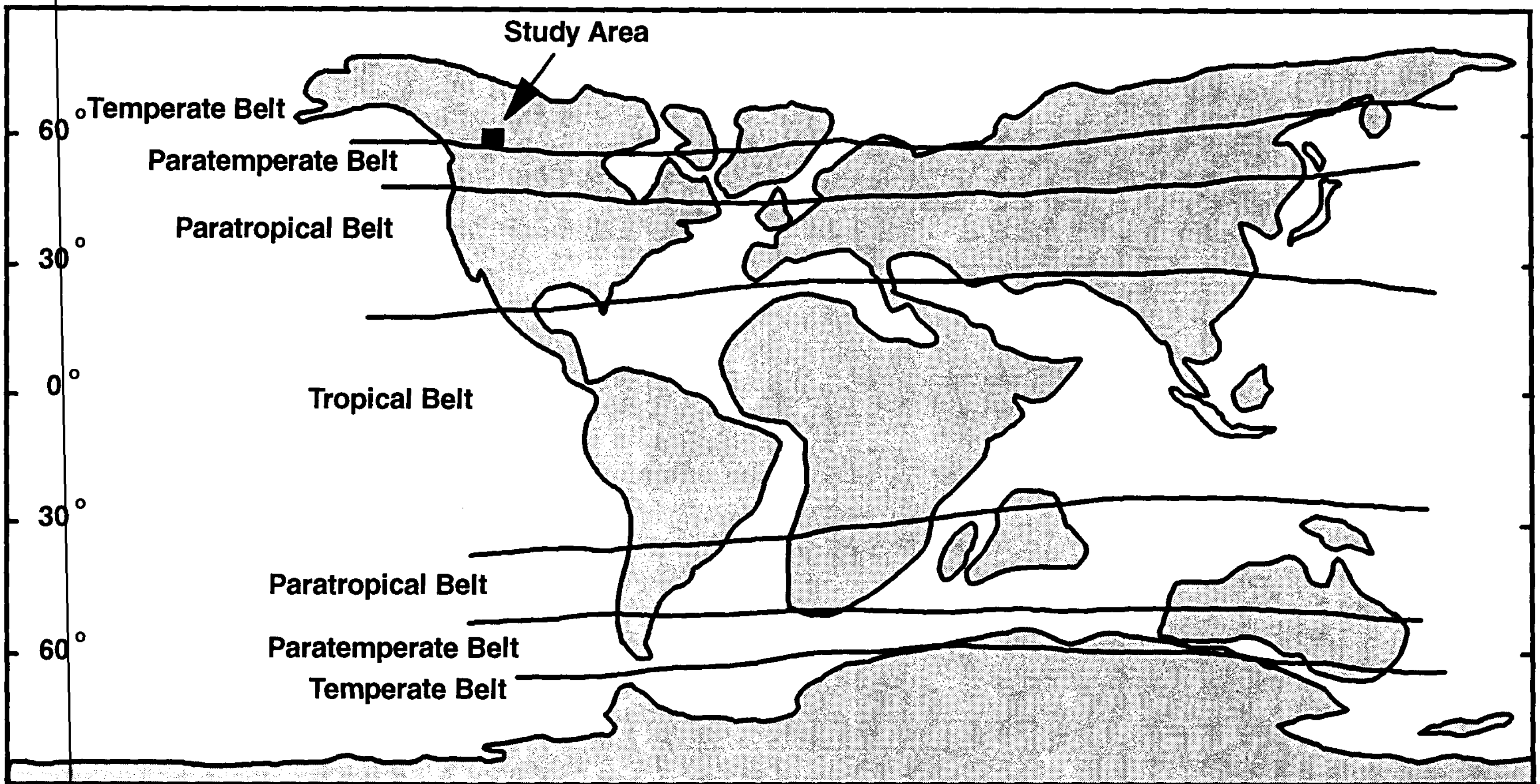

Figure 4-18. Interpreted climatic zones based on vegetation characteristics of mid-Cretaceous (Aptian - Cenomanian) megaflora. Modified after Saward (1992).

considerable evidence for seasonality at high latitudes (Spicer and Parrish, 1986) including the deciduous nature of Alaskan fossil floras (latitude 75°–85°N) as well as tree rings in fossil wood (Parrish and Spicer, 1988; Spicer and Parrish, 1990). Ongoing research on the megaflora of the Gates Formation (Zhihui and Basinger, personal communication, 1993) indicates that with the possible exception of one microphyllous conifer taxon and herbaceous plants (ferns, *Equisitites* sp., etc.), the entire flora was deciduous, including the cycadophytes. This suggests a seasonal variation in light and probably temperature. Unfortunately, neither the magnitude of seasonal variation nor the mean annual temperature of the study area is precisely known. Temperature estimates for terrestrial sediments are often interpreted on the basis of angiosperm leaf physiognomy (Wolfe, 1979; Spicer, 1987; Spicer and Parrish, 1986). Although the Gates Formation coals are Albian, angiosperm megafossils are rare or absent (Bell, 1956; Stott, 1982; Zhihui and Basinger, pers. comm., 1993), a reflection of its higher latitude position and depositional environment. The evidence for seasonality in the Alaskan floras (Spicer, 1987) and the Gates Formation floras at 60°N argues for possible colder (perhaps) freezing conditions for part of the winter.

Gates Formation peats formed in low lying, coastal plain mires east of the emerging Cordilleran highland (Kalkreuth and Leckie, 1989). The magnitude and distribution of retrodicted rainfall for the mid - Cretaceous continental interior differs somewhat from model to model, depending on the type (quantitative versus qualitative) of model and the time period represented. General circulation models (Barron and Washington, 1984; Barron et al., 1989) predict a seasonally distributed rainfall for the area; precipitation would be concentrated in the summer (July) months, much as it is today. However, neither of the model simulations illustrated in Barron et al., 1989) predict particularly high rainfall in the area of Gates deposition. A rainshadow effect is not expected either, with the subdued topography utilized in the model. The qualitative model of Parrish et al. (1982) for the Cenomanian retrodicts a drier (semi-arid to humid) continental interior due to rain shadow effect of the Cordilleran highland area; this effect is particularly pronounced further south along the Cordilleran chain in the low to mid-latitude region (30°N - 40°N). Although the effectiveness of the Cretaceous Interior Seaway as a moisture source is still debated (McCabe and Parrish, 1992), the seaway would probably be a locus of convective activity (with thunderstorms and lightning) during the summer months (Patzkowsky et al., 1991; Gyllenhaal, 1991). These storms would provide the ignition source for any forest fire activity.

The presence of significant quantities of fire-derived inertinite in the Gates Formation coals argues against ever-wet conditions, and for a seasonally distributed rainfall. It is difficult to assess exactly when the fires would have occurred. Thunderstorm activity is usually confined to the summer months (Gyllenhaal et al., 1991). At higher latitudes today these storms are rare, but with a lower equator to pole temperature gradient, this activity probably extended further north (Gyllenhaal, 1991) and the season was probably longer. Geographic regions with a deciduous flora today commonly have two fire seasons (Shroeder and Buck, 1970): early spring before a leafy canopy is established and late fall/early winter after the leaves have dropped and before temperatures drop too low to permit thunderstorm activity. If the drier season occurred during the winter months, with the warmer temperatures associated with Cretaceous climates, then the leaf litter would gradually dry out and early spring fires could occur. Although this is possible, fall fires were probably more likely. Fires in mires occur after an extended drawdown of the water table. The deciduousness of the flora indicates that there would effectively be no need to utilize water during the winter. The moisture retaining capacity of peat, combined with probable lower winter temperatures (and therefore lower evaporation rates) would result in maintenance of wet conditions. I interpret the conditions to be more analogous to the Okefenokee SMC; long, warm, summer days would result in high water usage despite high precipitation,. In periodically dry years, the mire would be dry enough in the fall, particularly after leaves drop, to promote fires. The amount of moisture delivered to the Gates depositional area would have been a function of movement of weather systems, position of the area relative to topographic breaks in the ancestral Rocky Mountains, and the effectiveness of the Cretaceous Interior seaway as a moisture source.

4.7.3 Concentration of inertinite in Gates Formation seams

On the basis of available data, it appears that the baseline quantity of inertinite in both treed and herbaceous wetland settings today is 5-10%, with occasional, thin, inertinite rich zones. How does inertinite get concentrated from 5-10% to 40-60%, and how does the cyclicity develop? The inertinite zones have been emphasized throughout this paper, but both inertinite and vitrinite rich zones are present in the coals. The seams which show a strong clastic influence, such as C, D and E, (Fig. 4-12 - 14) are higher in vitrinite; inertinite is primarily detrital and associated with mineral rich layers. These seams formed in more alluvial settings, where the water table was controlled by the associated river system and fire frequency is lower (Ewel, 1990). Seams A1 and B (Figs. 4-9 and 4-11) show little clastic influence, and formed in coastal plain (basinal) settings where the water table was regionally controlled by sea level fluctuations and rainfall (chapter 5), and fire frequency was higher. Seam A2 (Fig. 4-10) shows a mixed influence of the alluvial and basinal settings. The lack of clastic influence of both the A1 and B seams provides the best opportunity to interpret the process by which inertinite rich zones are developed in coals; this discussion will focus on the characteristics of these two seams.

Both the A1 and B seams contain a basal vitrinite rich zone, followed by a cyclic variation in inertinite content. The cyclicity is more obvious in the thicker B seam than in the A1 seam. One possible mechanism for concentration of the inertinite is differential compaction. Charred material tends to be brittle and vitrinitic material will tend to compact more, and bend around the inertinite grains. However, it is still difficult to attribute an increase from 5 - 10% inertinite at the peat stage to the 40%, 60% and more inertinite in the Gates Formation coals via differential compaction alone. Nor can this process explain the cyclicity. The most likely way to accomplish the enrichment is to have preferentially oxidized the vitrinite-precursors at the accumulation stage, resulting in an increase in inertinite. As discussed in a previous section, it is important to point out that I am ***not*** implying that more inertinite is ***formed*** by oxidation at normal surface temperatures, just concentrated.

The inertinite enrichment of the Gates coals, as well as many others within the Western Canada Sedimentary Basin (Kalkreuth and Leckie, 1989; Cameron, 1991; Bustin and Dunlop, 1992) suggests a large scale process, such as climate, is operating to control the composition. The leeward position of the original peat-forming environments relative to the rising Cordillera, moderating the delivery of moisture laden air from the largest reliable moisture source (the paleo-Pacific Ocean) resulted in overall drier conditions than are found in many peat-forming areas today. Where local water supply was more abundant, such as near the coast or in alluvial/fluvial settings, vitrinite-rich coals resulted. However, if the water supply was dependent on rainfall, inertinite enrichment resulted. The concentration of inertinitic material, and the cyclic nature of the concentration suggests that at times the net accumulation rate for the wetlands of the Gates was lower than that of the Okefenokee SMC, suggesting that the peat-forming wetland was somewhat different than the classic model. This subject is discussed in detail in Lamberson et al. (chapter 5). Accumulation is controlled by the balance between the rates of subsidence, productivity and decomposition. Productivity and decomposition are closely linked, and are essentially a function of climate (temperature and moisture supply) whereas subsidence is a primarily a function of tectonics.

A cyclic alteration of either climate or subsidence could have caused the stratigraphic variation in composition within the Gates A1 and B seams. Because inertinite formation (bulk peat composition) in modern settings is a function of climate, I believe the compositional variation exhibited in the Gates coals is more likely to have been a function of climate. The forcing mechanism for climatic change within the foreland basin requires further study. Quite a few studies have been published (reviewed in Fischer, 1986, 1991; Einsele et al., 1991) which support solar luminosity and orbital (Milankovitch-type) variations as primary mechanisms for 10 - 400 ka climate changes. At this stage, with only one compositional profile of each seam, it is difficult to assess whether or not the variations seen can be attributed to these processes.

4.8 CHARCOAL IN THE GATES COAL SEAMS, IMPLICATIONS FOR PALEO-ATMOSPHERIC COMPOSITION

Several authors (Robinson, 1989; 1991; Jones and Chaloner, 1991) have used the presence of charcoal in coals and sediments as indicative of the relative percentage of oxygen in the atmosphere at various times through geologic history. Robinson (1989, 1991) has attempted to correlate the abundance of fusinite and semifusinite with Berner and Canfield's (1989) variation in Phanerozoic O_2 atmospheric composition curve. The attempt was met with limited success due to "...problems with data quality and interpretation" (Robinson, 1991, p. 51). For the most part, the data set used almost exclusively represented low-inertinite coal. It is questionable whether or not the average value of inertinite present in seams of variable thickness and widely disparate geologic and paleogeographic settings can be used as a basis for meaningful interpretation of the stratigraphic record. Robinson's (1991) petrographic data were presented on a log scale such that low inertinite values were emphasized. The statistical significance of these data is questionable as low percentage, point count data have a high standard error (Bustin, 1990).

Despite these problems, Robinson's (1991) research points to the importance of understanding the distribution of burned material in coal seams as it relates to understanding the evolution of global climate and vegetation through time. Reconstruction of fire history from bulk quantity of inertinitic material, however, with no discussion or appreciation for paleogeographic setting or stratigraphic variation (both in lateral and vertical succession), is impossible. To understand fire systems in the geologic record, data must be collected and presented to reflect time slices over a broad range of geographic regions. Conclusions based on the petrographic composition of single whole seam samples from different coals of the Gates might result in different paleoclimate interpretations, from reasonably wet to very dry. Or, alternately, from times of high oxygen content to lower oxygen content in the atmosphere. Shifts in oxygen content are not necessary to explain the petrographic variation seen in the Gates. Fire frequencies of 20–40 years, with few extreme fire events coupled with low accumulation rates due to an overall drier (subhumid?) climatic setting would explain the variation. These interpreted fire frequencies would not be unusual for modern wetland settings.

4.9 SUMMARY AND CONCLUSIONS

The amount of inertinite present in modern wetland peats is primarily a function of climate; inertinite is abundant where a rainfall is seasonally distributed, rather than ever-wet. Periodically, the precipitation supply is interrupted, such that a drawdown in the water table allows for the upper surface of the peat to dry and wildfire is initiated by lightning. Fire frequency in these environments varies according to the source of water; rain-fed wetlands have a higher fire frequency than alluvial swamps. Fire-derived inertinite in modern peats is on, average, only 5–10% by volume. Enrichment of inertinite results from preferential destruction of vitrinite precursors at the peat accumulation stage either via burning or low temperature degradation processes, rather than formation of inertinite by low temperature oxidation (or fungal attack).

Image analysis and manual petrographic data were used to interpret the amount, source and variation in fire-derived inertinite in coal seams of the Gates Formation. Fire derived inertinite is on average quite high, and within seams may vary cyclically. The high overall inertinite content within Gates Formation coals is interpreted to reflect overall drier depositional conditions than the most commonly cited modern taxodiaceous wetland setting, the Okefenokee swamp-marsh complex of southern Georgia and northern Florida (U.S.A.). These drier conditions are interpreted to reflect a rain-shadow effect of the Cordilleran Highland which was located west of the site of Gates deposition. This rain shadow effect may have operated during much of the Late-Jurassic through Cretaceous and early Tertiary times as indicated by the abundance of high-inertinite coals in the WCSB.

Cyclic compositional variation of low to high to low inertinite concentration within the A1 and B seams, and the limited clastic influx section of the remaining seams is interpreted to reflect either a variation in subsidence, or in climate. Climate is interpreted to be the most likely forcing factor, although the mechanism for cyclic climatic change cannot yet be interpreted based on the limited data available.

The research reported in this paper provides more information for understanding climatic changes in the Cretaceous of North America, a period which has been dubbed the "Greenhouse Earth" (Spicer and Corfield, 1992). More research is necessary which compares the characteristics of the coals which formed throughout the Cretaceous on a latitudinal gradient stretching from the North Slope of Alaska to Arizona, in order to better interpret the continental climatic record. Utilizing coal petrographic data as a proxy for variation in oxygen, or any other element through time can only be done by considering the influence of paleogeography (paleoclimate) on the organic, physical and chemical processes governing peat formation and preservation.

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CHAPTER 5

THE EFFECT OF ECOSYSTEM DISTURBANCE ON THE DEVELOPMENT OF CRETACEOUS PEAT-FORMING DEPOSITIONAL ENVIRONMENTS: AN EXAMPLE FROM THE LOWER CRETACEOUS MIDDLE GATES FORMATION, NORTHEASTERN BRITISH COLUMBIA, CANADA

5.1 ABSTRACT

Compositional variation in coal seams fundamentally reflects differences in depositional conditions within the original peat-forming wetland, both laterally and through time. A maceral-based interpretation of wetland succession in seven coal seams of the mid-Cretaceous Gates Formation (Rocky Mountain Foothills, northeastern British Columbia, Canada) is presented. Maceral, ash yield (mineral matter) and sulphur analyses of lithotype subsamples representing the entire thickness of the seams, as well as lithotype stratigraphy are used to interpret the types of depositional environments, and the factors controlling the structure and function of the wetlands. Two calculated petrographic indices, the tissue preservation index (TPI) and the gelification index (GI), are used to describe texture and composition, respectively. The compositional and textural characteristics of the Gates coals are compared with the characteristics of peats forming in modern taxodiaceous wetland environments. Mires which formed the Gates coals are interpreted to have formed in environments ranging from low nutrient, stillwater taxodiaceous swamps with little or no fluvial influence, to eutrophic, higher energy alluvial taxodiaceous swamps subject to frequent flooding, to marsh environments. The peats formed in almost exclusively nonmarine environments, as sulphur content is very low in the coals. Scrub savanna wetlands, rather than stillwater swamps, were one of the most common wetland environments. The scrub savanna peats gave rise to low ash yield, inertinite rich coals. Gates Formation wetlands were maintained by periodic disturbance, and the stratigraphy of the coals reflects short and long term changes in sedimentological and tectonic setting and climate. In ombrotrophic settings, fire was fundamental to both nutrient cycling and maintenance of hydric conditions over long time intervals, whereas periodic flooding was important in alluvial settings. Constant (or near constant) subsidence associated with deposition in a foreland basin facilitated the accumulation and preservation of the Gates

Formation peats in an area where, due to climatic conditions, significant peat accumulation might not normally occur.

5.2 INTRODUCTION

Variation in coal composition and texture primarily results from differences between and within peat-forming environments. In order to be able to interpret these variations, research (Cohen, 1968, 1973, 1974; 1984; Spackman et al., 1976; Styan and Bustin, 1983a, 1983b, Cohen et al., 1987; Esterle, 1990; Cameron et al., 1989) has focused on the structure and function of modern peat-forming depositional environments. These studies have attempted to: (1) delineate peat forming plant communities; (2) assess the characteristics of the peat associated with particular plant communities: and (3) interpret possible and idealized successional relationships of the plant communities. Interpreting successional relationships from the stratigraphic record is difficult even for modern settings, where the plants are still in the area. Two patterns have been recognized from modern environments (Moore, 1987; Cameron et al., 1989): (1) *terrestrialization* - essentially a filling in sequence where succession proceeds from an aquatic (lake) to a dry terrestrial environment; and (2) *paludification* - where the mire environment begins in an isolated area and spreads out over the surrounding terrestrial setting.

Are simple, progressive autogenic processes adequate for understanding the development and (perhaps even more important) maintenance of hydric conditions over long periods of time? Probably not. Modern ecologists recognize that many wetland ecosystems are adapted to regular perturbations and/or disturbances (Odum, 1969; Odum, 1984; Sousa, 1984, Mitsch and Gosselink, 1986). These ecosystems are not transitional stages directed toward some type of regional climax vegetation, but represent what Odum (1969) termed "pulse stability", - an ecosystem constantly in flux.

Thick, laterally extensive coal seams formed during the Cretaceous within the Cordilleran foreland basin of western Canada. Within the last few years there have been several articles (Kalkreuth and Leckie, 1989; Lamberson et al., 1991, Marchioni and Kalkreuth, 1991; and Kalkreuth et al., 1991) dealing with broad relationships between depositional setting, maceral composition, megascopic appearance, lithotype sequence and wetland environment of the Gates coals. In this paper, a maceral–based interpretation of wetland succession within the Gates Formation mires is presented, based on new petrographic data and re-evaluation of existing data. These coals formed in an area where constant subsidence allowed the preservation of peats which formed in fire prone taxodiaceous wetland settings. The variation in composition and texture within the peat deposits fundamentally reflects the importance of periodic disturbance on the maintenance of wet conditions where climatic conditions may not have been ideal for peat formation.

The general geologic and paleogeographic setting of the Gates Formation are reviewed in order to place the coals within a sedimentological and tectonic framework. The depositional environments within the peat-forming mires are then investigated in detail. Mire development is interpreted in terms of regional variations in taxodiaceous wetlands caused by differences in local hydrology and nutrient availability, as well as response to fire events. In order to set the stage for this interpretation, a review of the various types of modern taxodiaceous wetlands is presented following the discussion of geologic setting. This chapter concludes with an analysis of the effect of disturbance on the Gates ecosystem as interpreted from the petrography of the coals.

5.3 GEOLOGIC AND PALEOGEOGRAPHIC SETTING OF THE GATES FORMATION

5.3.1 Regional stratigraphy and controls on sediment distribution

The coals examined for this study were collected from exposures within two mines, Quintette and Bullmoose, located in the vicinity of the town of Tumbler Ridge, British Columbia (Fig. 5-1). The Moosebar and Gates Formations, and correlative strata in northeastern British Columbia (Fig. 5-2) were deposited on the eastern side of the rising Canadian Cordillera in a foreland basinal setting (Cant, 1989). Cretaceous strata of the Western Canada Sedimentary Basin (WCSB) record a history of deposition influenced by the interplay between tectonism (orogeny) associated with continental accretion events (Stott, 1984; Cant, 1989; Cant and Stockmal, 1989) to the west and eustatic changes in sea level. The coal-bearing Gates Formation and the underlying Moosebar Formation (Fig. 5-2) comprise an unconformity-bound, time-transgressive sedimentary package which coarsens upward from marine shales to nonmarine strandplain and fluvial deposits. Leckie (1986) interpreted the Gates–Moosebar

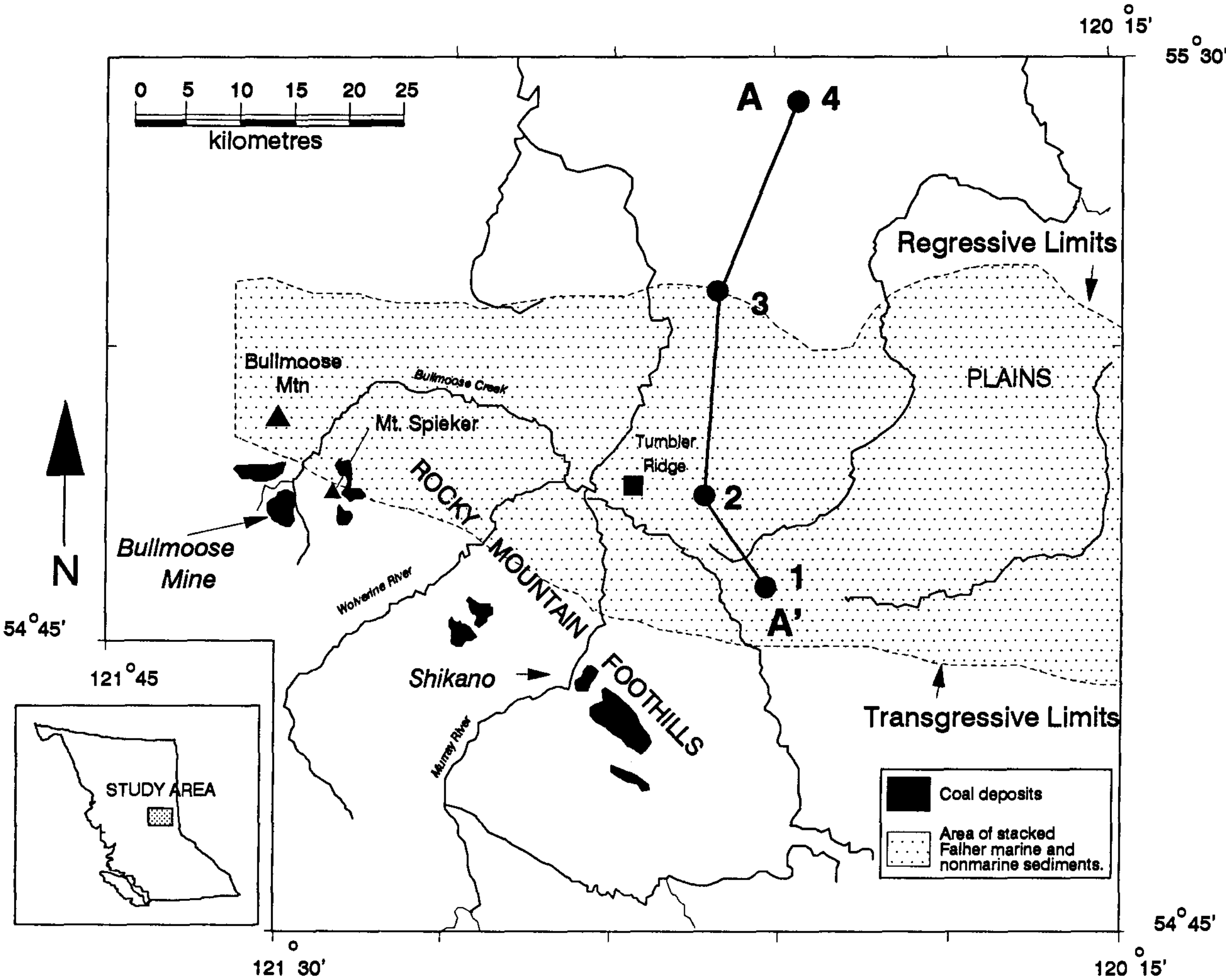

Figure 5-1. Map of study area. Samples were collected from Bullmoose mine and Shikano Pit (Quintette mine). Cross section of Falher interval along A - A' shown in figure 5-3. Also shown is the area of stacked marine sandstones of the Falher D, C, B and A units. Note the zone is oriented west - northwest. Modified after Matheson (1986) and Leckie (1986).

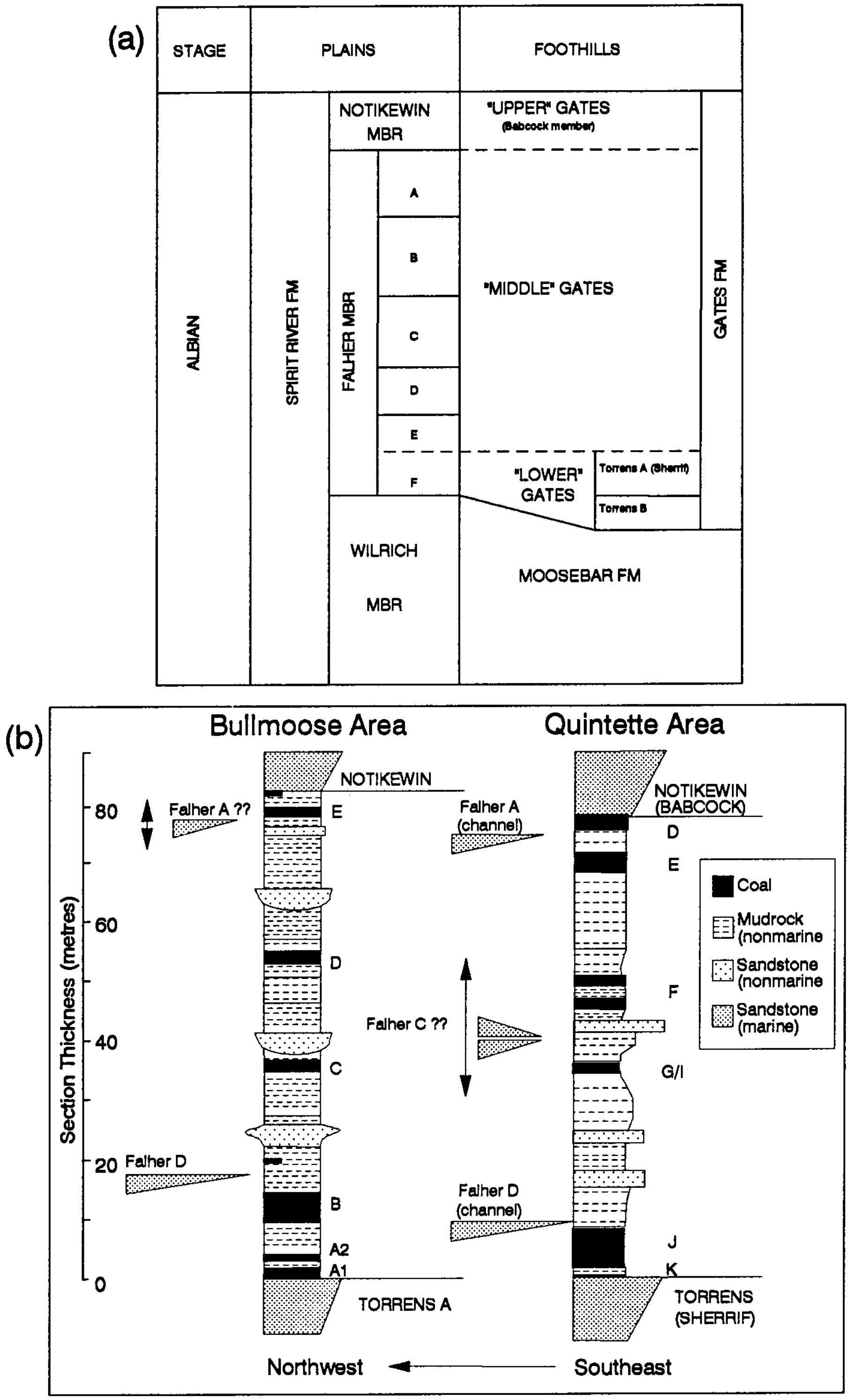

Figure 5-2. (a) Stratigraphic chart of a portion of Lower Cretaceous strata in northeastern British Columbia. Adapted from Leckie (1986). (b) Generalized stratgraphic section using mine-specific nomenclature of study area. Section includes possible locations of marine sand units present to the north and east of study area. Modified after Drozd (1985), using Leckie (1983), Carmichael (1983, 1988), Stott (1982, 1984).

package as a third-order depositional sequence. In a gross sense, the Moosebar represents the basal, fine-grained marine part of the sequence, whereas the Gates represents the overlying coarser nearshore deposits and nonmarine sediments. The Gates and Moosebar Formations are stratigraphically equivalent to the Spirit River Formation (Upper Manville Group) in the subsurface of the Plains to the east (Fig. 5-2 and Cant, 1983; Smith et al., 1984). Deposition of the sequence commenced in the Early Albian; the system prograded northward from perhaps as far south as 49°N current latitude to the vicinity of the Peace River by Middle Albian time (Stott, 1982, 1984; Caldwell, 1984), a period of 3 - 6 million years (Leckie, 1986). Northward progradation of the clastic wedge was not uniform. Superimposed on the third order sequence are at least seven fourth-order sequences (Fig. 5-3; Leckie, 1986).

The fourth-order cycles correspond to the individual Falher cycles A, B, C, D, E and F (Fig. 5-3; Jackson, 1984; Cant, 1983; Smith et al., 1984; Leckie, 1986; MacDonald et al., 1988). Leckie (1986) concluded that the sequences were fundamentally "...controlled by thrusting and tectonic loading of the rising cordillera to the west" (Leckie, 1986, p. 532), rather than eustatic sea level variations or delta lobe switching. The transgressive-regressive limits of the Falher A through D cycles, and the regressive limit of the Falher F cycle, lie within a belt oriented west–northwest which is tens of kilometres in width (Leckie, 1986; Fig. 5-1). There is general agreement (Stott, 1982; Leckie, 1986; Cant, 1989) that this stacking pattern was influenced by the Peace River arch, which was re-activated during the Cretaceous. The arch, a basement complex which has been both a positive and negative structural feature at various times throughout the history of the WCSB (O'Connell et al., 1989), trends northeast from the vicinity of Bullmoose Mountain through Peace River, Alberta (Stott, 1982; Leckie, 1986; Cant, 1989). North of this area the Gates sediments are predominately marine, whereas to the south, they are predominately nonmarine, and coal-bearing. In the study area, particularly in Bullmoose mine, the ocean was probably never very far away from where the coals were forming.

5.3.2 Local stratigraphy of study area

The Rocky Mountain Foothills are structurally and stratigraphically complex, rending correlation between outcrops and drill holes difficult in places. A simplified, working stratigraphy of the area is utilized in this paper

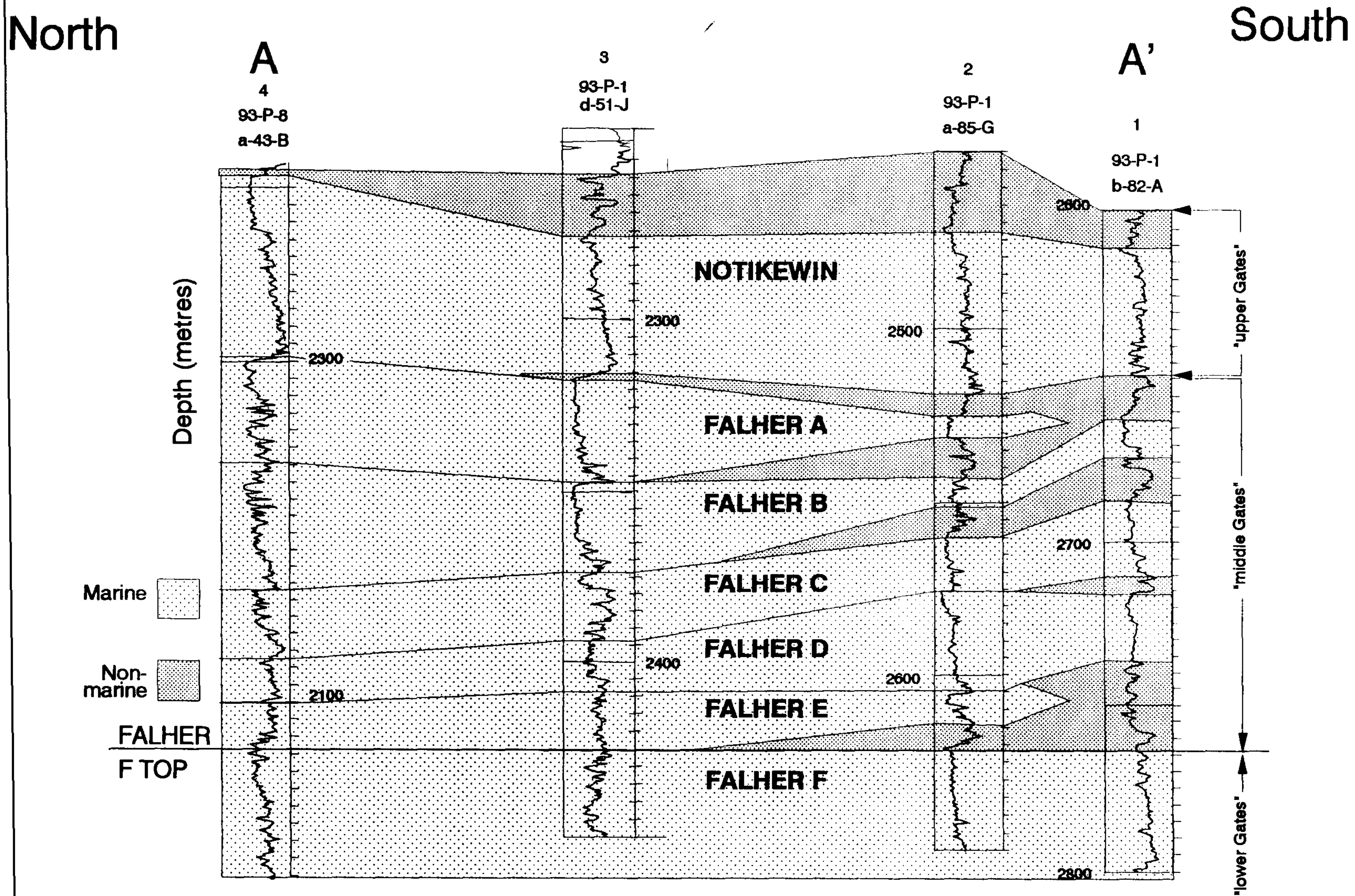

Figure 5-3. North-south gamma ray log cross section of portion of Gates/Spirit River interval along A - A' (Figure 1) showing intertonguing of marine and non-marine intervals, nature of stacked progradational Falher and Notikewin shelf sands and regional stratigraphic nomenclature. Modified after Leckie (1986).

and is presented in Figure 5-2b. All of the coal seams exhibit lateral variability in thickness and stratigraphy. This paper primarily focuses on the stratigraphy of the seams within the Bullmoose mine area proper (Fig. 5-2b) and the stratigraphy of the uppermost seam in the Quintette area, the Shikano D seam.

The only coal zone which can be traced laterally for any distance is the Bullmoose A/B - Quintette K/J seams. The unit can be traced eastward into the Elmworth Deep Basin Gas Field in west central Alberta, where the zone is informally called the "Fourth Coal". According to Carmichael (1983), the zone can be traced along the Foothills trend a distance of over 100 kilometres southeast to the Mount Belcourt area, where its equivalent is the #5 seam. In the Mount Belcourt area, the zone containing the #5 is located approximately 55 metres above the basal Torrens unit, among sediments which Carmichael interprets as nonmarine, upper coastal plain deposits. Some confusion in stratigraphic nomenclature exists, as the base of the Gates is defined as the bottom of the first thick sandstone above marine shales of the Moosebar Formation (Stott, 1968; 1982). However, because the Gates Formation consists of a series of stacked, predominately northward (seaward)-stepping progradational sequences, the first sandstone (Torrens) occurs stratigraphically lower in the south than in the north (Stott, 1982). To the southeast, in the Luscar coal field near Grand Cache, Alberta (MacDonald et al., 1988; Kalkreuth and Leckie, 1989), the Jewell seam occurs directly atop this sandstone unit. The Bullmoose A1, A2 and B seams, and the Quintette J and K seams (Fig. 5-2), also rest directly above a thick, upward coarsening shoreface and beach sandstone unit which superficially resembles the Torrens. Hence, local workers in northeastern B.C. began calling the sandstone directly beneath the thick coal sequence the "Torrens" as well. Leckie (1983) solved this problem by distinguishing Torrens A and B units, whereas Carmichael (1983), utilizing local mine stratigraphy, called the lower sandstone unit the Sheriff sandstone (Fig. 5-2). The preceding discussion serves as an illustration of the general stratigraphic correlation and nomenclature problems in northeastern British Columbia. The stratigraphic nomenclature of the area is, at times difficult to unravel. Each coal company uses a mine-specific terminology, whereas petroleum industry personnel utilize names adopted from sub-surface terminology. In addition, federal government geologists and provincial survey geologists differ on the boundaries of each unit (Stott, 1968; Duff and Gilchrist, 1981; Stott, 1984).

5.3.3 Paleoclimatic setting:

The paleoclimatic setting of the Gates Formation is reviewed in chapter 4. Gates strata were deposited along the western margin of the Cretaceous interior seaway, on the eastern side of the rising Canadian Cordillera. Plate tectonic reconstructions (Barron, 1987) place the study area at approximately 60^{o} N, 4 - 5^{o} north of its current position (Fig. 5-1). However, the area was warmer, and a temperate deciduous forest flourished, rather than the evergreen coniferous forest we see today (Saward, 1992; Fig. 4-19). In chapter 4 it is argued that the position of the area leeward of a significant mountain range resulted in relatively dry (though at least subhumid) conditions. Rainfall has been interpreted to be seasonally distributed in the area (Barron and Washington, 1989; Beeson, 1984 *in* Parrish and Barron, 1986). As interpreted by the presence of abundant fire-derived inertinite in the coals, periodic drought occurred. Where the water supply of the wetland was solely dependent on rainfall, the peats became enriched in fire-derived inertinite. Although the peat accumulation rate is interpreted to have been relatively low due to the climatic conditions, the constant or near constant subsidence of the foreland basin allowed for preservation of the deposit.

5.4 CHARACTERISTICS OF MODERN TAXODIACEOUS WETLAND ENVIRONMENTS

5.4.1 Taxodium-type wetlands

It is generally believed that many Cretaceous wetlands were dominated by taxodiaceous conifers (LaPasha and Miller, 1984; Collinson and Scott, 1989; Cross and Phillips, 1990). The trees in modern taxodiaceous wetlands, including the large (35 - 40 metres height) *Taxodium distichum*, (bald cypress), and the more stunted (3 - 10 metres height) *Taxodium distichum* var. *nutans* (pond cypress), are adapted to surviving in a wide range of hydrologic conditions, as well as in fluctuating hydrologic conditions (Brown, 1984; Mitsch and Gosselink, 1986; Collinson and Scott, 1987). Although the trees found in the Gates wetlands were not *Taxodium*, taxodiaceous-type conifers present in the Gates, including *Elatides* sp. and *Athrotaxites* sp. (Bell, 1956; Lamberson et al., 1991), may have occupied similar ecological niches. It is likely that the trees growing in nutrient rich mires were of considerable stature (a thirty metre log impression was observed on the floor of the Bullmoose B seam), whereas the trees growing in nutrient poor mires were probably smaller. In this section the characteristics of modern taxodiaceous wetlands of the southeastern United States are reviewed, particularly those of southern Florida, as a general guide to interpreting the textural characteristics of the coals deposited in the taxodiaceous wetlands of the Gates Formation.

One of the most cited modern analogs for a coal forming depositional environment is that of the Okefenokee swamp-marsh complex (SMC) , located in the southeastern United States (Cohen, 1973; 1974; 1984). Three major sub environments exist within that system, namely: (1) open water marshes dominated by floating aquatics (*Nymphea*); (2) glades or island fringes dominated by emergent plants; and (3) tree islands and swamps. However, the Okefenokee SMC is not the only type of taxodiaceous wetland. In the southeastern United States, and particularly in the state of Florida, a variety of taxodiaceous wetland geomorphologic types are developed (Table 5-1). The wetland types listed in Table 5-1 represent a continuum of environments, rather than strict categories.

The structure and function of taxodiaceous wetlands in the southeastern United States are dependent upon water source and energy, nutrient source and availability, and hydroperiod (Mitsch and Gosselink, 1986; Ewel, 1990). These factors in turn influence fire frequency. Nutrient availability and water energy increase from stillwater swamps such as the Okefenokee, to slow flowing water types (strands) to flowing water types such as floodplain forests (Brown, 1981; Ewel, 1990; Table 5-1). River swamps are characterized by short hydroperiods, relatively high nutrient levels, high dissolved oxygen, low organic matter accumulation rates and low fire frequencies. These higher energy riparian wetlands with a short hydroperiod grade into the permanently flooded alluvial deepwater cypress swamps (backswamps, outliers) described in Mitsch and Gosselink (1986) and in Table 5-1. The permanently flooded wetlands occur in oxbows and sloughs. Stillwater swamps are nutrient limited (often acid) wetlands, with variable but usually long hydroperiods, high organic matter accumulation (except in driest savanna sites), and a moderate to high fire frequency , including cypress domes and dwarf cypress swamps (savanna). Lake edge swamps and slow-flowing cypress strands are intermediate between the two flow regimes.

Table 5-1. Classification and description of taxodiaceous wetland types present in the southeastern United States. Descriptive information and classification from Odum (1984), Mitsch and Gosselink (1986). Fire frequency information from Ewell (1990).

Swamp Type	Description
cypress domes	Poorly drained to permanently flooded stands of approximately 1-10 hectacres in areal extent. Water source is surface inflow and precipitation (generally not from groundwater). Dome teminology derived from profile with tallest trees in middle, more stunted trees on edges. Profile not always consistent). Fire frequency moderate (5 per 100 years)
dwarf cypress swamps (cypress savanna)	Scattered, stunted trees on low nutrient sites in marshland. Usually has a short flooded (high water) season with fires a common event (1 per 10 years).
lake edge swamps	Stands along lake margins; characterised by a seasonally fluctuating water table. These areas may trap and retain water and sediment from surrounding upland areas. Fire frequency low (1 per 100 years).
slow-flowing cypress strands	Growths of cypress in slow flowing water (streams with little erosive power). Marked by seasonal wet and dry periods. Fire frequency moderate (5 per 100 years).
alluvial river swamps	Cypress stands in permanently flooded depressions which are hydrologically isolated from the nearby river except during seasonal flooding. Fire frequency is low (1 per 100 years).

Differences in hydrology of each wetland fundamentally affects productivity, nutrient cycling, and decomposition rates. Mitsch and Gosselink (1986) present data which show that net productivity is highest in the environments where there is the biggest seasonal fluctuation in wet/dry conditions, and lowest in the wettest and driest areas. Seasonal flooding in the alluvial and lake edge swamps brings in fresh nutrients, while removing any built up toxins from the system. However, at the same time, the through-flowing water may remove material from the system, resulting in less net accumulation. Isolation from seasonal flooding results in a low nutrient input, low net productivity and stunted vegetation such as in the cypress domes and dwarf cypress swamps. Mitsch and Gosselink (1986) compiled data from a variety of sources from which they conclude that the highest decomposition rates occurred in the wettest, but not permanently flooded sites. As might be expected, the anaerobic conditions associated with stagnant water decreases decomposition rates, whereas the addition of oxygenated water during flooding events increases decomposition. Drier sites also have slow decomposition rates, but decomposition is strongly dependent on the type of material (*e.g.,* twig *vs.* leaves, with leaves more degradable). Lastly, temperature plays a role, as rates of decomposition increase with increasing temperature (Mitsch and Gosselink, 1986).

5.4.2 Effects of Fire

Fire frequency is linked to site moisture conditions and site fertility, with fire more frequent in drier, oligotrophic areas such as dwarf cypress swamps and cypress domes than in wetter, eutrophic areas such as alluvial swamps (Christensen, 1987; Table 5-1). In the Okefenokee SMC droughts occur on a somewhat regular basis (approximately every 20 years, Cypert, 1961, 1972; Spackman et al., 1976), so fires are common. Schlesinger (1978) found that fires in the Okefenokee SMC favoured the dominance of cypress via reduction of both the total number of species present and the relative importance of broad-leaved species. In addition, the fires are believed to maintain the (above ground) biomass of the wetland at a nearly constant level (Fig. 5-4; Mitsch, 1975; Schlesinger, 1978; Odum, 1984). In general fires have a cleansing effect on wetland environments, eliminating the less water tolerant vegetation which colonize areas during times of lower water. Many wetland trees, including *Taxodium*, have physiological adaptations to fire, including thick, fire-resistant bark and the ability to resprout from

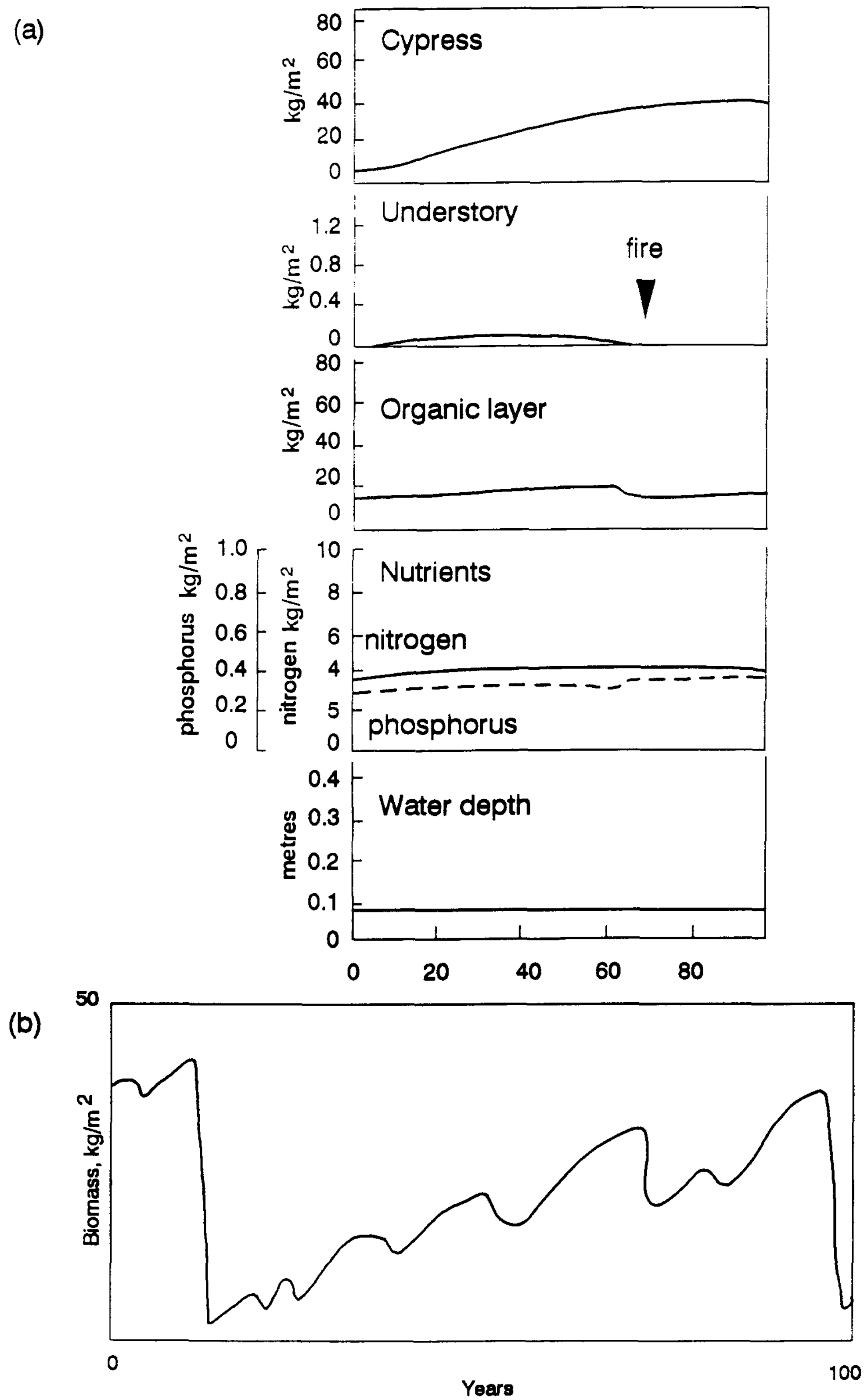

Figure 5-4. (a) Model simulation of Mitsch (1975, in Odum, 1984) showing the effect of fire on the various components of a cypress ecosystem. Fire removes understory, thus ensuring the dominance of the cypress. (b) Odum's (1984) schematic sketch of biomass changes in a cypress ecosystem through time.

adventitious roots and branches following fire (Cypert, 1972; Brown 1984, Ewel, 1990). Trabaud (1987) discusses fire adaptations in plants which occupy so called "fire communities".

What is perhaps the most important, yet the most poorly understood effect of fire is on nutrient cycling. Fire-caused nutrient cycling is discussed in MacLean et al. (1983) and Christensen (1987) and is summarized here. Figure 5-5 diagramatically illustrates the types of effects of fire. In most systems, there are two basic nutrient pools; the standing biomass (vegetation, pool I, Fig. 5-5) and organically-bound nutrients in soil (pool II, Fig. 5-5). A third pool is contained within peats (pool III, Fig. 5-5) in wetland environments. Schlesinger (1978) concluded that this nutrient pool is inaccessible, and essentially lost from the system. However, if a peat catches fire, some of the nutrients contained within the peats could be remobilized. For most vegetation communities, particularly oligotrophic systems, phosphorus and nitrogen are the limiting nutrients for plant growth (Brown, 1981; MacLean et al., 1983 et al.; Christensen, 1987), so most studies have focused on these elements. Some proportion of both elements are lost from the nutrient pools during fires, with nitrogen more readily volatilized than phosphorus. The total loss is dependent on fire intensity (temperature), which is in turn linked to site moisture conditions (MacLean et al., 1983; Christensen, 1987). Nutrients can be lost through direct volatilization, or removed by ash convection during fire (Fig. 5-5).

The loss of overall nutrient capital during fire may be balanced by increased nutrient concentration or availability in soil by several mechanisms, including: (1) direct mineralization during the fire and addition in ash; (2) changes in microbial activity; and (3) alteration of soil ion exchange capacities (Christensen, 1987; Fig. 5-5). The ash layer formed by burning the vegetation, the top soil layers (which in a wetland is commonly peat), and more rarely, the deeper peat deposits, is a source of nutrients. Some nutrients are lost by wind, leaching, and surface runoff. Loss of nutrients by leaching is a function of the permeability and ion exchange capacity of the substrate; sandy substrates are more permeable, and have lower ion exchange capacities than most clayey or organic substrates (MacLean et al., 1983). Runoff varies with respect to local topography and water source. An increase in soil pH occurs associated with the addition of alkali cations (e.g., magnesium, calcium and potassium) from the ash. This increase may only be slight and the duration short (Christensen, 1987), but it is capable of altering the soil pH such that microbial decay is enhanced. For acidic systems, like most wetlands, an increase

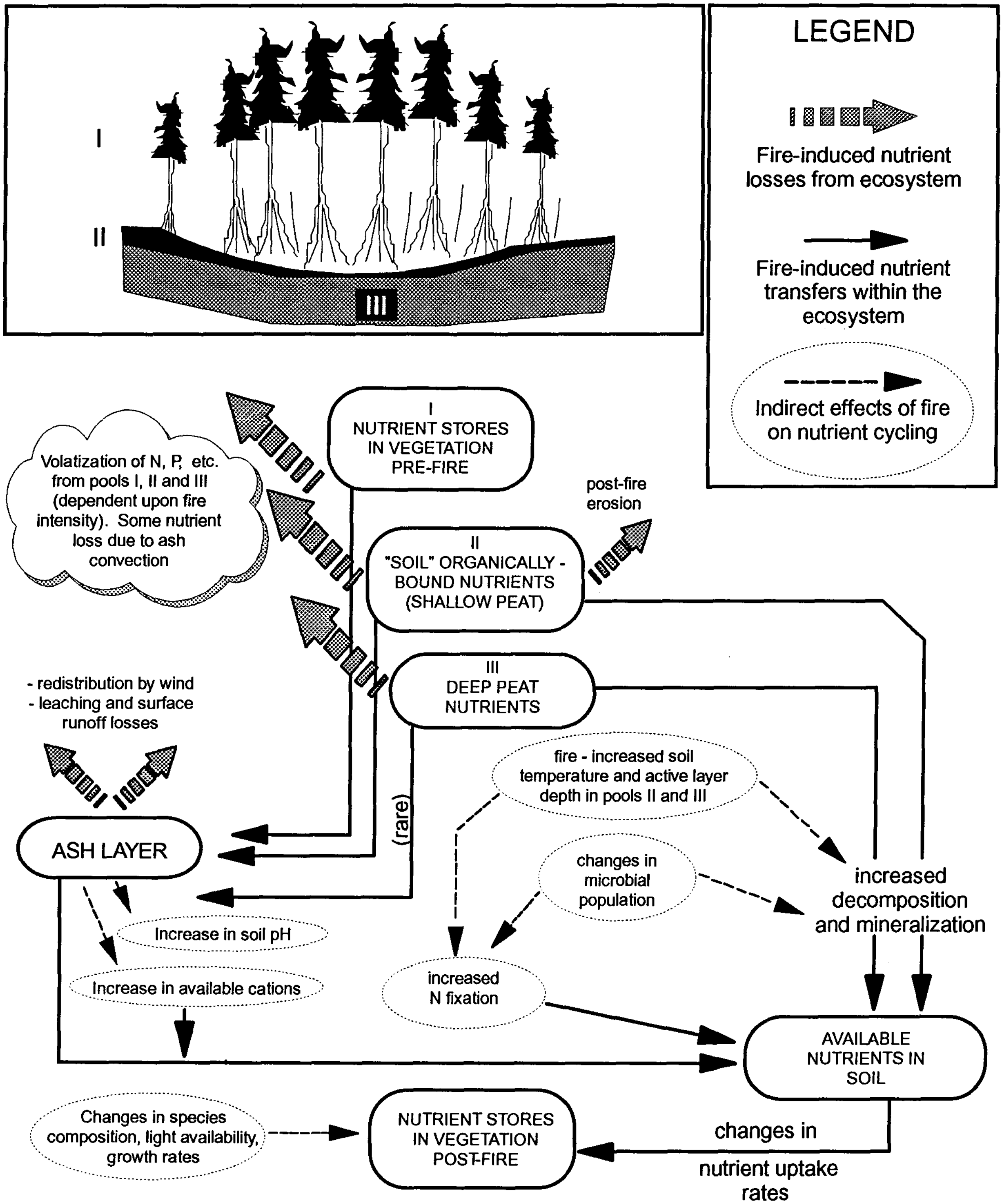

Figure 5.5. Schematic illustration of some of the fire-caused changes in nutrient cycling in a peat-forming area. Figure at top shows three nutrient pools I, II and III(deep peat). Modified after MacLean et al. (1987) using information in MacLean et al. (1983) and Christensen (1987). Details discussed in text section 5.4.2.

in decomposition rates can result. Increased decomposition rates following fires may also be due to higher temperatures in the upper soil layers. Changes in light availability, surface albedo and species composition are also indirect effects.

Ultimately, higher available nutrient concentrations in the ecosystem may result as a consequence of the fire, allowing enhanced productivity. Wein (1983) presented a concept termed the "paludification-nutrient release hypothesis" in which an "...ageing ecosystem can be revitalized through improved nutrient cycling conditions brought about by fire" (Wein, 1983, p. 91). His research dealt specifically with northern, colder ecosystems typified by peat mosses. Light surface fires, where essentially very little material is removed, favour the continuation of nutrient poor conditions and dominance of moss; deeper fires lead to warmer soils (due to change in albedo), faster nutrient cycling and the growth of vascular plants. In warmer areas, such as the Okefenokee SMC, deeper peat fires not only release nutrients locked up in peat, but Schlesinger (1978) noted that an increment of nutrients becomes available from trees killed by fire.

5.4.3 Ecosystem model of the cypress system

Odum (1984) examined the types of disturbances which affect cypress ecosystems on a variety of time scales (diurnal, seasonal, yearly, etc.). Disturbances can be characterized by their frequency and duration, as well as the energy of impact. Sun and wind influences, for example, may have a high long term total energy, but are minimal in the short term. Catastrophic events, such as exceptional drought causing a severe fire, are of short duration, but have a high energy of impact. Disturbances, if repeated frequently, may end the dominance of cypress. Mitsch (1975) modeled the effects of fire and harvesting for timber, both separately and in combination. Separately, the two events do not destroy the cypress ecosystem, whereas a combination of the two will. Similarly, Cypert (1972) proposed that repeated fires will alter the nature of the cypress-dominated wetland such that a prairie marsh will form.

Odum (1984, p. 422) concluded that "...the normal long - range pattern for (cypress) swamps is a long

period of production followed by consumptive regression, followed by regrowth — both in the past and the present.

...Climax in the sense of steady state is not so much a short period when mature trees dominate prior to removal, but rather is the average condition over a long interval during which the forest alternates between gradual growth with pulsed consumption and export". Figure 5-4b, taken from Odum (1984) illustrates the pattern of flux in the biomass on a scale of years. This biomass flux reflects the cyclic nature of change in the composition and productivity of the ecosystem through time.

5.5 MACERAL BASED FACIES INTERPRETATION: GENERAL CONCEPTS

The vegetational and physico-chemical changes occurring within a wetland through time are recorded as changes in composition, texture and total amount of organic matter preserved. Hence, the task of reconstructing the characteristics of an ancient wetland environment from a peat deposit is an exercise in interpreting the forest from the debris. Both composition (maceral and mineral) and texture reflect the sedimentological conditions of the original peat–forming wetland in terms of energy and decompositional process. Peats which form in consistently wet, though not subaqueous, conditions will be enriched in vitrinite (given exclusion of clastics), with variable amounts of liptinite and fungal–derived inertinite. Interruptions in precipitation allow for a drawdown of the water table. As a result, the peat is exposed to destruction by detrivores or lightning-induced wildfires, and becomes enriched in fire-derived inertinite at the expense of vitrinite.

As discussed in Diessel (1982, 1986) some macerals can be considered "facies-diagnostic", i.e., a distinctive origin and/or depositional condition(s) can be assumed. A review of this concept has recently been provided by Marchioni and Kalkreuth (1991) and only the basic concepts which apply to paleo-wetland interpretation of the Gates settings will be summarized here. Although there are exceptions, telinite, telocollinite and pseudovitrinite generally are derived from the more resistant lignin-rich tissues such as wood from stems, branches and roots of trees and shrubs. Fusinite and semifusinite are also primarily derived from these tissues, but they can also be from less resistant tissues such as leaves and herbaceous stems, and rhizomes. Resinite in cell cavities within wood, suberinite (bark tissues) and cutinite which is attached to woody stems are also predominately derived from arborescent or shrub vegetation. Inertodetrinite has the same origin as fusinite and semifusinite (woody tissues). When associated with detrital minerals such as dispersed clay mineral and quartz, inertodetrinite, vitrodetrinite and sporinite can be considered to have been transported. Desmocollinite is considered non-diagnostic (Diessel, 1982, 1986; Marchioni and Kalkreuth; 1991), as it is the product of a variety of degradative processes. However, if interpreted in the context of the remaining macerals, its origin can usually be postulated. For instance, enrichment in desmocollinite, vitrodetrinite and mineral matter most likely formed in a frequently flooded, open marsh environment. Alginite, particularly when associated with other liptinitic macerals, is indicative of subaqueous, open water conditions.

As discussed in Chapter 2, two petrographic ratios (originally defined by Diessel, 1986) are commonly calculated from maceral point count data in order to interpret depositional conditions: (1) the tissue preservation index (TPI), defined as the ratio of the percentage of vitrinite and inertinite macerals with cell structure to those without; and (2) the gelification index (GI) defined as the ratio of the percentage of gelified to ungelified macerals, or essentially the ratio of vitrinite to inertinite. These two indices, plotted against one another on a graph (Fig. 5-6), define "facies" fields which are thought to be characteristic of particular environments.

The TPI-GI facies diagram enables interpretation of two major parameters, composition (GI) and texture (TPI). GI can be used as a measure of the persistence of wet, reducing conditions. If the GI remains appreciably above 1, the water table remained high, and conditions were rarely dry enough to sustain a fire. A decrease in GI corresponds to lower water tables which allow fire to be sustained. In addition, a lower water table results in more oxidizing conditions and the preferential destruction (degradation) of vitrinite-precursor material. As a result, fire-derived inertinite is concentrated in the peat deposit. The TPI is a measure of the texture of the deposit: high TPI values indicate that the precursor material suffered little mechanical and/or biochemical degradation in the original peat forming setting, although it could have been burned. Because the preservation of cell structure is indicative of the resistance of the precursor material to degradation, the TPI is also an approximation of the dominance of lignin-rich tissue, i.e., how woody the original vegetation was. If a significant portion of the fusinite and semifusinite is from herbaceous plants and is well preserved (e.g., rhizomes of ferns), the TPI is not valid as an approximation of vegetation type.

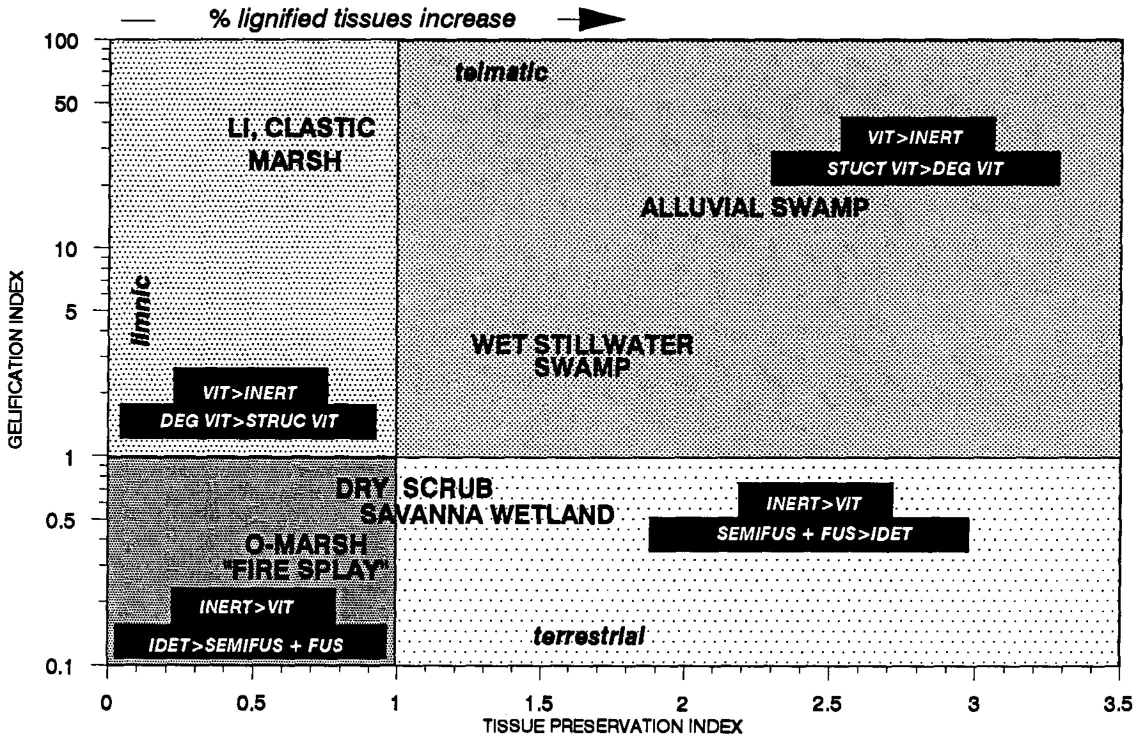

Figure 5-6. Generic facies diagram (modified from Diessel, 1986) as used in this study showing wetland environment fields and bulk maceral composition. O-MARSH =open marsh; VIT =vitrinite; INERT =inertinite; SEMIFUS = semififusinite; FUS = fusinite; IDET = inertodetrinite; STRUC = structured; DEG = degraded; LI = limited influx

5.6 METHODS

5.6.1 Laboratory and Field

The procedure utilized in this study is described in chapter 4 (fig. 4-3), and is only briefly summarized here. Samples representing the entire thickness of Bullmoose A1, A2, B, C, D and E and Shikano D seam were collected. The Bullmoose samples are primarily block samples, except where the interval was too sheared or friable. Shikano D seam samples were all channeled and sampled by lithotype. Lithotypes of each seam were described according to modified version of the classification of Diessel (1965), utilizing a minimum thickness of 1 centimetre. Representative samples of each described interval from each seam was crushed to fit through a 250 μm screen. A pellet was prepared for maceral analysis, following standard procedures (Bustin et al., 1985). A 300 point maceral analysis using standard coal petrographic nomenclature was performed on each pellet. In total 386 pellets were examined for this study. Ash yield and total sulphur data analysis were performed on all samples, unless there was insufficient coal for analysis.

In order to assess lateral and vertical variation in lithotype stratigraphy, at least three other sections of seams A1, B, C, D and E were described in the field (bringing the total to at least four) utilizing a minimum thickness of 1 centimetre. Exposure of seam A2 was poor, so no lithotype correlations were possible. Sections were drawn and correlated according to similarity in lithotype composition and visual breaks in lithotype pattern. In places it was difficult to assess whether or not all of the section was present as the roof was often stripped off. Flowing water was present in other places, particularly in the basal section of both the A1 and B seams. The floors of seams C, D and E were difficult to determine in some areas as the basal contact tended to be gradational, and characteristically were composed of bright (vitrain) layers and lenses interlaminated with mudstone.

5.6.2 Interpretation of Wetland Environment

Although the Diessel-type (1986) diagram was utilized in chapter 2 to describe wetland succession of the Shikano D seam, three technical problems arise where a large number of samples are analyzed for each seam. The first problem is that sample thickness, an approximation for duration of a particular environment, is not easily assessed. For example, within the B seam there are commonly thick sections of banded dull coal with scattered thin lenses of bright coal which represent individual logs. A vertical section through a banded dull coal (e.g., TPI = 1.2, GI = 0.8) which contains occasional lenticular bright layers (e.g., TPI = 10; GI = 50) representing individual logs, would magnify the importance of the thin bright layers as they would appear as large deviations from the background norm. These types of deviations compound the second problem; if a large number of samples are used (e.g., the B seam is represented by approximately 100 samples), lines connecting sample points repeatedly cross, and the diagram gets very confusing. The third problem is that there is no easy way of assessing mineral matter content since mineral matter is not included in either the TPI or GI calculation.

An alternate method of assessing wetland succession in seams represented by a large number of samples is to plot GI and TPI versus depth. A deflection in GI from higher to lower values is interpreted to indicate a drop in the water table; sections with a consistently low GI indicate persistently low water tables. High TPI values indicate woodier vegetation, whereas low TPI values are interpreted to mean either more herbaceous vegetation or, if combined with mineral matter enrichment, a higher energy environment. By utilizing both indices and ash yield data, the vegetation type, water table height (persistently wet versus periodically dry conditions) and sedimentological energy of the system can be interpreted. The graphs are constructed using midpoint values of each sample. Although this does magnify the effect of thin layers deviation somewhat, the actual thickness is readily seen from the lithotype profile.

The arrangement of the maceral groups in the compositional profiles discussed in sections 5.9.1 to 5.9.7 is specifically designed to emphasize the textural variation in the seams rather than bulk maceral composition. The macerals with residual cell structure are placed on the left, attrital/detrital material on the right and the "non-diagnostic" macerals (almost exclusively desmocollinite) in the middle. (The profiles in chapter 4, Figs. 4-9 through 4-13, were constructed to emphasize bulk maceral compositional changes.).

5.7 GENERAL RESULTS: COMPOSITION

As discussed in the previous chapters, the coals of the Gates Formation are enriched in vitrinite and inertinite, and lacking in liptinite. The brighter coal lithotypes are vitrinite-rich, particularly structured vitrinite.

The duller coal varieties are dull either due to high inertinite content, high mineral matter content, or to a combination of the two. Where samples are enriched in mineral matter, they are also commonly enriched in either inertodetrinite or vitrodetrinite, or both macerals. The relationship between megascopic appearance and maceral composition is explored thoroughly in Lamberson et al. (1991, chapter 2) and Marchioni and Kalkreuth (1991). The bulk compositional changes within each of the Bullmoose seams is discussed in chapter 4.

Fire frequency in the Gates Formation is interpreted to be relatively high (chapter 4), as evidenced by the abundant inertinitic material. Why then, are there very few charcoal horizons preserved? As discussed earlier, fires have a major impact on nutrient recycling. After a fire event, particularly following rain, new growth is rapid, and usually luxuriant as a result of the available nutrients in the ash (MacLean et al., 1983; Christensen, 1987). The brittle charcoal material readily breaks up, and may be transported from the site. The more resistant, semi-charred material will tend to stay on site and be concentrated in the upper peat layers. However, the turbation caused by new rooting will disrupt bedding, and redistribute the new and remaining old semi-charred material through the active peat profile. An additional mechanism by which material can be redistributed is via the action of floating peat mats (W. Spackman, personal communication, 1993). After an extended period of water table drawdown, the peat surface subsides (compacts). The addition of new water in the rains following a fire buoys up the surface, such that peat mats can be separated from the main peat body, and a water lens is present beneath the upper mat surface. These mats eventually re-expand, and the peat is redistributed, disrupting bedding and obscuring the original stratigraphy. Either of these processes could account for the massive, duller appearance of the inertinite-rich horizons in the Gates coals. Charcoal horizons probably only occur in the case of a severe fire where an aqueous environment succeeds the fire, and sedimentation is not dominated by rooting.

The Gates Formation coals are liptinite-poor. There is very little cutinite, sporinite and resinite. Alginite is effectively absent. The low quantity of resinite is attributable to the characteristics of the wetland flora. Although largely coniferous, the plants were not large resin producers. Liptinite is commonly concentrated in quieter, open water/aquatic settings due to its resistance to degradation. The lack of liptinite suggests that the quiet, open water settings so common in the modern Okefenokee SMC, were rare or absent in the Gates wetlands. The lack of liptinite in the coals is also interesting from another environmental perspective. The abundance of fires indicates periodically dry conditions. One might expect adaptations such as thick cuticles on the leaves. However, the entire flora, with the exception of annual herbs such as ferns, is interpreted as deciduous (Zhihui and Basinger, personal communication, 1993). During periodic drier conditions, these plants could have dropped their leaves, rather than develop thick cuticles.

Another maceral which is rare in the Gates is sclerotinite. Although fungal material is relatively scarce in pre-Late Cretaceous coals, the environmental conditions may also have played a role. Fungal decay of wood is strictly an aerobic process, and normally requires moist/damp conditions. The paucity of fungal material supports the interpretation of overall drier conditions interpreted for the Gates wetlands. Demchuk (in press) also noted a low fungal contribution to the fire-derived inertinite-rich coals of the Late-Cretaceous to Early Tertiary strata in the Western Canada Sedimentary Basin of Alberta.

5.8 DISCUSSION: INTERPRETED DEPOSIT TYPES OF TAXODIACEOUS WETLAND ENVIRONMENTS

Variation in coal facies is essentially a function of the vegetation type, water depth (ground water table level), decomposition rate and accumulation rate of the original wetland (Ting, 1989, Lamberson et al., 1991). Under ideal conditions (rapid burial, high water table, little clastic influx), a tree swamp such as the cypress swamp will give rise to a coal enriched in structured vitrinite (high TPI, high GI), whereas herbaceous vegetation will give rise to a coal enriched in unstructured vitrinite (low TPI, high GI) and (depending on the energy of the system) probably mineral-matter. However, discussed in chapter 2 one wetland type can give rise to a spectrum of coal facies depending on variations in the aforementioned conditions (Ting, 1989; Lamberson et al., 1991).

In order to interpret successional changes in the Gates Formation coals, I have derived a series of "baseline" characteristics, based on published descriptions (Table 5-2), in terms of broad maceral and mineral characteristics, of the various taxodiaceous swamps, as well as the associated herbaceous environments. The bulk of any taxodiaceous swamp (biomass) is wood. However, it is only when the tree dies and falls over, or the system is catastrophically flooded and killed will large logs be preserved. *Taxodium* sp. are deciduous plants, which shed entire branchlets with their leaves attached, as opposed to just the leaves (Brown, 1984). Thus, the plant produces abundant leafy and woody material on a seasonal basis (Spackman et al., 1976). This material coats the forest floor and contributes structured vitrinite precursors to the peat. The degree of preservation of the leaf and wood litter depends on the length of time the material spends in the aerobic zone, as well as outside influences such as fire. In addition, wood is contributed by an extensive root system which spreads out laterally in the peat.

If material is buried rapidly, the deposits of the wetter stillwater taxodiaceous swamps (domes and strands) will probably resemble the *Taxodium* peat type described by Cohen (1973, 1974) from the Okefenokee SMC. The peat is coarsely granular to woody, containing a large proportion of twigs, leaves and roots and occasionally contains abundant charcoal material. In terms of maceral content, Cohen estimated that the resultant coal would contain approximately 60% structured vitrinite, 24% granular material (micrinite and/or unstructured vitrinite with variable, but low mineral matter), 10% resinite or phlobaphenite, 1% sclerotinite and 5% structured inertinite. This type of peat, Cohen (1973) interprets, would be a precursor to a duroclairan (banded dull) type coal. Any brighter bands would be relatively restricted in extent, and correspond to individual logs or roots. The associated aquatic and marginal peats, due to a higher proportion more easily degraded cellulose-rich (leafy) material, would give rise to duller coal varieties, with a lower TPI (Cohen, 1973; Lamberson et al., 1991). Although not reported from Cohen's (1973; 1974) research, the herbaceous environments would probably also have a higher liptinite content, including sporinite, alginite and perhaps cutinite.

Peat accumulation is lower in the drier dwarf cypress/savanna areas such as the Big Cypress Swamp region of southern Florida due to high fire frequency. Duever et al. (1984) describe the swamp as a savanna-like area of small, scattered cypress trees interspersed with denser domes and strands of larger cypress trees. Subordinate environments include marshes, pinelands and hardwood hammocks. Hydroperiod and fire frequency determine the distribution of plant communities, with the domes and strands (hydroperiod approximately 290 days, water depth approximately 70 cm, peat accumulation up to 2 metres) occupying deeper, wetter environments and the dwarf cypress occupying slightly higher, drier environments (hydroperiod approximately 120 days, water level maximum of 15-20 cm). The drier savanna sites grade into the strand and dome sites; where hydroperiod is longer, tree density and height increases in the savanna sites (Duever et al. (1984). Fire frequency increases from

Table 5-2. Petrographic characteristics of interpreted wetland environments of Gates Formation coals. Classification used in Figures 5-7 to 5-17. Classification adapted from information in Table 5-1.

Wetland	GI	TPI	Mineral Matter	Comments
alluvial swamp	high	high	high	dependent on proximity to active system
wet stillwater swamp	medium to high	medium to high	low	fire layers may be common, TPI high due to abundance of structured vitrinite
dry savanna scrub wetland	medium to low	medium to high	low	grades to wet stillwater swamp, vitrinite becomes oxidized, TPI high due to abundant burned material
periodically flooded, open scrub wetland	medium to low	medium to high	high	mineral and inertinite concentrated due to low accumulation rates.
clastic marsh (fringe marsh)	high	low	high	dependent on proximity to active system
limited influx marsh	high	low	low	rare environment, usually as part of a wet stillwater swamp
fire-splay - shallow lake	low	low	high	receiving basin for material from more regional fires

high = appreciably greater than 1   low = appreciably lower than 1
medium = approximately 1

the strand and dome sites to the savanna sites. The characteristics of the peats from this area have not been documented, but based on the relative higher fire frequency, one might expect the inertinite content to be higher relative to the vitrinite content.

From a gross compositional viewpoint, the amount of mineral matter can be expected to increase from the still water swamps (cypress domes, dwarf cypress swamps, Okefenokee-type hybrids) and slow-flowing strands to the marginal environments of the lake edge and alluvial river swamps. The actual amount of mineral matter would depend on the proximity of the wetland to the source of sediment. The wet conditions and frequent rapid influx of clastic sediments associated with marginal environments tend to favor the preservation of vitrinite, particularly structured vitrinite. A large part of the organic material would consist of individual stems and branches; as a result the TPI would be higher in the alluvial setting than the stillwater setting where decompositional processes are more active prior to burial. However, the organic material would be diluted with clastics, resulting in the deposition of carbonaceous mudstones interbedded with thin vitrain/bright layers. The lowest ash yield peats would probably occur in the cypress dome/head deposits, as the dense vegetation stand would serve to keep clastics out of the environment. The dwarf cypress swamps and slow flowing strands would have low ash yield values, depending on the carrying capacity of the streams which drain the area.

An interpretation of the petrographic characteristics of seven wetland and associated organic depositional environments is presented in Table 5-2, and included within the facies diagram of Fig. 5-6. The types of treed wetlands (swamps) are generalized to four varieties, depending on the petrographic indices and mineral matter influx. Fire plays a major role in modern environments (see chapter 4), as the classification constructed in Table 5-2 reflects. One environment is rather unique to the Gates wetlands, the fire splay-shallow lake. These deposits are enriched in mineral matter and inertodetrinite, and have both a low GI and TPI. Staub and Cohen (1979) describe the characteristics of two types of splays in the Snuggedy Swamp peat-forming wetlands of South Carolina. The first is a crevasse splay, a break in a levee system delivering mud-rich waters into the wetland. The second type of splay is what they termed a "fire-splay" which resulted from a break in a levee as a result of a peat fire. The fire burns a hole in the peat mass, such that a pond develops. These ponds are eventually filled, and peat accumulation continues. Repeated or severe fires in a wet forest ecosystem are known to destroy a part of a swamp, and a pond or lake develops. This origin is postulated for the larger lakes of the Okefenokee (Cypert, 1961, 1972; Cohen, 1974)). In the Okefenokee, these quiet water lake settings are accumulating peats from aquatic plants. In a more sedimentologically active peat-forming area, the fire-created depressions would likely accumulate clastic sediments and transported organic material. The characteristics of the deposits which may be analogous to the fire splay are discussed in the results section of this chapter.

5.9 RESULTS: INTERPRETED WETLAND SUCCESSION OF BULLMOOSE SEAMS AND SHIKANO D SEAM

5.9.1 Maceral and lithotype stratigraphy of seam A1

Seam A1 is a low-ash yield seam which exhibits very little vertical variation in petrographic composition (Fig. 5-7) and lithotype stratigraphy. It is predominately a banded dull coal. Bright coal is found as thin streaks and lenses. As shown in section F of the lithotype correlation (Fig. 5-8), more than one lens of bright material is present in the A1 seam. However, it was not possible to separate the bright from the matrix during sample preparation for maceral analysis. The highest GI values are present in the basal 20 cm. Structured vitrinite rarely exceeds 40 % of the seam, and averages 25%, raw coal basis (Table 4-6).

Based on composition and texture, three zones can be distinguished in seam A1 (Fig. 5-7): two lower vitrinite-rich zones distinguishable on the basis of texture, and an upper zone enriched in structured macerals. These three zones are interpreted to correspond to differences in depositional environment. TPI values are consistently high for all but zone II due to enrichment in semifusinite and fusinite. Enrichment in structured material suggests a woodier vegetation throughout much of seam development. In addition, the floor of the A seam contains large logs and broad, thick roots which spread out laterally and penetrate the underlying shoreface sandstone. The wettest conditions existed during the initiation of seam development (zone I, Fig. 5-7), favouring decomposition by microbial processes rather than fire, and desmocollinite formation. The drop in TPI and GI (as a result of an increase in desmocollinite and inertodetrinite), following the basal wet forest swamp suggests that an herbaceous flora (limited influx marsh) may have developed (Fig. 5-7, zone II), perhaps as a result of increased fire

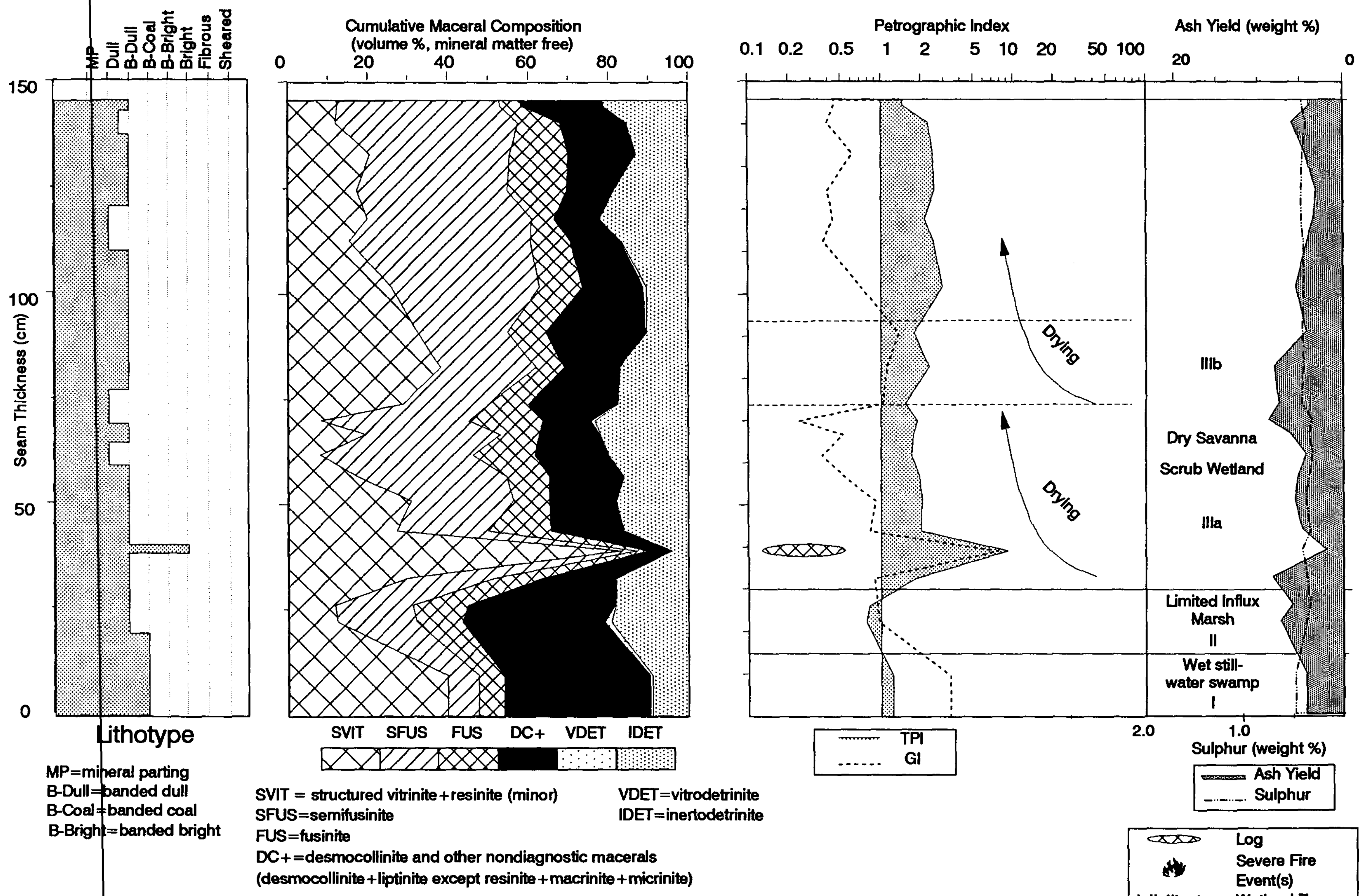

Figure 5-7. Lithotype, maceral, tissue preservation index (TPI), gelification index (GI), ash yield and sulphur content profiles of seam A1.

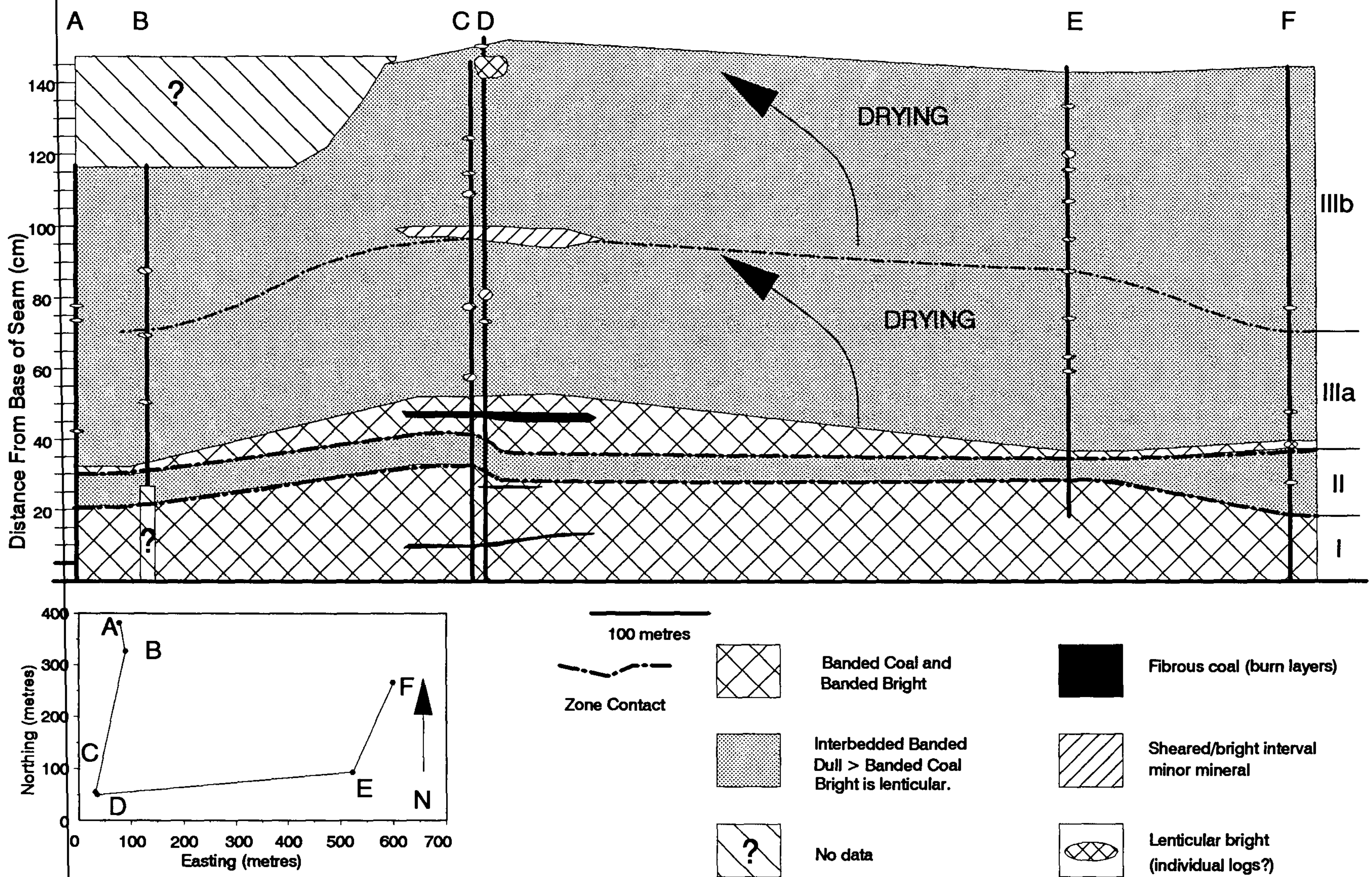

Figure 5-8. Generalized lithotype correlation of seam A1. Heavy vertical lines are section locations. Petrographic samples from section F. Abbreviations and symbols same as illustrated on section profile in Figure 5-7.

activity. Above this zone, the forest swamp re-establishes itself in drier conditions. Two cycles of higher to lower GI, interpreted as drying cycles, are present in the upper part of the seam (Fig. 5-7, zones IIIa, b). The high TPI as a result of high structured vitrinite, low ash yield and medium to low GI values suggest that the dominant wetland setting was a dry savanna scrub wetland. These environments may have initiated as wet stillwater swamps, but eventually evolved into overall drier wetlands.

Correlation of lithotypes of seam A1 (Fig. 5-8) indicates that the maceral-defined wetland zones (Fig. 5-7) of section F were relatively widespread in the area, although some differences exist. The basal part of the seam is composed of brighter lithotypes, and hence contains a higher proportion of vitrinite. The basal bright zone thickens to the south, and Zone II, the limited influx marsh, is not as well developed. in sections C, D and E. There is very little megascopic expression of the petrographically determined drying cycles.

5.9.2 Maceral stratigraphy of seam A2

Seam A2 (Fig. 5-9) is a relatively thin seam which was influenced by flooding events. The flooding events were probably from a low energy stream as the mineral matter is fine grained and dominated by clay. The seam was established on a muddy substrate, characterized by high GI and low TPI, suggesting a clastic marsh. Above this zone, the TPI increases to greater than 1, and with the exception of the thin bright/individual logs, the GI drops below 1 for almost the remainder of seam development. Similar to the A1 seam, the combination of a low GI and high TPI suggests that the dominant environment was a dry savanna scrub wetland. The environment opened to clastic influx for a period of time (located approximately 40 centimetres above the base). Toward the top of the seam, the GI increases, indicating that wetter conditions prevailed. A thin (1.5 cm) high sulphur (approximately 4% by weight) zone occurs at the top of the seam, suggesting a marine influence, perhaps a flooding or storm event. The roof of the seam is a mudstone similar to the floor, characterized by a high GI and low TPI; this unit is interpreted to be a clastic marsh.

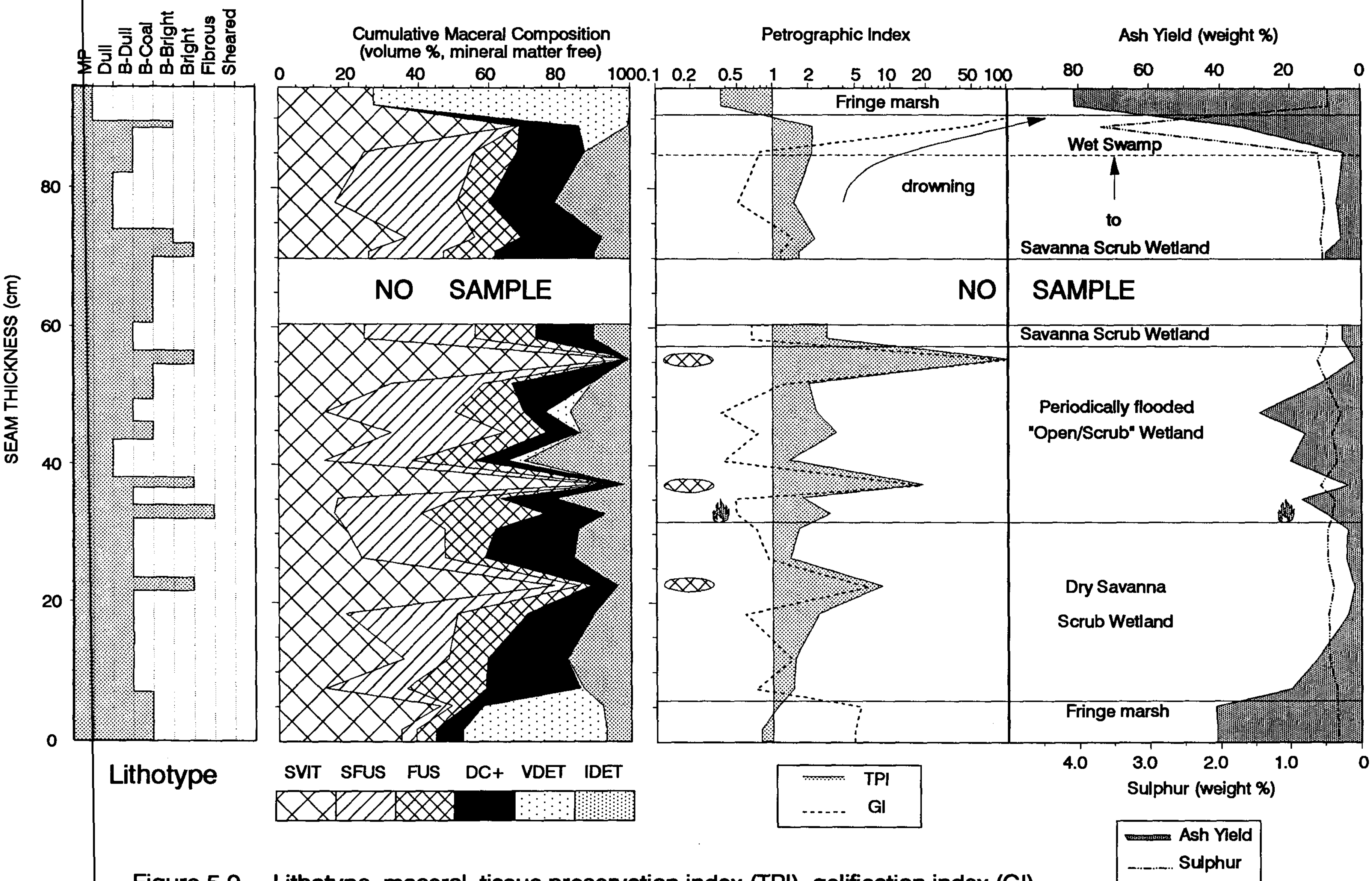

Figure 5-9. Lithotype, maceral, tissue preservation index (TPI), gelification index (GI), ash yield and sulphur content profiles of seam A2. Abbreviations and symbols same as in Figure 5-7.

5.9.3 Maceral and lithotype stratigraphy of seam B

The B seam is the thickest seam in the Bullmoose area (Fig. 5-10). Mineral matter is low, and enriched in secondary carbonates in the basal two-thirds of the seam. Clastic minerals are only abundant in the upper 1.5 metres of the seam (Fig. 5-10). The basal part of seam B is interpreted to be ombrotrophic, and severely nutrient limited, whereas the upper part of the seam was influenced by flooding. The seam is divisible into five zones on the basis of maceral composition. The base of the seam (Fig. 5-10, zone I), like the A1 seam, is more enriched in vitrinite than the remainder of the seam, with a high TPI and GI, and has a low ash yield. This zone is interpreted to be a wet stillwater swamp. Zone II is characterized by a cyclic variation in structured vitrinite (semifusinite) content. These variations may reflect a climatic variation in precipitation (chapter 4), and as a result, the wetland environments varied from dry savanna scrub to wet stillwater swamps. At the top II, and the base of zone III, a series of severe fires occurred, which may have led to the general increased inertinite content in zone III. Part of the basal fire unit of zone III is illustrated and discussed in chapter 4, and comprises a carbonate-impregnated, severely burned peat horizon. Zone III is characterized by low GI and high TPI, and low detrital influx, the characteristics of the dry savanna scrub wetland. Eventually, flooding was not prevented, and the environment developed into an open scrub wetland (zone IV). At the top of the seam, an increase in GI occurs, suggesting a brief wetter period. Fine grained (low energy) fluvial sediments occur on top of the seam.

The lithotype correlation (Fig. 5-11) reveals lateral variation in seam stratigraphy, although the general dulling up trend can be seen. The seam becomes brighter overall from west to east, as shown in sections C and D. The five part division of the seam interpreted from the maceral profile is resolvable in the lithotype section: (1) a basal brighter zone (sheared); (2) an alternating banded bright and banded coal; (3) alternating banded dull; (4) banded dull and dull; and (5) an upper bright zone. Differences in lithotype stratigraphy from section to section may reflect local differences in hydrologic conditions. However, more petrographic work is necessary to substantiate any trends, as lithotype description can only broadly be correlated with maceral composition (chapter 2).

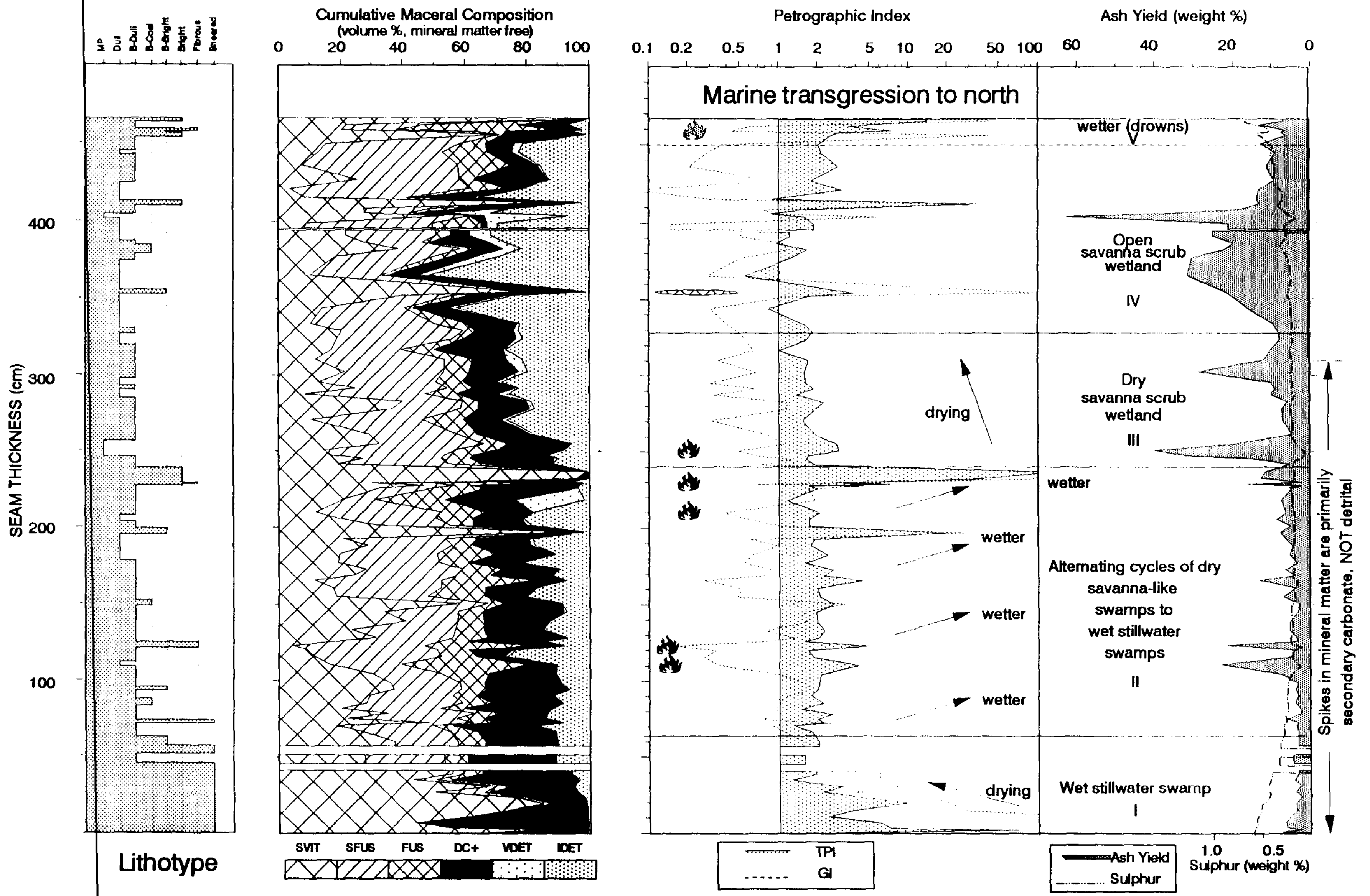

Figure 5-10. Lithotype, maceral, tissue preservation index (TPI), gelification index (GI), ash yield and sulphur content profiles of seam B. Abbreviations and symbols same as in Figure 5-7.

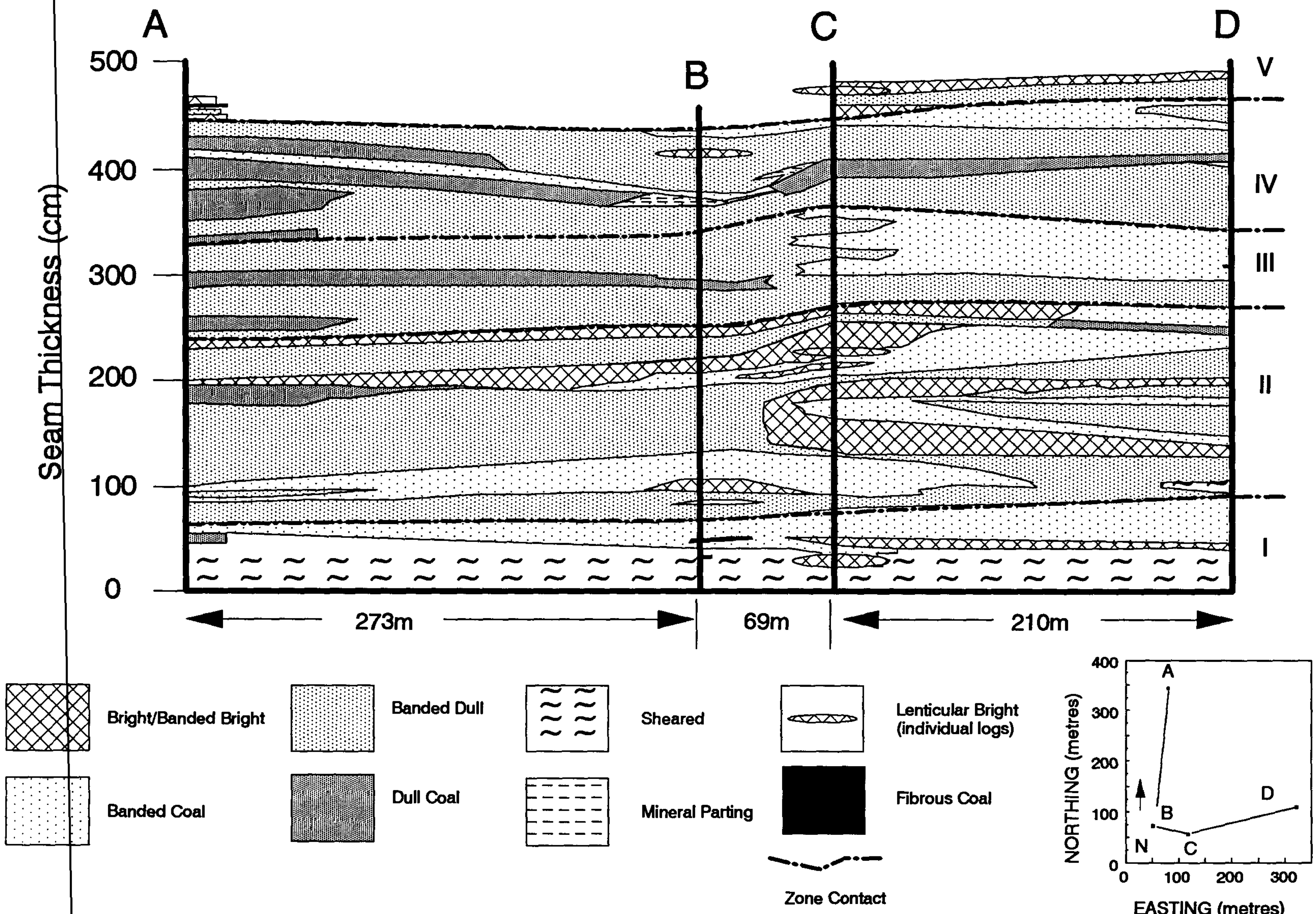

Figure 5-11. Generalized lithotype correlation of seam B. Heavy vertical lines are section locations. Petrographic samples from section A. Abbreviations and symbols same as illustrated on section profile in Figure 5-7.

5.9.4 Maceral and lithotype stratigraphy of seam C

Overall, the C seam is a mineral rich coal (Figs. 5-12, 5-13), suggesting that the wetlands which developed during the C interval were strongly influenced by flooding. The splits are fine grained, indicating a distal position or a low gradient, suspended load stream. Like the Bullmoose B seam, the floor of the C seam characteristically contains numerous large log impressions as well as whole branches. The lower part of the C seam formed in a quiet stillwater, or strand swamp (zone I, Fig. 5-12, 5-13). Mineral matter influx increased, and an alluvial swamp developed in zone II. The upper part of the unit is rather unique for Gates coals, as there is very little inertinite present. Mineral matter influx decreases toward the top of Zone II. Mineral matter flux increased again in zone III, and the TPI and GI fluctuate widely, indicating variable depositional conditions - perhaps a mixture of a clastic marsh and alluvial swamp complex. Based on the presence of inertinite, as well as a radical drop in GI and increase in TPI, at least one fire event occurred within this interval.

Above the marsh, a unit developed which shows an increase, then a decrease in mineral matter concentration, as well as an overall enrichment in inertodetrinite (zone IV). Three possible modes of formation exist for this unit. The first possibility is that of a fire splay; repeated fires in the bottom part of the unit (high fusinite and semifusinite) caused a depression in the peat surface, which was gradually filled by mineral- and inertodetrinite-rich sediment. A second possibility is that a single flooding event, or series of flooding events took place, bringing in mineral matter and inertodetrinite from regional fires. Finally, the unit could represent the deposits of a marsh subject to frequent fires and flooding events. It is currently not possible to determine which possibility, or combination of events is most likely. After filling, an open scrub wetland (zone V) colonized the area. Slightly wetter conditions prevail at the top of the seam (zone VI).

The zones described above have good lateral continuity, as indicated in the correlation depicted in Figure 5-13. Zone II alluvial swamp is represented by a sheared zone throughout the area. This interval grades to a mineral parting in sections D, E and F. The upper, low-mineral matter part of zone II thickens to the south. The fire events in zone III of section B complicate the stratigraphy, as well as the interdigitated nature of the wetland

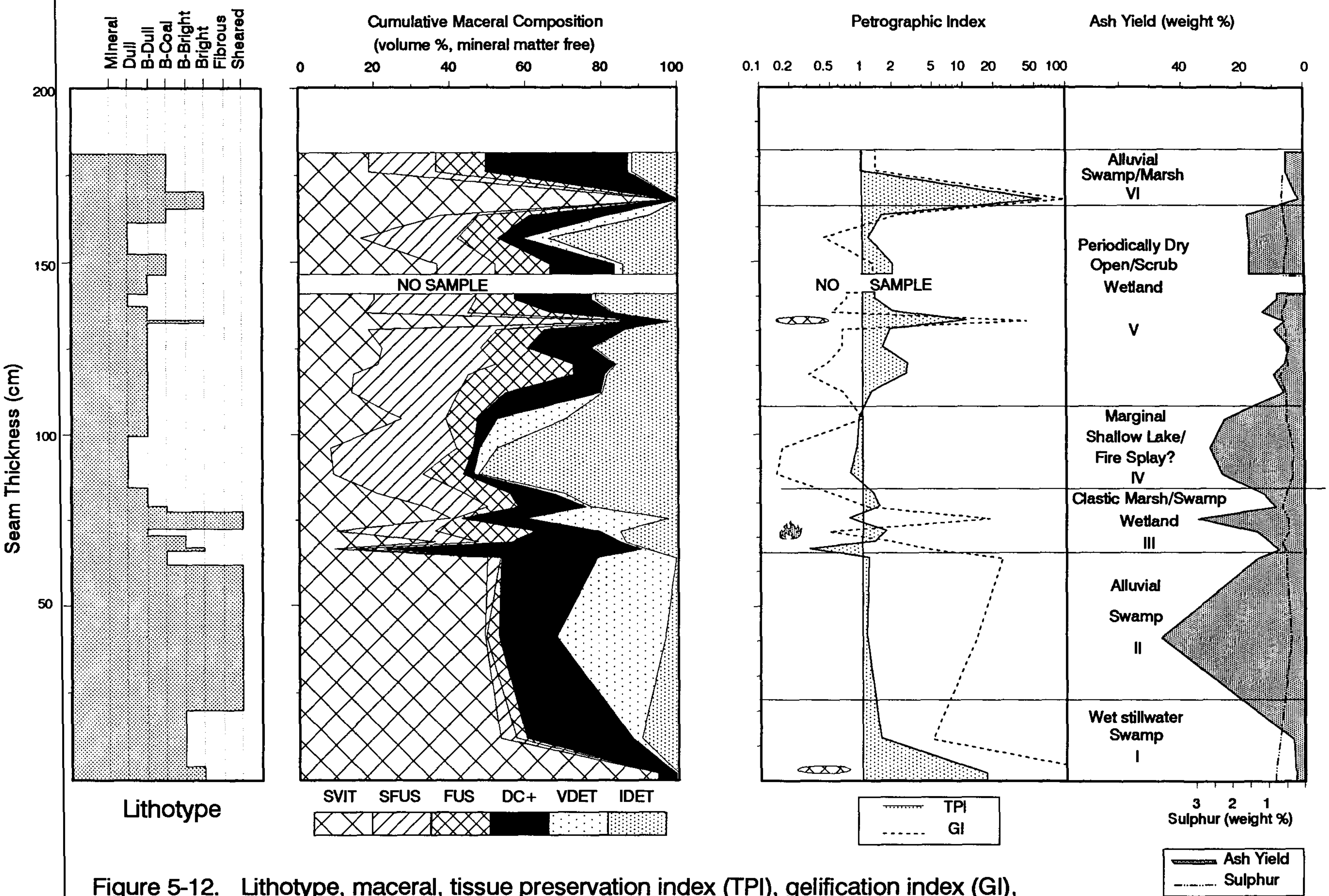

Figure 5-12. Lithotype, maceral, tissue preservation index (TPI), gelification index (GI), ash yield and sulphur content profiles of seam C. Abbreviations and symbols same as in Figure 5-7.

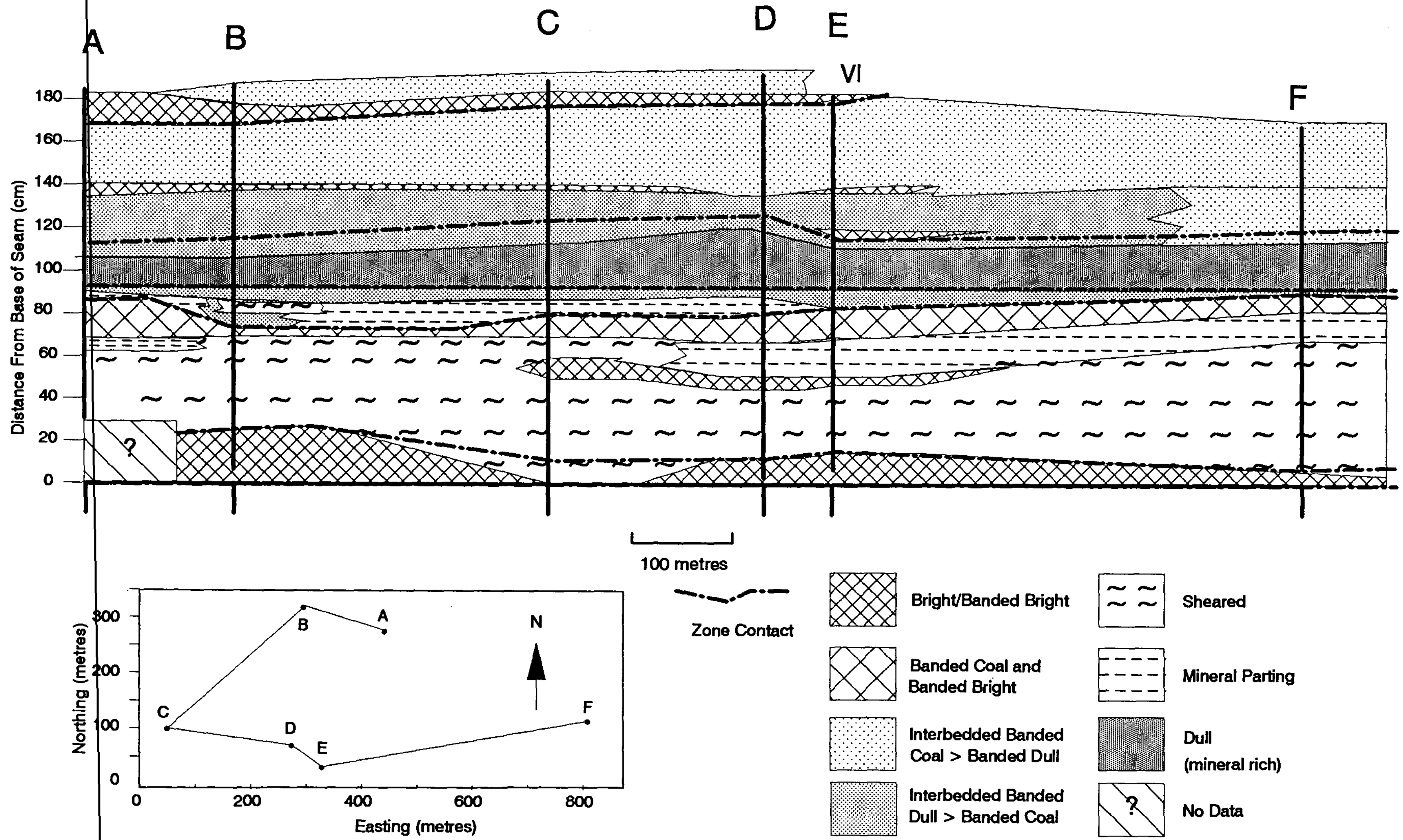

Figure 5-13. Generalized lithotype correlation of seam C. Heavy vertical lines are section locations. Petrographic samples from section B. Abbreviations and symbols same as illustrated on section profile in Figure 5-7.

environments, rending correlation difficult through that interval. The fire splay unit shows excellent continuity, and serves as a datum for the correlation in Figure 5-13.

5.9.5 *Maceral and lithotype stratigraphy of seam D*

Like the C seam, the D (Figs. 5-14, 5-15) seam shows the influence of a low energy, low gradient stream. On a mineral matter free basis, the D seam is more enriched in vitrinite than any of the other seams. Peat forming activity began in an alluvial swamp as evidenced by high TPI, GI and ash yield values (Fig. 5-14, 5-15, zone I). The swamp gave way to a clastic marsh (low TPI, high GI, variable, but high mineral matter content) complex. Input of detrital inertinite is high in parts of this unit, suggesting that forest fires were common in the region, and washed into the wetland. Alternately, fires may have caused depressions in the peat surface, allowing detrital material to wash in. An alluvial swamp was again re-established (zone III); mineral matter decreases toward the top of this unit, such that a wet stillwater swamp may have developed. A thin charcoal-rich horizon is found at the base of zone IV, topped by a thin vitrodetrinite rich zone, followed by a thick, mineral and inertodetrinite rich unit. This unit is correlative across the section (Fig. 5-15), grading to a dull or banded dull coal in places. Zone IV may represent a fire splay. The depression caused by the fire was probably relatively shallow and well oxygenated, as indicated by the low vitrinite and high inertinite concentrations. Like the analogous unit in seam C, it may also represent a past flooding event (or events), or an open, frequently flooded and burned marsh complex. The upper part of the seam (zone V) is enriched in structured vitrinite, with one mineral split. The unit is interpreted as an alluvial swamp, which at times developed into a stillwater swamp.

5.9.6 *Maceral and lithotype stratigraphy of seam E*

Fire and a low sinuosity stream are interpreted to control the stratigraphy of Bullmoose seam E (Figs. 5-16, 5-17). Five zones are distinguishable on the basis of petrography. As evidenced by the high GI values, the water table remained relatively high during the earlier part of seam development (Figure 5-16, zones I and II). A basal, alluvial swamp (zone I) developed into a wet stillwater swamp (zone II). A series (?) near the top of zone II, formed a depression in the peat surface, leading to a shallow lake/depression (zone III). This lake gradually filled,

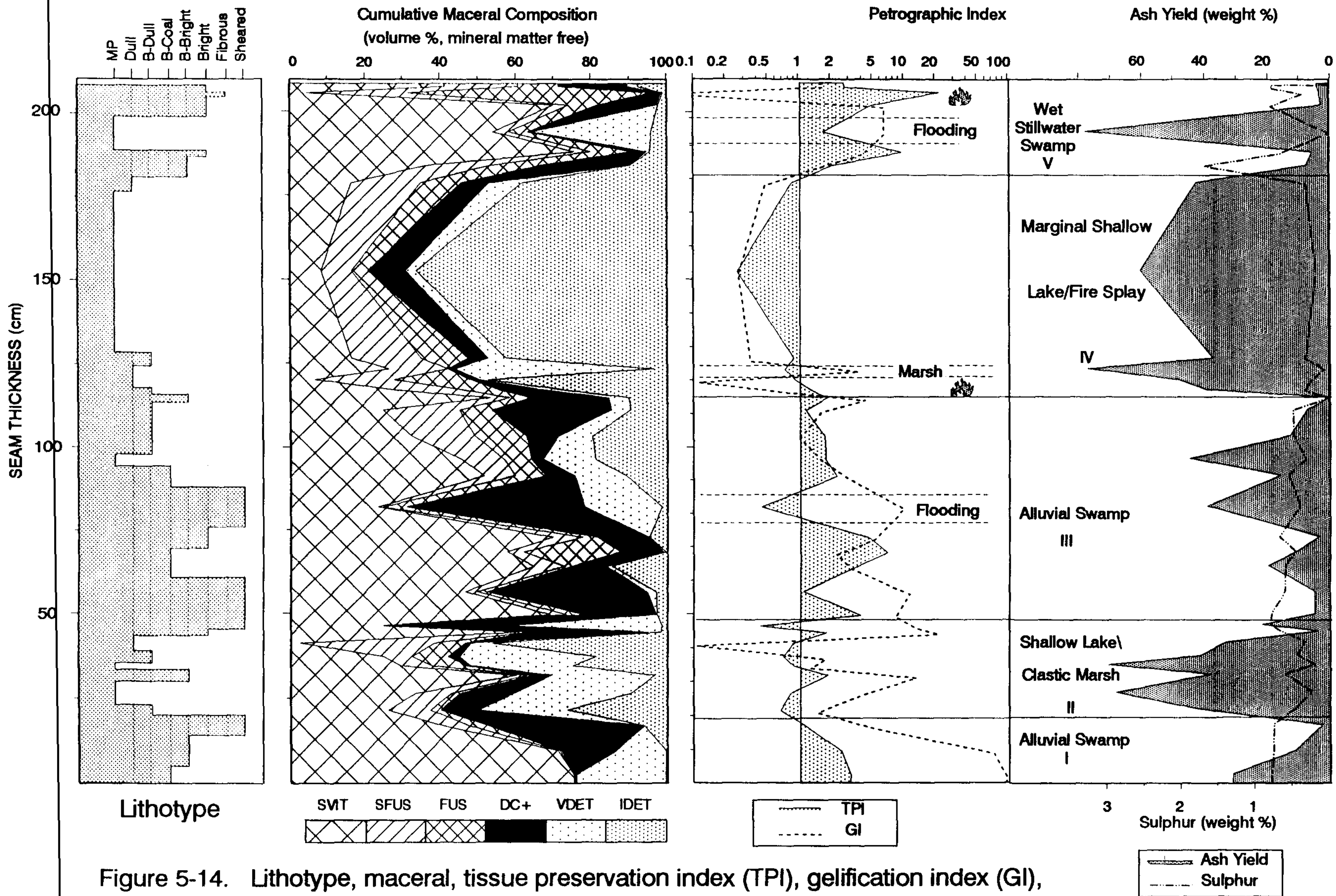

Figure 5-14. Lithotype, maceral, tissue preservation index (TPI), gelification index (GI), ash yield and sulphur content profiles of seam D. Abbreviations and symbols same as in Figure 5-7.

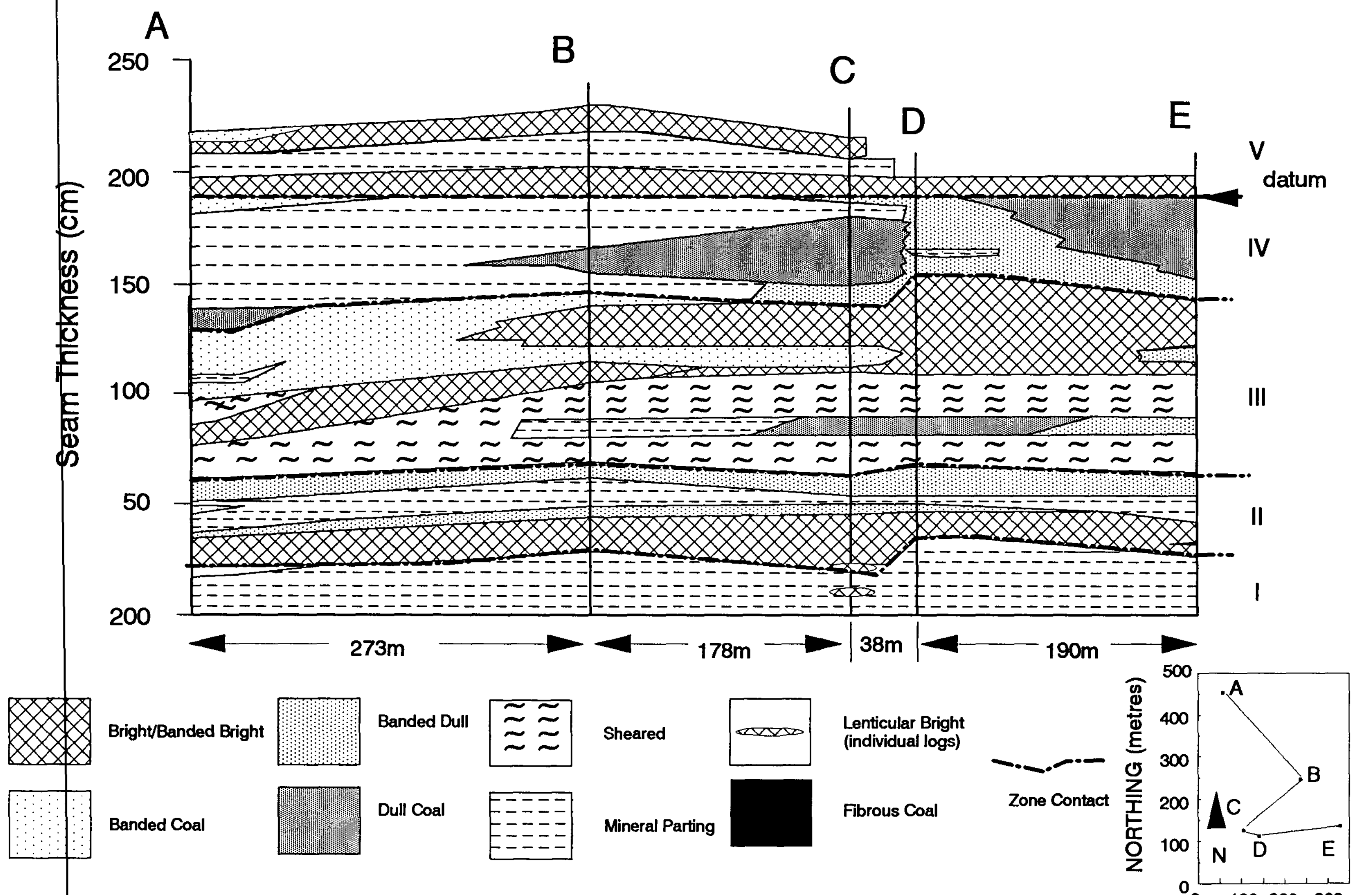

Figure 5-15. Generalized lithotype correlation of seam D. Heavy vertical lines are section locations. Petrographic samples from section A. Abbreviations and symbols same as illustrated on section profile in Figure 5-7.

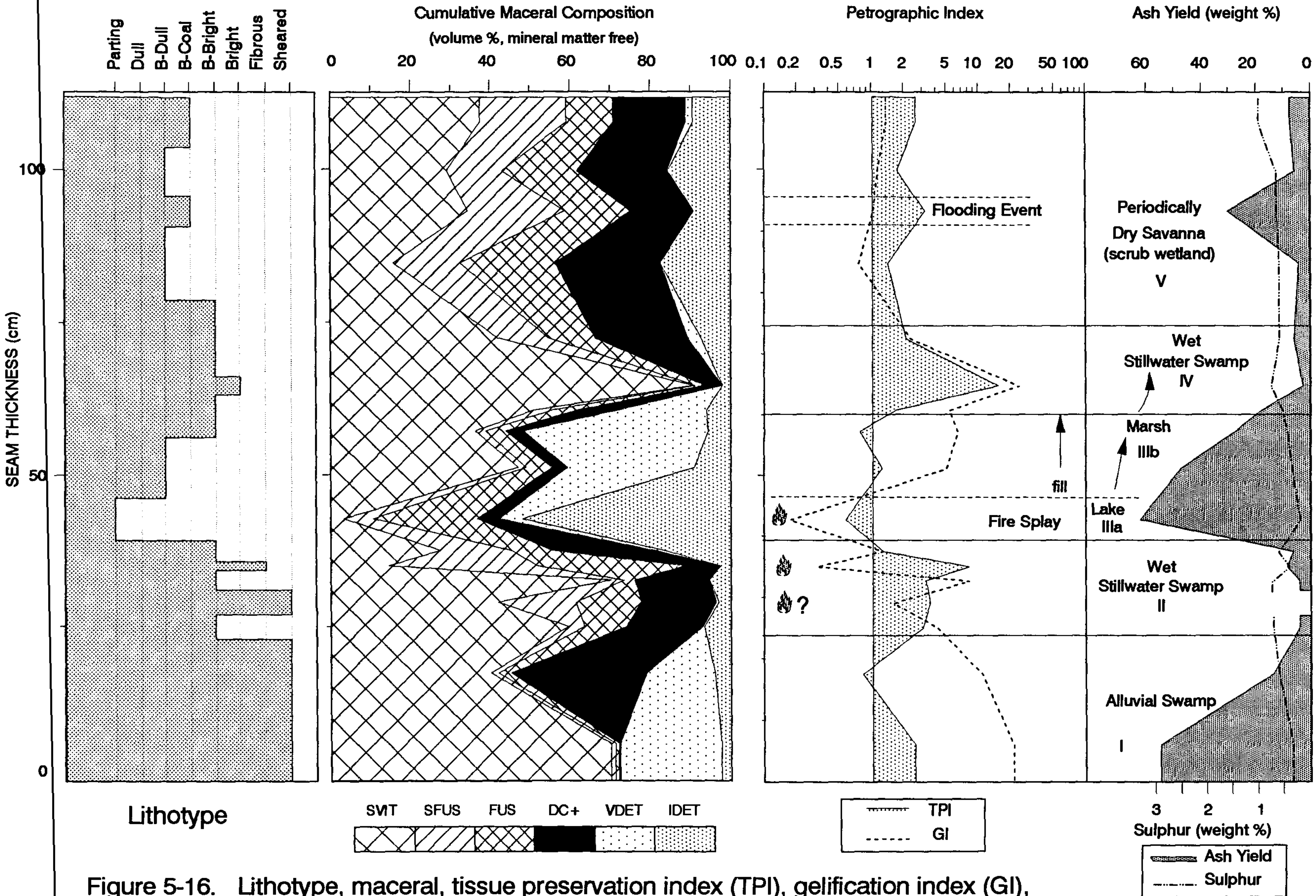

Figure 5-16. Lithotype, maceral, tissue preservation index (TPI), gelification index (GI), ash yield and sulphur content profiles of seam E. Abbreviations and symbols same as in Figure 5-7.

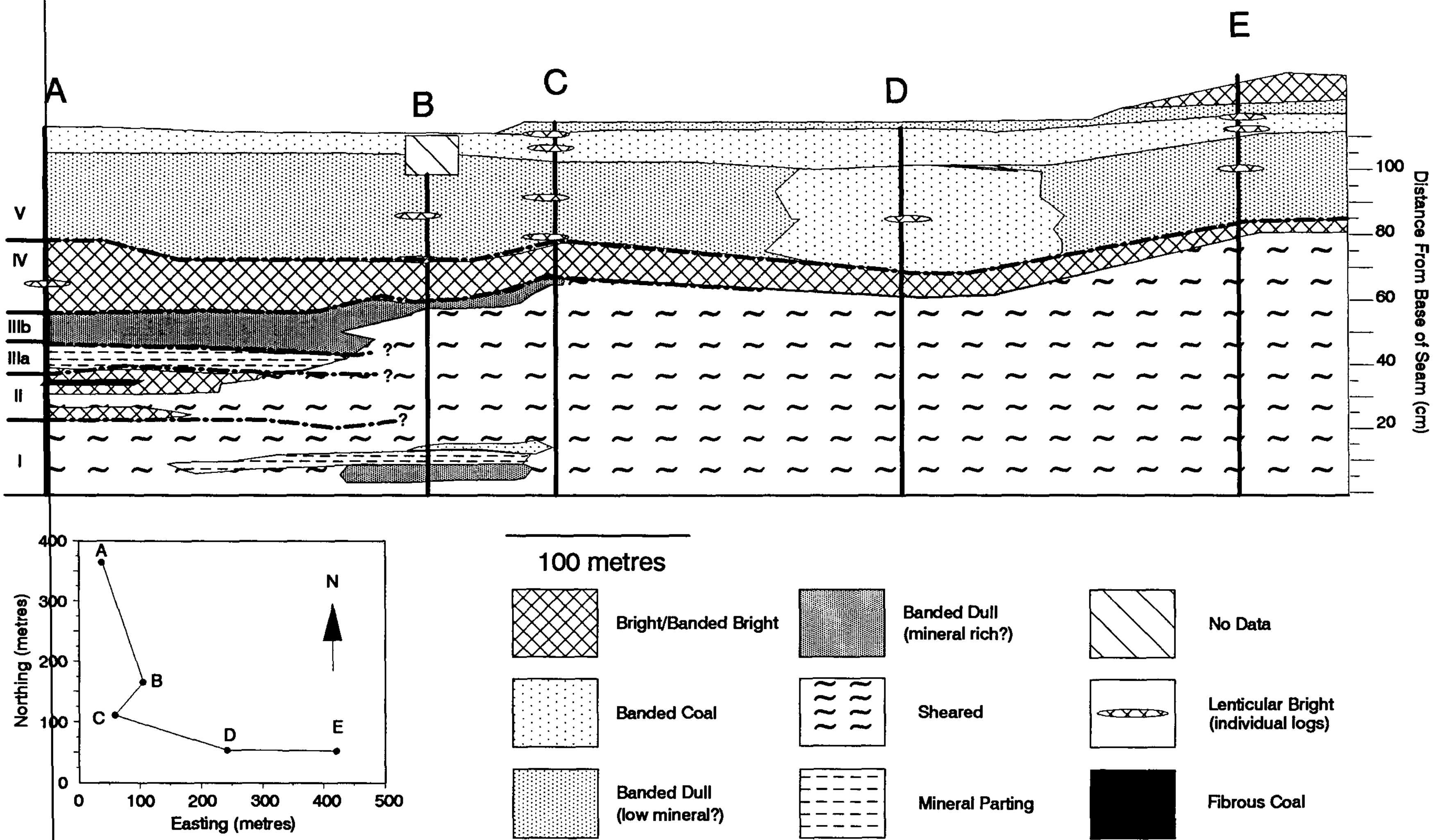

Figure 5-17. Generalized lithotype correlation of seam E. Heavy vertical lines are section locations. Petrographic samples from section A. Abbreviations and symbols same as illustrated on section profile in Figure 5-7.

giving way to a marsh, and eventually the stillwater swamp complex recovered (zone IV). The stillwater swamp gradually dried out, yielding to a scrub wetland which was occasionally open to clastic influx (zone V).

The lithotype stratigraphy of the E seam is presented in Figure 5-17. Much of the basal part of the section is sheared, as illustrated in Figure 5-17, rending correlation of the basal zones difficult. Due to the shearing, only the uppermost part of the splay/lake unit can be correlated southward from section A to B (Fig. 5-17). The wet stillwater swamp can be correlated as a bright/bright banded unit which grades to a banded coal in section B. Above this unit, the lithotypes can be correlated, but as in other units, the relationship between the lithotype stratigraphy and interpreted depositional environment is not clear.

5.9.7 Interpreted Wetland Environments, Shikano D seam

Wetland succession within the Shikano D seam was discussed in Chapter 2, utilizing the Diessel facies diagram. The petrography of the seam was not presented in chapter 2, and is illustrated in Figure 5-18. High water tables characterize the entire history of the Shikano D, as indicated by the overall high GI values. The seam was established in open herbaceous wetland (zone I, Fig. 5-18). A wet stillwater swamp established itself on this substrate (zone II), which periodically suffered severe fires (zone IIb). A long interval characterized by fluctuating water tables (zone IV) developed following a fire splay/flooding event (zone III). Although predominately wet conditions prevailed, the wetland environment probably oscillated between a wet stillwater swamp and the scrub savanna wetland. An abrupt change from a swamp to a marsh (zone V) occurs at the top of zone IV; this change is marked by a significant drop in both TPI and GI. At the top of marsh unit, (zone V b) an abrupt increase in sulphur content occurs, marking a change from fresh water to more saline conditions. The growth of this marsh was interrupted by a coarser grained (sandstone and siltstone) flooding event (zone Vc), following which the coastal marsh was re-established (zone Vd). The roof of the Shikano D seam is a thick marine sandstone unit known locally as the Babcock Sandstone (Carmichael, 1983; 1988), which marks the Notikewin transgressive event (Leckie, 1986), and the end of middle Gates deposition..

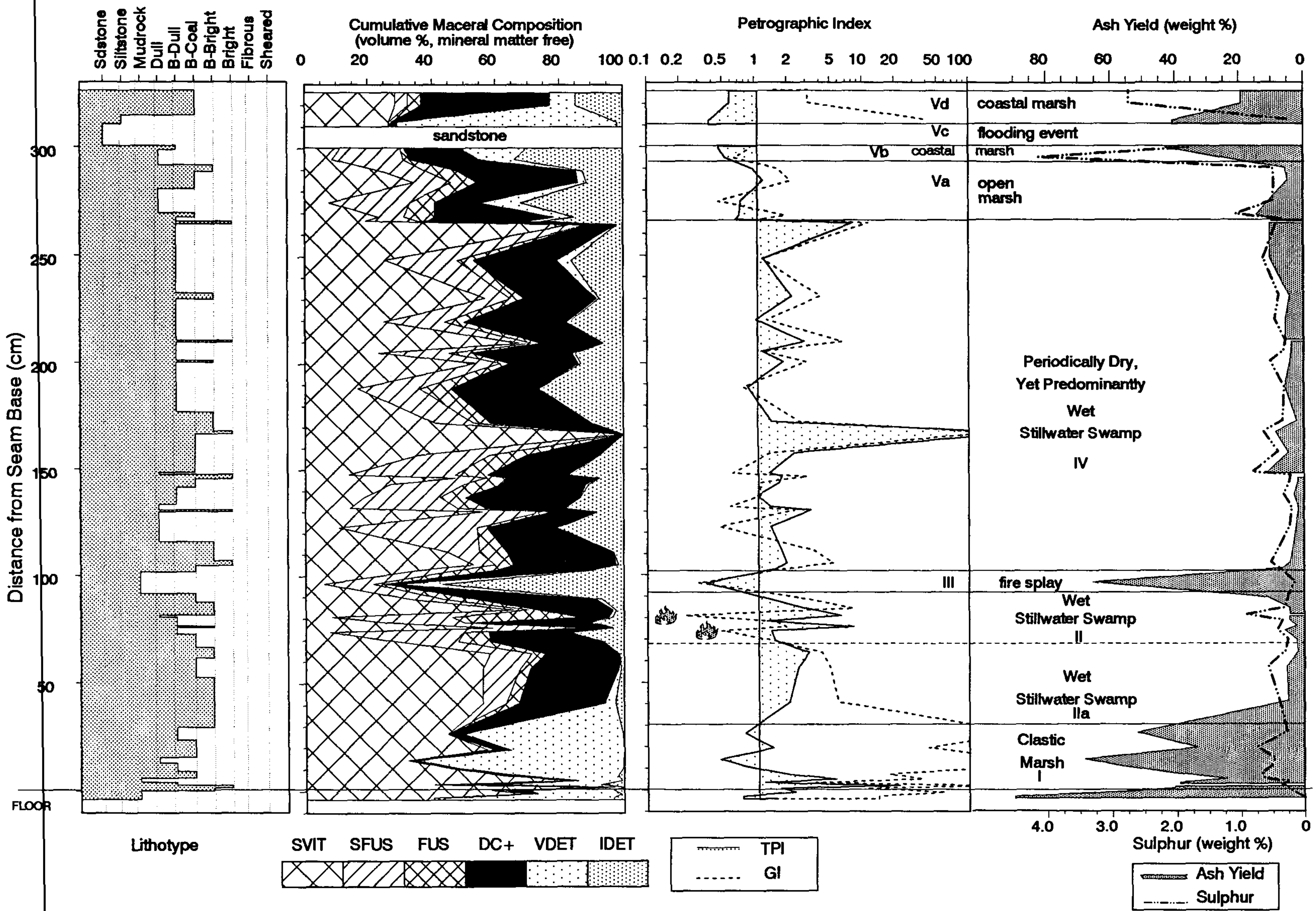

Figure 5-18. Lithotype, maceral, tissue preservation index (TPI), gelification index (GI), ash yield and sulphur content profiles of Shikano D seam. Abbreviations and symbols same as in Figure 5-7.

5.10 DISCUSSION: GATES FORMATION PEAT FORMING MIRES CONSIDERED ON THE ECOSYSTEM SCALE

Two basic types of depositional settings are interpreted to be present in the Gates coals: (1) low lying mires adjacent to active fluvial settings, typified by the Bullmoose C, D and E seams, and parts of Bullmoose A2 and Shikano D seams; and (2) more elevated (raised?) mires exemplified by the Bullmoose A1 and B seams, as well as the majority of the Shikano D seams. Coals which formed in low lying mires are enriched in mineral matter and structured vitrinite; inertinite is primarily allochthonous. The stratigraphy can be complicated, with lateral facies changes from brighter lithotypes to dull, mineral -rich lithotypes common. These types of changes reflect the importance of flooding effects from nearby streams. In contrast, the raised or elevated mires are typically composed of banded dull lithotypes, which grade to brighter horizons in places. The dullness of these lithotypes is a function of inertinite, rather than mineral matter or liptinite. Lateral facies changes involving mineral rich horizons do not appear to be typical of the raised mires. Facies changes in the raised mires are most likely a function of hydrological differences within the wetland which cause differences in vegetation and decomposition rates, or long term changes in precipitation patterns.

Peat reflects excess productivity (energy) in an ecosystem and is essentially a measure of the inefficiency of decompositional processes. If decomposition were 100% effective, and all the organic matter were recycled and re-used by an ecosystem, no evidence would remain of an ancient thriving vegetation. The type of ecosystems represented by efficient decomposition and nutrient recycling (closed nutrient cycles), a stable biomass level and low productivity relative to the standing biomass are referred to by Odum (1969) as "mature", and or as representing a climax state (Mitsch and Gosselink, 1986). Developing ecosystems, on the other hand, have open nutrient cycles, relatively inefficient decomposition and nutrient recycling, and a high productivity relative to the standing biomass. Wetland systems have aspects of both of these systems (Odum, 1969; Mitsch and Gosselink, 1986).

The low lying mires (seams C, D and E) are typical of developing ecosystems. The associated fluvial system regularly brought nutrients into the wetlands, and productivity rates were probably quite high. High productivity and rapid burial rates as a result of frequent flooding favoured the preservation of vitrinite precursors in the wetlands of the C, D and E seams, particularly structured vitrinite precursors. Vitrinite is only preferentially destroyed in the shallow, well oxygenated, open water settings such as that associated with the "fire splay" units, or where the wetland evolves into a savanna scrub protected from clastic influx. The lack of liptinite in the open water settings attests to a higher energy (frequently flooded) environment, rather than a quiet open water setting.

In terms of nutrient cycling, raised mires are more typical of mature ecosystems. The sole nutrient source of these mires is from rainfall, so efficient nutrient cycling is necessary. In tropical, ever wet environments high rainfall and warm temperatures result in high productivity, and the deposit domes above the surrounding area. In temperate, seasonally distributed rainfall areas, the domed expression of an ombrotrophic mire is not as well pronounced due to lower productivity (Cameron et al., 1989; Roberts and McCabe, 1992). If the nutrient source of the ombrotrophic mire is interrupted, such as during a seasonal or periodic drought, the system must compensate for the lower levels. As the water table drops, plant moisture levels drop and plants may start to die. Fires are readily started, and the surface litter, vegetation and possibly the peat itself will catch on fire. The burned material, as illustrated in Figure 5-5, becomes a new nutrient source, and upon resumption of rainfall, the system regenerates. In the case of a tectonically stable area, no significant peat development could take place. However, the mires of the Gates Formation formed in an actively subsiding area (the Cordilleran foreland basin). The fires, then, become necessary to recycle the nutrients in an ombrotrophic mire in an area with a variable rainfall.

Hence, in both the low lying and raised mire, disturbance, in the form of flooding or fire events is necessary to maintain the ecosystem as a wetland setting. Catastrophic events which radically change the environment are marked by an abrupt change in texture or composition. Fires result in an abrupt increase in structured inertinite (fusinite and semifusinite). Flooding events are marked by an abrupt increase in mineral matter. Several events may combine in energy such that peat accumulation stops altogether, and either erosion of the peat or deposition of another lithology will take place.

The disturbance-mediated, cyclic pattern of biomass change through time in cypress forests derived by Odum (1984, Fig. 5-4b) is recognizable in the coal seams of the Gates Formation. The cyclic variation is particularly well pronounced in the thickest seam, the Bullmoose B. The amount of structured material in the basal, ombrotrophic part of the seam fluctuates about a mean of approximately 60-70%, or a TPI range of 1.5 - 2.3. This may reflect the relatively constant biomass levels in the system. The amount of fusinite is relatively constant, except in the fibrous (charcoal) layers. The largest variation in petrographic composition of the structured material occurs in the flux between vitrinite and semifusinite. The lowermost zone represents a long period with relatively high rainfall, such that very few fires occurred and a significant peat deposit formed (approximately 65 cm of coal is equivalent to 6.5 metres of peat). During this phase of wetland formation, the coals are petrographically similar to the composition expected of an Okefenokee-type swamp-marsh complex: high structured vitrinite, lesser degraded vitrinite and trace amounts of fire derived inertinite. A similar wet zone is present in the basal part of A1 seam.

The transition from zone I to zone II (Fig. 5-10) of the B seam represents a marked change in the precipitation pattern from effectively ever-wet to a cyclic variation in precipitation. As a result, the Gates Formation mires were subjected to periodic drought, fires began to be common and a long term, fire-mediated disturbance pattern emerged. As the precipitation increased, the texture of the deposit changed, with more and more material stored as structured vitrinite. As the precipitation decreased, more material degraded, the texture of the deposit changed, and less organic material was stored as peat. Inertinite, being less easily degraded, was concentrated in the deposit. Semifusinite, in particular becomes enriched as it is less mechanically degradable than fusinite. The enrichment in structured vitrinite represents the production phase of Odum (1984), whereas the enrichment in structured inertinite represents the consumptive regression phase.

Not only a cyclic variation in precipitation, but a long term decrease in precipitation can be interpreted from the profile of the B seam. In zones I and II, the ecosystem was able to recover to the wet stillwater swamp phase. In zone III, more inertinite is preserved than vitrinite, indicating that accumulation rates were on average lower than in zones I and II. A shift to a predominately savanna scrub forest is interpreted. As discussed in chapter 4, a decrease in the amount of preserved vitrinite could also result from a decreased subsidence rate. However, because the actual forcing mechanism for fires in mire environments is fluctuation in precipitation, it seems more likely that a decrease in precipitation was responsible for the observed changes. In zone IV, the climatic conditions deteriorated such that plant productivity was not high enough to allow the system to build above the surrounding area, and mineral matter entered the system. Conditions eventually resulted in cessation of peat forming activity altogether, and terrestrial sedimentation prevailed. These conditions could have been caused by increased subsidence rates combined with lower productivity (as a result of drier conditions), which allowed a stream to move into the area.

5.11 SUMMARY AND CONCLUSIONS

The maceral composition of a coal can be used to interpret the characteristics of the original peat-forming wetland. By describing the variation in megascopic appearance of a seam, and analyzing the composition (maceral, mineral and sulphur content) and texture of the individual megascopic units, wetland succession can be interpreted. Mires which formed the Gates coals are interpreted to represent a spectrum of environments ranging from low nutrient, still water swamps with little or no fluvial influence, to higher energy alluvial swamps in frequent contact with an active fluvial influence.

The Gates Formation wetlands were maintained by periodic disturbance, and reflect short and long term changes in sedimentological/tectonic setting, as well as climate. In the case of the alluvial swamp and marsh settings (e.g., seams C, D, and E), the disturbance agent is periodic flooding which revitalizes the system by transporting nutrients into the wetland. In ombrotrophic mires (e.g., seams A1 and B), where the sole nutrient source is from rainfall, the disturbance agent is fire. When the wetlands are subjected to periodic drought, fires play a key role in maintaining the wetland as a swamp by cleaning out invading, understory vegetation which has a low flood tolerance. In addition, the fires stimulate nutrient cycling from dead vegetation and from an otherwise inaccessible nutrient pool, deeper peat sources.

At the beginning of this chapter the question was raised as to whether or not the concepts of terrestrialization and paludification were adequate processes for explaining the maintenance of long term peat-forming conditions. Terrestrialization does seem to have been an active, although temporary, process in the Gates mires. The inertodetrinite-rich splay units are apparently the result of filling in depressions. However, once the depression filled, peat forming activity continued. Paludification may have been important in the early phases of peat development of ombrotrophic mires, as indicated by the basal wet zones in the A1 and B seams. However, if the basin were not subsiding, interruptions in rainfall would probably have resulted in destruction of the peat by fire. Similarly, without constant subsidence in the alluvial settings, the fluvial system probably would have eventually reworked the peat deposits which formed. Hence, acting alone, the autogenic processes of paludification and terrestrialization are insufficient mechanisms to form significant peat deposits.

The inertinite-rich petrographic character of the Gates Formation coals, and the disturbance patterns recorded in the coals during seam development indicate that fire was an important process in the maintenance of hydric conditions in the Gates peat-forming mires. However, without constant subsidence, no significant peat deposits would have formed in the western interior of Canada during the Cretaceous due to adverse climatic conditions. Favourable subsidence rates is one of three possible mechanisms suggested by McCabe and Parrish (1992, chapter 4) for the occurrence of coals in the Cretaceous western interior. The petrography of the Canadian deposits, with their high fire-derived inertinite content, provides evidence to support this conclusion. Whether or not this mechanism can be invoked for similar age coals to the south in the conterminous United States, must still be addressed.

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CHAPTER 6

CONCLUSIONS

6.1 INTRODUCTION

Coal seams are compositionally heterogeneous sediments which reflect an interaction between the biosphere and the geosphere. The heterogeneity fundamentally reflects the nature of the source vegetation and the hydrological characteristics of the original wetland setting, which in turn are functions of the climate and tectonic setting of the peat forming area (chapter 2). Compositional variation is a major control on the utilization characteristics of a coal (chapter 3). By analyzing the composition and texture of coals, the depositional conditions of the original peat-forming environment can be interpreted (chapters 4 and 5). Within this thesis, the nature, controls and implications of compositional variability in coal seams have been addressed, with specific application to Gates Formation coals deposited during the mid-Albian in northeastern British Columbia. The Gates Formation was deposited in the terrestrial environments of a broad, low relief coastal plain bordering the Cretaceous epeiric seaway at a relatively high (60°N) paleolatitude (Kalkreuth and Leckie, 1989). The vegetation, climate and tectonic setting of the site of Gates deposition was quite different in the mid Cretaceous from what is seen now in this geographic area. Rather than boreal forest and grassland, a temperate deciduous forest thrived (Saward, 1992). Angiosperm contribution to the flora (chapter 2), was low; the vegetation was predominantly gymnospermous (conifers and cycads), with ferns occupying understory open marsh vegetation. The climate (chapter 4) was warmer (Barron, 1989), and is interpreted to have been wetter than current conditions. However, precipitation was seasonally distributed such that periodic drawdown of the water table in wetland settings resulted in frequent fires. The sediments were deposited in a foreland basin (Cant, 1989), such that sediments were buried relatively rapidly, allowing peat preservation (chapter 5).

6.2 COMPOSITIONAL DIFFERENCES BETWEEN LITHOTYPES

The coals of the mid-Albian Gates Formation (northeastern British Columbia, Canada) are banded bituminous coals, that is, at the megascopic scale they are composed of alternating bands of bright, dull and rarely, fibrous (charcoal) layers. The megascopic variation in bright and dull lithotypes reflects differences in composition which are quantifiable by petrographic methods. The coals are essentially a three component system consisting of vitrinite, inertinite and mineral matter. Other Cretaceous banded bituminous coals in North America (data compiled in Meissner, 1984), formed outside of the Western Canada Sedimentary Basin,contain more liptinite, and less inertinite, and can be considered four-component systems. The lack of liptinite is attributable to a paucity of quiet water, aquatic settings in the depositional environment.

Compositional boundaries between lithotypes are gradational. From bright to dull coal, there is an increase in the percentage of inertinite, with a concomitant decrease in vitrinite. The dullness of the coals is primarily due to inertinite, not liptinite. The dull appearance of some lithotype samples is also attributable to mineral matter and unstructured vitrinite concentrations. Fibrous coals are composed primarily of structured inertinite, with lesser concentrations of structured vitrinite; the pristine cell structure preserved and its association with structured vitrinite is indicative of its origin from wildfire.

The coals formed on broad, low relief coastal plains. Differences in lithotype stratigraphy are due to variations in ground water level as well as differences between wetland types. Peats formed in areas protected from clastic influx (Bullmoose A1 and B seams) are generally duller, with rather uniform stratigraphy. Coals developed in less protected areas (Bullmoose C, D and E seams) have more variable stratigraphy, and a higher component of the brighter lithotypes. The lithotypes represent a continuous spectrum of depositional environments from predominantly forest swamps (both wet and dry) to dry, herbaceous and/or shrubby marshes. The wetlands were dominated by coniferous trees, with a significant component of ferns as herbs or low trees. However, angiosperms and cycads may have contributed to the vegetation in the form of shrubs, and in the case of angiosperms, marginal herbs.

6.3 IMPLICATIONS OF COAL MACERAL VARIATION

The differences in (maceral and mineral) composition exhibited at the megascopic scale as lithotype variation reflect a fundamental difference in the chemical structure of the coal as a result of maceral composition (chapter 3). Vitrinite in bituminous coals has been shown to be microporous (Harris and Yost, 1979), whereas inertinite is meso- to macroporous. The porosity contrast between the two macerals results in a difference in gas adsorptive capacities of coal lithotypes. The adsorptive capacity of a coal has been traditionally attributed to be a function of pressure (burial depth), coal rank, ash yield and moisture content (Ruppel et al., 1972; Joubert et al., 1973; Kim, 1977; Rightmire, 1984; Wyman, 1984; Choate et al., 1986). The data presented in chapter 3 clearly indicate that surface area and adsorptive capacity of a coal is also a function of the maceral composition. Indeed, the variation that is seen within a single coal deposit as result of maceral composition differences is just as large as that found in previous studies between coals of different rank (Kim, 1977, Fig. 3-8). As a result, a coal which has a lower rank, but is enriched in vitrinite can have a higher methane adsorption capacity than a coal which is enriched in inertinite, but of higher rank. This observation has important implications for coalbed methane exploration. In the selection of samples for analysis, whether it be for adsorption or desorption, one must ensure that the sample is representative of the reservoir of concern.

6.4 CAUSE OF INERTINITE ENRICHMENT IN THE GATES FORMATION COALS

The inertinite rich nature of many of the coals of the Gates Formation, as well as other Mesozoic coals formed within the Western Canadian Sedimentary Basin (Demchuk and Strobl, 1989; Bustin and Dunlop, 1992; Demchuk, in press), is puzzling in that inertinite rich peats are rare in modern settings (5-10% by volume). Like modern settings, inertinite in the Gates coals is almost exclusively fire-derived. Within modern settings, the occurrence of fire is linked to more seasonally distributed rainfall, rather than ever-wet conditions such as occur in the tropics. Periodic interruptions in precipitation supply cause a drawdown in the peat water table, allowing the upper surface to dry; wildfire is initiated by lightning. Fire frequency in these environments varies according to the source of water. Rain-fed wetlands have a higher fire frequency than alluvial-type swamps. Enrichment of inertinite results from preferential destruction of vitrinite precursors at the peat accumulation stage either via burning or low temperature degradation processes, rather than formation of inertinite by low temperature oxidation (or fungal attack).

Image analysis and manual petrographic data were used to interpret the amount, source and variation in fire-derived inertinite in coal seams of the Gates Formation. Fire derived inertinite is on average quite high, and within seams may vary cyclically. The high overall inertinite content within Gates Formation coals is interpreted to reflect overall drier depositional conditions than the most commonly cited modern taxodiaceous wetland setting, the Okefenokee swamp-marsh complex of southern Georgia - northern Florida (U.S.A.). These drier conditions during Gates deposition are interpreted to reflect a rain-shadow effect of the Cordilleran Highland which was located west of the site of Gates deposition. This rain shadow effect may have operated during much of the Late-Jurassic through Cretaceous and early Tertiary times as indicated by the abundance of Cretaceous high-inertinite coals in the WCSB.

6.5 INTERPRETATION OF PALEOWETLAND ENVIRONMENT

Detailed interpretation of wetland succession can be accomplished with a ply-by-ply compositional analysis (including maceral distribution, mineral matter content and weight percent sulphur) of a seam. Gates (peat-forming) mires ranged from low nutrient, still water swamps with little or no fluvial influence, to higher energy alluvial swamps in frequent contact with an active fluvial influence. These wetlands were maintained by periodic disturbance, and reflect short and long term changes in sedimentological/tectonic setting, as well as climate. In the case of the alluvial swamp and marsh settings (e.g., seams C, D, and E), periodic flooding revitalized the system by transporting nutrients into the wetland, and removing toxins. In ombrotrophic mires (e.g., seams A1 and B), where the sole nutrient source is from rainfall, the disturbance agent is fire. When the wetlands are subjected to periodic drought, fires play a key role in maintaining the wetland as a swamp by cleaning out invading, understory vegetation which has a low flood tolerance. In addition, the fires stimulate nutrient cycling from dead vegetation and from an otherwise inaccessible nutrient pool, deeper peat sources.

Two autogenic processes, terrestrialization (progressive fill of depressions), and paludification (progressive drowning of an area by spreading of mire vegetation) were active processes in the coal forming environments of the Gates Formation. However, without the constant subsidence associated with the tectonic setting of the Cordilleran foreland basin, no significant peat (coal) formation would have occurred in the area. Either fluvial reworking, or wildfires would have destroyed the peat accumulations.

6.6 POSSIBILITIES FOR FUTURE RESEARCH

The research reported in this thesis provides more information for understanding climatic changes in the Cretaceous of North America, a period which has been dubbed the "Greenhouse Earth" (Spicer and Corfield, 1992). More research is necessary comparing Cretaceous coals on a latitudinal gradient stretching from the North Slope of Alaska to the Gulf of Mexico coast of the conterminous United States in order to better interpret the continental climatic record. Utilizing coal petrographic data as an indicator of oxygen variation, or any other element through time can only be done by considering the influence of paleogeography (paleoclimate) on the organic, physical and chemical processes governing peat formation and preservation.

Image analysis in coal petrology has primarily been used for rapid, routine petrographic (compositional) analysis (Chao et al., 1982a, 1982b; Goodarzi, 1987). The most common application of the method is for assessing the coking characteristics of a coal. The research described in this thesis (chapter 4) indicates that image analysis is a viable method for determining small scale stratigraphic compositional variation. The results of this study can only be used in a preliminary fashion to support the concept that coal seams can record aspects of paleoclimate. The most obvious next stage in this research is to collect more profiles of the seams and establish the lateral extent of the identified cycles within the local area, and then the regional area. Thick, laterally extensive shoreface sands sequences topped by laterally extensive coal seams are widespread in the Cretaceous strata of the western United States and Canada. In addition, coals are found on the western (Pacific) side of the Cordilleran orogen. Research into the compositional variation of the coals will provide detailed data concerning terrestrial, organic-rich Cretaceous environments that can compliment the published and ongoing research on organic rich marine sedimentary sequences (Arthur et al., 1985; Calvert et al., 1992).

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APPENDICES

Appendix 1
Raw point count, ash yield and sulpur data

SAMPLE		PEL#	LT	THICK_CM	TOTMF	TOTMC	TCOL	PV	TEL	DESMO	VDET	SFUS	FUS	IDET	MAC	MIC	SPOR	CUT	RES
BULLMOOSE A1																			
	A1 1	401	BC	19.0	300	305	18	51	51	105	1	23	19	24	0	1	3	1	0
	A1 2	402	BD	6.0	300	303	5	6	26	106	4	60	34	56	1	0	2	0	0
	A1 3	403	BD	2.0	300	302	1	5	29	110	0	59	41	52	0	0	3	0	0
	A1 4	118	BD	11	300	308	36	43	11	51	0	65	36	51	0	3	3	1	0
	A1 5b	119	B	2	300	301	1	245	2	17	0	12	8	12	0	2	0	0	1
	A1 5a	120	BD	7.5	300	303	20	42	20	53	0	68	47	44	0	2	4	0	0
	A1 6	121	BD	7	300	306	29	57	7	47	0	76	27	48	0	1	6	2	0
	A1 7	122	BD	4.5	300	304	34	16	2	53	0	112	32	46	0	3	2	0	0
	A1 8	123	D	5.5	300	304	11	6	7	55	0	115	46	52	0	1	7	0	0
	A1 9b	124	BD	4.5	300	304	29	14	15	44	0	101	29	62	0	2	4	0	0
	A1 9a	125	D	2	300	311	19	0	5	32	2	111	55	65	0	3	5	2	1
	A1 10	126	D	6	300	304	42	28	17	65	0	64	29	51	0	1	2	1	0
	A1 11	127	BD	11.5	300	306	28	74	12	42	0	71	21	46	0	0	5	0	1
	A1 12	128	BD	5	300	304	17	64	16	76	0	67	28	30	0	0	1	0	1
	A1 13	129	BD	16.5	300	305	26	36	16	44	2	111	31	29	0	1	3	1	0
	A1 14	130	D	5	300	304	13	22	9	36	0	136	30	47	0	0	3	2	2
	A1 15	131	D	5.5	300	302	13	29	18	30	0	123	17	62	0	2	4	2	0
	A1 16	132	BD	8	300	302	13	19	20	32	0	113	44	49	0	2	7	1	0
	A1 17c	133	BD	5	300	306	32	38	10	46	0	93	47	29	0	1	4	0	0
	A1 17b	134	BD	2.2	300	301	25	12	11	61	0	110	39	39	0	0	3	0	0
	A1 17a	135	BD	1.9	300	300	26	4	0	47	0	129	41	51	0	1	1	0	0
	A1 18	136	BD/D	5.5	300	303	14	2	20	47	0	137	31	41	1	0	5	2	0
	A1 19	137	BD	2.5	300	305	21	3	13	55	0	122	14	64	0	6	2	0	0
BULLMOOSE A2														0					
	A2 16	161	BC	3.5	300	423	75	23	6	23	122	13	17	21	0	0	0	0	0
	A2 1	138	BC	3.4	300	415	111	26	1	15	101	10	12	24	0	0	0	0	0
	A2 2b	139	BD	1.5	300	341	29	9	1	80	3	69	68	33	0	0	7	0	1
	A2 2a	140	BD	7	300	312	32	55	16	67	1	39	33	45	0	1	8	0	3
	A2 3	141	BD	6	300	300	25	20	10	55	0	96	58	30	0	2	2	0	2
	A2 4	404	B	2.0	300	300	9	32	191	22	0	21	10	9	0	0	2	1	3
	A2 5	142	BD	6	300	308	41	23	5	74	0	72	31	51	0	1	0	1	1
	A2 6b	143	BD	2.5	300	305	34	6	17	67	0	85	43	42	0	0	2	4	0
	A2 6a	144	B/F	2	300	304	23	6	17	50	2	75	104	21	0	0	1	0	1
	A2 7b	145	BD	2.5	300	315	25	21	4	45	1	104	35	59	0	0	4	2	0
	A2 7a	146	B	1.5	300	301	13	259	3	9	0	6	3	6	0	1	0	0	0
	A2 8	147	D	5.5	300	321	15	8	15	28	13	75	54	78	0	0	13	0	1
	A2 9c	148	BC	2.7	300	304	38	25	32	28	2	96	36	35	0	0	7	0	1

OLIP	OTHER	CLAY	QTZ	PYR	CARB	OMIN	ASH YIELD	SULPHUR	SAMPLE	COMMENTS
3	0	3	2	0	0	0	4.4	0.48	A1 1	
0	0	2	1	0	0	0	7.4	0.37	A1 2	
0	0	1	1	0	0	0	6	0.33	A1 3	
0	0	1	7	0	0	0	8.35	0.37	A1 4	
0	0	0	0	0	1	0	2.02	0.41	A1 5b	
0	0	0	2	0	1	0	4.86	0.33	A1 5a	
0	0	0	3	0	3	0	5.70	0.38	A1 6	
0	0	0	2	0	2	0	5.31	0.34	A1 7	
0	0	0	4	0	0	0	4.39	0.31	A1 8	
0	0	1	2	0	1	0	6.27	0.34	A1 9b	
0	0	1	10	0	0	0	8.77	0.32	A1 9a	
0	0	0	1	0	3	0	7.58	0.41	A1 10	
0	0	0	1	4	1	0	8.09	0.40	A1 11	
0	0	0	3	0	1	0	4.37	0.41	A1 12	
0	0	1	0	0	2	2	5.53	0.39	A1 13	
0	0	2	2	0	0	0	4.19	0.40	A1 14	
0	0	0	2	0	0	0	3.47	0.42	A1 15	
0	0	0	1	0	1	0	3.17	0.41	A1 16	
0	0	1	0	0	5	0				ASH AND SULPHUR
0	0	0	0	0	1	0	4.53	0.40	A1 17	ARE COMPOSITE
0	0	0	0	0	0	0				SAMPLES
0	0	0	2	0	1	0	6.03	0.37	A1 18	
0	0	0	1	0	4	0	4.03	0.41	A1 19	
0	0	41	82	0	0	0	41.04	0.33	A2 16	
0	0	84	24	0	1	6	41.25	0.33	A2 1	
0	0	3	35	0	1	2	19.72	0.34	A2 2b	
0	0	0	11	0	1	0	12.38	0.45	A2 2a	
0	0	0	0	0	0	0	3.49	0.46	A2 3	
0	0	0	0	0	0	0	1.8	0.38	A2 4	
0	0	5	2	0	0	1	4.18	0.47	A2 5	
0	0	4	1	0	0	0	3.70	0.47	A2 6b	
0	0	3	0	0	1	0	9.33	0.40	A2 6a	
0	0	1	1	0	13	0	16.65	0.36	A2 7b	
0	0	0	0	0	1	0	3.77	0.57	A2 7a	
0	0	11	4	0	6	0	19.92	0.33	A2 8	
0	0	3	1	0	0	0	15.66	0.40	A2 9c	

SAMPLE		PEL#	LT	THICK_CM	TOTMF	TOTMC	TCOL	PV	TEL	DESMO	VDET	SFUS	FUS	IDET	MAC	MIC	SPOR	CUT	RES
	A2 9b	149	BD	3.2	300	392	22	3	13	19	21	111	58	47	0	0	4	0	2
	A2 9a	150	BC	5.1	300	313	26	39	28	66	1	79	24	29	0	1	4	0	3
	A2 10b	151	B	2	300	301	0	285	0	0	0	1	0	2	0	0	0	0	12
	A2 10a	152	BD	4	300	305	35	33	4	46	0	95	52	29	1	2	2	0	1
	A2 11	153	BC	9.5	0	0								0					
	A2 12	154	B	2	300	316	64	10	3	83	0	64	43	28	0	2	3	0	0
	A2 13	156	BB	1	300	306	37	64	8	69	0	59	39	22	0	0	2	0	0
	A2 14b	157	D	5	300	305	16	16	10	55	0	105	27	59	0	0	5	1	6
	A2 14a	158	BD	6	300	305	43	17	12	58	0	95	34	37	0	0	3	0	1
	A2 15b	159	BB-MR	1	300	389	171	22	6	50	41	3	1	2	0	0	0	0	3
	A2 15a	160	MDST/V	5	37	301	9	0	1	0	27	0	0	0	0	0	0	0	0
BULLMOOSE B																			
	B B1b	17	BD	1.5	300	306	154	45	8	57	6	1	0	0	0	0	0	0	2
	B B1a	18	S/B	1	300	300	3	275	0	4	0	0	0	0	0	0	0	0	0
	B B2	19	S	2	300	301	151	8	9	22	1	0	0	0	0	0	2	1	0
	B B3	20	S/B	5	300	300	94	21	17	21	1	0	0	0	0	0	1	1	0
	B B4	21	S/B	2.5	300	307	72	68	43	74	0	1	0	0	0	36	2	3	1
	B B5	22	S/BB	5.5	300	304	80	101	41	62	0	7	4	0	0	2	2	1	0
	B B6	23	S/BB	4	300	303	50	90	114	25	0	7	4	2	0	4	1	2	1
	B B7	24	S/BB	4	300	300	42	117	63	47	0	10	6	3	0	3	2	0	7
	B B8	25	S/BB	3	300	303	45	90	14	84	0	48	7	8	0	0	3	0	1
	B B9	26	S/BB	4.5	300	300	57	119	25	59	1	7	14	10	0	2	4	0	2
	B B10	27	S/BB	4	300	303	54	71	4	122	2	22	14	6	0	1	3	0	1
	B B11	28	S/BB	4	300	300	35	123	8	87	0	12	17	13	0	0	4	0	1
	B B12		NO SAM	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B B13	29	BD	6	300	300	29	39	13	84	1	77	22	27	0	0	5	1	2
	B B14		NO SAM	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B B15	30	BB	6	300	301	55	34	23	69	0	61	27	28	0	0	3	0	0
	B B16	31	BD	7	300	301	51	17	13	75	0	83	27	30	0	0	2	1	1
	B B17b	32	BD	1.5	300	300	28	19	9	83	0	93	19	43	0	1	5	0	0
	B B17a	33	S/BB	2	300	301	15	119	10	68	0	41	21	22	0	0	3	0	1
	B B18	34	BD	3	300	310	35	27	3	59	1	106	26	37	0	1	4	0	1
	B B19	35	BD	4	300	301	28	72	6	45	0	83	24	37	0	2	3	0	0
	B B20b	36	BD	2.5	300	301	21	17	21	84	1	96	23	33	0	0	2	1	1
	B B20a	37	BC	5	300	304	40	25	19	67	0	93	28	25	0	1	1	1	0
	B B21b	38	BD	5	300	301	44	23	20	74	0	80	23	32	0	1	2	0	1
	B B21a	39	BB	2.5	300	303	38	67	5	80	0	65	25	18	0	0	1	0	1
	B B22	40	BD	5.5	300	305	36	59	13	73	0	67	23	22	0	2	5	0	0
	B B23b	41	D	3	300	302	33	16	0	28	0	69	123	30	0	0	1	0	0
	B B23a	42	BD	8	300	308	38	48	3	65	0	67	47	31	0	0	1	0	0
	B B24	43	BD	7.5	300	301	19	12	3	25	3	123	34	74	0	2	5	0	0
	B B25c	44	BD	1.5	300	302	11	6	9	41	4	126	30	62	0	1	9	0	1

OLIP	OTHER	CLAY	QTZ	PYR	CARB	OMIN	ASH YIELD	SULPHUR	SAMPLE	COMMENTS
0	0	50	7	0	33	2	28.89	0.29	A2 9b	
0	0	12	0	0	1	0	12.02	0.46	A2 9a	
0	0	0	0	0	1	0	1.68	0.62	A2 10b	
0	0	0	3	0	0	2	5.13	0.47	A2 10a	
							N/A	N/A	A2 11	
0	0	1	9	1	5	0	9.73	0.54	A2 12	
0	0	1	4	0	1	0	5.43	0.56	A2 13	
0	0	0	5	0	0	0	6.78	0.51	A2 14b	
0	0	3	0	1	1	0	4.73	0.60	A2 14a	
0	1	79	0	9	1	0	34.64	3.67	A2 15b	1 SCLEROTINITE
0	0	0	213	1	49	1	81.13	0.46	A2 15a	
0	27	4	2	0	0	0	7.11	0.57	B B1b	DEG VIT
0	18	0	0	0	0	0	2.45	0.58	B B1a	DEG VIT
0	106	0	0	0	1	0	6.3	0.56	B B2	DEG VIT
0	144	0	0	0	0	0	6.47	0.54	B B3	DEG VIT
0	0	4	0	0	3	0	5.23	0.54	B B4	
0	0	1	0	0	3	0	3.49	0.51	B B5	
0	0	3	0	0	0	0	3.79	0.49	B B6	
0	0	0	0	0	0	0	2.53	0.42	B B7	
0	0	0	0	0	3	0	4.05	0.40	B B8	
0	0	0	0	0	0	0	2.59	0.44	B B9	
0	0	0	0	0	3	0	4.18	0.41	B B10	
0	0	0	0	0	0	0	3.06	0.39	B B11	
0	0	0	0	0	0	0		0.00	B B12	
0	0	0	0	0	0	0	4.44	0.31	B B13	
0	0	0	0	0	0	0	0	0.00	B B14	
0	0	1	0	0	0	0	3.15	0.30	B B15	
0	0	1	0	0	0	0	3.17	0.26	B B16	
0	0	0	0	0	0	0	3.5	0.26	B B17b	
0	0	0	0	0	1	0	3.02	0.27	B B17a	
0	0	2	0	0	8	0	6.34	0.23	B B18	
0	0	0	0	0	0	1	2.59	0.25	B B19	
0	0	0	0	0	1	0	2.74	0.23	B B20b	
0	0	3	1	0	0	0	4.09	0.22	B B20a	BEAUTIFUL FUS SFUS
0	0	0	1	0	0	0	3.01	0.23	B B21b	
0	0	2	0	0	1	0	3.73	0.23	B B21a	
0	0	0	0	0	5	0	3.28	0.23	B B22	
0	0	0	0	0	2	0	7.11	0.20	B B23b	
0	0	6	1	0	1	0	23.03	0.10	B B23a	
0	0	0	1	0	0	0	5.21	0.18	B B24	
0	0	0	1	0	1	0	4.09	0.18	B B25c	

SAMPLE	PEL#	LT	THICK_CM	TOTMF	TOTMC	TCOL	PV	TEL	DESMO	VDET	SFUS	FUS	IDET	MAC	MIC	SPOR	CUT	RES
B B25b	45	D/F	4	300	356	8	3	2	27	0	126	109	23	0	0	1	0	1
B B25a	46	BD	1.3	300	302	34	3	13	69	4	106	26	40	0	0	3	2	0
B B26	47	BD	4	300	302	44	44	6	77	0	74	34	20	0	0	1	0	0
B B27b	48	BD	6	300	304	42	18	10	56	0	100	28	31	0	0	13	2	0
B B27a	50	BD	5	300	301	32	85	6	63	0	50	25	36	0	0	2	1	0
B B28b	51	BD	7.5	300	304	40	41	19	76	3	71	24	20	0	0	2	2	2
B B28a	52	BC	3.5	300	302	28	135	9	53	0	28	15	26	0	2	0	2	2
B B29	53	BD	6	300	302	14	24	18	39	0	88	55	55	0	0	5	2	0
B B30	54	BD	5.5	300	304	31	16	5	50	0	105	43	48	0	0	2	0	0
B B31	55	BD	4	300	314	21	3	7	29	3	123	87	22	0	0	1	1	3
B B32	56	BD	2.5	300	303	27	39	6	56	1	100	33	33	0	1	3	1	0
B B33	57	BD	5.5	300	311	25	51	9	56	0	92	39	25	0	0	3	0	0
B B34	58	BD	2.5	300	300	30	12	13	47	2	98	29	61	0	0	3	1	2
B B35	59	D	9	300	302	20	29	9	55	1	95	57	30	0	1	2	1	0
B B36	60	D	3	300	301	23	53	9	55	4	81	20	45	0	2	7	0	1
B B37	61	D	5	300	302	36	19	6	46	4	99	33	50	0	2	4	0	1
B B38	62	BB	4	300	334	1	266	7	8	1	4	1	5	0	1	0	0	6
B B39b	63	BD	4.5	300	311	29	45	21	51	4	70	22	52	0	2	4	0	0
B B39a	64	D	4	300	313	28	29	2	47	2	93	35	57	1	0	6	0	0
B B40	65	BD	4.5	300	305	15	10	11	44	1	121	43	49	1	1	4	0	0
B B41	66	BD	12	300	313	25	26	9	68	66	33	67	0	0	0	5	0	1
B B42	67	BD	3	300	302	25	41	32	90	0	51	50	8	0	0	3	0	0
B B43c	68	B	1	300	303	47	82	11	96	1	29	17	7	2	4	3	0	0
B B43b	69	F	1	300	322	19	58	13	31	0	58	112	4	0	3	1	0	1
B B43a	70	B	1	300	300	38	117	14	60	0	25	18	16	0	12	0	0	0
B B44	71	B	4	300	327	2	266	3	7	0	0	2	1	0	2	0	0	17
B B45	72	B	5	300	327	0	269	0	1	0	1	0	1	0	0	0	0	28
B B46	73	BD	5	300	304	34	8	13	67	0	106	33	33	0	1	2	1	2
B B47b	74	BD	2	300	331	30	3	49	81	4	75	28	26	0	0	4	0	0
B B47a	75	MP	2	300	303	43	1	7	71	1	108	27	37	0	0	3	1	1
B B48	76	MP/D	5	300	514	37	0	7	50	0	127	41	21	0	1	3	0	0
B B49	77	MP	3.5	300	336	21	59	15	58	2	100	24	16	0	2	0	0	3
B B50	78	BD	9	300	301	28	28	29	42	4	85	20	51	0	9	2	0	2
B B51	79	BD	9.5	300	301	19	4	8	34	5	108	40	75	0	3	4	0	0
B B52	80	BD	5.5	300	311	19	75	13	43	5	66	17	49	0	6	3	1	3
B B53c	81	BD	4	300	305	30	82	7	27	4	57	16	54	0	20	2	0	1
B B53b	82	D	5.5	300	309	17	5	3	36	11	117	30	77	0	1	0	3	0
B B53a	83	BD	2.5	300	306	17	48	9	37	3	88	25	59	0	4	9	0	1
B B54	84	D	5	300	317	18	11	9	24	5	114	27	80	0	4	4	4	0
B B55	85	BD	9	300	305	25	21	18	48	9	96	24	58	0	0	1	0	0
B B56	86	BD	7	300	318	13	13	6	28	15	125	26	62	0	3	2	3	4
B B57	87	BD	6	300	318	24	24	2	64	2	68	31	79	0	3	1	1	1

OLIP	OTHER	CLAY	QTZ	PYR	CARB	OMIN	ASH YIELD	SULPHUR	SAMPLE	COMMENTS
0	0	0	0	0	56	0	21.78	0.09	B B25b	
0	0	0	0	0	2	0	3.64	0.19	B B25a	
0	0	0	0	0	0	2	3.62	0.20	B B26	
0	0	2	1	0	1	0	5.34	0.18	B B27b	
0	0	0	0	0	1	0	5.36	0.18	B B27a	
0	0	0	0	0	4	0	3.39	0.19	B B28b	
0	0	1	0	0	1	0	2.8	0.19	B B28a	
0	0	0	0	0	2	0	7.04	0.14	B B29	
0	0	2	2	0	0	0	3.76	0.17	B B30	
0	0	0	0	0	14	0	13.28	0.12	B B31	
0	0	2	0	0	1	0	3.81	0.18	B B32	
0	0	0	0	0	11	0	6.5	0.16	B B33	
0	2	0	0	0	0	0	3.4	0.16	B B34	
0	0	1	0	0	1	0	5.41	0.16	B B35	
0	0	0	1	0	0	0	4.52	0.17	B B36	
0	0	0	0	0	2	0	6.34	0.16	B B37	
0	0	0	0	0	34	0	7.78	0.15	B B38	
0	0	10	0	0	1	0	5.27	0.16	B B39b	
0	0	1	2	0	10	0	8.7	0.15	B B39a	
0	0	0	0	0	5	0	6.28	0.16	B B40	
0	0	7	1	1	4	0	7.54	0.17	B B41	
0	0	1	0	0	0	1	5.01	0.19	B B42	
0	1	2	0	0	1	0	2.72	0.21	B B43c	(OX-VIT)
0	0	1	0	0	21	0	16.28	0.12	B B43b	
0	0	0	0	0	0	0	2.34	0.21	B B43a	
0	0	0	0	0	27	0	12.71	0.15	B B44	
0	0	0	0	0	27	0	11.54	0.16	B B45	
0	0	0	0	0	4	0	5.46	0.17	B B46	
0	0	1	1	0	29	0	14.96	0.15	B B47b	
0	0	0	0	0	3	0	32.13	0.07	B B47a	
0	13	0	1	0	213	0	39.93	0.05	B B48	
0	0	0	0	0	36	0	19.92	0.12	B B49	
0	0	0	0	0	1	0	4.78	0.18	B B50	
0	0	1	0	0	0	0	6.97	0.17	B B51	
0	0	1	0	0	10	0	7.32	0.19	B B52	
0	0	1	0	0	4	0	6.09	0.20	B B53c	
0	0	3	2	0	4	0	10.17	0.16	B B53b	
0	0	0	2	0	4	0	9.12	0.18	B B53a	
0	0	1	8	0	8	0	10.06	0.17	B B54	
0	0	1	0	0	4	0	28.95	0.19	B B55	
0	0	1	3	0	14	0	11.8	0.17	B B56	
0	0	7	3	0	8	0	10.09	0.20	B B57	

SAMPLE		PEL#	LT	THICK_CM	TOTMF	TOTMC	TCOL	PV	TEL	DESMO	VDET	SFUS	FUS	IDET	MAC	MIC	SPOR	CUT	RES
	B B58	88	D	7.5	300	309	21	27	7	42	6	112	11	59	0	7	5	2	1
	B B59b	89	BD	3.7	300	303	19	32	8	32	4	118	11	65	0	6	3	0	2
	B B59a	90	D	5.5	300	305	10	5	16	50	3	119	31	57	0	0	9	0	0
	B B60	91	D	15	300	313	15	2	22	19	7	80	8	126	0	14	3	1	3
	B B61b	92	D	1.5	300	318	36	80	4	31	8	46	18	66	1	2	6	1	1
	B B61a	93	BB	2.8	300	367	22	199	13	57	1	1	0	2	0	3	1	0	1
	B B62	94	D	19	300	365	16	5	8	25	10	69	6	153	0	4	2	0	1
	B B63c	95	BD	4.5	300	357	50	0	4	25	22	96	16	86	0	0	1	0	0
	B B63b	96	BC	6	300	331	38	14	64	28	18	60	12	64	0	1	1	0	0
	B B63a	97	BD	2.5	300	323	21	10	54	55	16	54	8	79	0	2	1	0	0
	B B64b	98	D	6.5	300	353	23	20	21	17	20	88	13	95	0	2	0	0	1
	B B64a	99	D	1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B B65	100	D	6.7	300	323	13	1	8	6	10	123	47	84	0	0	4	0	4
	B B65/66	101	MP/B	2.7	122	300	48	11	6	6	33	10	0	8	0	0	0	0	0
	B B66d	102	BD	1	300	360	58	23	1	23	45	43	10	88	0	0	6	2	1
	B B66c	103	BD	4.5	300	331	41	38	4	40	5	65	29	73	0	3	2	0	0
	B B66b	104	B	3	300	325	1	252	16	1	0	2	1	7	0	15	0	0	5
	B B66a	105	D	3.5	300	319	6	4	14	30	9	98	8	105	0	17	1	6	2
	B B67b	106	D	8	300	315	7	2	1	8	3	174	37	59	0	2	4	1	1
	B B67a	107	BD	3.5	300	317	12	24	39	67	1	99	14	36	0	3	2	1	1
	B B68	108	BD	14.5	300	314	14	3	6	24	3	151	50	47	2	0	0	0	0
	B B69	109	D	2.5	300	302	16	14	8	21	6	120	44	66	0	1	2	2	0
	B B70	110	BD	8.5	300	317	22	1	22	27	9	130	25	61	0	0	2	0	1
	B B71	405	B	3	300	305	20	162	31	79	1	1	3	3	0	0	0	0	0
	B B72d	111	BB	1	300	307	26	8	103	59	1	51	34	14	0	1	3	0	0
	B B72c	112	F	1.5	300	301	27	1	33	29	0	53	151	6	0	0	0	0	0
	B B72b	113	BD	4.5	300	322	54	9	3	45	3	76	90	18	0	0	2	0	0
	B B72a	114	B	2	300	309	11	265	0	16	1	3	1	3	0	0	0	0	0
BULLMOOSE	C																		
	C 1	406	B	4.0	300	302	36	203	43	15	2	0	0	0	0	0	0	0	1
	C 2	407	BB	16.0	300	302	12	124	23	82	7	13	8	29	1	0	0	1	0
	C 3	408	S	42.0	300	429	43	83	21	46	86	1	10	10	0	0	0	0	0
	C 4	409	BC	4.0	300	312	14	116	19	74	62	10	1	1	0	0	1	0	0
	C 5	410	B	1.0	300	308	7	15	6	204	4	17	22	11	0	0	14	0	0
	C 6b	162	BB	3.5	300	311	26	31	51	87	4	34	26	34	0	0	7	0	0
	C 6a	163	BD	2.5	300	340	13	7	9	50	16	78	78	42	0	0	4	2	1
	C 7	411	S	5.0	300	411	27	75	18	51	111	3	5	8	2	0	0	0	0
	C 8	164	BC	2	300	310	36	21	39	49	4	49	24	62	1	2	7	2	4
	C 9	165	BD	5.5	300	307	17	14	30	31	9	69	36	88	0	2	2	1	1
	C 10	166	D	6	300	340	17	2	7	8	4	71	32	156	0	0	2	0	1
	C 11	167	D	9	300	349	19	2	4	1	14	100	13	139	2	1	4	1	0
	C 12	168	BD	8	300	331	36	28	17	13	54	35	25	85	0	1	4	2	0

OLIP	OTHER	CLAY	QTZ	PYR	CARB	OMIN	ASH YIELD	SULPHUR	SAMPLE	COMMENTS
0	0	2	6	0	1	0	7.84	0.18	B B58	
0	0	2	1	0	0	0	8.25	0.18	B B59b	
0	0	2	1	0	2	0	9.45	0.18	B B59a	
0	0	2	9	0	2	0	15.92	0.19	B B60	
0	0	3	3	0	12	0	20.35	0.20	B B61b	
0	0	5	0	0	62	0	21.5	0.23	B B61a	
0	1	14	35	1	7	8	31.72	0.18	B B62	(LIPTODET)
0	0	11	43	0	3	0	30.54	0.21	B B63c	
0	0	13	8	0	10	0	22.27	0.26	B B63b	
0	0	14	3	0	6	0	19.7	0.29	B B63a	
0	0	22	19	1	11	0	24.94	0.24	B B64b	
0	0	0	0	0	0	0	0	0	B B64a	
0	0	10	11	0	2	0	21.13	0.25	B B65	
0	0	176	1	0	1	0	62.58	0.14	B B65/66	
0	0	11	46	0	2	1	38.49	0.20	B B66d	
0	0	4	6	0	14	7	17.95	0.25	B B66c	
0	0	4	2	0	19	0	13.15	0.31	B B66b	
0	0	3	16	0	0	0	13.62	0.28	B B66a	
0	1	4	7	0	1	3	13.17	0.28	B B67b	(RESIN-SOAKED VIT)
0	1	2	4	0	5	6	9.21	0.37	B B67a	OX-VIT
0	0	5	5	0	4	0	11.29	0.35	B B68	
0	0	0	2	0	0	0	9.01	0.39	B B69	
0	0	1	13	2	1	0	12.56	0.38	B B70	
0	0	0	3	0	2	0	6.3	0.47	B B71	
0	0	3	0	0	0	4	7.41	0.54	B B72d	
0	0	1	0	0	0	0	6.38	0.40	B B72c	
0	0	12	5	0	5	0	12.89	0.44	B B72b	
0	0	3	0	0	5	1	6.95	0.65	B B72a	
0	0	0	2	0	0	0	2.8	0.80	C 1	
0	0	2	0	0	0	0	3.6	0.69	C 2	
0	0	88	37	0	4	0	47	0.38	C 3	
2	0	7	5	0	0	0	15.2	0.52	C 4	
0	0	7	0	0	1	0	8.3	0.53	C 5	
0	0	9	2	0	0	0	11.10	0.63	C 6b	
0	0	29	4	0	7	0	15.40	0.44	C 6a	
0	0	84	23	0	4	0	34.9	0.46	C 7	
0	0	2	3	1	4	0	9.35	0.61	C 8	
0	0	2	5	0	0	0	13.16	0.53	C 9	
0	0	9	31	0	0	0	26.86	0.34	C 10	
0	0	1	47	0	1	0	30.75	0.32	C 11	
0	0	5	24	0	2	0	26.11	0.49	C 12	

SAMPLE		PEL#	LT	THICK_CM	TOTMF	TOTMC	TCOL	PV	TEL	DESMO	VDET	SFUS	FUS	IDET	MAC	MIC	SPOR	CUT	RES
	C 13b	169	BD	7.5	300	303	14	0	26	73	1	84	37	56	2	0	4	1	2
	C 13a	170	BD	3	300	300	23	0	18	25	2	91	83	52	0	0	4	0	2
	C 14	171	BD	3	300	301	18	1	41	30	1	93	61	45	0	1	4	2	3
	C 15	172	BD	6.5	300	300	39	14	12	48	2	78	37	62	0	2	4	1	1
	C 16	173	BD	4	300	310	27	7	21	62	0	102	37	41	0	2	1	0	0
	C 17	412	B	1.0	300	300	1	157	110	19	1	1	1	5	0	0	1	0	4
	C 18b	174	BD	4	300	328	37	2	13	48	1	82	66	50	0	0	1	0	0
	C 18a	175	D	3.5	300	309	40	0	19	61	3	80	31	63	0	0	2	0	1
	C 19	176	BD	5.5	0	0								0					
	C 20	177	BC	6	300	320	70	27	12	50	7	46	43	42	0	0	1	1	1
	C 21	178	D	9	300	313	21	10	19	19	20	76	31	97	0	1	6	0	0
	C 22	179	BC	4	300	320	40	47	25	61	33	30	40	22	0	0	0	1	1
	C 23	413	B	5.0	300	301	0	255	31	5	0	1	2	0	0	0	0	0	6
	C 24	414	BC	11.0	300	307	7	15	32	112	3	53	39	33	1	0	3	0	2
BULLMOOSE D														0					
	D 1	180	BC	5	300	354	177	23	25	0	71	0	1	1	0	1	0	0	1
	D 2	415	BB	9.0	300	318	13	111	89	44	39	2	1	1	0	0	0	0	0
	D 3	416	S	6.0	300	301	24	87	11	124	0	21	15	14	0	0	4	0	0
	D 4	417	BD	3.0	300	399	9	29	39	29	71	34	8	77	1	0	2	0	1
	D 5	418	SH	7.0	135	301	11	19	15	19	42	13	3	12	0	0	1	0	0
	D 6	181	BB/MDST	3.5	300	392	135	35	10	12	82	8	5	8	2	0	2	0	0
	D 7	182	MDST/VIT	2	129	302	18	17	3	0	35	11	12	32	0	1	0	0	0
	D 8b	183	BD	3.5	300	368	54	16	3	8	109	22	29	56	0	0	0	0	2
	D 8a	184	D	4.4	300	368	5	2	1	4	17	107	24	136	0	0	3	1	0
	D 9	419	B	2.0	300	302	12	69	98	90	10	7	3	3	0	0	2	3	3
	D 10	420	S	2.0	300	316	15	28	30	82	122	13	5	3	0	0	1	0	1
	D 11	185	S/D	4.5	300	301	83	121	2	55	1	13	14	4	0	0	4	2	1
	D 12	421	S	9.0	300	305	8	120	12	127	7	9	8	7	0	0	2	0	0
	D 13	186	BC	6	300	359	27	160	4	21	4	24	7	38	3	0	6	3	3
	D 14	187	BC	2.5	300	315	79	87	7	34	2	13	77	1	0	0	0	0	0
	D 15	188	B	6.5	300	300	77	125	5	41	0	24	12	11	0	0	3	0	2
	D 16	422	S	12.0	300	383	19	32	19	142	61	4	19	4	0	0	0	0	0
	D 17b	189	BC	6.5	300	312	62	65	28	22	41	24	25	25	0	0	7	1	0
	D 17a	190	MDST/VIT	3.5	234	297	75	28	4	7	33	26	17	43	0	0	1	0	0
	D 18	191	BD	10.5	300	311	55	31	11	25	27	51	40	53	0	0	6	1	0
	D 19	423	BD	5.0	300	318	3	25	46	95	15	61	26	27	0	0	2	0	0
	D 20c	192	BB	2.5	300	341	94	43	20	61	16	15	17	23	1	0	7	0	3
	D 20b	193	BD	2	300	358	50	22	12	31	17	55	28	77	0	1	3	2	1
	D 20a	194	D	4	300	429	12	2	3	3	7	63	61	140	3	0	2	1	3
	D 21b	195	D	2.5	57	301	14	0	1	0	30	9	0	2	0	1	0	0	0
	D 21a	196	BD	4	300	373	35	10	4	14	14	56	37	127	1	1	1	0	0
	D 22	424	CSH	48.0	178	300	5	3	7	17	5	14	8	118	1	0	0	0	0

OLIP	OTHER	CLAY	QTZ	PYR	CARB	OMIN	ASH YIELD	SULPHUR	SAMPLE	COMMENTS
0	0	0	2	1	0	0	6.60	0.51	C 13b	
0	0	0	0	0	0	0	10.05	0.71	C 13a	
0	0	0	0	0	1	0	6.31	0.47	C 14	
0	0	0	0	0	0	0	4.97	0.51	C 15	
0	0	1	0	0	9	0	9.84	0.53	C 16	
0	0	0	0	0	0	0	6.3	0.59	C 17	
0	0	2	0	1	25	0	13.64	0.63	C 18b	
0	0	7	0	0	0	2	8.94	0.50	C 18a	
							0	0.00	C 19	
0	0	16	4	0	0	0	17.83	0.58	C 20	
0	0	5	7	0	1	0	17.88	0.46	C 21	
0	0	15	4	0	0	1	18.46	0.58	C 22	
0	0	1	0	0	0	0	1.7	0.62	C 23	
0	0	7	0	0	0	0	5.9	0.59	C 24	
0	0	50	1	0	2	1	30.70	0.77	D 1	
0	0	14	4	0	0	0	11.1	0.75	D 2	
0	0	0	1	0	0	0	2.4	0.74	D 3	
0	0	81	18	0	0	0	41.8	0.46	D 4	
0	0	146	19	1	0	0	68.2	0.22	D 5	
0	1	86	4	1	0	1	38.18	0.59	D 6	
0	0	156	15	0	1	1	70.52	0.19	D 7	
0	1	13	53	0	2	0	41.33	0.42	D 8b	
0	0	4	63	1	0	0	33.38	0.33	D 8a	
0	0	1	1	0	0	0	4	0.66	D 9	
0	0	12	2	2	0	0	21.7	0.79	D 10	
0	0	1	0	0	0	0	4.96	0.77	D 11	
0	0	5	0	0	0	0	5.1	0.60	D 12	
0	0	6	52	1	0	0	19.98	0.60	D 13	
0	0	1	0	1	13	0	10.49	0.46	D 14	
0	0	0	0	0	0	0	3.69	0.67	D 15	
0	0	59	16	0	8	0	39	0.39	D 16	
0	0	6	6	0	0	0	15.90	0.54	D 17b	
0	0	42	20	0	1	0	44.73	0.31	D 17a	
0	0	8	2	0	0	1	12.75	0.47	D 18	
0	0	13	4	0	1	0	7.3	0.49	D 19	
0	0	38	2	0	0	1	0	0.00	D 20c	
0	1	45	12	0	0	1	39.29	0.33	D 20b	
0	0	105	21	0	0	3	48.27	0.24	D 20a	
0	0	234	9	0	0	1	77.11	0.07	D 21b	
0	0	16	49	1	7	0	37.17	0.31	D 21a	
0	0	41	81	0	0	0	60.5	0.18	D 22	

SAMPLE		PEL#	LT	THICK_CM	TOTMF	TOTMC	TCOL	PV	TEL	DESMO	VDET	SFUS	FUS	IDET	MAC	MIC	SPOR	CUT	RES
	D 24b	197	D/MDST	4.5	300	384	28	12	7	22	26	56	32	109	0	0	6	0	2
	D 24a	198	BB	6	300	306	77	17	13	70	0	50	40	24	0	0	5	2	2
	D 25	425	B	2.0	300	307	32	88	106	12	3	13	32	13	0	0	0	0	1
	D 26	426	PTG	10.0	98	300	20	16	17	1	31	4	5	4	0	0	0	0	0
	D 27c	199	B	6	300	300	86	89	34	44	1	12	23	4	0	0	3	3	1
	D 27b	200	F	1.5	300	300	13	1	0	9	1	81	192	3	0	0	0	0	0
	D 27a	201	B	2	300	303	17	81	26	52	9	58	33	17	0	0	5	2	0
BULLMOOSE	E													0					
	E 1	396	S	12.0	246	464	47	53	72	1	62	3	2	6	0	0	0	0	0
	E 2	397	S	11.0	300	314	37	12	71	100	51	6	9	10	0	0	2	2	0
	E 3	202	BB	4	301	301	57	109	10	57	1	12	29	15	0	0	7	0	3
	E 4	398	S/F?	4	300	301	18	100	8	56	2	58	49	7	0	0	2	0	0
	E 5	203	BB	3.2	300	302	33	173	4	56	0	10	8	14	0	0	2	0	0
	E 6b	204	F/B	1.5	300	303	23	7	13	27	0	112	109	6	0	0	3	0	0
	E 6a	205	BB	3.5	300	308	50	20	10	75	7	54	28	46	1	0	6	1	2
	E 7	399	CSH	7.0	123	300	3	0	1	7	7	9	32	64	0	0	0	0	0
	E 8	400	BD	10.0	300	418	56	43	41	12	95	6	19	24	0	0	3	0	1
	E 9	401	BB	2.0	300	365	24	18	66	12	138	8	15	17	1	0	0	0	0
	E 10b	206	BB	5	300	314	74	57	21	30	66	14	18	14	0	0	4	1	1
	E 10a	207	B	3	300	301	12	257	2	14	0	2	6	4	0	0	2	0	1
	E 11	208	BB	12.5	300	303	33	80	12	69	10	38	35	14	0	0	8	0	1
	E 12b	209	BD	12	300	303	30	5	11	76	0	50	70	42	2	0	12	1	1
	E 12a	210	BC	5	300	301	43	25	33	48	0	73	47	23	0	0	6	0	2
	E 13b	211	BD	8	300	300	35	36	15	67	1	42	55	37	1	0	10	0	1
	E 13a	212	BC	8	300	308	53	44	15	53	5	65	35	23	0	1	5	1	0
ADSORPTION	SAMPLES																		
	C LTC-1		B		300	304	174	18	44	17	33	2	3	5	0	0	2	0	2
	C LTC-7		BB		300	302	101	16	34	35	3	71	28	11	0	0	1	0	0
	C LTC-15		BB		300	312	105	8	25	28	16	64	23	30	0	0	1	0	0
	A1 LTA1-6		BD		300	301	74	10	40	50	3	77	13	29	0	3	0	0	0
	C LTC-9		D		300	330	10	0	8	39	68	4	163	0	0	0	2	0	1
	C LTC-11		BD		300	313	47	2	17	20	20	113	9	68	0	1	0	0	0
	C LTC-14		D		300	316	16	1	23	5	42	111	13	87	0	0	2	0	0
	C LTC-5		F		300	320	14	0	19	18	3	61	158	20	0	4	0	1	1
FIELD SAMPLES														0					
	A1 1A1-1	N/A	BD		300	412	11	5	12	36	38	114	32	47	1	0	3	0	0
	A1 2A1-1	N/A	BC		300	301	15	1	54	91	2	64	32	31	2	0	6	2	0
	A1 2A1-3	N/A	F		300	301	24	14	56	37	0	87	63	13	2	2	0	0	2
	A1 3A1-4	N/A	B		300	300	42	31	53	84	1	32	30	20	1	0	6	0	0
	A1 3A1-5	N/A	B		302	304	0	173	17	75	0	13	9	12	0	0	3	0	0
	A1 3A1-6	N/A	BB		300	301	29	20	42	106	1	31	49	12	1	2	5	1	1

OLIP	OTHER	CLAY	QTZ	PYR	CARB	OMIN	ASH YIELD	SULPHUR	SAMPLE	COMMENTS
0	0	17	67	0	0	0	42.62	0.31	D-24b	
0	0	2	0	3	1	0	7.50	1.68	D 24a	
0	0	4	1	0	2	0	5.6	0.65	D 25	
0	0	189	7	0	6	0	77.8	0.00	D 26	
0	0	0	0	0	0	0	3.04	0.79	D 27c	
0	0	0	0	0	0	0	3.30	0.36	D 27b	
0	0	3	0	0	0	0	4.07	0.77	D 27a	
0	0	216	2	0	0	0	54.9	0.33	E 1	
0	0	10	4	0	0	0	13.7	0.60	E 2	
1	0	0	1	0	0	0	4.03	0.72	E 3	
0	0	1	0	0	0	0	0.00		E 4	
0	0	2	0	0	0	0	3.97	0.74	E 5	
0	0	0	0	0	3	0	8.70	0.40	E 6b	
0	0	2	2	2	2	0	6.28	0.62	E 6a	
0	0	156	21	0	0	0	62.2	0.19	E 7	
0	0	98	20	0	0	0	47.3	0.35	E 8	
1	0	24	41	0	0	0	27.7	0.44	E 9	
0	0	10	4	0	0	0	18.05	0.54	E 10b	
0	0	0	1	0	0	0	2.84	0.75	E 10a	
0	0	1	1	0	1	0	5.96	0.60	E 11	
0	0	2	1	0	0	0	4.11	0.60	E 12b	
0	0	0	1	0	0	0	30.11	0.64	E 12a	
0	0	0	0	0	0	0	5.88	0.66	E 13b	
0	0	4	2	2	0	0	7.48	1.00	E 13a	
0	0	2	1	0	1	0	9.2	0.656	C LTC-1	
0	0	2	0	0	0	0	7.04	0.648	C LTC-7	
0	0	11	1	0	0	0	10.2	0.773	C LTC-15	
1	0	0	0	0	1	0	4.37	0.365	A1 LTA1-6	
5	0	9	20	0	1	0	33.6	0.31	C LTC-9	
3	0	10	3	0	0	0	17.1	0.433	C LTC-11	
0	0	5	11	0	0	0	17.02	0.449	C LTC-14	
1	0	0	0	0	20	0	20.7	0.187	C LTC-5	
1	0	109	3	0	0	0	N/A	N/A	A1 1A1-1	
0	0	1	0	0	0	0	N/A	N/A	A1 2A1-1	
0	0	0	1	0	0	0	N/A	N/A	A1 2A1-3	
0	0	0	0	0	0	0	N/A	N/A	A1 3A1-4	
0	0	2	0	0	0	0	N/A	N/A	A1 3A1-5	
0	0	1	0	0	0	0	N/A	N/A	A1 3A1-6	

SAMPLE	PEL#	LT	THICK_CM	TOTMF	TOTMC	TCOL	PV	TEL	DESMO	VDET	SFUS	FUS	IDET	MAC	MIC	SPOR	CUT	RES
A1 4A1-2	N/A	BD		300	306	13	27	37	91	2	66	33	29	1	0	1	0	0
B B2-12	N/A	BC		300	301	6	19	47	67	0	95	50	7	4	0	4	1	0
B B2-15	N/A	F		300	306	19	60	17	63	1	53	63	14	1	1	7	0	1
B B2-16	N/A	F		300	300	5	2	22	17	0	123	124	6	0	0	1	0	0
B B2-4	N/A	BB		300	331	37	23	66	83	5	27	32	20	3	1	1	0	1
B B2-6	N/A	BD		300	321	0	1	13	39	8	149	20	58	9	0	3	0	0
B B3-14	N/A	D		300	360	7	19	17	61	0	54	128	13	0	0	0	0	1
B B3-15	N/A	BD		300	322	3	55	27	44	6	57	97	7	1	0	2	1	0
B B3-16	N/A	D		300	342	6	5	23	27	0	74	156	6	0	0	2	0	1
B B3-4	N/A	BC		300	315	9	42	89	60	9	11	22	32	3	14	6	1	2
B B3-5	N/A	B		300	318	3	65	113	70	23	2	1	13	0	5	1	0	4
B B3-7	N/A	D		300	303	4	1	99	95	0	38	50	9	0	0	3	0	1
C C1-2	N/A	BD		300	319	21	0	27	29	46	60	49	63	0	1	1	3	0
C C1-3	N/A	BC		300	301	9	14	61	39	3	50	80	30	1	8	4	0	1
C C1-4	N/A	D		300	330	4	1	6	3	19	61	31	172	1	0	1	1	0
C C1-5	N/A	B		300	300	1	283	7	0	1	6	1	0	0	0	0	0	1
C C2-2	N/A	BC		300	357	99	56	10	12	103	12	6	2	0	0	0	0	0
D D2-1	N/A	BB		300	302	5	31	62	72	1	42	65	12	0	0	10	0	0
D D2-6	N/A	BB		300	313	40	134	49	12	59	3	1	0	0	0	0	2	0
D D3-5	N/A	B		300	300	1	166	26	66	1	13	15	4	1	0	5	1	1
D D3-7	N/A	BD		300	375	3	2	2	9	24	61	40	149	2	1	5	2	0
SHIKANO D																		
SHIK-D	753/89	SH	2.0	30	307	10	1	1	0	16	0	1	1	0	0	0	0	0
SHIK-D	723/89	CSH	2.0	300	509	149	47	13	7	79	1	1	3	0	0	0	0	0
SHIK-D	724/89	BB	1.5	300	380	106	23	46	21	79	2	12	10	1	0	0	0	0
SHIK-D	725/89	B	1.0	300	302	73	210	2	4	9	1	1	0	0	0	0	0	0
SHIK-D	726/89	BD	1.5	300	361	54	28	39	15	99	31	13	21	0	0	0	0	0
SHIK-D	727/89	SH	2.0	300	351	31	206	12	2	41	5	1	2	0	0	0	0	0
SHIK-D	728/89	BC	3.0	300	383	92	50	45	7	90	0	10	6	0	0	0	0	0
SHIK-D	729/89	BD	4.0	300	527	77	16	41	8	157	0	0	1	0	0	0	0	0
SHIK-D	730/89	D	2.5	280	569	52	10	28	7	182	0	0	1	0	0	0	0	0
SHIK-D	731/89	BC	8.0	300	349	56	74	41	15	107	7	0	0	0	0	0	0	0
SHIK-D	732/89	BD	6.0	300	416	58	47	29	15	150	0	0	1	0	0	0	0	0
SHIK-D	733/89	BB	23.0	300	301	45	108	14	79	10	22	12	8	1	0	0	0	0
SHIK-D	734/89	BC	9.0	300	308	74	69	24	80	1	35	10	4	0	1	1	1	0
SHIK-D	735/89	BB	5.0	300	300	48	99	27	68	0	39	13	4	2	0	0	0	0
SHIK-D	736/89	BC	6.0	300	300	25	25	35	96	1	59	31	25	2	1	0	0	0
SHIK-D	737/89	BD	3.0	299	309	6	1	16	73	2	126	23	49	3	0	0	0	0
SHIK-D	738/89	BB	1.0	300	301	47	40	89	21	1	84	2	14	2	0	0	0	0
SHIK-D	739/89	BD	4.0	300	306	32	21	24	100	1	73	11	28	5	2	3	0	0
SHIK-D	740/89	D	1.0	300	314	1	1	23	27	3	113	120	11	1	0	0	0	0
SHIK-D	741/89	BB	6.0	300	301	30	87	79	68	1	14	8	7	2	1	2	1	0

OLIP	OTHER	CLAY	QTZ	PYR	CARB	OMIN	ASH YIELD	SULPHUR	SAMPLE	COMMENTS
0	0	0	0	0	6	0	N/A	N/A	A1 4A1-2	
0	0	0	0	0	1	0	N/A	N/A	B B2-12	
0	0	0	0	0	6	0	N/A	N/A	B B2-15	
0	0	0	0	0	0	0	N/A	N/A	B B2-16	
1	0	19	1	0	11	0	N/A	N/A	B B2-4	
0	0	6	15	0	0	0	N/A	N/A	B B2-6	
0	0	1	0	0	59	0	N/A	N/A	B B3-14	
0	0	1	0	0	21	0	N/A	N/A	B B3-15	
0	0	1	0	0	41	0	N/A	N/A	B B3-16	
0	0	8	1	0	6	0	N/A	N/A	B B3-4	
0	0	11	3	0	4	0	N/A	N/A	B B3-5	
0	0	1	0	0	2	0	N/A	N/A	B B3-7	
0	0	10	7	0	2	0	N/A	N/A	C C1-2	
0	0	0	0	0	1	0	N/A	N/A	C C1-3	
0	0	5	24	0	1	0	N/A	N/A	C C1-4	
0	0	0	0	0	0	0	N/A	N/A	C C1-5	
0	0	48	6	0	3	0	N/A	N/A	C C2-2	
0	0	1	1	0	0	0	N/A	N/A	D D2-1	
0	0	12	1	0	0	0	N/A	N/A	D D2-6	
0	0	0	0	0	0	0	N/A	N/A	D D3-5	
0	0	5	69	0	1	0	N/A	N/A	D D3-7	
0	0	270	1	0	6	0	0.1166	90.2	753/89	
0	0	180	6	3	20	0	0.3777	56.4	723/89	
0	0	70	3	0	7	0	0.5279	40.4	724/89	
0	0	2	0	0	0	0	0.7014		725/89	
0	0	41	19	0	1	0	0.4679	39	726/89	
0	0	10	5	2	34	0	1.2437	24.5	727/89	
0	0	68	10	1	4	0	1.3231	40.5	728/89	
0	0	203	19	4	1	0	1.0176	57.4	729/89	
0	0	261	11	4	13	0	0.9112	68.3	730/89	
0	0	42	2	3	2	0	1.4545	33.5	731/89	
0	0	94	21	1	0	0	0.5518	52.2	732/89	
1	0	1	0	0	0	0	0.7751	4.9	733/89	
0	0	0	0	1	7	0	1.1292	5.4	734/89	
0	0	0	0	0	0	0	0.6057	2	735/89	
0	0	0	0	0	0	0	0.5246	2.3	736/89	
0	0	0	6	2	2	0	0.8415	6.1	737/89	
0	0	1	0	0	0	0	0.7694	2.5	738/89	
0	0	3	1	1	1	0	0.6894	4.6	739/89	
0	0	0	0	4	10	0	1.8103		740/89	
0	0	1	0	0	0	0	0.5988	4.5	741/89	

SAMPLE	PEL#	LT	THICK_CM	TOTMF	TOTMC	TCOL	PV	TEL	DESMO	VDET	SFUS	FUS	IDET	MAC	MIC	SPOR	CUT	RES
SHIK-D	742/89	BC	4.0	300	307	31	37	31	110	6	31	30	20	2	2	0	0	0
SHIK-D	743/89	SH	10.0	139	305	1	1	6	4	20	22	5	79	1	0	0	0	0
SHIK-D	744/89	BC	3.0	300	307	14	71	22	83	5	36	37	30	2	0	0	0	0
SHIK-D	745/89	B	2.5	300	301	10	130	18	93	1	21	17	5	0	4	1	0	0
SHIK-D	746/89	BB	9.0	300	303	21	84	30	99	0	29	26	9	1	1	0	0	0
SHIK-D	747/89	D	14.0	300	300	17	3	12	62	1	130	9	61	3	0	0	1	0
SHIK-D	748/89	B	1.0	300	300	21	90	54	44	0	56	8	25	0	0	0	0	2
SHIK-D	749/89	D	2.5	296	296	12	8	22	68	0	100	26	55	3	1	1	0	0
SHIK-D	750/89	BD	8.0	300	301	12	24	20	102	0	71	24	41	0	4	0	0	0
SHIK-D	751/89	BC	4.0	300	300	28	26	27	76	0	68	36	34	0	2	3	0	0
SHIK-D	752/89	B	2.0	300	301	17	91	32	83	1	29	20	23	0	1	1	0	1
SHIK-D	754/89	D	1.0	300	311	12	7	21	74	1	100	31	50	0	1	1	1	1
SHIK-D	755/89	BC	18.0	300	304	19	42	46	67	1	67	35	22	0	1	0	0	0
SHIK-D	756/89	B	1.5	300	317	41	211	46	0	0	1	1	0	0	0	0	0	0
SHIK-D	757/89	BB	9.0	300	301	20	79	24	94	0	36	16	29	1	1	0	0	0
SHIK-D	758/89	BD	23.0	300	304	13	12	25	81	0	58	29	79	1	1	1	0	0
SHIK-D	759/89	BB	1.0	300	301	41	99	21	63	1	24	7	40	1	2	1	0	0
SHIK-D	760/89	BD	8.5	300	300	23	6	41	92	0	66	21	45	3	0	3	0	0
SHIK-D	761/89	B	1.0	300	300	7	119	75	58	0	11	9	19	1	0	0	0	1
SHIK-D	762/89	BD	19.0	300	300	14	5	55	93	1	57	18	51	1	2	1	1	1
SHIK-D	763/89	BB	3.0	300	300	7	67	96	69	2	24	12	23	0	0	0	0	0
SHIK-D	764/89	BD	32.0	300	307	8	0	68	75	10	68	15	49	3	1	3	0	0
SHIK-D	765/89	B	1.0	300	301	3	217	27	26	1	15	2	6	1	0	0	0	2
SHIK-D	766/89	BD	2.0	300	308	21	16	21	86	15	49	10	77	3	0	2	0	0
SHIK-D	767/89	BC	2.0	300	313	18	24	28	109	17	24	28	46	2	1	2	0	0
SHIK-D	768/89	D	11.0	300	305	3	0	19	40	29	76	23	96	1	0	8	3	1
SHIK-D	769/89	BC	8.0	300	302	8	37	58	94	7	35	24	34	1	0	1	1	0
SHIK-D	770/89	BB	3.0	300	307	25	12	34	107	6	43	30	38	1	0	0	3	0
SHIK-D	771/89	D	7.0	300	330	4	1	21	58	31	67	6	102	3	0	3	4	0
SHIK-D	772/89	BD	2.0	300	415	8	1	23	54	57	58	4	92	1	0	1	0	1
SHIK-D		SS	10.0															
SHIK-D	773/89	SLTST	4.0	117	300	19	9	3	2	81	0	1	2	0	0	0	0	0
SHIK-D	774/89	BC	11.5	300	354	16	7	62	117	24	12	12	44	0	3	0	2	1

OLIP	OTHER	CLAY	QTZ	PYR	CARB	OMIN	ASH YIELD	SULPHUR	SAMPLE	COMMENTS
0	0	5	0	0	2	0	0.5226	11.6	742/89	
0	0	161	5	0	0	0	0.299	65.9	743/89	
0	0	2	0	1	4	0	0.7948	6.7	744/89	
0	0	0	0	1	0	0	1.0318	4.1	745/89	
0	0	0	0	2	1	0	0.8256	3.5	746/89	
1	0	0	0	0	0	0	0.434	2.4	747/89	
0	0	0	0	0	0	0	0.3923	1.7	748/89	
0	0	0	0	0	0	0	0.4209	1.9	749/89	
2	0	0	0	0	1	0	0.6401	3.2	750/89	
0	0	0	0	0	0	0	0.4712	2	751/89	
1	0	0	1	0	0	0	0.4482		752/89	
0	0	2	0	3	6	0	1.6095	11.3	754/89	
0	0	1	1	1	1	0	0.8213	4.8	755/89	
0	0	1	0	2	3	11	1.2698	8.9	756/89	
0	0	0	1	0	0	0	0.6626	2.2	757/89	
0	0	1	1	1	1	0	0.6307	5.9	758/89	
0	0	1	0	0	0	0	1.0476	4.2	759/89	
0	0	0	0	0	0	0	0.6266	3.9	760/89	
0	0	0	0	0	0	0	0.5849		761/89	
0	0	0	0	0	0	0	0.9087	5.6	762/89	
0	0	0	0	0	0	0	0.7662	4.4	763/89	
0	0	3	2	1	1	0	1.2744	10.4	764/89	
0	0	1	0	0	0	0	0.8358		765/89	
0	0	5	3	0	0	0	0.6928	10	766/89	
1	0	6	2	5	0	0	2.1122	14.7	767/89	
1	0	2	2	1	0	0	0.9358	10.6	768/89	
0	0	2	0	0	0	0	0.9166	4.7	769/89	
1	0	6	0	1	0	0	0.9474	5.6	770/89	
0	0	5	4	21	0	0	8.204	26	771/89	
0	0	64	46	5	0	0	3.5934	42.9	772/89	
									SS	
0	0	74	109	0	0	0	0.5328	40.8	773/89	
0	0	44	1	9	0	0	5.4177	19.4	774/89	

Appendix II

Adsorption Isotherm Data

	PRESSURE (psia)	ADSORBED RAW SCF/TON	METHANE MAF SCF/TON	PRESSURE P (MPa)	ADSORBED RAW cc/g	METHANE MAF cc/g
LTC-1	180	217.9	240	1.24	6.80	7.49
ASH=9.2	427	354.6	390.5	2.94	11.07	12.19
VmR=618.1 psia or 4.26 MPa	645	412.2	454	4.45	12.87	14.17
VmM=680.8 psia or 4.68 MPa	921	459.5	506.1	6.35	14.34	15.80
EQM=2.08	1219	490.3	540	8.40	15.30	16.86
	1531	520.6	573.4	10.56	16.25	17.90
	2006	527.3	580.7	13.83	16.46	18.13
LTC-7	199	262.7	282.6	1.37	8.20	8.82
ASH=7.04	399	364.9	392.6	2.75	11.39	12.25
EQM=1.7	644	436.9	470	4.44	13.64	14.67
VmR=705.5 psia or 4.86 MPa	931	499	536.8	6.42	15.58	16.76
VmM=758.9 psia or 5.23 MPa	1261	548	589.5	8.69	17.11	18.40
	1532	581.2	625.2	10.56	18.14	19.52
	1961	591.4	636.2	13.52	18.46	19.86
LTC-15	212	275.7	307.2	1.46	8.61	9.59
ASH=10.27	419	404	450.2	2.89	12.61	14.05
EQM=1.7	627	465.4	518.7	4.32	14.53	16.19
Vm=657.3 psia or 4.53 MPa	969	515.8	574.8	6.68	16.10	17.94
Vm=732.6 psia or 5.05 MPa	1224	543.8	606.1	8.44	16.97	18.92
	1553	570.6	635.9	10.71	17.81	19.85
	1988	570.5	635.8	13.71	17.81	19.85
LTA1-6	185	244	255.1	1.28	7.62	7.96
ASH=4.37	449	355.3	374.5	3.10	11.09	11.69
EQM=1.95	616	405.1	423.6	4.25	12.64	13.22
VmR=598.3 psia or 4.13 MPa	937	461.5	482.6	6.46	14.41	15.06
VmM=625.6 psia or 4.31 MPa	1247	493.3	515.8	8.60	15.40	16.10
	1518	503.8	526.8	10.47	15.73	16.44
	1929	519.5	543.2	13.30	16.22	16.96
LTC-11	203	255.1	307.7	1.40	7.96	9.60
ASH=17.11	394	304	366.7	2.72	9.49	11.45
EQM=1.6	619	332.7	401.3	4.27	10.38	12.53
VmR=392.5 psia or 2.71 MPa	994	353.3	426.2	6.85	11.03	13.30
VmM=473.6 psia or 3.27 MPa	1260	354.7	427.9	8.69	11.07	13.36
	1521	364.4	439.7	10.49	11.37	13.72
	1995	373.3	450.3	13.76	11.65	14.06
LTC-14	248	226.2	272.5	1.71	7.06	8.51
ASH=17.02	496	332.4	400.6	3.42	10.38	12.50
EQM=1.4	653	348.5	420	4.50	10.88	13.11
VmR=495.5 psia or 3.42 MPa	1124	400.8	483.1	7.75	12.51	15.08
VmM=597.1 psia or 4.12 MPa	1364	416	501.3	9.40	12.99	15.65
	1608	427.6	515.3	11.09	13.35	16.08
	1994	432.5	521.2	13.75	13.50	16.27

	ADSORBED		METHANE		ADSORBED	METHANE
	PRESSURE	RAW	MAF	PRESSURE	RAW	MAF
	(psia)	SCF/TON	SCF/TON	P (MPa)	cc/g	cc/g
LTC-9	234	155.7	234.7	1.61	4.86	7.33
ASH=33.68%	443	201.8	304.3	3.05	6.30	9.50
EQM=1.50	677	210.1	316.8	4.67	6.56	9.89
VmR=251.6 psia or 1.73 MPa	969	222	334.7	6.68	6.93	10.45
VmM=379.3 psia or 2.62 MPa	1217	222.3	335.1	8.39	6.94	10.46
	1537	230.9	348.1	10.60	7.21	10.87
	1961	237.2	357.6	13.52	7.40	11.16
LTC-5	271	92.4	116.6	1.87	2.88	3.64
ASH=20.7	426	118.7	149.7	2.94	3.71	4.67
EQM=1.40	650	154.7	195	4.48	4.83	6.09
VmR=258.2 psia or 1.78 MPa	925	163.4	206.1	6.38	5.10	6.43
VmM=326.5 psia or 2.25 MPa	1217	185.1	233.4	8.39	5.78	7.29
	1535	192.4	242.7	10.58	6.01	7.58
	1883	207.8	262.1	12.98	6.49	8.18

VmR= monolayer capacity, raw basis

EQM=equilibrium moisture

VmM= monolayer capacity, moist, ash free basis

MAF = moist, ash free basis