Coal Geology
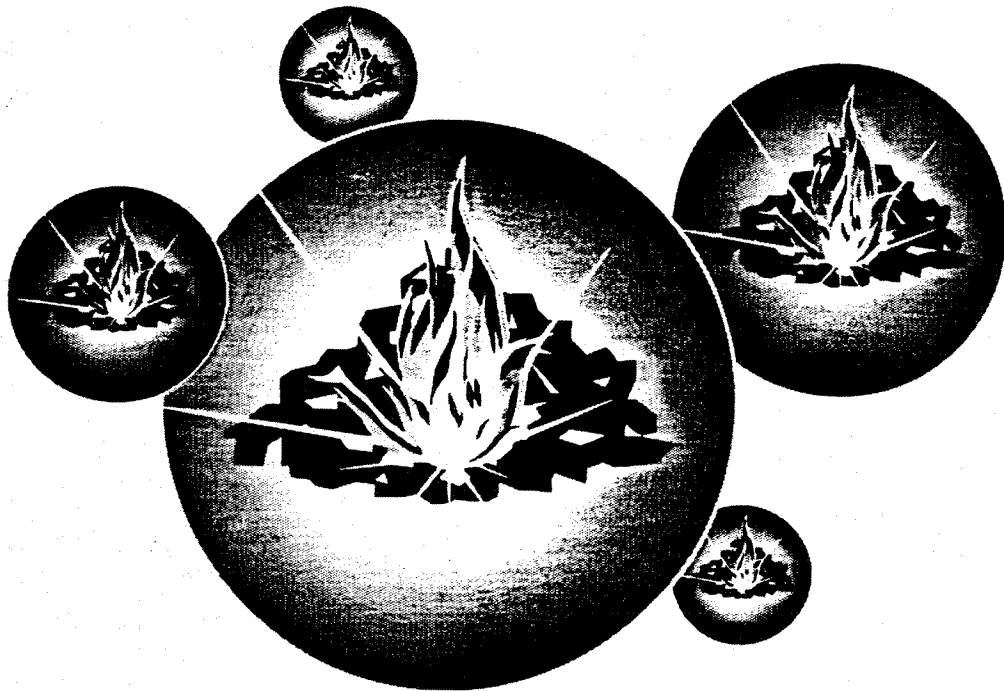# and its Application to
Coal-Bed Methane Reservoirs
Lecture notes for short course

Information Series No. 109

COAL GEOLOGY AND ITS APPLICATION TO COAL-BED METHANE RESERVOIRS

Lecture notes for short course

Edmonton
August 20-24, 1990

Willem Langenberg
Wolfgang Kalkreuth
Jeffrey Levine
Rudy Strobl
Thomas Demchuk
Georgia Hoffman
Tomasz Jerzykiewicz

Acknowledgements

CONTENTS

INTRODUCTION

Coal geology is the field of science, that studies the occurrence and origin of coal on the planet earth. This knowledge can be used to the benefit of man in the discovery and wise management of coal.

Coal can be defined as a readily combustible rock containing more than 50% by weight and more than 70% by volume of carbonaceous material including inherent moisture, formed from compaction and induration of variously altered plant remains similar to those in peat. Differences in the kinds of plant materials (type), in degree of metamorphism (rank), and in the range of impurity (grade) are characteristic for coal and are used in classification (AGI, 1987).

Total resources of coal are huge. Energy derived from coal constitutes the largest of the world's available supplies of conventional energy, with over 60% of the total proven recoverable reserves and around 80% of the estimated additional resources (Ward, 1984).

This short course will give an introduction to the field of coal geology and it will stress the relevance of coal geology to the finding and exploitation of coal-bed methane resources. Although the course is introductory in nature, the participants will nevertheless be exposed to exciting new concepts in coal geology. In addition, representative coal fields of Alberta will be visited and explained by local experts. The course will be of interest to both petroleum geologists and reservoir engineers.

REFERENCES

AGI (1987): Glossary of Geology, third edition; American Geological Institute, Falls Church, Virginia

Ward, C.R. (1984): Coal geology and coal technology; Blackwell Scientific Publishers, 345p.

PEAT ACCUMULATION AND COAL BASINS

Willem Langenberg
Alberta Research Council

Coal is where you find it. The precursor of coal is peat and consequently we can look at present-day peat occurrences. Peats are deposited in mires, where a mire is a non-saline wetland in which organic material accumulates. The term mire encompasses all environments described as swamp, bog, fen, moor, muskeg and peatland (Gore, 1983). For peats to accumulate, a setting is required in which there is high organic productivity and slow, continuous subsidence, such that the groundwater table is at or close to the peat surface, otherwise the plant material will be oxidized and decay. Poorly oxygenated waters are often present in mires, because of slow water movement in the flat vegetated areas. Some mire waters are very acidic as a result of the formation of humic acids during plant decay. This acidic groundwater retards or prevents bacterial life, which is responsible for the breakdown of plant material. Nice examples of well-preserved organic tissue in anaerobic and acidic mire conditions are the Bronze Age bodies from the Netherlands.

The peat has to be protected during long periods of time from marine waters or fluvial clastic influx. An equilibrium has to be present between precipitation and evaporation. An examination of today's peat deposits shows that the majority of peat is accumulating in cool climates, mostly between 50 and 70 degrees North. Correlation of paleo-latitudes with areas of coal deposition shows that coal has been deposited in all latitudes with the majority forming in mid-latitudes (McCabe, 1988).

For thick peat deposits to accumulate, there need to be prolonged continuous subsidence, where organic accumulations can keep up with the subsidence. Areas where these conditions are met range from tectonically active foreland basins to relatively stable intracratonic basins. Areas intermediate between these extremes are passive continental margins and intramontane basins.

FORELAND BASINS

Foreland basins are asymmetric subsiding troughs that form adjacent to active fold and thrust belts. A causal relationship exists between the emplacement of thrusts and the subsidence in the adjacent foreland basin. A fold and thrust belt results from the collision of largescale tectonic plates. All of Alberta's coal deposits originated in a foreland basin. The major coal-bearing rock units and coal zones of Alberta are shown in figure 1 and will be the

	Foothills/mountains	Plains	Major coal zones
Tertiary	Paskapoo Fm.	Paskapoo Fm.	Obed
	Coalspur Fm. (Saunders Gp.)	Scollard Mbr.	Ardley/Coalspur
	Entrance Cgl.		
Upper Cretaceous	Brazeau Fm. (Saunders Gp.)	Battle Fm.	Carbon/Thompson
		Horseshoe Canyon Fm. (Wapiti Fm.)	Drumheller/Cloverbar
		Bearpaw Fm. (Belly River Gp.)	Lethbridge
		Oldman Fm.	Taber
		Foremost Fm.	McKay
	Alberta Gp.	Lea Park Fm.	
		Colorado Gp.	
Lower Cretaceous	Gates Fm. (Luscar Gp.)		Luscar Mannville
	Moosebar Fm.	Mannville Gp.	
	Gladstone Fm.		
	Cadomin Fm.		
Jurassic	Kootenay Gp./Nikanassin Fm.		Kootenay

Figure 1. Table of coal-bearing rock units and coal
zones in Alberta.

subject of many discussions in this short course. The fold
and thrust belt, that we are concerned with for these
deposits, is known as the Rocky Mountains. The sedimentary
rocks, that constitute these mountains, were once flat lying,
but as a result of orogenic (or mountain building) forces ,
they are now deformed and display folds and faults. Faults
are fractures along which relative movements has taken place.
The formation of the mountains and the foreland basin are
shown in cartoon form in figure 2. Periods of intense
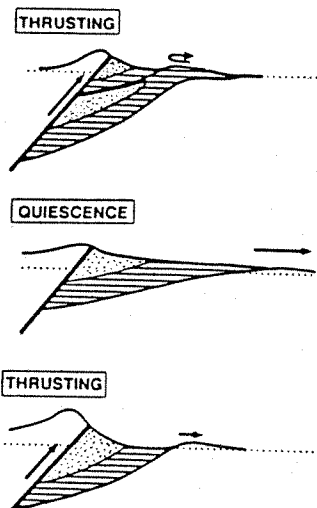
Figure 2. Model for the formation of a foreland basin.
Peripheral bulge indicated by arrows. Coarse
sediments stippled; fine sediments striped.

4

deformation (thrusting) alternate with periods of quiescence. During these periods of quiescence, which could last several million years, peat could accumulate.

INTRAMONTANE BASINS

The Bowser Basin of northern British Columbia is an example of an intramontane basin with large coal resources (figure 3). The Western Canadian Cordillera is a collage of terranes of varied origens, that became attached to the continent at different times. The Bowser Basin lies uncomformably on a terrane known as Stikinia. Sediments were supplied from uplifted rocks around the basin. Parts of the basin did not receive sediments and peat could accumulate, for example in the Groundhog coal field.
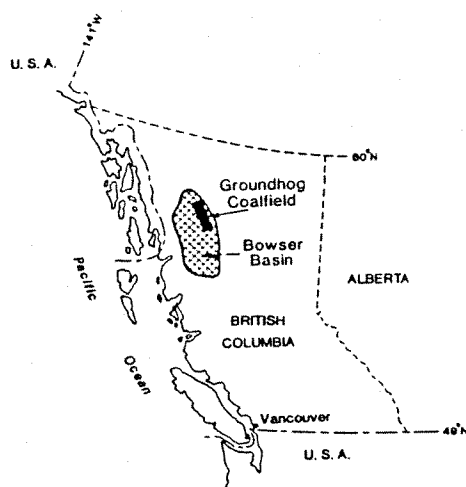
Figure 3. Map showing the outcrop of the location of the Bowser Basin and Groundhog coal field.

PASSIVE CONTINENTAL MARGINS

The Gulf coast is a passive continental margin. During the Tertiary coal deposits of the Wilcox Group (lignites) were formed (figure 4).
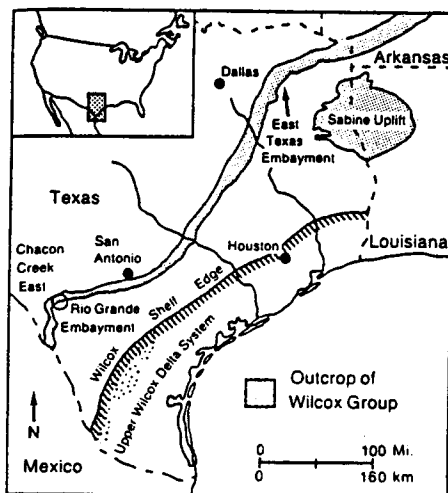
Figure 4. Map showing the outcrop of the coal-bearing
Wilcox Formation in Texas and Arkansas.

INTRACRATONIC BASINS

An example of peat accumulation in intracratonic basins are the Carboniferous coals of the Illinois Basin (figure 5). Intracratonic basins are dominated by vertical tectonic forces. Such areas seldom experience intense deformation and the rank of the coal is often generally low.
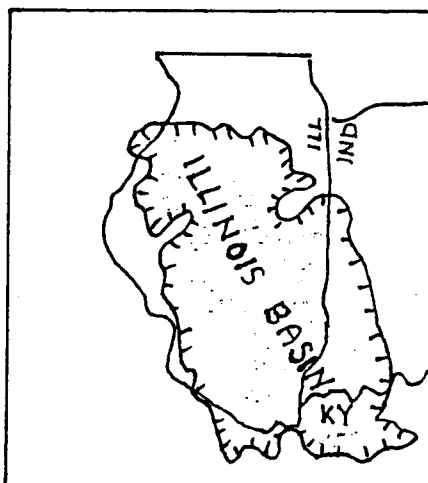
Figure 5. Map showing limit of Carboniferous coal-
bearing rocks in the Illinois Basin.

REFERENCES

Gore, A.J.P. (1983): Introduction; in Gore, A.J.P. (ed),
    Ecosystems of the world. Vol 4A, Mires: Swamp, Bog, Fen
    and Moor, General studies, Elsevier, Amsterdam, pp.1-34.

McCabe, P.J. (1988): Depositional environments of coal and
    coal-bearing strata; Short course in conjunction with
    Sequences, Stratigraphy, Sedimentology: surface and
    subsurface Conference, Canadian Society of Petroleum
    Geologists, Calgary.

COAL COMPOSITION
Wolfgang Kalkreuth
Geological Survey of Canada

1   Transformation of Peat to Coal

The progressive transformation of plant material into peat and coal (Fig. 1) is described by the term coalification and is usually divided into two stages: an early biochemical coalification (diagenesis) which is followed by geochemical coalification (metamorphism).   The degree of transformation of the organic material (peat, lignite, subbituminous, bituminous, semianthracite, anthracite) is referred to as the coal rank.
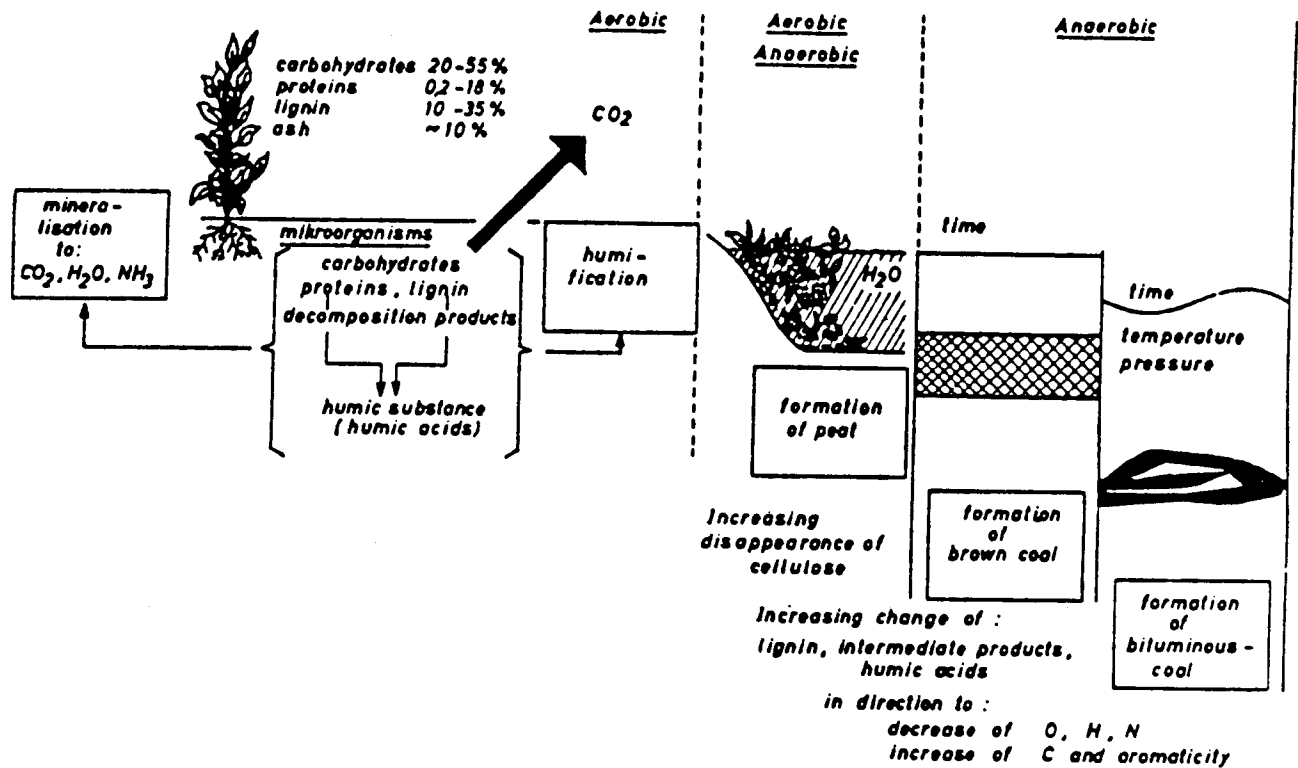
Fig. 1.   Mineralization and humification; the formation of peat, brown coal and bituminous coal (from Flaig, 1968).

1.1   Biochemical Coalification

The biochemical stage of coalification encompasses those changes that occur within the peat swamp during accumulation of the organic matter and in coals up to the transition from lignite into subbituminous coals.   The degradation of the organic matter during the early stage of biochemical coalification is controlled mainly by the height of the water tables within the swamps, oxygen availability and the degree of biological degradation by bacteria and fungi.   The plant materials are likely to undergo one of four processes whose results are very different (Fig. 2):

8

Process   Product

disintegration   usually no solid residue,
                        possibly liptobioliths

mouldering   mould

peatification   peat   humic coals

putrefaction   sapropel   sapropelic coals

                                        sapropelites

                        petroleum

Aerobic   Decrease of O₂ supply   Anaerobic

And nitrogen in   Increase of hydrogen   Transformation products

Fig. 2.   Effects of oxygen availability on transformation of peat
           (modified from Potonie, 1920 in Teichmüller and Teichmüller,
           1982)

1. *Disintegration*. Decay of the organic matter as a function of exposure to atmosphere oxygen. Products are carbon dioxide, biogenic methane and water.

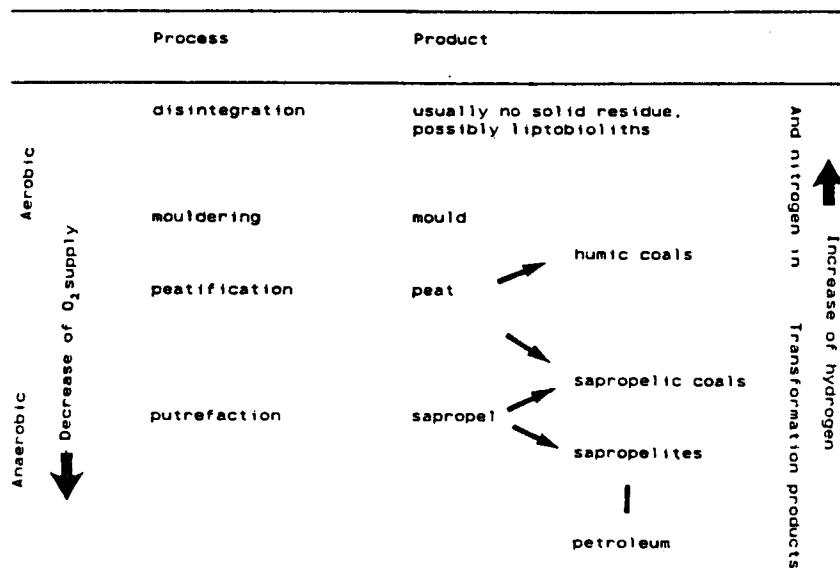2. *Mouldering or rotting*. Access of atmospheric oxygen is restricted because of high moisture (dampness) of the environment. The organic matter is converted into humus.

3. *Peatification*. In cases of permanently high water tables the plant debris is to a large extent preserved in a predominantly reducing environment. The end products are the humic coals which constitute the majority of the economically important coalfields.

4. *Putrefaction*. This process takes place in predominantly stagnant water under highly reducing conditions. The organic material accumulates as debris of aquatic plants (mainly algae), drifted humic materials and plankton. The result is a sapropelic mud from which sapropelic coals (cannel and boghead coals) are formed.

With increasing burial of the peat chemical and physical changes occur. As a result of compaction the moisture content decreases and carbon content increases shown by decreasing atomic O/C - ratios (Fig. 3). This process is accompanied by humification and gelification of the plant materials. The main coal precursor materials (lignin and cellulose) are progressively oxidized to form humic acids and humins. The chemical processes associated

with the formation of humic acids and humins (humification) and the gelification process, by which the humic matter passes through a soft plastic gel are as yet poorly understood. The resulting organic matter is referred to as the huminite group in lignite and subbituminous coals. The lipid-rich fraction of the peat such as spore and pollen exines are relatively resistant to aerobic and anearobic degradation and do not undergo humification and gelification. The same holds true for that proportion of woody material in peat that has been derived from wood and/or peat fires. Those components have attained a relatively high degree of aromatization prior to sedimentation and undergo no or very little alteration during the course of coalification. Examples for the various organic components in lignites and subbituminous coals as determined by coal petrographic methods will be illustrated in the chapter on petrographic characterization of coal.
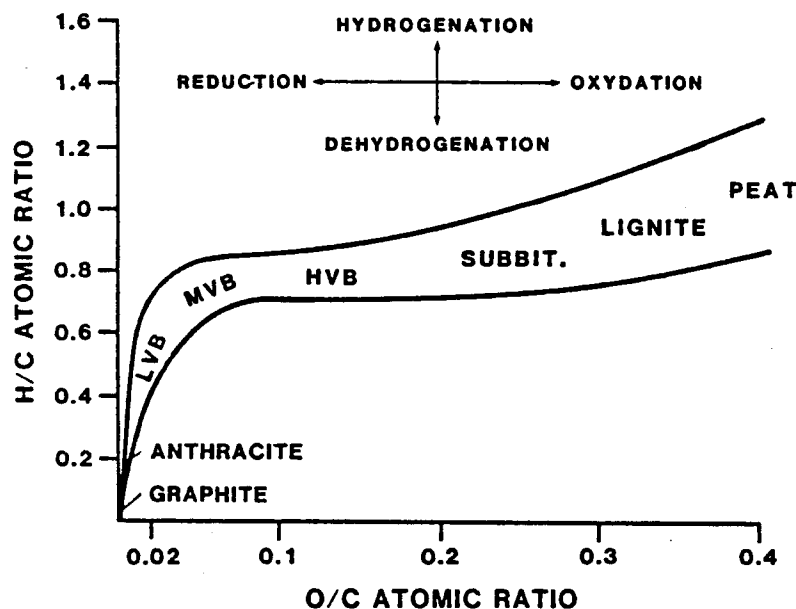
Fig. 3.   van Krevelen diagram illustrating range of H/C and O/C
           atomic ratios for various coalification stages
           (from van Krevelen, 1961)

1.2   Geochemical Coalification

The geochemical coalification stage encompasses the coal rank stages from lignite/subbit. coals to meta-anthracite. The degree of transformation of the organic matter in this range is controlled mainly by depth of burial (temperature) and to some extent to the time the coal has been exposed to that temperature. Pressure, although important in the early stage of biochemical coalification, resulting in compaction of the peat and expulsion of water, is not considered to have a significant effect during the geochemical stage of coalification.

molecules parallel to bedding

molecular structure
-o-= hydrogen bonding
— =molecular bonding
lenses =aromatic clusters
lines =non-aromatic elements

high volatile bituminous coal
(~35% vol. m.)

medium volatile bituminous coal
(~22% vol.m.)

anthracite
(~5% vol.m.)

molecules perpendicular to the bedding

chemical properties in relation to carbon content (daf)

aromacity

ring condensation

dimension of aromatic clusters
(crystallites ———)

free radicals

solubility in ethylenediamine

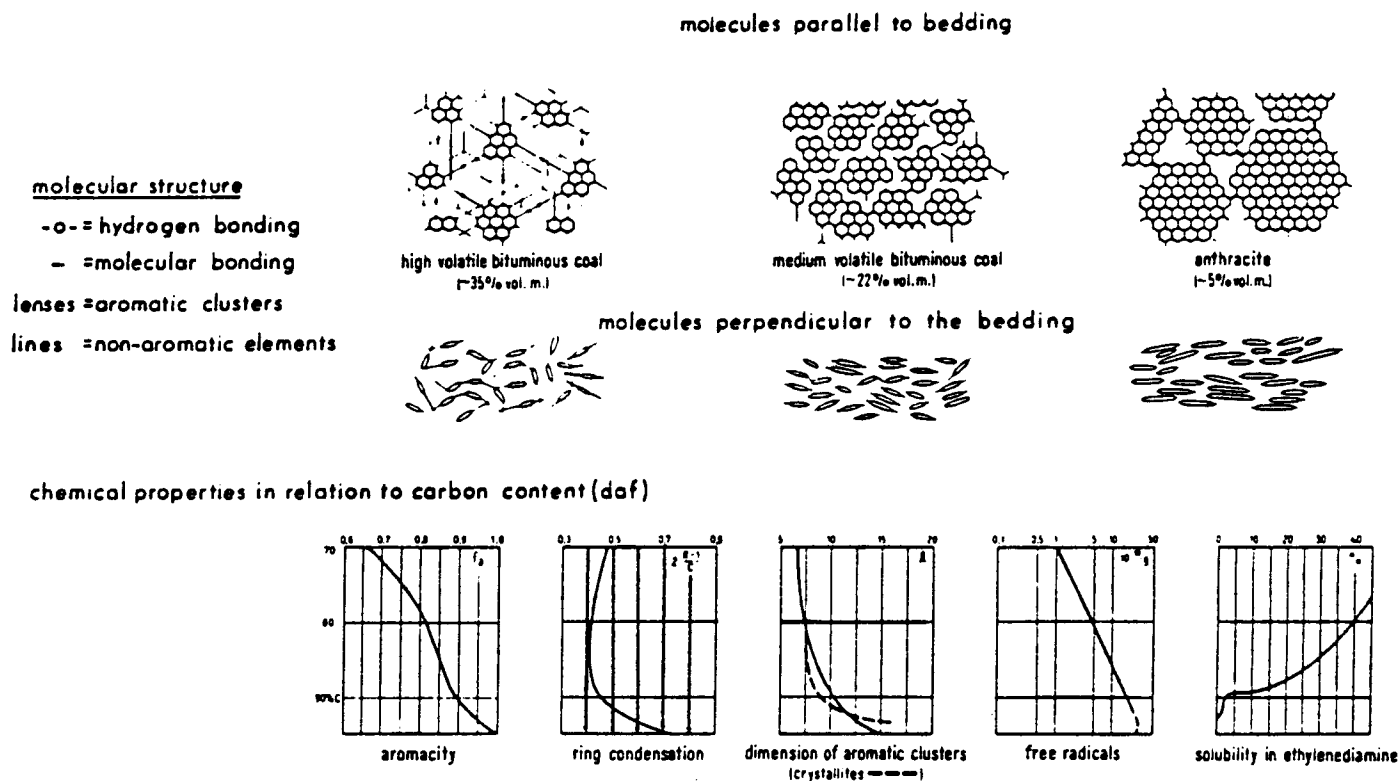Fig. 4. Changes in the chemical and physical properties of coal with increasing
rank. Modified from Teichmüller and Teichmüller (1982)

With increasing rank the carbon content continues to increase, while at the same time oxygen and hydrogen contents decrease (Fig. 3). The main by-products of coalification at this stage are carbon dioxide and methane. Associated with the loss of volatile compounds is an increase of aromaticity within the coal molecular structure (Fig. 4). The increase in carbon contents in coals as rank increases and the relation to the North American and German coal rank classifications is shown in Fig. 5. This figure shows also the relationship of coal rank to other important rank parameter such as volatile matter, moisture content, calorific value and vitrinite reflectance. The relationship between coal rank and vitrinite reflectance will be discussed in more detail in the chapter on vitrinite reflectance measurement.

Petrographically the coals are characterized by an increased homogenization of the organic matter and increasing reflectances of the various organic components. Examples will be given in the chapter on petrographic characterization of coal.

| RANK | | Refl. Rm oil % | Vol. M. d.a.f. % | Carbon d.a.f. Vitrite | Bed Moisture | Cal. Value Btu/lb (kcal/kg) | APPLICABILITY OF DIFFERENT RANK PARAMETRES |
GERMAN	USA						

Table (figure) content:

- 0.2
- 68

TORF — PEAT

- 64
- ca. 60 — ca. 75

WEICH-
BRAUNKOHLE
LIGNITE
- 0.3 — 60
- 56 — ca. 35 — 7200 (4000)

MATT-
SUB- BIT. C
- 0.4 — 52
B — ca. 71 — ca. 25 — 9900 (5500)
- 48

GLANZ-
C A
- 0.5
- 0.6 — 44 — ca. 77 — ca. 8-10 — 12600 (7000)

FLAMM-
B HIGH VOL. BIT.
- 0.7 — 40

GASFLAMM-
A
- 0.8
- 0.9 — 36
- 1.0

GAS-
STEINKOHLE
- 32
MED. VOL. BIT.
- 1.2 — 28 — ca.87 — 15500 (8650)

FETT-
- 1.4 — 24

LOW VOL. BIT.
- 1.6 — 20

ESS-
- 1.8 — 16

MAGER-
SEMI-ANTHR.
- 2.0 — 12

ANTHRAZIT
- 8 — ca. 91 — 15500 (8650)

ANTHR.
- 3.0
- 4.0 — 4

META-ANTHR. — META-A.

Right-side parameter bars:
BED MOISTURE (ASH-FREE)
CALORIFIC VALUE (MOIST, ASH-FREE)
CARBON (DRY, ASH-FREE)
VOLATILE MATTER (DRY, ASH-FREE)
REFLECTANCE OF VITRINITE
HYDROGEN (d.a.f.)
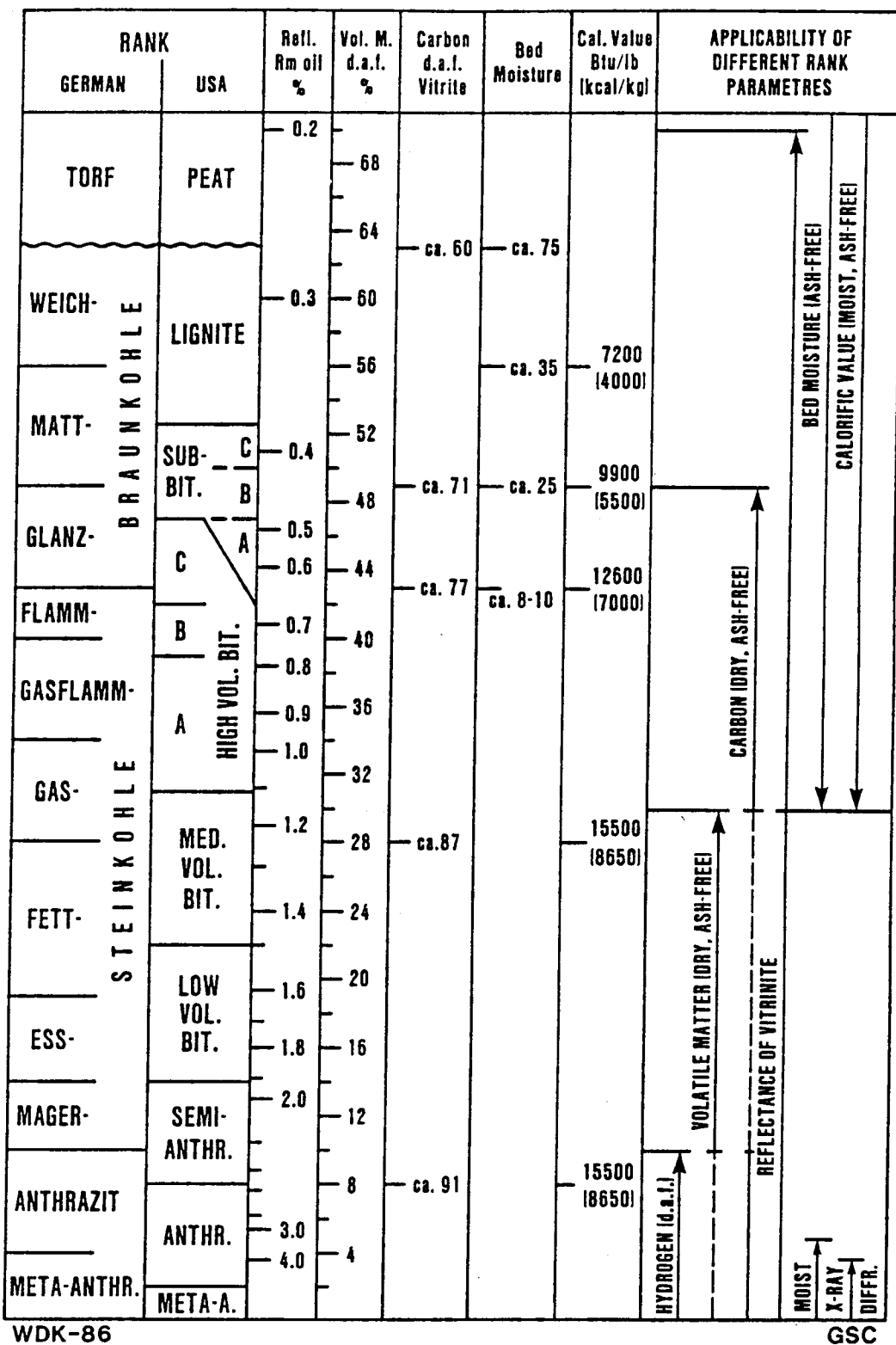MOIST — X-RAY — DIFFR.

WDK-86   GSC

Fig. 5. Stages of coalification based on physical and chemical properties of coals and the range of applicabilities for the various rank parameter (from Teichmüller and Teichmüller, 1982)

2   Petrographic Characterization of Coal

Petrographic characterization of coal can be carried out on a macroscopical and microscopical scale. The macroscopically recognizable bands of humic coals are called lithotypes, whereas microscopically recognizable organic components are called macerals. In addition a number of minerals can be identified both in the megascopical and microscopical scale.

2.1   Lithotypes

Vertical and lateral changes of lithotypes in humic coals reflect changes of plant communities, which gave rise to different layers in the parent coal. They also reflect changes in chemical and physical conditions, which affected the preservation and accumulation of plant materials in the ancient peat swamp and the input of mineral matter. The Stopes system of the ICCP (Int. Comm. of Coal Petrology) identifies four lithotypes (Fig. 6), whereas for example the system used in Australia defines six lithotypes according to estimated proportions of bright and dull layers (Fig. 6). Commonly a layer has to be thicker than 1 cm to constitute a lithotype. One example of the macroscopic appearance of lithotypes in a bituminous coal is shown on Plate I. In contrast to humic coals there is no banding recognizable in sapropelic coals. These coals are instead characterized by typical conchoidal fracture and a greasy lustre (Plate 1).

Divisions after Stopes	Divisions as used for Australian coals	Description
Vitrain	Bright coal	Subvitreous to vitreous lustre, or conchoidal fracture <10 per cent dull
	Banded bright coal	Bright coal with some thin dull bands 10-40 per cent dull
Clarain	Banded coal	Bright and dull coal bands in equal proportion 40-60 per cent dull
	Banded dull coal	Dull coal with some thin bright bands 10-40 per cent bright
Durain	Dull coal	Matt lustre, uneven fracture <10 per cent bright
Fusain	Fibrous coal	Satin lustre, friable

Fig. 6.   The correlation between lithotypes after Stopes and those distinguished in N.S.W. (Australia) coals. (Modified from Diessel, 1965)

A lithotype classification scheme for lignites and subbituminous coals is shown in Fig. 7. This classification scheme is based on the proportions of groundmass to woody (xylitic) remains and the relative abundance of impurities.

Recent results on vertical and lateral lithotype variation in western Canadian bituminous coals (Lamberson et al, in press; Marchioni and Kalkreuth, in press) have been used to define relationships between coal facies, petrographic composition and depositional environments of Lower Cretaceous peat swamps and the interested reader is referred to the above papers. In the context of this guidebook two examples are given to illustrate lithotype variations in coal seams from the Smoky and Cadomin-Luscar Coalfields, both of which will be visited during the field trip.

Smoky River Coalfield. Fig. 8 shows vertical lithotype variations for three seams. The lithotype variations observed in these seams are considered to reflect fluctuations in water table heights accompanied by a change of vegetation. The bright lithotype varieties indicate an accumulation of the organic matter in a wet forest-type moor (Fig. 9), whereas the banded and banded dull varieties indicate a shift to somewhat drier conditions.

MACROPETROGRAPHIC CLASSIFICATION OF LIGNITES (A AND B)						
categories	lithotype-classes	lithotypes	lithotype-varieties			
reading column matrix	10	20	30	40	50	
quality parameter	structure;presence of xylite and/or contamination by mineral matter	texture: ratio between groundmass and plant remains	intensity and hue of colour	evidence of gelification	inclusions	additional features
macropetro-graphic description	1 pure coal, non-xylitic pure coal, xyl. fibrous xylite brittle xylite 2 -------- tree stumps tree trunks etc. impure coal, non-xylitic 3 clayey coal sandy coal calcareous coal iron sulphides etc. 4 impure coal, xylitic	1 unbanded coal moderately 2 banded coal 3 banded coal 4 highly banded coal	1 pale-yellow 2 medium light-yellow 3 pale-brown 4 medium light-brown 5 dark-brown 6 dark-black	1 gelified groundmass (+,++,+++) 2 gelified tissues (+,++,+++) 3 microgranu-lar humic gel parti-cles (+,++,+++) 4 -	1 resin bodies (+,++,+++) 2 cuticles (+,++,+++) 3 charcoal (+,++,+++) 3 -	a) surface tex-ture extensive cracking moderate cracking no cracking b) fracture even imbricated c) size degra-dation coarse frag-mentation fine frag-mentation crumbling

Fig. 7. Macropetrographic classification of lignite
(from Hagemann and Hollerbach, 1979)

An accumulation of the organic matter towards limnic conditions is indicated by some of the dull varieties by their positioning in the ternary diagram (Fig. 9).

Cadomin-Luscar Coalfield. Vertical lithotype variations for the Jewel seam of the Cadomin-Luscar Coalfield are shown in Fig. 10. This figure shows that the lithotypes are characterized by varying amounts of organic components (maceral groups). Certain organic components tend to be enriched in the brighter lithotype varieties (Fig. 11) whereas others are concentrated in the duller varieties. In other words, lithotype analysis can to a certain extent be used to estimate the type and amount of organic components contained in a seam.
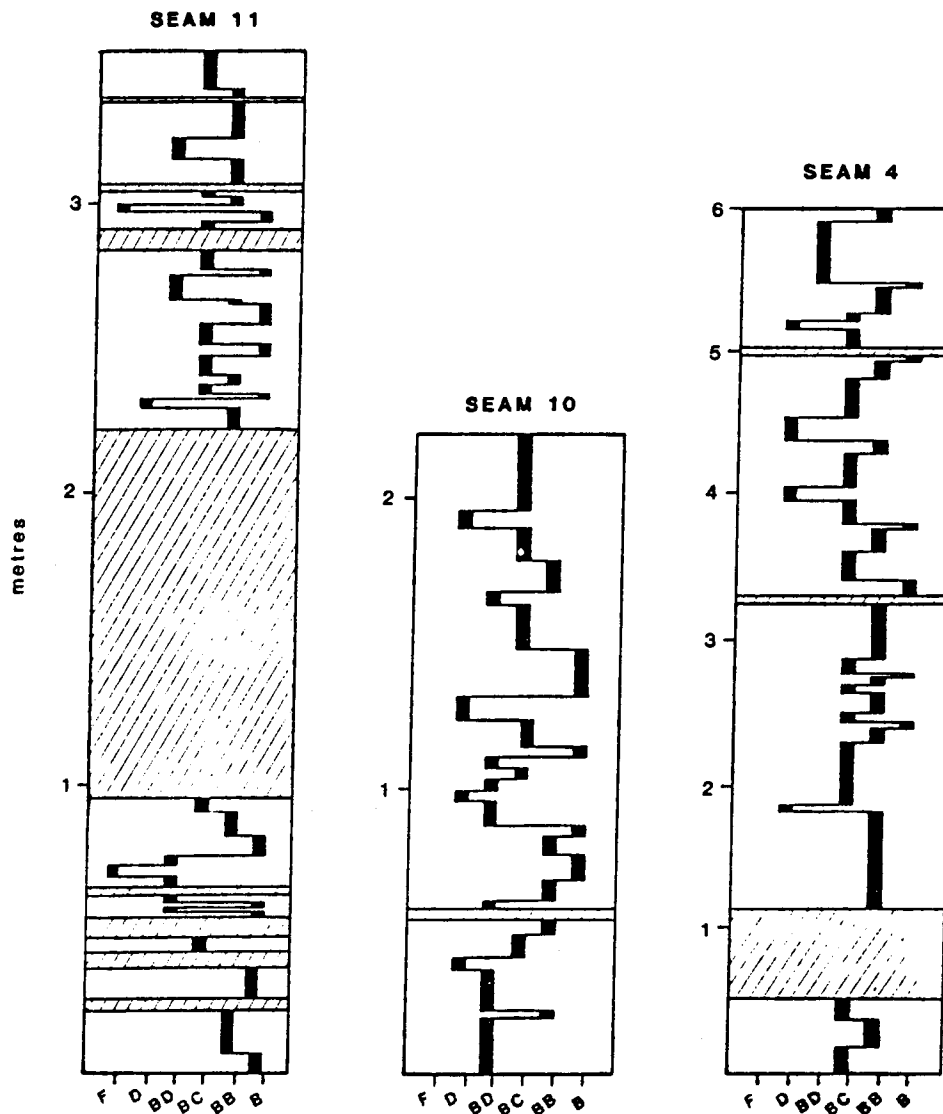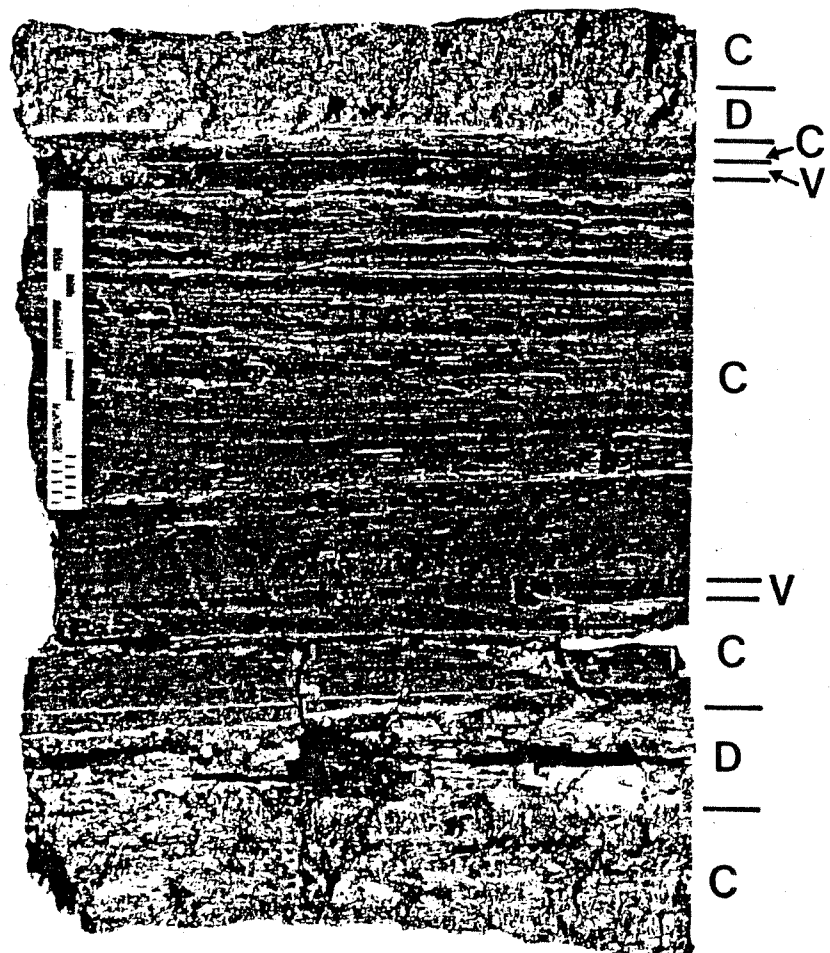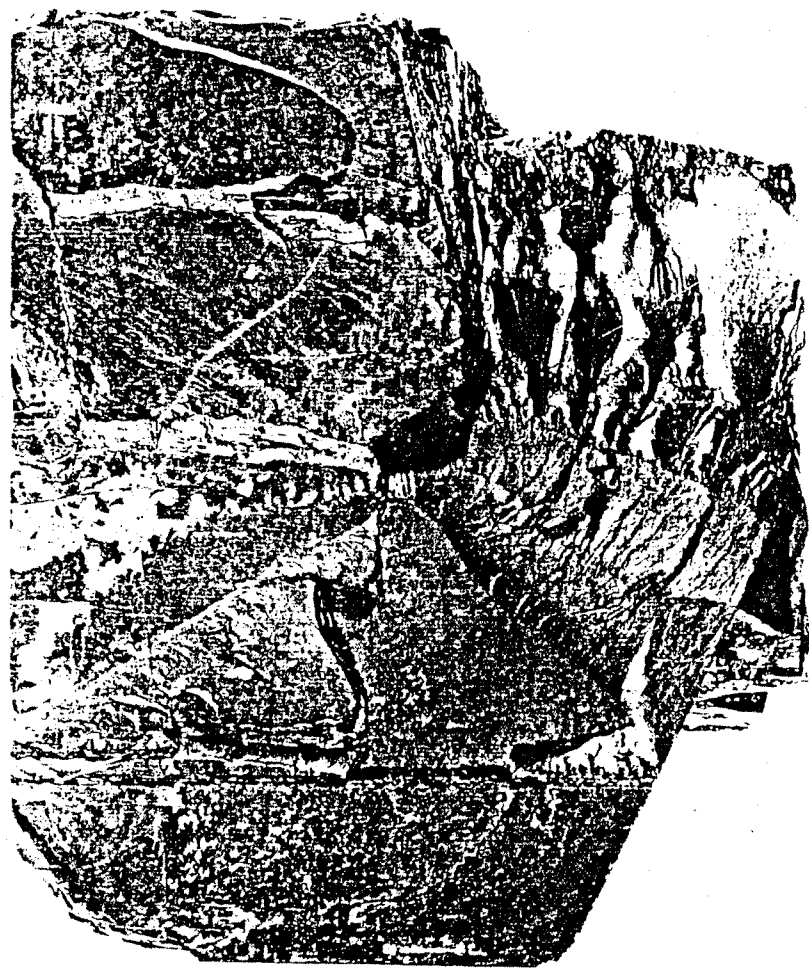

Fig. 8. Lithotype Profiles for Seams 11, 10 and 4; Smoky River Coalfield
(from Marchioni and Kalkreuth, in press)

Fig. 9. Facies diagram of mean composition of lithotypes for selecteds seams
in the Smoky River Coalfield (from Marchioni and Kalkreuth, in press)
Apices of ternary diagram:
T = telenite + telocollinite (+ rare in-situ resinite)
F = fusinite + semifusinite (+ rare groundmass macrinite)
D = Inertodetrinite (+ rare vitrodetrinite, sporinite, and
    discrete macrinite)

PLATE I   (see following page)

Macroscopic appearance of coal lithotypes.

A)   Naturally broken cleat face of Pennsylvanian age bituminous coal
(Harbour seam, Sydney Coalfield, Nova Scotia) showing examples of
three lithotypes; vitrain (V), clarian (C), and durain (D). Note the
extremely rapid lateral thickness change in some of the vitrain layers.

B)   Naturally broken surface of cannel coal of Pennsylvanian age from
West Virginia. Note the uniformly dull appearance of this lithotype;
upper right-hand corner of block shows typical conchoidal fracture and
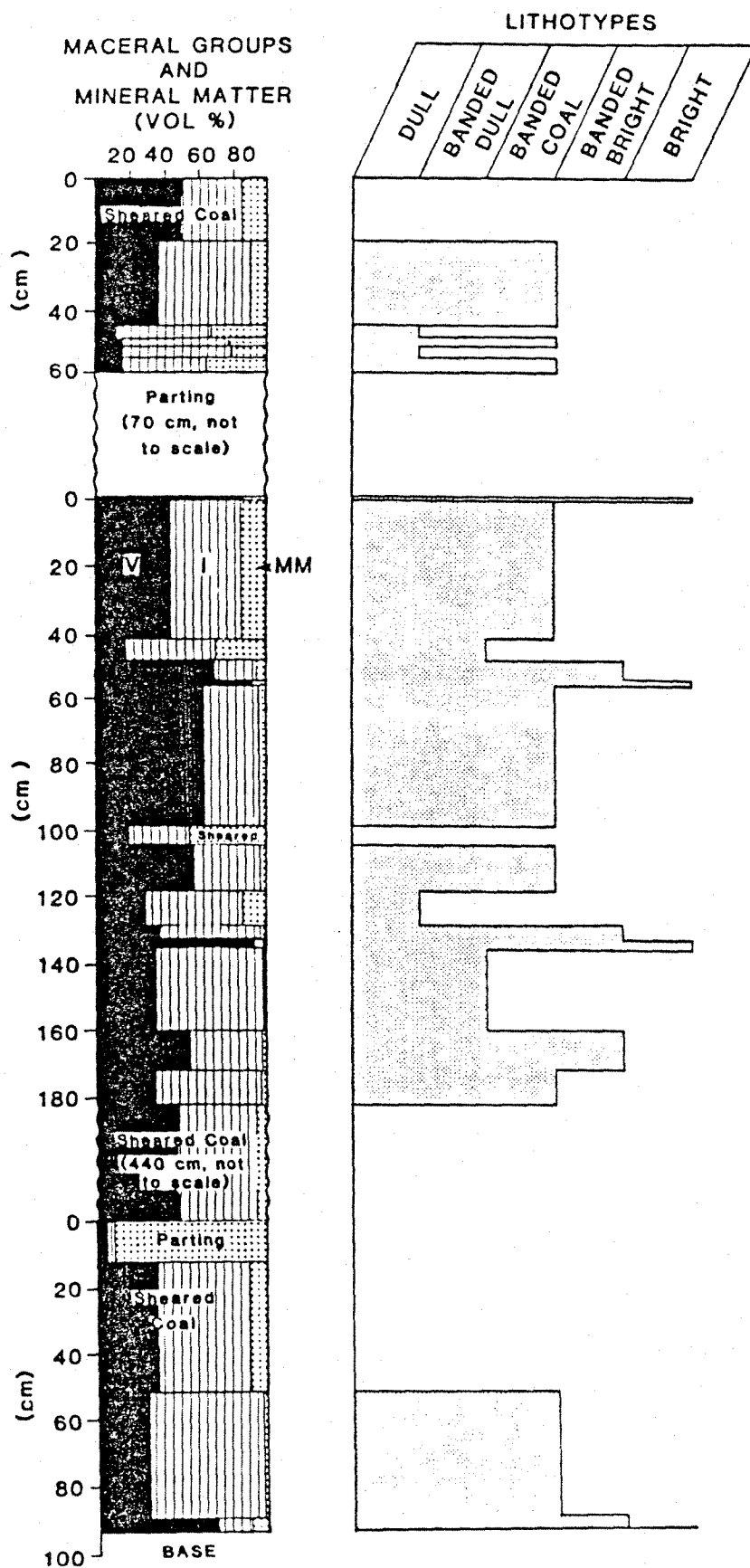greasy luster.

Plate I

Fig. 10. Macroscopic and microscopic log of the Jewel Seam, CD Pit, D limb. Right column shows lithotype variations for undeformed sections of the Jewel Seam. Abundance of lithotypes for this section: 2% bright, 10% banded bright, 69% banded, 12% banded dull and 7% dull coal. Left column shows contents of vitrinite (V), inertinite (I) and mineral matter (MM) for each lithotype. Data from Kalkreuth, Paul and Steller, unpublished.
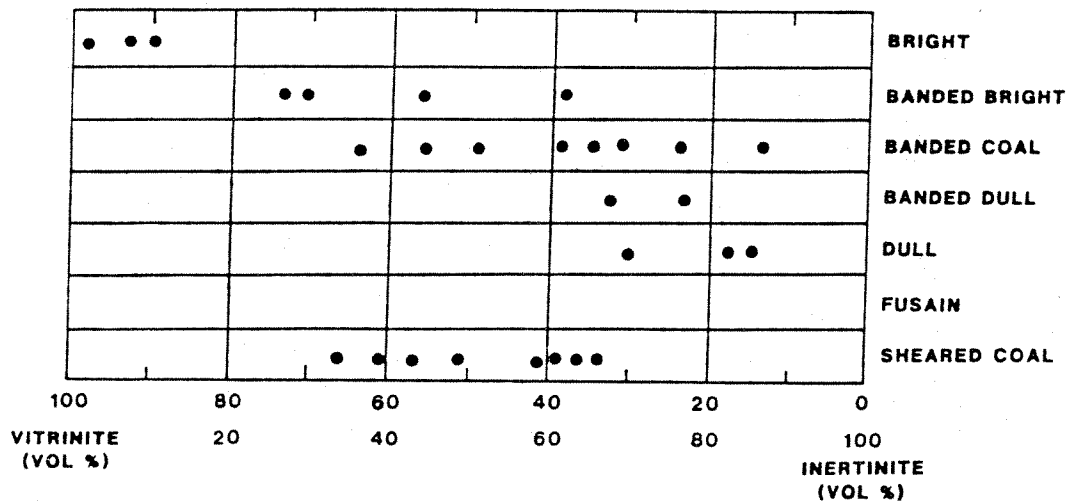
Fig. 11. Ranges in vitrinite and inertinite contents for lithotypes
identified in the Jewel Seam, CD Pit, D limb. Vitrinite and
inertinite contents of sheared intervals are also shown.
Data from Kalkreuth, Paul and Steller, unpublished.

2.2 Macerals

Coal is not a homogeneous substance but consists of various basic components analogous to the minerals

of inorganic rocks. In coal these components are called macerals. In low rank coals in particular they can be

further divided into maceral types and maceral varieties. The macerals are classified into three groups: vitrinite,

liptinite, and inertinite either because of similar origin (liptinite group) or because of differences in preservation

(macerals of vitrinite and inertinite groups). In low rank coals the term huminite is used instead of vitrinite,

along with a greater variety of distinguishable macerals, submacerals, and maceral varieties (Fig. 12). Macerals

of the liptinite and inertinite groups are used under the same names in low and high rank coals (Fig. 13).

Chemical and physical properties of the macerals such as elemental composition, moisture content,

hardness, density, etc. and petrographic features differ widely and are also subject to changes in the course of

diagenesis and coalification. Fig. 14 shows the coalification tracks of liptinite, inertinite and huminite/vitrinite

groups as a function of atomic H/C-O/C-ratios. These differences in chemical and physical properties are also

reflected in the technological behaviour of the macerals.

Brown Coal — Lignite					Bituminous Coal		
Maceral Group	Maceral Subgroup	Maceral	Maceral Type	Maceral Variety	Maceral Type	Maceral	Maceral Group
huminite	humotelinite	textinite		A (dark) B (light)			vitrinite
		ulminite	texto-ulminite	A (dark) B (light)	telinite 1	telinite	
			eu-ulminite	A (dark) B (light)	telinite 2		
	humodetrinite	attrinite densinite				vitrodetrinite	
	humocollinite	gelinite	levi-gelinite detrogelinite telogelinite eugelinite		desmocollinite telocollinite	collinite	
			porigelinite		gelocollinite		
		corpo-huminite	phlobaphinite pseudo-phlobaphinite		corpocollinite		

Fig. 12. Correlation of the huminite macerals of brown coals and lignites with the vitrinite macerals of bituminous coals (from Stach, 1982)

Maceral Group	Maceral	Maceral Type	Maceral Variety
Liptinite	Sporinite		Tenuisporinite Crassisporinite Microsporinite Macrosporinite
	Cutinite Resinite Alginite		Pila-Alginite Reinschia-Alginite
	Liptodetrinite Fluorinite Bituminite Exsudatinite Suberinite		
Inertinite	Micrinite Macrinite Semifusinite Fusinite	Pyrofusinite Degradofusinite	
	Sclerotinite	Fungosclerotinite	Plectenchyminite Corposclerotinite Pseudocorposclerotinite
	Inertodetrinite		

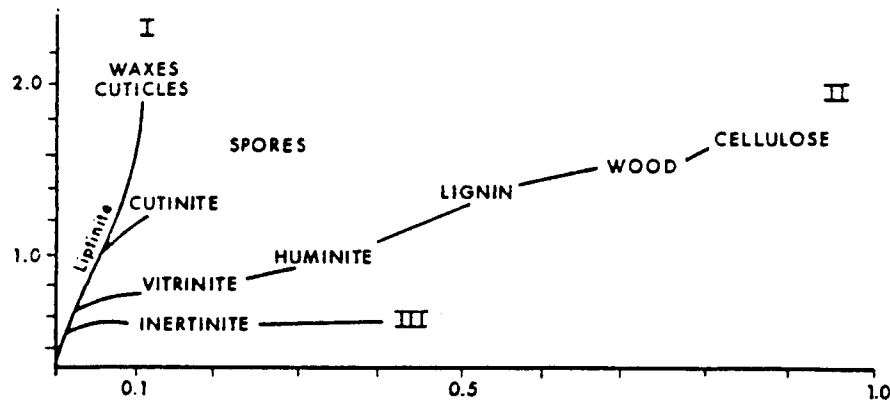Fig. 13. Macerals of Liptinite and Inertinite Groups

Fig. 14. van Krevelen diagram showing the coalification tracks of
liptinite, inertinite, and huminite-vitrinite.
Modified from Tissot and Welte (1978)

The petrographic properties of macerals are described either by means of transmitted light or incident

light microscopy. Transmitted light can be used readily up to the rank of low volatile bituminous, at higher rank

levels the organic material becomes opaque. Incident light microscopy has the advantage that coals over the

complete range of rank from peat to anthracite and graphite can be analysed both qualitatively and quantitatively.

The main parameters used to distinguish the macerals in incident light are:

(1)   Reflectance, anisotropy;

(2)   Morphology, relief, size;

(3)   Etching;

(4)   Fluorescence

(1)   Reflectance and Anisotropy

In low to intermediate rank coals (lignites to low-volatile bituminous), the three maceral groups can be

distinguished by different grey levels. With increase in rank the differences in reflectance between

macerals diminish due to an overall convergence of chemical and physical properties (Figure 15). With

increase in rank, coal becomes distinctly anisotropic due to increasing aromatization and orientation of

the molecular structure. This effect is measured in terms of maximum reflectance and minimum

reflectance and is expressed as:

Anisotropy = Maximum reflectance - minimum reflectance.

As can be seen from Figure 15 anisotropic effects (Vmax, Vmin) can be observed in coals having vitrinite

reflectances of 0.6% and more. Macerals of the liptinite and inertinite groups are in general isotropic.
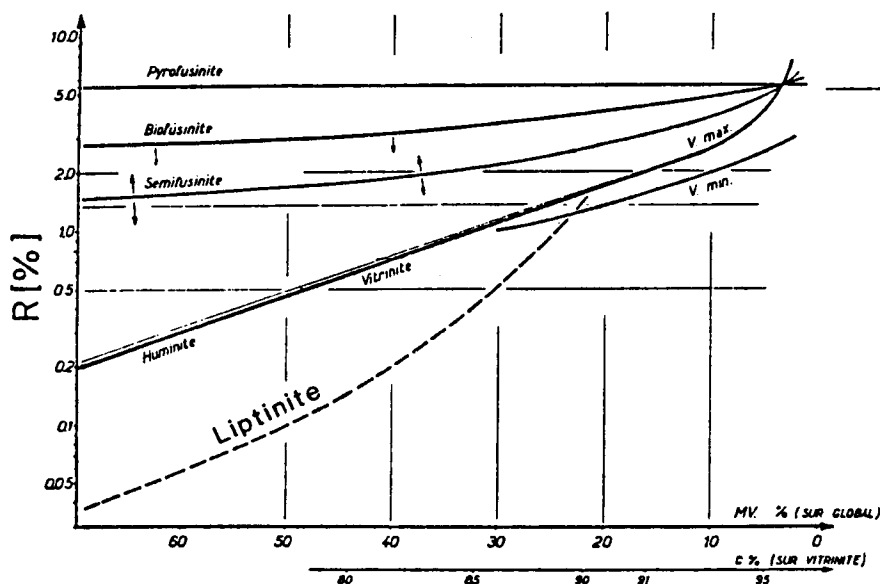
Fig. 15. Changes in reflectance of liptinite, vitrinite, and
inertinite macerals with increasing rank
(modified from Alpern and Lemos de Sousa, 1970)

(2)   Morphology, Relief, Size

Shape (form), size, and internal structures are used to distinguish macerals where reflectance is similar

but morphology is different. Besides differences in morphology and size, the macerals are characterized

by differences in relief when observed in incident light. This effect is caused by variations in hardness.

Liptinite macerals, such as alginite, sporinite, and cutinite, tend to show positive relief as compared to

the vitrinite matrix, whereas others such as resinite or exsudatinite do not show any significant change

in relief as compared to vitrinite. Macerals of the inertinite group are in general characterized by

positive relief.

(3)   Etching

Etching the polished surface of coal can give better insight into the nature of the macerals and can be

used to enhance differences among macerals, in particular by comparison of etched and unetched

portions of the same maceral. The etching procedure is essentially an oxidizing process. The surface

of the coal is exposed to a strong oxidizing agent, for example, a mixture of $KMnO_4$, H_2SO_4, and H_2O. The duration of exposure to this agent depends on the rank of the coal.

(4)   Fluorescence

The macerals, in particular those of the liptinite group, show autofluorescence under blue light and ultraviolet light excitation. Fluorescence intensities and colours vary from one maceral to the other and are also subject to changes in the course of coalification.

Brief descriptions of the more common macerals follow. For further details see International Handbook of Coal Petrology (1971, 1975), Stach's Textbook of Coal Petrology (1982) and Bustin et al (1989).

2.2.1   *Huminite/Vitrinite Group*

The huminite/vitrinite group is commonly the most abundant group in coals. The macerals have been derived from woody tissues and bark of trees. The cell structure can often still be found, in particular in low rank coals. The term huminite applies to this group when used in the description of lignites and subbituminous coals, see Fig. 12.

The main characteristics of the huminite macerals are listed below:

Maceral	Origin	Petrological Features
textinite	woody tissue	primary cell wall structure still distinguishable. cell lumina mostly open
ulminite	woody tissue	higher degree of humification: *texto-ulminite* = cell wall structure still visible. *eu-ulminite* = no visible cell wall structure. cell lumina mostly closed
attrinite	finely comminuted	particle size < 10 micron degradation product of the other huminite macerals
densinite	same as attrinite	tighter packed than attrinite
gelinite	derived from collodal humic solutions which migrate into existing cavities and precipitate as gels	secondary cell filling
corpohuminite	condensation products of tannins, characteristic for bark tissues	in cross-section globular to tabular shaped

Increase of rank leads to homogenization of the macerals of the huminite/vitrinite group. In bituminous coals the term telinite is used to describe vitrinite characterized by faint cell structure. The term collinite is used to describe homogeneous structureless vitrinite. The term pseudovitrinite is applied to a special form of vitrinite, found and described first in Appalachian coking coals by Benedict et al (1968). The petrological characteristics of pseudovitrinite are: reflectance at least 0.025 per cent higher than normal vitrinite; slit-like openings; presence of cell structure; serrated boundaries of grains. Examples for macerals of huminite and vitrinite groups are illustrated on Plate II.

2.2.2   *Liptinite Group*

This group of macerals can be divided into two subgroups. Macerals of the first subgroup can be distinguished by means of normal reflected light supplemented by observations in the fluorescent mode. It comprises coalified exines of pollen and spores (sporinite), resins (resinite), cuticles (cutinite), algae (alginite), and suberinite, a liptinitic cell-wall material typically found in bark tissues. In the lower part of the rank scale these liptinite macerals are characterized by a much lower reflectance than the corresponding vitrinite of the same rank. With increase in rank, the reflectance increases slowly up to the stage of medium-volatile bituminous coals. At this point (ca. 1.1 per cent vitrinite reflectance) the reflectance of the liptinites increases rapidly and reaches the reflectance of the vitrinite (second coalification jump) when the rank of low-volatile bituminous is attained (ca. 1.35 to 1.5 per cent). Macerals of the second group can only be detected and distinguished from mineral matter and mounting medium by fluorescent light. It comprises the macerals fluorinite, bituminite, and exsudatinite (Fig. 13). The petrological properties of liptinite macerals are summarized as follows:

Maceral	Origin	Petrological Features
sporinite	pollen, spores	individual bodies with distinct cell walls, high relief
cutinite	cuticles	serrated edges, high relief
alginite	algae	individual bodies or colonies, high relief
resinite	resin, waxes	secondary cell-filling, often zonation and internal reflections
suberinite	bark tissues	cell-wall material associated with phlobaphinite
liptodetrinite	degradation product of liptinitic macerals	
exsudatinite	secondary maceral, formed from lipid constituents of liptinites and huminites	filling veins and cell lumina, strong fluorescence intensities of varying colours, black in normal reflectance light
fluorinite	uncertain, probably from plant oil	ng fluorescence, black in normal reflected light, no definite shape
bituminite	uncertain, probably decomposition product of algae, animal plankton, and bacterial lipids	no definite shape, ground-mass for other macerals, weak fluorescence, strong alteration after UV-excitation

Examples for macerals of the liptinite group are illustrated on Plate III.

2.2.3   *Inertinite Group*

The inertinite group comprises macerals which in general are characterized by higher reflectances than the corresponding vitrinite of the same rank. The processes which produce some of the inertinite macerals, for example, fusinite and semifusinite, are different from those which produce vitrinite from the same parent material. During the course of coalification the petrographic properties of the inertinites vary very little due to the fact that aromatization has taken place before or at a very early stage after deposition (charring, oxidation, mouldering, fungal attack). Exceptions are the maceral semifusinite, which represents an intermediate stage between vitrinite and fusinite and whose properties are believed to change considerably during the course of coalification and the maceral micrinite, which is considered to be formed as a secondary maceral at the transition between subbituminous to bituminous coals.

The petrological properties of inertinite macerals are summarized as follows:

Maceral	Origin	Petrological Features
fusinite	woody tissue	high reflectance, colour white to yellowish, open cell lumina, thin cell walls, 'bogen' structure
semifusinite	woody tissue	reflectance between vitrinite and fusinite, smaller cell lumina often closed, often cloudy appearance, anisotropic
macrinite	uncertain, probably formed through oxidation of gelified plant materials	amorphous bodies of irregular shape, high reflectance
micrinite	secondary maceral, genesis in part related to occurrence of liptinite macerals	small size, ca. 1 micrometre granular appearance, high reflectance
sclerotinite	fungal mycelia, fungal spores	cellular structure, high reflectance
inertodetrinite		fragments of other inertinitic macerals (normally < 30 micrometres)

Examples of inertinite macerals are illustrated on Plate IV.

2.2.4 *Maceral Analysis*

The maceral content of a given coal sample is determined by random point count of a larger number of points. ASTM (D-2799) suggests that a minimum of 1000 points on each of two samples should be counted. If the results from two samples agree within 2 per cent mean variance, the average of the two results is acceptable. The mean variance is calculated by: Mean Variance = $(\Delta V_{Vi} + \Delta V_{In} + \Delta V_{Li}) / 3$

where ΔV = difference in volume per cent of each maceral between the two samples.

Prior to the point counting the coal has to be crushed to a prescribed grain size, split, pelletized, ground and polished. For details of sampling and sample preparation the reader is referred to Bustin et al (1989).
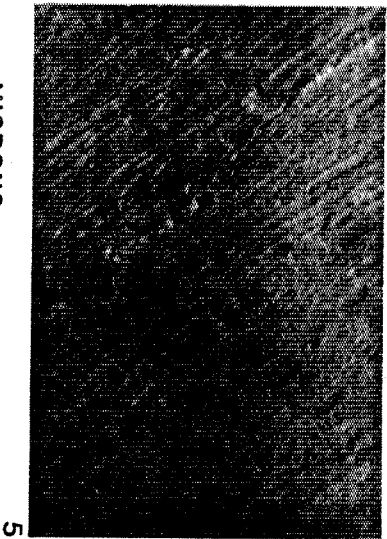
PLATE II   (see following page)

Macerals of the huminite/vitrinite group (reflected light, oil immersion).

Figure 1.   *Textinite* characterized by wide open cell-lumina and cell-wall layering associated with *corpohuminite* (C) in a lignite from Greece, Tertiary in age.

Figure 2.   *Texto-ulminite*, most of the cell-lumina are compressed. Lignite, Areece, Tertiary in age.

Figure 3.   *Eu-ulminite* associated with *corpohuminite* (C) in a lignite from Greece, Tertiary in age.

Figure 4.   *Eu-ulminite* and *corpohuminite* (C) in a subbituminous coal. Drumheller area, Alberta, Late Cretaceous in age.

Figure 5.   *Telinite* in a high-volatile A bituminous coal. Peace River Coalfield, British Columbia, Early Cretaceous in age.

Figure 6.   *Attrinite* in Rhenish brown coal, Cologne area, West Germany, Tertiary in age (from Hagemann, RWTH, Aachen).

Figure 7.   *Densinite* (D) and *gelinite* (G) in a subbituminous coal. Drumheller area, Alberta, Late Cretaceous in age.

Figure 8.   *Desmocollinite* (Dc) associated with macerals of the liptinite and inertinite groups. Sclerotinite (Sc), inertodetrinite (I), and cutinite (Cu). Subbituminous coal, Drumheller area, Alberta. Late Cretaceous in age.

Figure 9.   Homogeneous band of *telocollinite* (Tc) and *desmocollinite* (Dc) associated with macerals of liptinite and inertinite groups. Sporinite (S), semifusinite (Sf), and inertodetrinite (I). High-volatile A bituminous coal, Peace River Coalfield, British Columbia, Early Cretaceous in age.

Figure 10.   *Telocollinite* (Tc) associated with macerals of the inertinite group, semifusinite (Sf) and inertodetrinite (I). Low-volatile bituminous coal, Peace River Coalfield, British Columbia, Early Cretaceous in age.
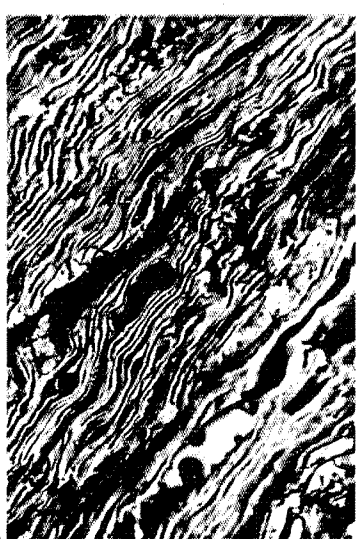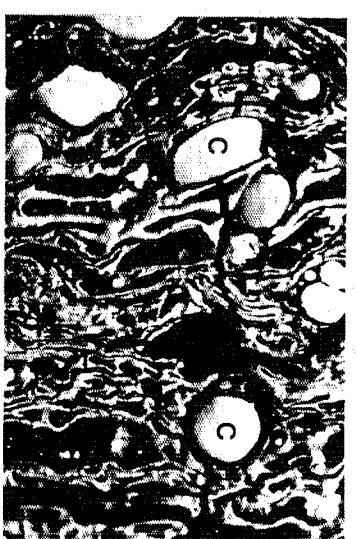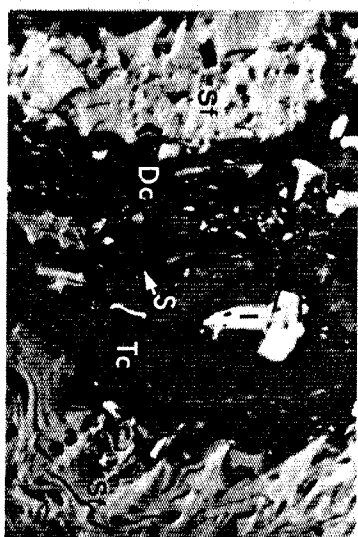
Plate II
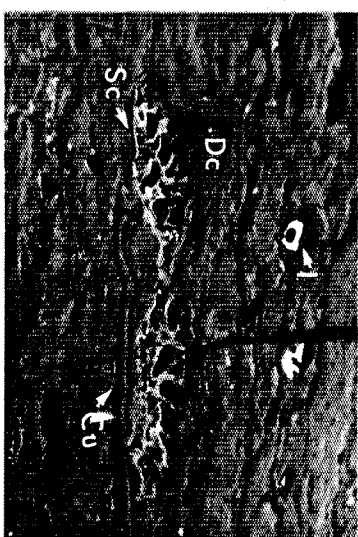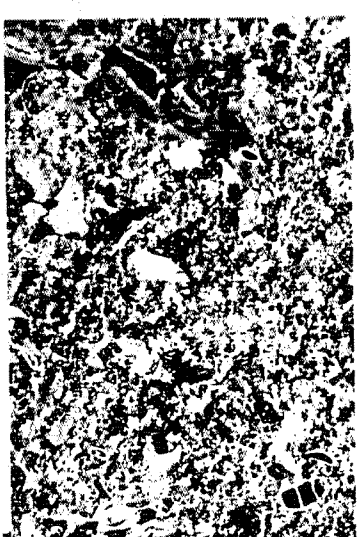
PLATE II (continued)

Figure 11.   Dark *eu-ulminite A* (A) and light *eu-ulminite B* (B) in a Greek lignite, Tertiary in age.

Figure 12.   *Eu-ulminite A?* (dark) and *eu-ulminite B?* (light) in a lignite from Saskatchewan, Paleocene in age.

Figure 13.   *Desmocollinite* (Dc) associated with thin walled cutinite (Cu). Medium-volatile bituminous coal, Peace River Coalfield, British Columbia, Early Cretaceous in age.

Figure 14.   *Desmocollinite* (Dc) associated with macerals of the liptinite group; thick walled cutinite (Cu) and small fragments of liptinite macerals (liptodetrinite). High-volatile A bituminous coal, Peace River Coalfield, British Columbia, Early Cretaceous in age.

Figure 15.   Highly detrital coal. *Vitrodetrinite* associated with inertodetrinite and liptodetrinite. Medium-volatile bituminous coal, Peace River Coalfield, British Columbia, Early Cretaceous in age.

Figure 16.   *Phlobaphinite* (P) and eu-ulminite (E) in a longitudinal section of a bark tissue. The black cell-wall material between the phlobaphinite bodies consists of the liptinite maceral suberinite. Lignite from Greece, Tertiary in age.

Figure 17.   *Pseudovitrinite*, characterized by serrated boundary of the grain, slit-like openings and the presence of faint cell-structure. High-volatile A bituminous coal, Peace River Coalfield, British Columbia, Early Cretaceous in age.

Figure 18.   *Telocollinite* (Tc) associated with the liptinite maceral resinite (R). High-volatile A bituminous coal, Peace River Coalfield, British Columbia, Early Cretaceous in age.

Figure 19.   *Desmocollinite* associated with macerals of liptinite and inertinite groups. Sporinite (S), fragments of cutinite (Cu), macrinite (M), and inertodetrinite (I). High-volatile subbituminous coal, Peace River Coalfield, British Columbia.

Figure 20.   *Resino-vitrinite?* (R) associated with desmocollinite (Dc) and macerals of liptinite and inertinite groups. Sporinite (S), megasporinite (M), and semifusinite (Sf). High-volatile A bituminous coal, Sydney Coalfield, Nova Scotia. Carboniferous in age.
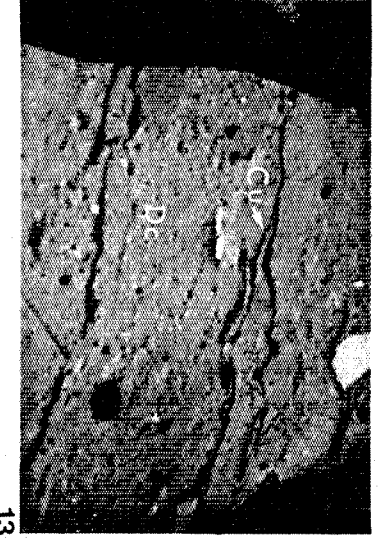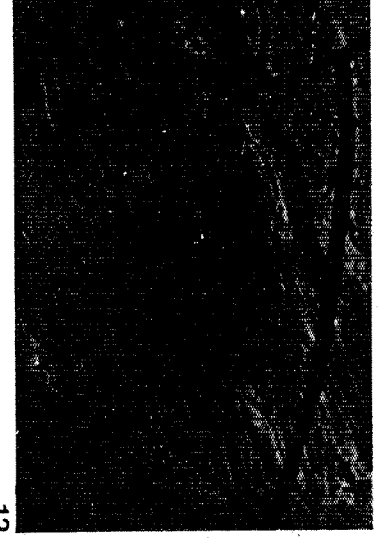
Plate II (cont.)
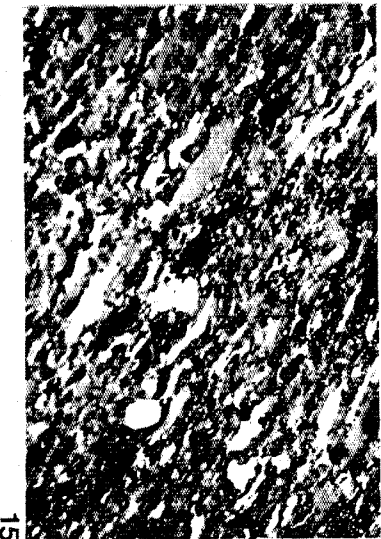
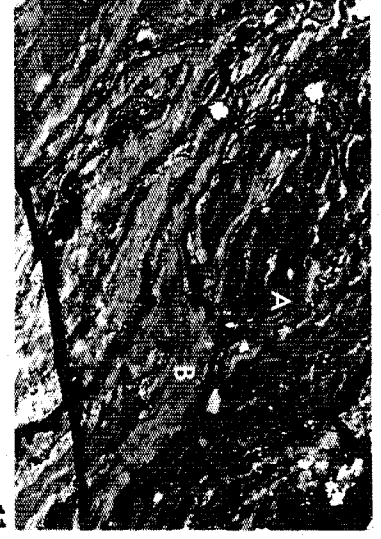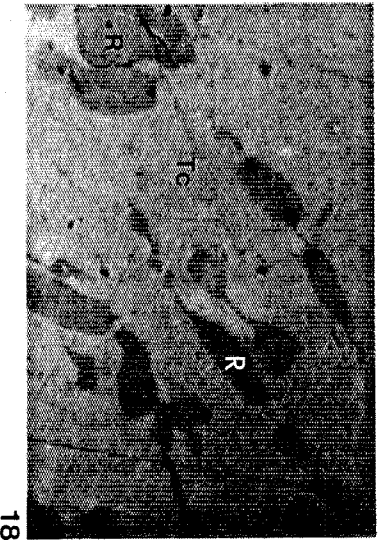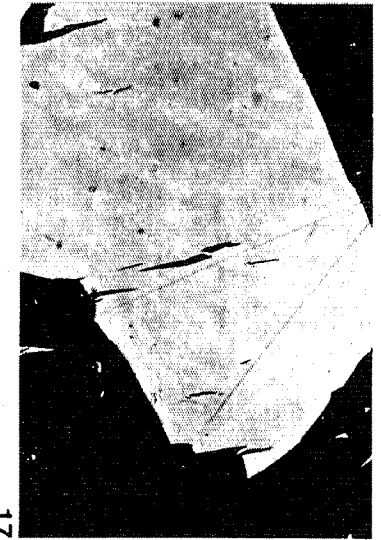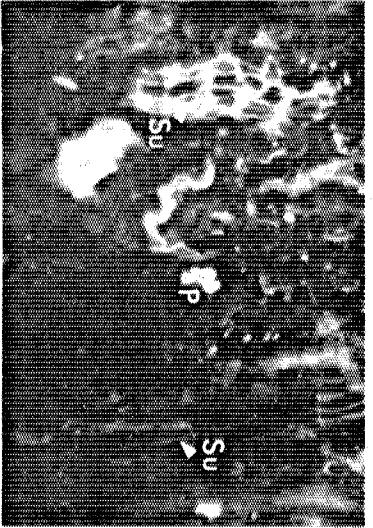## PLATE III (see following page)

Macerals of the liptinite group.

Figure 1a.   Normal reflected light; phlobaphinite (P) in attrinitic peat matrix. Peat from Villeroy-Lotbiniere district, Quebec, Pleistocene in age.

Figure 1b.   Same section after blue-light excitation; the large amount of liptinite macerals contributing to the peat matrix becomes now visible. *Suberinite* (Su) displays greenish-yellowish fluorescence colours. In the centre a greenish-yellowish fluorescing *pollen grain* (P).

Figure 2a.   Normal reflected light; *resinite* (R) characterized by reddish to brown colours caused by internal reflections of the incident light. Greek lignite, Tertiary in age.

Figure 2b.   Same section after blue-light excitation; *resinite* (R) displays greenish-yellowish fluorescence colours.

Figure 3a.   Normal reflected light; *sporinite* (S) associated with desmocollinite (Dc) and inertodetrinite (I). High-volatile B bituminous coal, Sydney Coalfield, Nova Scotia, Carboniferous in age.

Figure 3b.   Same section after blue-light excitation; *sporinite* displays yellow fluorescence colour. Desmocollinite and inertodetrinite do not fluoresce.

Figure 4a.   Normal reflected light; *cutinite* (Cu) characterized by serrated edges associated with desmocollinite (Dc). High-volatile A bituminous coal, Peace River Coalfield, British Columbia, Early Cretaceous in age.

Figure 4b.   Same section after blue-light excitation; *cutinite* displays orange-brownish fluorescence colour. Desmocollinite does not fluoresce.

Figure 5a.   Botryococcus-type *alginite* (A) associated with desmocollinite (Dc) and inertodetrinite (I). Alginite-rich coal from an oil shale zone in the Pictou Coalfield, Nova Scotia; high-volatile A bituminous in rank, Carboniferous in age.

Figure 5b.   Same section after blue-light excitation; in contrast to normal reflected light, shape and internal structure of the *alginite* (A) show up much better under blue-light excitation. In fact it is the only safe way to determine whether the dark area in Figure 5a consists of liptinitic material, mineral matter or epoxy resin. At this rank alginite displays a yellow-brownish fluorescence colour. Desmocollinite and inertodetrinite do not fluoresce.
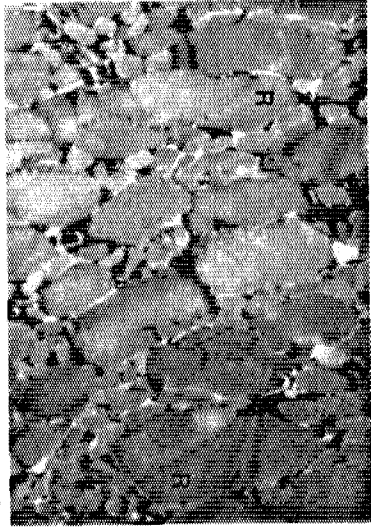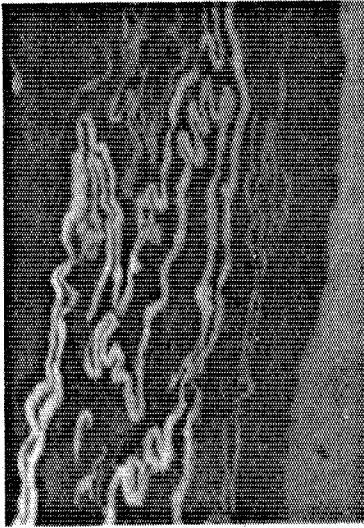
Plate III

s

PLATE IV   (see following page)

Macerals of the inertinite group (reflected light, oil immersion).

Figure 1.   *Fusinite* in a medium-volatile bituminous coal, Peace River Coalfield, British Columbia, Early Cretaceous in age.

Figure 2.   *Fusinite* showing characteristic "Bogen-structure." High-volatile A bituminous coal, Peace River Coalfield, British Columbia; Early Cretaceous in age.

Figure 3.   *Semifusinite* (Sf) associated with desmocollinite (Dc) and *inertodetrinite* (I). Medium-volatile bituminous coal, Peace River Coalfield, British Columbia; Early Cretaceous in age.

Figure 4.   *Semifusinite* (Sf) associated with *inertodetrinite* (I), desmocollinite (Dc), and liptodetrinite (Ld). High-volatile A bituminous coal, Peace River Coalfield, British Columbia; Early Cretaceous in age.

Figure 5.   High reflecting *macrinite* (M) associated with desmocollinite (Dc), *inertodetrinite* (I), and sporinite (S). High-volatile A bituminous coal, Peace River Coalfield, British Columbia; Early Cretaceous in age.

Figure 6.   Low reflecting *macrinite* (M) associated with desmocollinite (Dc) and *semifusinite* (Sf). High-volatile A bituminous coal, Peace River Coalfield, British Columbia; Early Cretaceous in age.

Figure 7.   Lenses of *micrinite granules* (Mi) associated with desmocollinite and telocollinite (Tc) and mineral matter (MM). Low-volatile bituminous coal, Peace River Coalfield, British Columbia; Early Cretaceous in age.

Figure 8.   Occurrence of massive concentration of *micrinite* granules (Mi) associated with desmocollinite. Low-volatile bituminous coal, Peace River Coalfield, British Columbia, Early Cretaceous in age.

Figure 9.   Fungal *sclerotinite* (Sc) associated with telocollinite (Tc) and desmocollinite (Dc). Subbituminous coal, Hat Creek deposit, British Columbia; Tertiary in age.

Figure 10.   Plectenchymatous *sclerotinite* (Sc) in a subbituminous coal. Hat Creek deposit, British Columbia; Tertiary in age. Photo F. Goodarzi.

Figure 11.   Fungal *sclerotinite* (Sc) in a subbituminous coal. Drumheller area, Alberta. Late Cretaceous in age.

Plate IV
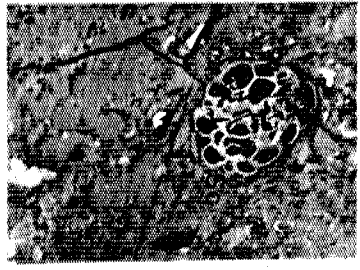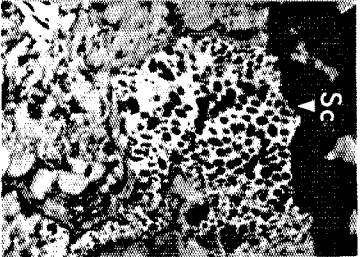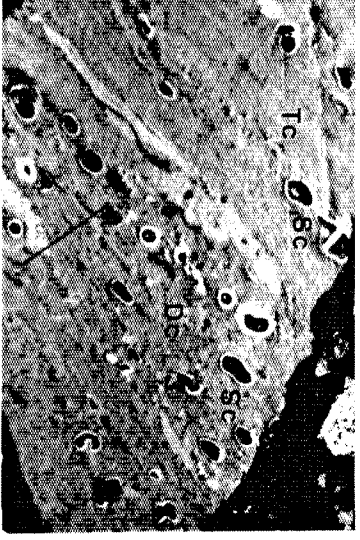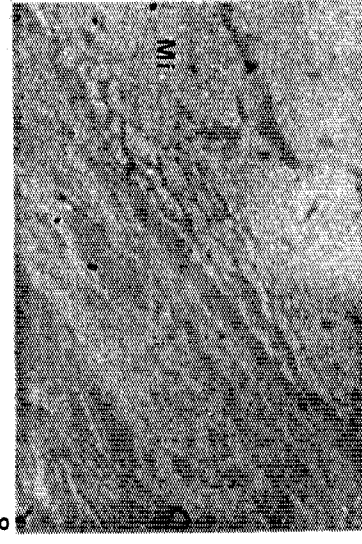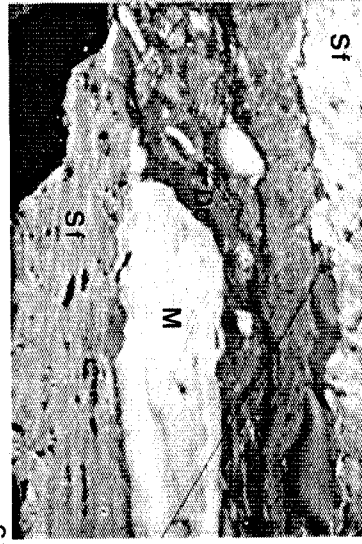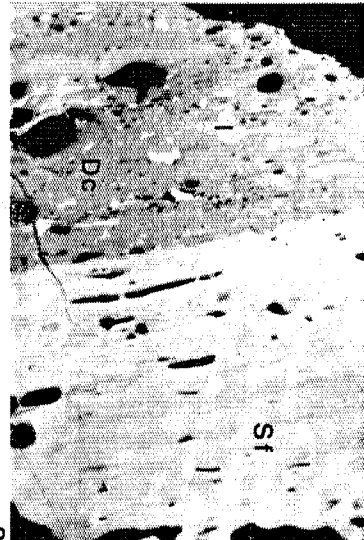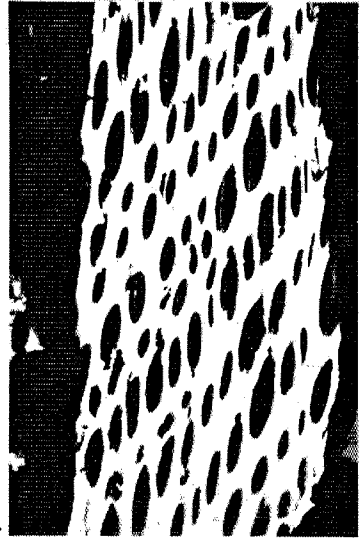
2.3   Microlithotypes

Microlithotypes are defined in the ICCP Handbook (ICCP, 1963) as "typical associations of macerals with a minimum band width of 50 microns". As the name implies, they can only be determined microscopically. The three main groups of microlithotypes are designated monomaceralic, bimaceralic and trimaceralic according to whether they contain representative macerals of one, two or three maceral groups, see Figs. 16 and 17. A fourth group is called carbominerites and is subdivided according to the minerals present.

Microlithotype analyses have been used extensively in the interpretation of paleodepositional environments, for example by Hacquebard and Donaldson (1967, 1969) in their studies on the coals from the Sydney Coalfield, N.S. To a lesser extent microlithotype analysis has been used to predict carbonization and hydrogenation properties of coals (Brown et al, 1964; Nomura et al, 1982: Steller et al, 1987). To the author's knowledge, no information is available as to the relationships between microlithotypes and their gas generation and/or gas adsorption potential.
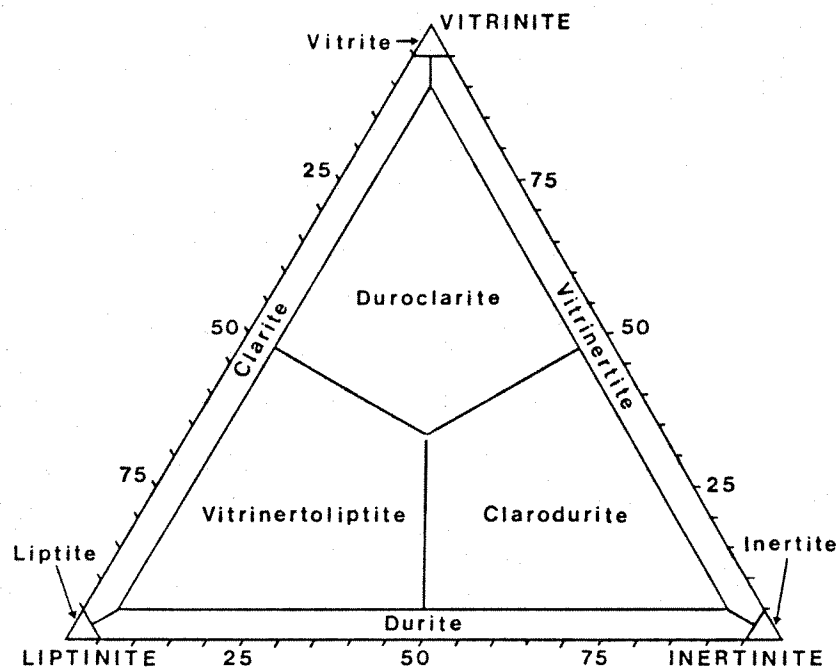
Fig. 16.   Diagrammatic representation of microlithotype classification
(from Bustin et al., 1985)

	Microlithotype	Maceral-Group composition mineral-free
Monomaceralic	Vitrite Liptite Inertite	V > 95% L > 95% I > 95%
Bimaceralic	Clarite Vitrinertite Durite	V + L > 95% V + I > 95% L + I > 95%
Trimacerite *	Duroclarite Clarodurite Vitrinertoliptite	V > L and I I > V and L E > V and I

V = vitrinite, L = liptinite, I = inertinite.

* in trimacerites at least 5% of each maceral must be present.

Fig. 17.   Table of Microlithotypes (from ICCP Handbook, 1963 and Stach, 1982)

2.3.1   *Microlithotype Analysis*

The 20-point graticule used for microlithotype analysis is shown in Fig. 18. In this graticule the distance between the outermost intersections is 50 microns. The area falling under the whole graticule is considered one point. The microlithotype composition of that area depends on the macerals occurring under each intersection and is determined according to Figs. 19 and 16. At least 20 intersections have to be on organic matter or minerals before a point is counted. Examples for the determination of microlithotypes are illustrated on Plate V. As in the case of maceral analysis, a large number of points (at least 500) is counted per sample.
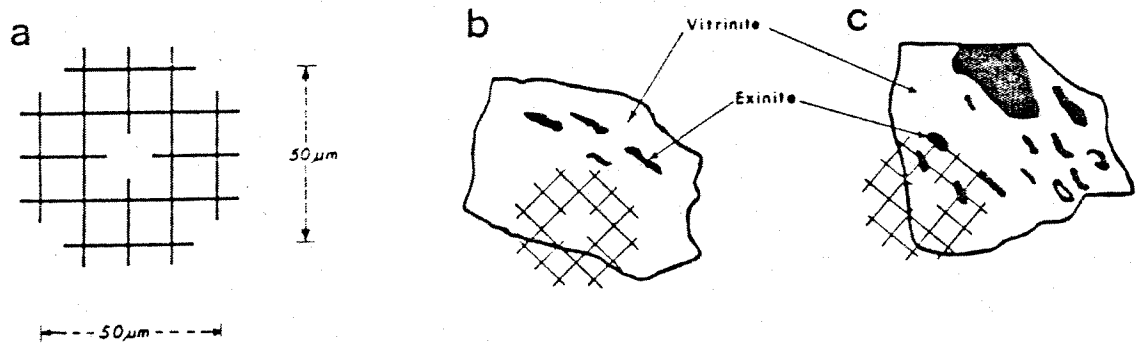
Fig. 18.   20-point graticule used for microlithotype analysis.   An encounter such as shown in b would be counted as vitrite.   An encounter such as shown in c would be counted as clarite.

Microlithotype	Position of the graticule intersections with respect to macerals
Vitrite	All intersections on vitrinite
Liptite	All intersections on exinite
Inertite	All intersections on inertinite
Clarite	All intersections on virtinite and exinite with at least 1 intersection on each
Durite	All intersections on inertinite and exinite, with at least 1 insection on each
Vitrinertite	All intersections on vitrinite and inertinite, with at least 1 intersection on each
Trimacerite*	At least one intersection on each of the three maceral groups

*Trimacerite can be subdivided into:
Duroclarite (V>I+E), Clarodurite (I>V+E), Vitrinertoliptite (E>V+I).

Fig. 19.   Microlithotype analysis using a 20-point graticule

PLATE V   (see following page)

Representative photomicrographs of microlithotypes. All photos taken with reflected light and immersion; the 20-point graticule is superimposed on all. At the proper magnification the are covered by the graticule on the specimen should be 50 x 50 micrometres; in this plate the size the graticule has been exaggerated.

V = vitrinite, L = liptinite, I = inertinite, P = pyrite, C = clay minerals

Figure 1.   Vitrite - all points on vitrinite

Figure 2.   Liptite - all points on liptinite

Figure 3.   Inertite (graticule on left side) - all points on inertinite
              Vitrinertinite (graticule on right side) - one point on inertinite, remainder on vitrinite

Figure 4.   Clarite - one point on liptinite, remainder on vitrinite

Figure 5.   Durite - 10 points each on inertinite and liptinite

Figure 6.   Duroclarite - one point on liptinite, three on inertinite, remainder on vitrinite

Figure 7.   Clarodurite - two points on vitrinite, three on liptinite, remainder on inertinite

Figure 8.   Vitrinertoliptite - 10 points on liptinite, five points each on inertinite and vitrinite

Figure 9.   Carbopyrite - two points on pyrite, remainder on vitrinite and liptinite

Figure 10.   Carbargilite - nine points on clay minerals, remainder on vitrinite

Plate V
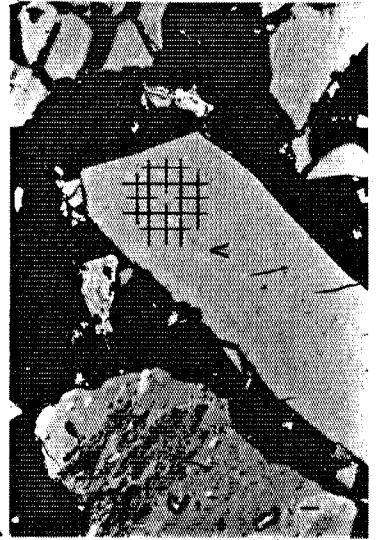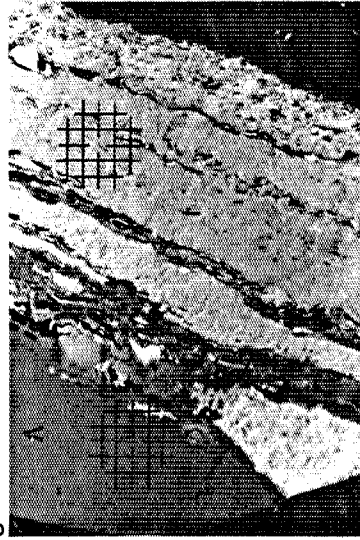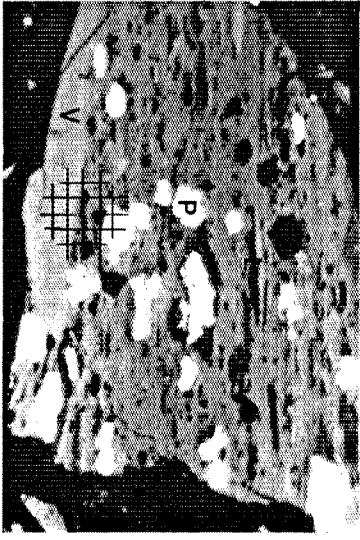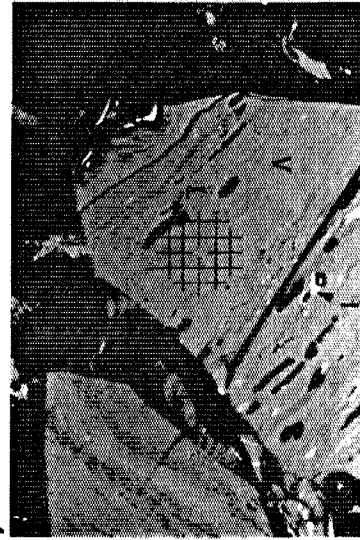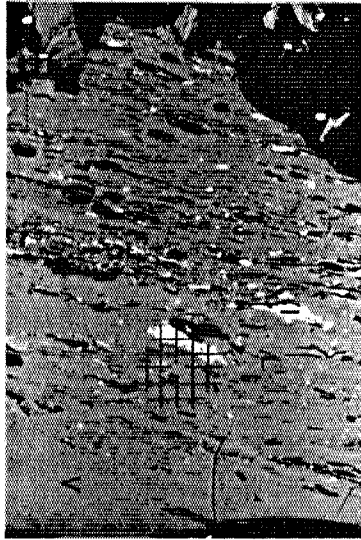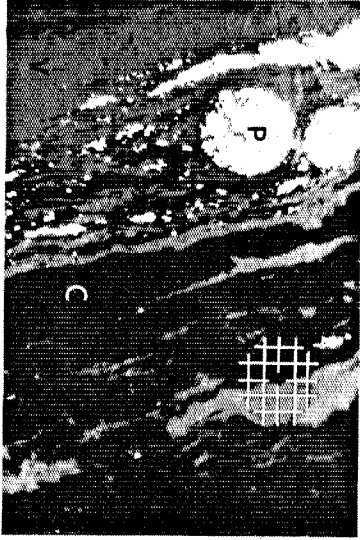
2.4   **Mineral Matter**

Mineral matter in coal occurs both as finely disseminations and as discrete partings. Macroscopic identification of mineral matter in coal is sometimes possible, as tonsteins (clay bands), coal balls and siderite concretions, for example, are distinguishable in outcrop or mine wall. More concise identification of the inorganic constituents of coal, however, requires detailed analysis.

There are three basic approaches to identification of mineral matter in coal: chemical analysis of high-temperature (combustion) ash; petrography; and X-ray and SEM analysis of low-temperature ash. The first is the mst readily carried out, but its major drawback is that original minerals are destroyed and so mineral matter must be expressed in terms of oxides. Petrographic analysis is difficult to carry out, mainly due to the generally fine-grained nature of coal mineral matter. The X-ray and SEM method requires expensive analytical equipment, but definitely provides the most accurate picture of the true mineral matter content.

Mineral matter in coals may be divided into three groups (Fig. 20):

	PRIMARY FORMATION		SECONDARY FORMATION	
	Detrital	Authigenic	Deposited in cleat, fractures and cavities	Transformation of primary minerals
Clays	kaolinite, illite, mixed-layer clays,	sericite, smectites		illite, chlorite (from other clays)
Carbonates		siderite, dolomite, ankerite, calcite,	ankerite, dolomite, calcite	
Sulphides		pyrite, marcasite, melnikovite	pyrite, marcasite, sphalerite, galena, chalcopyrite	pyrite (from siderite)
Silicas	quartz	quartz, chalcedony	quartz, chalcedony	
Oxides and hydroxides	rutile	hematite limonite	goethite	
Phosphates	apatite	(phosphorite) apatite		
Silicates	zircon, feldspars, tourmaline, micas			
Sulphates			hydrated iron sulphates, gypsum (oxidation products)	

Fig. 20.   Minerals in Coal (adapted from Mackowsky, 1981 and ICCP, 1963)

(1)   mineral matter contained in original plants (inherent ash);

(2)   primary mineral matter, emplaced during or shortly after deposition, including both detrital and authigenic minerals;

(3)   secondary mineral matter, formed at a later stage.

The first group is generally not recognized petrographically, except perhaps by SEM. The second and third groups are usually recognizable. Primary mineral matter is generally intimately intergrown with the coal, whereas secondary mineral matter tends to be coarsely intergrown and associated with cleat, fractures, and cavities. The latter may also, however, represent replacement of primary mineral matter and may therefore appear similar to primary minerals. Primary minerals are generally the more common. The major groups of minerals include the clays, carbonates, iron sulphides, and silicas. Other groups which occur more rarely, include oxides, hydroxides, other sulphides, phosphates, silicates, and sulphates. Some of the more common minerals in coal (clay, quartz, carbonate and pyrite) are illustrated on Plate VI.

Mineral matter is commonly difficult to recognize during maceral analysis and thus should be calculated from the ash content determined from proximate analysis and the sulphur content, if known. The weight per cent of mineral matter can be calculated using Parr's formula:

Mineral matter = 1.08 (per cent ash) + 0.55 (per cent sulphur)

The mineral matter content on a weight basis is then converted to volume per cent by first dividing the calculated mineral matter on a weight basis by two (because the specific gravity of mineral matter is about twice that of the organic fraction) and recalculating the maceral and mineral matter content.

PLATE VI   (see following page)

Mineral matter in coal (reflected light oil immersion, except 5b).

Figure 1.   Kaolinite graupen (G) in A-seam (medium-volatile) from the Kootenay Group, Crowsnest Coalfield, Sparwood, British Columbia.

Figure 2.   Kaolinite vermicules in tonstein band from subbituminous coal of the Horseshoe Canyon Formation, Drumheller, Alberta.

Figure 3.   Siderite concretion in subbituminous coal of the Horseshoe Canyon Formation, Drumheller, Alberta.

Figure 4.   Rare occurrences of elemental sulphur (S) filling cell lumina in fusinite from high-volatile A coal from the Gething Formation, north of Williston Lake, Peace River Coalfield, British Columbia.

Figure 5a.   Quartz in 10-seam (medium to low-volatile) from the Kootenay Group, Crowsnest Coalfield, Sparwood, British Columbia.

Figure 5b.   Same field of view as 5a. Dry lens.

Figure 6.   Clays (M.M.) and pyrite in high-volatile coal from the Bickford Formation, Peace River Coalfield, British Columbia. Note occurrence of large pyrite framboid.

Figure 7.   Pyrite in high-volatile coal from the Bickford Formation, Peace River Coalfield, British Columbia. Note stringers of pyrite aligned with liptinite macerals.

Plate VI
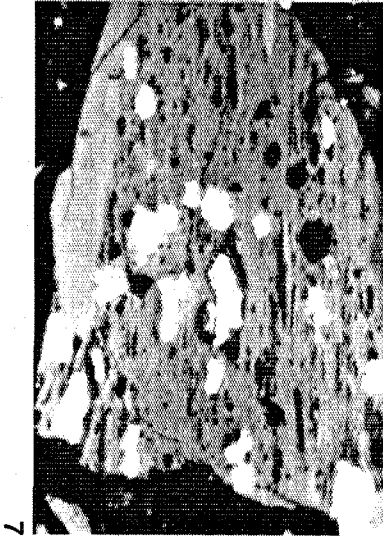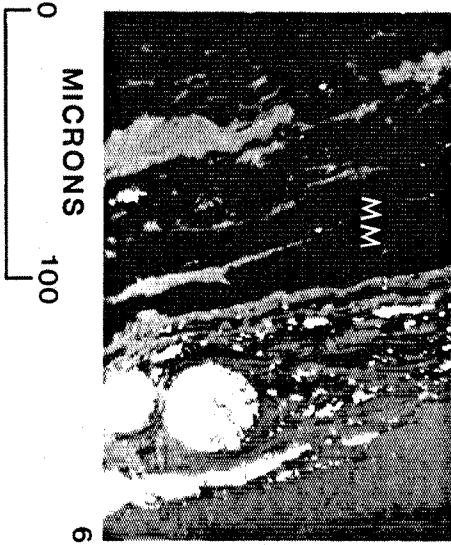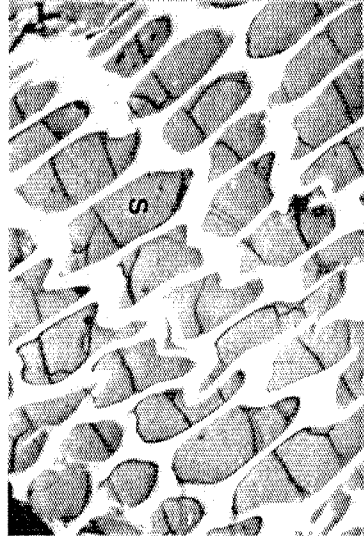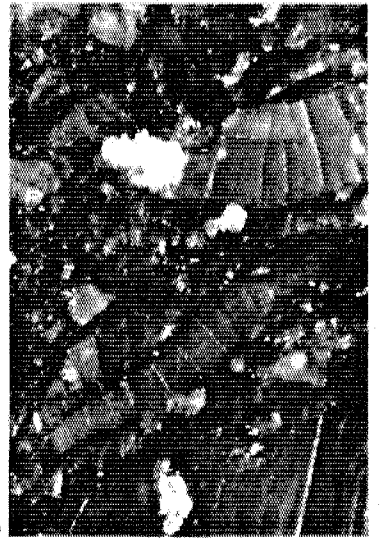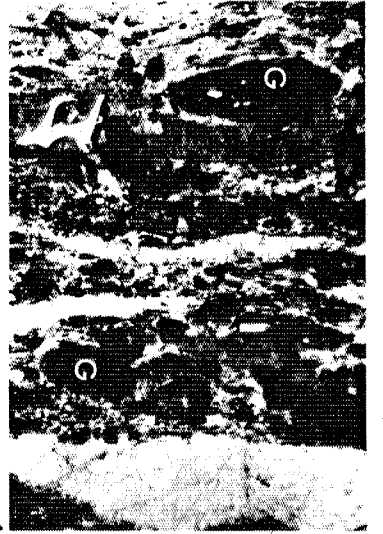
3   Coal Rank and Vitrinite Reflectance

During progressive coalification the organic components in coal (liptinite, inertinite and huminite/vitrinite groups) are subject to changes in chemical and physical properties. Microscopically these changes occur as an increase in reflectance levels, most noticeable in liptinite and huminite/vitrinite macerals. Fig. 15 shows these changes in reflectances in relation to increasing carbon and decreasing volatile matter contents. Reflectance may be measured on any of the coal macerals, although vitrinite (or a vitrinite precursor) is nearly always selected in rank studies. Vitrinite is preferred because of its tendency to occur in large homogeneous particles which are plentiful if not dominant in most coals, and because its reflectance shows good correlation with other coal rank parameters at most rank levels (Fig. 21).
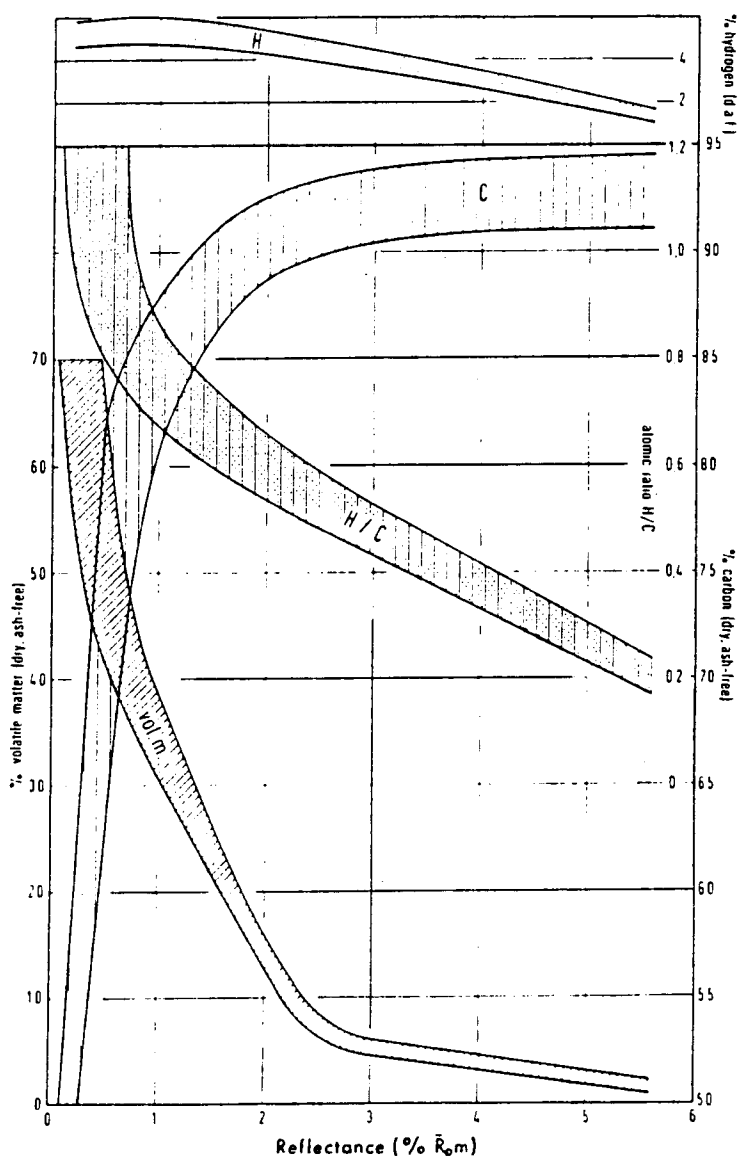
Fig. 21.   Relationship between vitrinite reflectance (R_om) and volatile matter, hydrogen and carbon contents, and the ratio hydrogen/carbon (from Teichmüller and Teichmüller, 1982)

As a rank parameter, determination of vitrinite reflectance is relatively rapid and precise and is independent of coal composition. Furthermore, reflectance is suitable for small samples such as dispersed organic matter in sedimentary rocks and may even make use of samples of oxidized coal.

Optical Characteristics of Vitrinite

Vitrinite is usually anisotropic in bituminous coals when measured in polarized light - showing maximum, minimum and intermediate values. Traditionally vitrinite has been considered to be uniaxial negative (Fig. 22A), in which the observed anisotropy is related to vertical compression during burial. More rent studies have shown that in tectonically disturbed areas such as the Appalachian foreland basin (Levine and Davis, 1989) and the foothills of the Canadian Rocky Mountains (Langenberg and Kalkreuth, in press) many of the coals are characterized by biaxial negative and biaxial positive vitrinites (Fig. 22B and C).

The following discussion will focus on the measurement of vitrinite reflectance using the uniaxial model since this method is routinely carried out by coal petrographic laboratories.

Vitrinite Reflectance Measurement

The coal samples are prepared according to standardized procedures, for details see Bustin et al. (1989).

The three principle components of a coal reflectance measuring system are: an incident light microscope, a photometric device (photomultiplier) and a display and recording system. A schematic diagram of components used in a reflectance microscope is shown in Figure 23.

The reflectance is defined as the percentage of an incident light beam's intensity which is reflected from the polished surface. Reflectance in oil of a coal maceral is related to refractive and absorption indices of the maceral by Beer's equation:

$$R_o = \frac{(\mu-\mu_o)^2 + \mu\kappa^2}{(\mu-\mu_o)^2 + \mu^2\kappa^2}$$

where μ and κ are the refractive and absorption indices of the maceral, respectively, and μ_o is the refractive index of the immersion oil. Use of this complex relationship in coal petrography, however, is avoided by comparing the maceral reflectance with that of an optical standard of known reflectance.

Geologic Features

Stresses
Due To:

Typical Vitrinite
Reflectance Indicatrix

A.1

Vertical
Loading

X=Y>Z
Uniaxial (−)

A.2

X=Y>>Z
Uniaxial (−)

Vertical
Loading
+
Incipient
Tectonism

B.1

X>Y>Z
Biaxial (−)

C.1

X>>Y>Z
Biaxial (−)

Vertical
Loading
+
Intense
Tectonism

C.2

X>Y>Z
Biaxial (−)

A

B

C
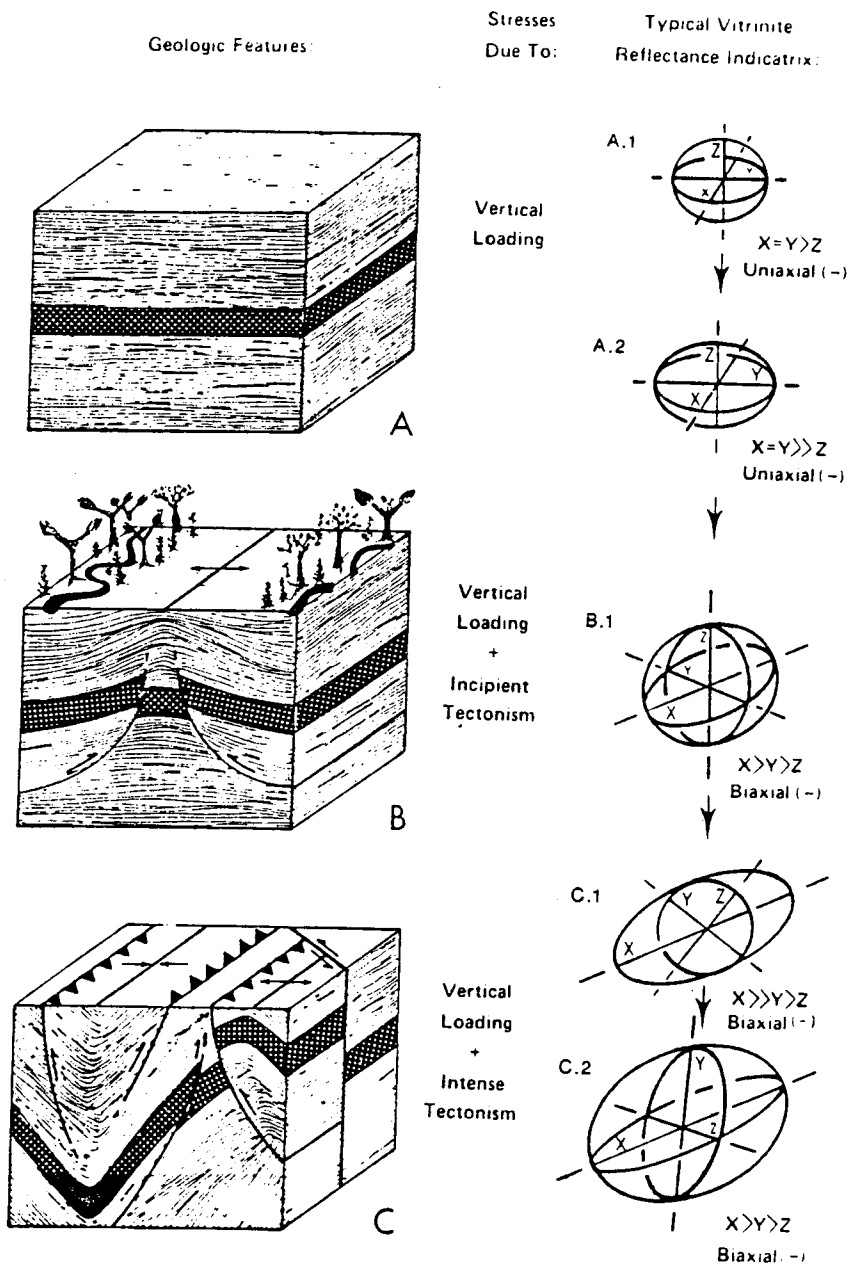
Fig. 22. Uniaxial and biaxial forms of vitrinite reflectance
ellipsoids in respect to tectonic setting of the parent coal,
from Levine and Davis (1989)

Since reflectance is related to absorption and refractive indices by Beers equation, both indices vary with wavelength of light used, and so, by convention, petrographers have settled on a single wavelength (546 nm) for routine analysis.

The principle relationships between maximum and minimum reflectances and the orientation of grain surfaces for uniaxial negative vitrinites is shown in Fig. 24. In this case the optic axis runs perpendicular to the bedding plane. In any grain being observed under plane-polarized light, therefore, no matter what its orientation with respect to original bedding, there is a true maximum value of reflectance in the direction which corresponds

P = Photomultiplier cathode
F = Monochromatic filter
E = Limiting aperture
L = Quartz halogen lamp
C = Collector lens
H = Heat absorbing filter
A = Aperture diaphragm

S = Half stop
N = Polarizer
I = Field diaphragm
B = Berek prism
O = Objective
M = Immersion Oil
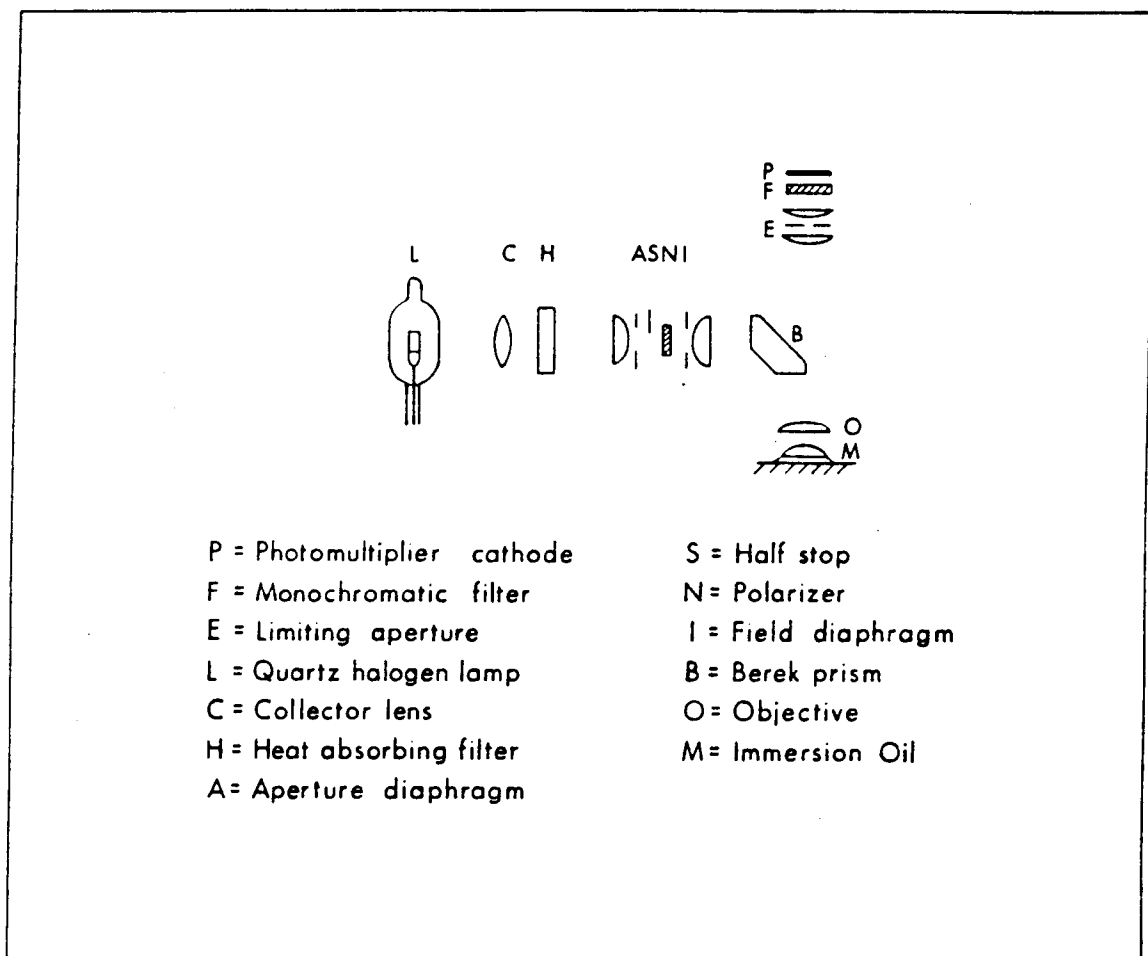
Fig. 23.   Schematic diagram of the components of the reflectance microscope.
(Adapted from Davis, 1978)
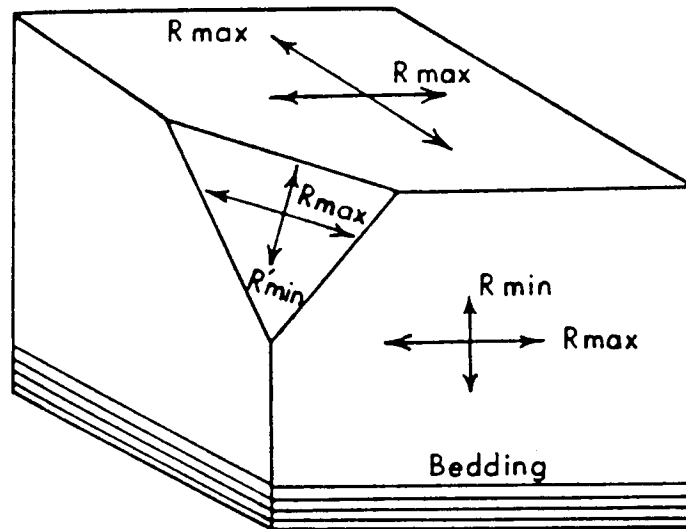
Fig. 24. Anisotropy of vitrinite. The range of reflectance in polarized light
depends on the orientation of grain surface with respect to bedding.
Rmax and Rmin are the maximum and true minimum reflectances, respectively,
while R′min is an apparent minimum direction.
(Adapted from Davis, 1978)

to the bedding plane. In grains oriented parallel to bedding, of course, anisotropy disappears and the maximum

value applies in all directions. There is also a minimum value, corresponding to the direction perpendicular to

the maximum, for any grain, although it will nearly always be greater than the true minimum direction, which

is present only when the grain surface is perpendicular to the bedding plane. Of the two values, therefore, the

maximum value of reflectance of any grain has more significance, that is, it corresponds to the true maximum,

while the minimum values only approach the true minimum.

A third measurable value is the random reflectance, which is the reflectance of a grain in the orientation

in which it is encountered. If incident light is plane-polarized, then the random reflectance reading of a grain

will be somewhere between its maximum and apparent minimum reflectances, depending on bedding orientation

and position of stage. The range of possible readings is therefore between the true minimum and true maximum

values for any grain. In nonpolarized light, however, the range of potential readings is less, as the reading on

any grain will be the average of its maximum and apparent minimum, again depending on bedding orientation,

but not depending on stage position. The lowest obtainable value of any grain will be the mean of the maximum and true minimum. Random reflectance of a grain in nonpolarized light is therefore related to the maximum and apparent minimum as follows:

$$R_om = 1/2 \, (Rmax + R'min)$$

where R_om is random reflectance and Rmax is maximum reflectance, and R'min is the apparent minimum.

Nonpolarized light is generally used in random reflectance determinations. Two different values are therefore available to quantify reflectance of a vitrinite grain: (1) *maximum reflectance in plane-polarized light*, and (2) *random reflectance in nonpolarized light*.

The two parameters, when derived from the same sample, are related as follows (Ting, 1978):

$$R_omax = 1.066 \, R_om$$

Use of either parameter has advantages. Mean maximum reflectance data have a smaller standard deviation, which in turn makes the discrimination of separate coals in a blend much more straightforward. Mean maximum reflectance also has precedence. Mean random reflectance, on the other hand, is faster to determine, as each grain is measured in the orientation in which it is encountered, obviating the need for rotating the stage to locate the maximum value. Errors encountered during rotation of the stage, related to lack of centring of stage and objective, and changes in focus, are thus avoided. The method is also, therefore, more suitable for very small grains, such as dispersed organic matter in sedimentary rocks, encountered during oil and gas exploration. Furthermore, since the method omits the incident-light polarizer, more light is available for observation and measuring. Random reflectance is the method utilized by new automated systems which measure reflectance continuously along lines of parallel traverse. Maximum reflectance is the method favoured at present by most coal petrographers, although in lower rank coals, where anisotropy is not well developed, the two are nearly interchangeable. Because it is difficult, however, to determine exactly at what rank level significant anisotropy first appears, it is probably safer to be consistent and use one method for all coals.

Due to natural scatter in reflectance values of vitrinite grains in a sample, in routine analysis 50-100 measurements are taken and the values are averaged. A typical vitrinite reflectance frequency histogram for a bituminous coal is shown in Fig. 25. The mean vitrinite reflectance value derived from that distribution is then

```
                    ISFG COAL SECTION TECHNOLOGY
                    REFLECTANCE MEASUREMENTS
                    RANK DETERMINATION
     ***************************************************************
     GRAIN PELLET              MAXIMUM REFLECTANCE
     STANDARD                  1.02
     SAMPLE                    P-55 COAL 710/83
     COMMENTS
     DATE                      14.43--04/11/1983
     OPERATOR                  WI
     ***************************************************************

                         STATISTICAL REPORT
     PARAMETER               MAXIMUM
     ------------------------------------------------------------------

               PROPERTIES OF THE MEAN
     MEAN VALUE                0.846 +/- 0.0050
     CONFIDENCE (95%, 99%)     0.0099 -- 0.0130

               PROPERTIES OF OBSERVATIONS
     NUMBER OF POINTS              50
     STANDARD DEVIATION        0.036 +/- 0.0036
     VARIANCE                  0.0013


     ***************************************************************

     MAXIMUM REFLECTANCE VALUES

     0.76   0.78   0.79   0.79   0.80   0.81   0.81   0.81   0.81   0.81
     0.82   0.82   0.82   0.82   0.83   0.83   0.83   0.84   0.84   0.84
     0.84   0.84   0.84   0.85   0.85   0.85   0.85   0.85   0.85   0.85
     0.86   0.86   0.86   0.86   0.86   0.86   0.86   0.87   0.87   0.87
     0.88   0.88   0.88   0.88   0.88   0.90   0.90   0.91   0.91   0.94
```
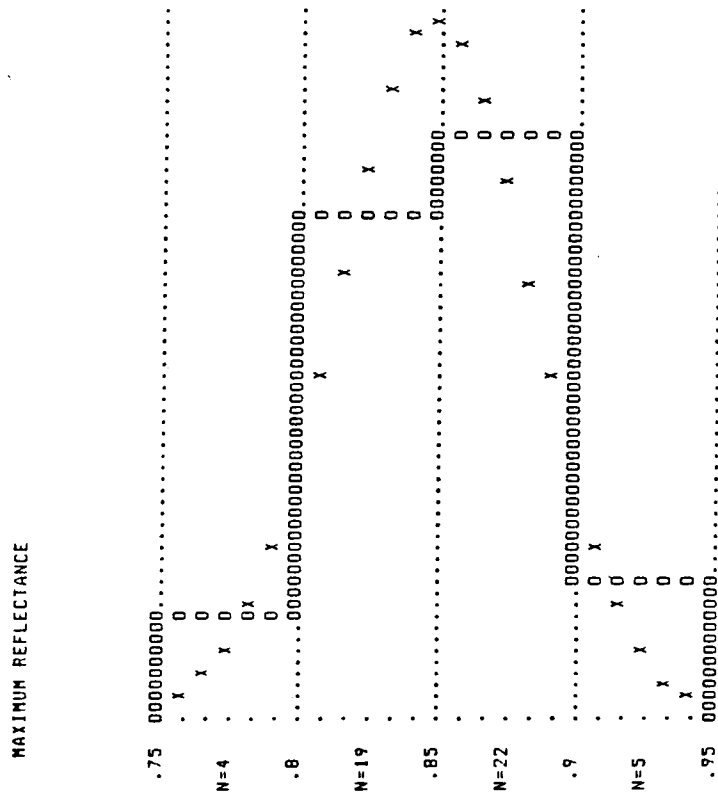

Fig. 25. Typical example of reflectance frequency histogram. This diagram represents analysis of a high volatile bituminous coal from the Picton Coalfield, Nova Scotia.

used to determine the rank of the coal (Fig. 5). The relationships established between mean maximum reflectances and ASTM rank groups are shown in Fig. 26. The ASTM coal rank classification is a current time based on calorific values in low rank coals and volatile matter contents in higher rank coals. The relationship between these two parameters and vitrinite reflectance are illustrated in Fig. 27.

Rank	Maximum Reflectance (% $\bar{R}_o$max)	Random Reflectance (% $\bar{R}_o$m)
Subbituminous	<0.47	
High-volatile bituminous	C 0.47 - 0.57 B 0.57 - 0.71 A 0.71 - 1.10	0.50 - 1.12
Medium-volatile bituminous	1.10 - 1.50	1.12 - 1.51
Low-volatile bituminous	1.50 - 2.05	1.51 - 1.92
Semi-anthracite	2.05 - 3.00 (approx.)	1.92 - 2.50
Anthractie	>3.00	>2.50

Fig. 26.   Suggested limits of A.S.T.M. Rank Classes
in terms of vitrinite reflectance
(from Davis, 1978; McCartney and Teichmüller, 1972)
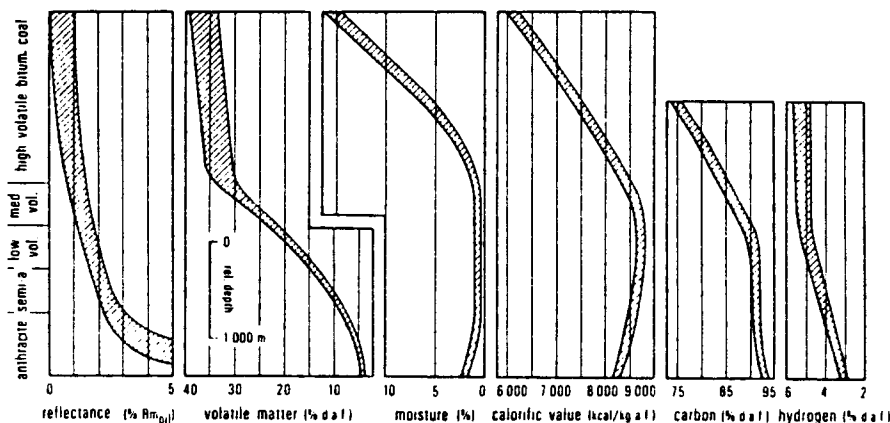
Fig. 27.   Variation of various chemical and physical parameters
with rank. Note especially the changes in volatile
matter and calorific value.(from Teichmüller, 1982)

4   References

Alpern, B. and Lemos de Sousa, M., 1970, Sur le pouvoir reflecteur de la vitrinite et de la fusinite des houilles; Centre Rech. Acad. Sc. Paris, 271, pp. 956-959.

Benedict, L.G., Thompson, R.R., and Wenger, R.O., 1968, Relationship between coal petrographic composition and coke stability; Blast Furnace and Steel Plant, vol. 56, no. 3, pp. 217-224.

American Society for Testing and Materials (ASTM), 1981, Annual book of ASTM standards; (Part 26), American Society for Testing and Materials, Philadelphia, Pennsylvania.

Brown, H.R., Taylor, G.H., and Cook, A.C., 1964, Prediction of coke strength from the rank and petrographic composition of Australian coals; Fuel, vol. 43, no. 1, pp. 43-54.

Bustin, R.M., Cameron, A., Grieve, D., and Kalkreuth, W., 1989, Coal petrology, its principles, methods and applications; Geological Association of Canada, Short Course Notes, vol. 3, 3rd edition, 230 p.

Davis, A., 1978, The reflectance of coal; in Karr, C., editor, Analytical Methods for Coal and Coal Products; vol. 1, Academic Press, New York, p. 27-81.

Diessel, C.F.K., 1965, Correlation of macro- and micropetrography of some New South Wales coals: Proceedings 8th Commonwealth Mining and Metallurgical Congress, vol. 6, pp. 669-677.

Flaig, W., 1968, Biochemical Factors in Coal Formation; in Coal and Coal-bearing Strata (eds. Murchison, D. and Westoll, T., Oliver, T. and Boyd Ltd., Edinburgh), p. 197-232.

Hacquebard, P.A., Birmingham, T.F., and Donaldson, J.R., 1967, Petrography of Canadian coals in relation to environment of deposition; Symposium in the Science and Technology of Coal, Ottawa, March, 1967, Energy, Mines, and Resources, Ottawa, pp. 84-97.

Hacquebard, P.A. and Donaldson, J.R., 1969, Carboniferous coal deposition associated with flood-plain and limnic environments in Nova Scotia; in Dapples, E.C. and Hopkins, M.E., editors, Environments of coal Deposition; Geological Society of America Special Paper 114, pp. 143-191.

Hagemann, H.W. and Hollerbach, A., 1979, Relationship between the macropetrographic and organic geochemical composition of lignites; in Douglas, A.G. and Maxwell, R., editors, Advances in Organic Geochemistry 1979; Pergamon Press, pp. 631-638.

International Committee for Coal Petrology (1963), International handbook of coal petrography - 2nd edition; Centre National de la Recherche Scientifique, Paris, France.

International Committee for Coal Petrology (1971), International handbook of coal petrography, 1st supplement to 2nd edition; Centre National de la Recherche Scientifique, Paris, France.

International Committee for Coal Petrology (1975), Analysis subcommission, fluorescence microscopy and fluorescence photometry; in International handbook of coal petrography, 2nd supplement to 2nd edition; Centre National de la Recherche Scientifique, Paris, France.

Lamberson, M., Bustin, R. and Kalkreuth, W., in press, Lithotype Composition and Variation in Selected Coal Seams of the Gates Formation, Northeastern British Columbia; Int. J. Coal Geology.

Langenberg, W. and Kalkreuth, W., in press, Tectonic controls on Regional Coalification and Vitrinite-Reflectance Anisotropy of Lower Cretaceous Coals in the Alberta Foothills; Proc. Int. Conf. Coal, Orleans, France, Sept. 12-15, 1989, Societe Geologie de France.

Levine, J. and Davis, A., 1989, Reflectance Anisotropy of Upper Carboniferous Coals in the Appalachian Foreland Basin, Pennsylvania, U.S.A.; Int. J. Coal Geology, 13, 341-373.

Mackowsky, M.-Th., 1982, Minerals and trace elements occurring in coal; in Stach, E., Mackowsky, M.-Th., Teichmüller, M., Taylor, G.H., Chandra, D., and Teichmüller, R., Coal Petrology, 3rd edition; Gebrüder Borntraeger, Berlin-Stuttgart, p. 153-171.

McCartney and Teichmüller, 1972, Classification of coals according to degree of coalification by reflectance of the vitrinite component, Fuel, vol. 51, p. 64-68.

Marchioni, D. and Kalkreuth, W., in press, Coal Facies Interpretation on Lithotype and Maceral Variations in Lower Cretaceous (Gates Formation) Coals of Western Canada; Int. J. Coal Geology.

Nomura, M., Yoshida, T., Kikkawa, S. and Philp, P. 1982, Effects of petrographic constituents in three Yallourn brown coal lithotypes on hydroliquefaction processes. Fuel, 61, 472-473.

Potonie, H., 1920, Die Entstehung der Steinkohle und der Kaustobiolithe überhaupt; 6, Aufl., Borntraeger Berlin, 233 pp.

Stach, E., Mackowsky, M.-Th., Teichmüller, M., Taylor, G.H., Chandra, D., and Teichmüller, R., 1975, Coal petrology, 2nd edition, 428 pp., 1982, 3rd edition, 535 pp., Gebrüder Borntraeger, Berlin-Stuttgart.

Steller, M., Kalkreuth, W. and Hodek, W. 1987, Hydrogenation of selected subbituminous and bituminous coals; Erdöl und Kohle, 40, 9, 383-393.

Teichmüller, M. and Teichmüller, R., 1982, The geological basis of coal formation; in Stach, E., Mackowsky, M.-Th. Teichmüller, M., Taylor, G.H. Chandra, D., and Teichmüller, R., editors, Coal Petrology, 3rd Edition; Gebrüder Borntraeger, Berlin-Stuttgart, pp. 5-86.

Ting, F.T.C., 1978, Petrographic techniques in coal analysis; in Karr, C. Jr., editor, Analytical Methods for Coal and Coal Products; Academic Press, vol. 1, pp. 3-26.

Tissot, B. and Welte, D.H., 1978, Petroleum formation and occurrence; Springer-Verlag, New York, 538 pp.

van Krevelen, D.W., 1961, Coal; Elsevier, Amsterdam, London, New York, Princeton, 514 pp.

5   Acknowledgements

COAL QUALITY

Willem Langenberg
Alberta Research Council

All coals were not created equally. Their composition and physical properties vary greatly, not only from coal field to coal field, but even within individual seams. Their main differences are reflected in rank, moisture content and amounts of mineral matter. Because coal is a heterogeneous mixture of organic compounds, moisture and mineral matter, its composition determines its behavior when used. The quality of the coal determines for which use it is best suited. A good introduction to coal quality and influences by geology on coal quality can be found in Ward (1984).

Coal is presently used mainly as either a fuel for electric power generation or as a raw material for the manufacture of metallurgical coke. Significant amounts are also used for cement manufacture and other industrial processes. The future may see increased use of coal in liquefaction and gasification. Coal is the generator of coal-bed methane and forms the gas reservoir. Although all coal will burn, the lower rank coals are generally better suited as feed for power plants, while higher rank coals are better for the forming of coke. Anthracites do not cake and are therefore not capable of forming coke, but are an excellent source of heat with many applications.

The quality of a coal determines its value and can be tested by various chemical and physical analyses. The best known chemical analyses are proximate and ultimate analysis. Physical analyses generally involves establishing coking properties and grindability. Petrographic analysis allows to determine these chemical and physical properties by optical means using a (generally reflecting) microscope. A geological understanding of coal quality allows prediction of vertical and lateral variability of coal quality parameters within coal seams.

Recent information on coal quality of Alberta coal fields can be obtained from several reports (Bonnell and Janke, 1986; Macdonald et al., 1989; Strobl et al., 1989; Langenberg et al., 1989; Nurkowski, 1985).

PROXIMATE ANALYSIS

Proximate analysis involves the determination of compounds in a mixture. For coal it gives the relative amounts of moisture, ash, volatile matter and fixed carbon in percent weight. The term "Proximate" should not be confused with the word "approximate", since this test is performed according to rigid specifications established by testing organizations (in North America this is the American Society

for Testing and Materials or ASTM). The analysis can be presented with all 4 components, or on a dry basis (relative percentages of ash, volatile matter and fixed carbon), or on a dry ash free basis (relative percentages of volatile matter and fixed carbon). An example of a proximate analysis on these various bases is presented in Table 1. The ASTM rank classification requires a dry mineral matter free basis, whereby the mineral matter content is assumed to be 10% higher than the ash content. The calculation is known as the Parr formula and states that (ASTM, 1985):

Fixed Carbon (DMMF)=FC/[100-(M+1.1A+0.1S)]x100
Whereby:
FC=percentage fixed carbon
M=percentage of moisture
A=percentage of ash
S=percentage of sulphur, which is 0.3 in this example.

All percentages (FC, M, A and S) are on a moist basis. The formula assumes that the weight loss of mineral matter during combustion is in the form of volatile components (see section on ash). Consequently, the ratio of fixed carbon over volatile matter has to be increased to get the analysis from a dry ash free basis to a dry mineral matter free basis. The same result can be obtained by calculating 10% of the dry ash percentage and decreasing the dry volatile matter content by that percentage (keeping the fixed carbon percentage the same). The dry mineral matter free percentages can be calculated from these values.

Table 1. Proximate analysis on different bases

	Moist (air dried)	Dry	DAF	DMMF
Moisture	0.9			
Ash	7.9	8.0		
Vol mat	19.6	19.8	21.5	20.8
Fixed C	71.6	72.2	78.5	79.2

Moisture

Moisture content determination forms part of a standard proximate analysis and can be reported as received, as determined, or as equilibrium moisture.

a) The total moisture of a coal sample can be divided into surface moisture (extraneous water held as a film on the coal particles, also called adherent or free moisture) and inherent moisture (water physically held by capillaries in the coal). Total moisture can be estimated from a sealed sample as it was received in the laboratory, which analysis is termed *as received moisture*.

b) The inherent or bed moisture can be estimated by first drying the sample at room temperature and then determining the moisture content, where it is assumed that the air-drying has removed the surface moisture. This analysis is termed **as determined moisture** (or air dried moisture). Residual moisture is another term sometimes used for this analysis.

c) However, coal may have lost some moisture during its history (either in the ground or during transport to the laboratory). For this reason, **equilibrium moisture** (also called capacity moisture) is determined after emerging the crushed coal for 3 hours in distilled water of 30° C. This analysis may better estimate the true inherent or bed moisture of the coal than the as determined analysis. The moisture content of coal is directly related to the rank. Higher rank coals have, in general, a lower moisture content. The ASTM advises to use equilibrium moisture in rank determinations, because it is the best estimate of true inherent or bed moisture.

Surface moisture is determined as the difference between total (as received) moisture and inherent moisture.

Table 2. Different forms of moisture

```
------------------------------------------------------------
  As received moisture    ---> Total moisture
  As determined (or air dried) moisture  --->bed moisture
  Equilibrium (or capacity ) moisture ---> bed moisture
  Total minus bed moisture ---> surface (or free) moisture
------------------------------------------------------------
```

Excess moisture causes problems to coal producers. Moisture uses up calories of useful heat during combustion. Moisture represents extra weight during transportation of coal. Moisture content will determine if spontaneous combustion could take place during storage. Moisture also influences the gas storage capacity of the coal.

Ash

Ash is the unburned product left from the burning of coal and is composed of mineral matter that is either finely disseminated in the coal (including both original material in the plants and mineral matter introduced at a later stage) or is present as rock partings within the coal seam. The original material in the plants is called inherent mineral matter and the material introduced at a later stage is termed extraneous mineral matter. The original mineral matter content of coal can be calculated from the observed ash contents. Mineral matter content is about 10 percent higher than ash contents, because volatile components of the mineral matter are lost during combustion.

Ash content and composition affect both thermal and metallurgical coals. In metallurgical coals, ash is one of the most serious problems in making coke. There are often penalty clauses in coal contracts for higher than agreed upon ash contents in coals delivered. In thermal coals, high ash content tends to reduce the calorific value of coal. Other problems related to high ash content in thermal coals are difficult ash handling, varying ignition stability and different heat transfer in boilers. High ash content may cause fusion of ash, which results in slagging and fouling in furnaces, and corrosion of high temperature surfaces. High ash coals will also imply lower volumes of coal-bed methane being generated. Sulphur, sodium and trace elements are very important components in ash and are dealt with separately.

Volatile matter

Volatile matter represents the gaseous components of coal, except for moisture, that are liberated at high temperatures (generally above 800°C) in the absence of air. It consists of combustible gases (carbon monoxide, hydrogen, methane and other organic hydrocarbons) and non-combustible gases (carbon dioxide, ammonia, hydrogen sulphide and some chlorides). Consequently, volatile matter is not a natural component of coal, but forms part of the organic matter in coal. It can only be released by heating the coal in the absence of air and these gases are not available for coal-bed methane.

Volatile matter contents can be used to establish the rank of coal, because the volatile contents decrease during coalification. The ASTM rank classes for anthracitic and bituminous coals, based on dry mineral matter free volatile matter contents, are shown in figure 1. During geochemical coalification large amounts of methane are generated, which may form coal-bed methane reserves.

Fixed carbon

Fixed carbon represents the material left after moisture, ash and volatile matter have been expelled. It is largely composed of carbon with minor amounts of nitrogen, sulphur, hydrogen and possibly oxygen. Fixed carbon is not determined directly in proximate analysis, but is simply the difference between the sum of the other components (moisture, ash and volatile matter) and the total.

Class	Group	Fixed Carbon Limits, percent (Dry, Mineral-Matter-Free Basis)		Volatile Matter Limits, percent (Dry, Mineral-Matter-Free Basis)		Calorific Value Limits, Btu per pound (Moist,[b] Mineral-Matter-Free Basis)		Agglomerating Character
		Equal or Greater Than	Less Than	Greater Than	Equal or Less Than	Equal or Greater Than	Less Than	
I. Anthracitic	1. Meta-anthracite	98	...	...	2	...	...	nonagglomerating
	2. Anthracite	92	98	2	8	...	...	
	3. Semianthracite[c]	86	92	8	14	...	...	
II. Bituminous	1. Low volatile bituminous coal	78	86	14	22	...	...	commonly agglomerating[e]
	2. Medium volatile bituminous coal	69	78	22	31	...	...	
	3. High volatile A bituminous coal	...	69	31	...	14 000[D]	...	
	4. High volatile B bituminous coal	...	...	...	...	13 000[D]	14 000	
	5. High volatile C bituminous coal	...	...	...	...	11 500	13 000	
						10 500	11 500	agglomerating
III. Subbituminous	1. Subbituminous A coal	...	...	...	...	10 500	11 500	nonagglomerating
	2. Subbituminous B coal	...	...	...	...	9 500	10 500	
	3. Subbituminous C coal	...	...	...	...	8 300	9 500	
IV. Lignitic	1. Lignite A	...	...	...	...	6 300	8 300	
	2. Lignite B	...	...	...	...	...	6 300	

[a] This classification does not apply to certain coals, as discussed in Note 1.

[b] Moist refers to coal containing its natural inherent moisture but not including visible water on the surface of the coal.

[c] If agglomerating, classify in low-volatile group of the bituminous class.

[D] Coals having 69 % or more fixed carbon on the dry, mineral-matter-free basis shall be classified according to fixed carbon, regardless of calorific value.

[e] It is recognized that there may be nonagglomerating varieties in these groups of the bituminous class, and that there are notable exceptions in high volatile C bituminous group.

Figure 1. ASTM (1985) classification of coal by rank.

ULTIMATE ANALYSIS

Ultimate analysis involves the determination of the elements in a compound. For coal it determines the total amounts in weight percent of carbon, hydrogen, oxygen, nitrogen, ash and sulphur. These elements occur in both the organic and inorganic components of coal, with the exception of nitrogen, which is only found in the organic components. Hydrogen and oxygen also make up the moisture in coal. Carbon, hydrogen and oxygen are of significance in determining the coking and combustion properties of the coal, while sulphur and nitrogen represent possible sources of pollution. The ultimate analysis of the same coal sample of which the proximate analysis is presented in table 1, is shown in table 3 as an example. The dry and dry ash free basis are calculated from the total analysis.

Table 3. Ultimate analysis on different bases

	Moist (air dried)	Dry	DAF
Moisture	0.9		
Ash	7.9	8.0	
C	82.6	83.4	90.6
H	4.1	4.1	4.4
N	1.4	1.4	1.5
S	0.3	0.3	0.3
O	2.8	2.8	3.2

Sulphur

Alberta coals are, in general, low in sulphur content compared to coals elsewhere. Knowledge about sulphur content of coals is very important, especially in thermal coals, because of potential environmental damage. Sulphur causes problems in power plant boilers by forming sulfuric acid, which causes corrosion in boilers. Sulphur also affects the electrical properties of fly ash, thereby affecting the electrostatic precipitators efficiency. High sulphur content in coking coals, if retained in the coke, can lead to brittleness in iron produced. Sulphur is contained in coals in a mineral matter form and in an organic form. Distinguishing between these two forms is important in deciding what technologies need to be applied to clean up the coal. Geology can play an important role in this area.

ASH ANALYSIS

Ash consists almost entirely of the decomposed residues of silicates, carbonates, sulphides and other minerals. The composition of the ash gives an evaluation of the minerals present in coal. Such data is of commercial significance for coking and thermal coals.

Sodium is an element that is particularly troublesome to the thermal coal industry. Sodium contents that exceed 0.4% (expressed as Na_2O by weight of the dry coal) will have fouling tendencies in boilers . In the past the total alkali content was taken as a measure of a coals fouling potential (potassium included with sodium). It is now realized that sodium is by far the most troublesome of the alkalis, therefore, measurement of this element is most important.

Low temperature oxidation (or low temperature ashing) methods remove the organic components by oxidation and leave the mineral matter (essentially unaltered) as a residue. The specific minerals present can now be determined by X-ray techniques.

TRACE ELEMENTS

Trace elements are relatively abundant in coals and are of interest from a number of different aspects. They are associated with both the organic and inorganic portions of coal. Early interest in trace elements in coal stemmed from the idea that they could be produced as possible byproducts of coal mining (germanium and uranium are two examples). Since the mid 1960's interest in trace elements was centered on the fear that toxic trace elements may be released into the environment, through coal combustion. Trace elements are also being examined with respect to hydrocarbon liquids, coke and other coal products. There is some evidence to suggest that trace elements may act as catalysts or inhibitors in coal conversion processes. Another new area of interest is, using trace elements to characterize individual coal seams to assist in seam correlations and in coal depositional environment research.

CALORIFIC VALUE

Calorific value or heating value is probably the single most important component in evaluating a thermal coal's potential. The ASTM rank classes of sub-bituminous and lignitic coals is based on calorific value (see figure 1). Many of the previously mentioned coal quality attributes (e.g. ash content and composition) affect the calorific value of a coal. Calorific value is one of the analyses that has been standardly performed in coal exploration for many decades. The rank map of surface coals of Alberta (figure 2) is based on calorific values. Cross section AA' of figure 3 (line of section on figure 2) shows the coal bearing formations and a subsurface isorank line, constructed by Nurkowski (1985) based on variation in rank of surface coals. This isorank line will have to be verified by maturation data (mainly vitrinite reflectances) from oil wells.

GRINDABILITY

The ease with which a coal can be ground to a fine powder (hardgrove grindability) is often also determined. Coals with a high Grindability Index are relatively soft and easy to grind. Those with a low value (less than 50), are hard and much more difficult to make into pulverized fuel. Alberta's Foothills and Mountain coals have generally higher indices than Plains coals (they are softer), because of intensive tectonic shearing in the Mountain regions.
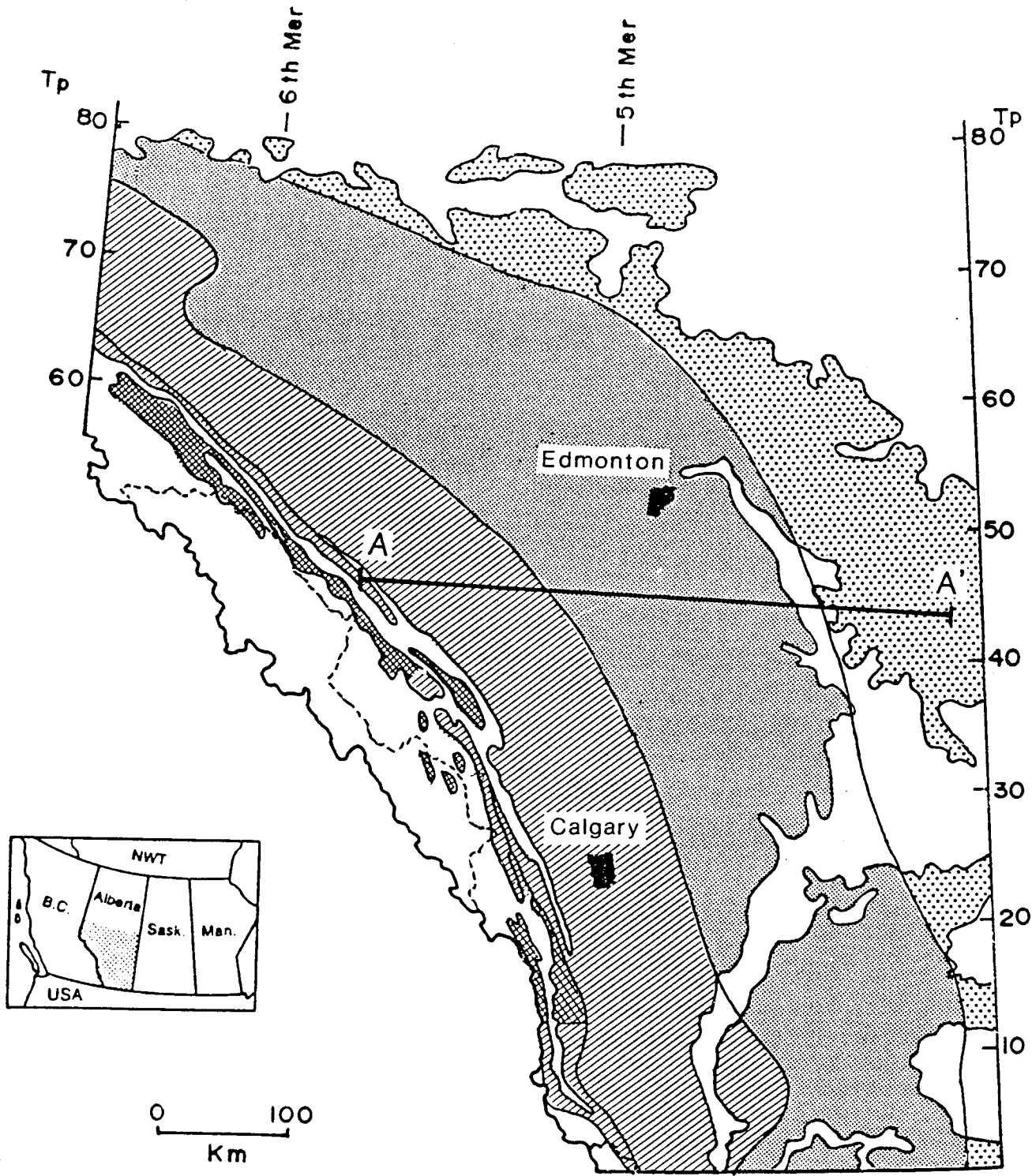
Figure 2. Map showing the rank of surface coals of Alberta (modified from a map by the ERCB).
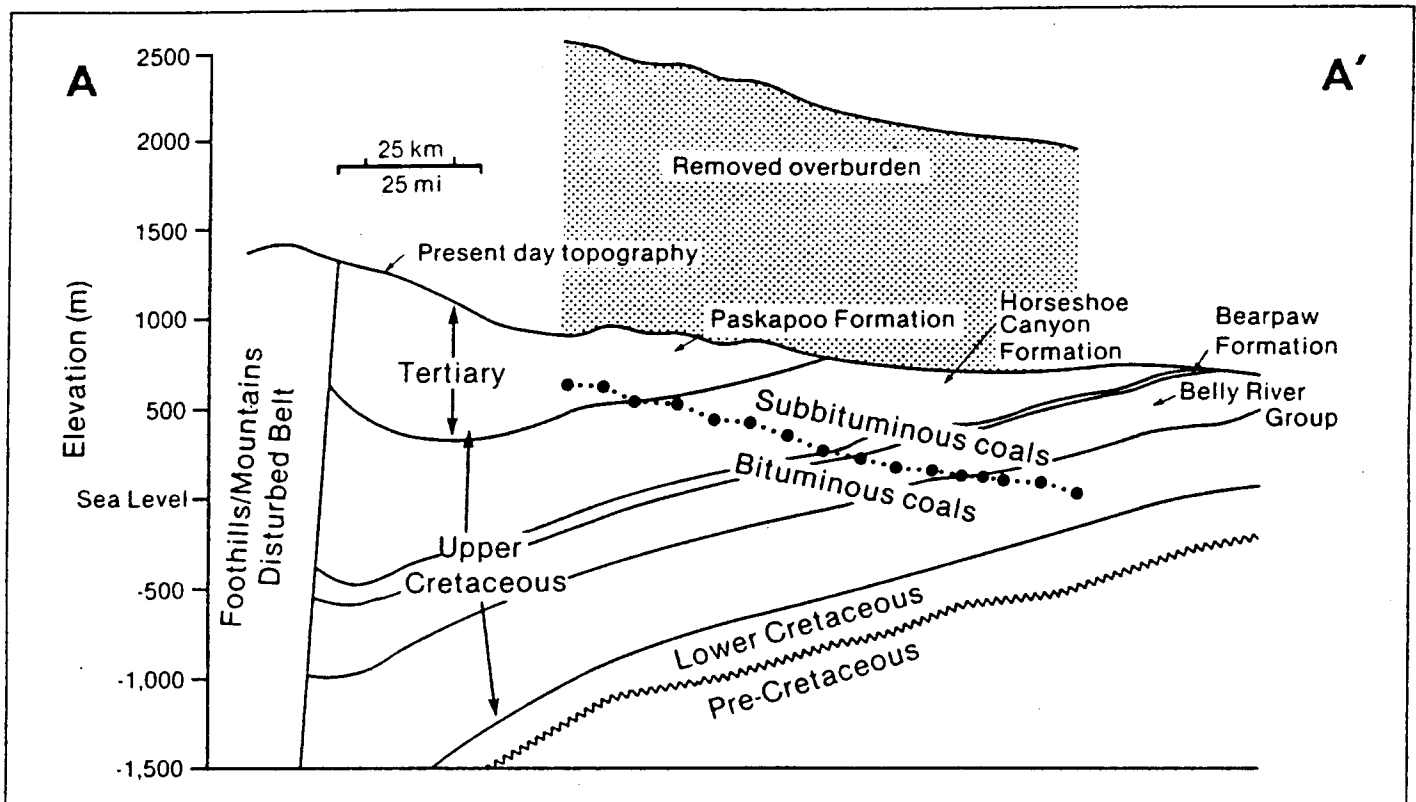
Figure 3. Generalized cross section through the central
Plains, showing coal bearing formations and
isorank line (Nurkowski, 1985).

COKING PROPERTIES

Coking (or metallurgical) coal is exploited in the
foothills and mountains of Alberta. They generally range
from medium to low volatile bituminous in rank. However,
high volatile bituminous coals can be used if blended with
higher rank coals. The free swelling index (FSI) will
predict if a coal is capable of forming coke, whereby an FSI
of 0 indicates no swelling and 9 maximum swelling. In order
to qualify as a coking coal, the FSI should be above 5,
although coals with lower FSI can be used in blends. The FSI
test, however, does not give a quantitative prediction of the
strength of the resultant coke. Other types of tests are
generally used in further evaluating the mechanical (or
rheological) properties of coke. They generally determine
dilatation or fluidity. These properties can also be
estimated from petrographic analysis

Coke, used for steel making, is generally made from
blends of several coals with varying properties. However,
the technology of steel making is changing and the desired
blends might in the future contain a larger percentage of
lower rank coals. Nevertheless, it seems certain that
bituminous coals will remain an important component of these
blends.

THICKNESS

Although thickness of coal seams is not a traditional coal quality parameter, it is such an important variable that we like to discuss it in this chapter. Variation in thickness of coal seams is related to either sedimentological or tectonic factors.

Sedimentological factors

The sedimentological environment of coal will be discussed elsewhere. Consequently, it suffices to note here that the geometry of coals near paleo channels is different from those near paleo shorelines. The geometry of individual seams tends to be elongate, parallel to the channels. Clastic partings in the seam become more common near the channels. On the coastal plain the thickest and cleanest coals will be found landward of the paleo shoreline and the geometry will be elongate parallel to the shorelines.

Tectonic factors

Coal which is structurally thickened, forms important exploration targets in the mountains and foothills. In the Cadomin-Luscar coal field, the coal is often thickened in the hinges of folds. The open pits of Gregg River Resources and Cardinal River Mines are generally situated along such hinges (Langenberg et al., 1989) as shown in figure 4. In the Smoky
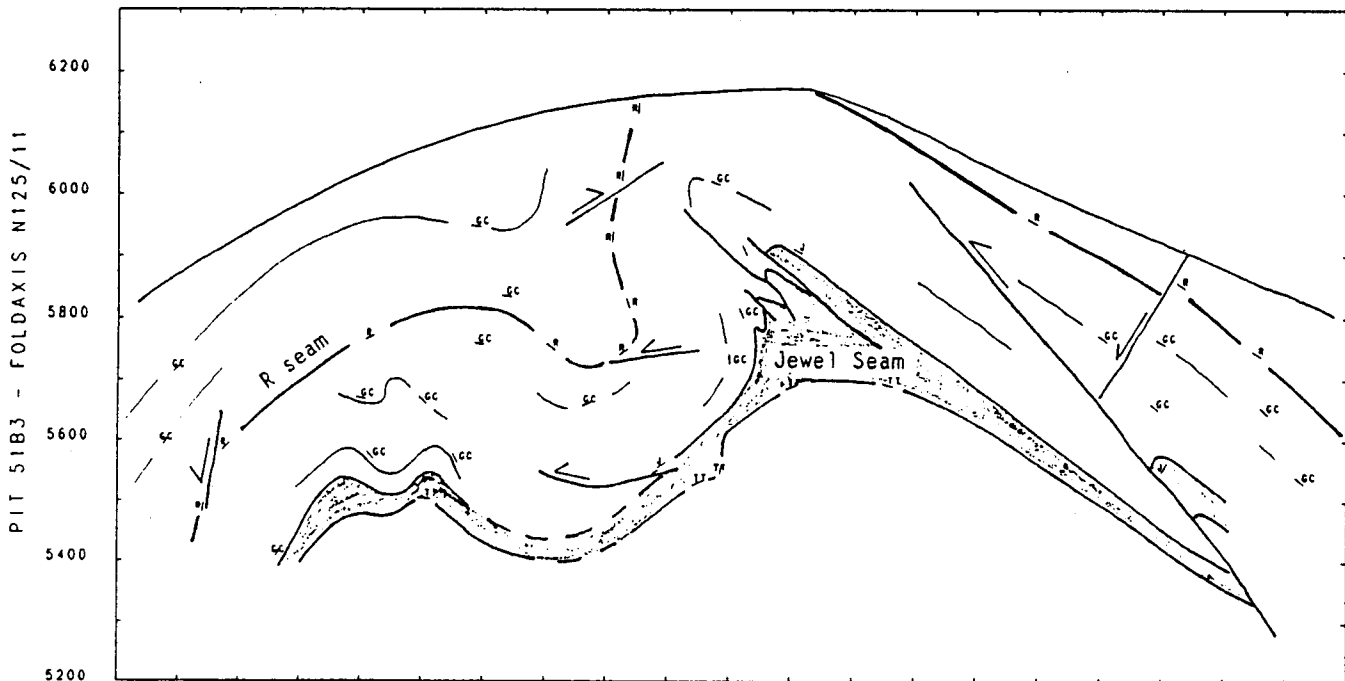
Figure 4. Vertical cross section through the end wall of the 51B3 Pit (Cardinal River Coal, Cadomin area), showing tectonic thickening of Jewel coal seam.

River coal field, coal is thickened up to two times in the hinges of folds. Another exploration target in this coal field is formed by thickened coal resulting from imbricate faulting (Langenberg et al., 1987). The thickening can be up to three times its normal thickness, which results in very favorable stripping ratios. This type of thickening is generally present in the limbs of folds. In the Coalspur coal field, coal has been thickened up to 20 times its stratigraphic thickness of 4 m by imbricate faulting and the resulting pods are mined at Coal Valley (Charlesworth and Gagnon, 1985).

GAS CONTENT

Generation of gas and coal as a gas reservoir is discussed in another section of this short course. Here it will suffice to say that gas in coal, which is generally about 95% methane, is an important coal quality parameter. Large amounts of methane may be generated during coalification (figure 5). Total amounts of gas present depend on rank, volume of coal and methane retention. Methane is retained in pores in the coal and distinction is made between microporosity and macroporosity. Microporosity is the most significant in methane retention in coal (Rightmire, 1984). Methane molecules are adsorbed on the organic surfaces in the micropores. Consequently, pore volume data should not be used for retention calculations. The primary controlling factor for the amount of gas stored in coal is the surface area contained within the coal micro-pore system.
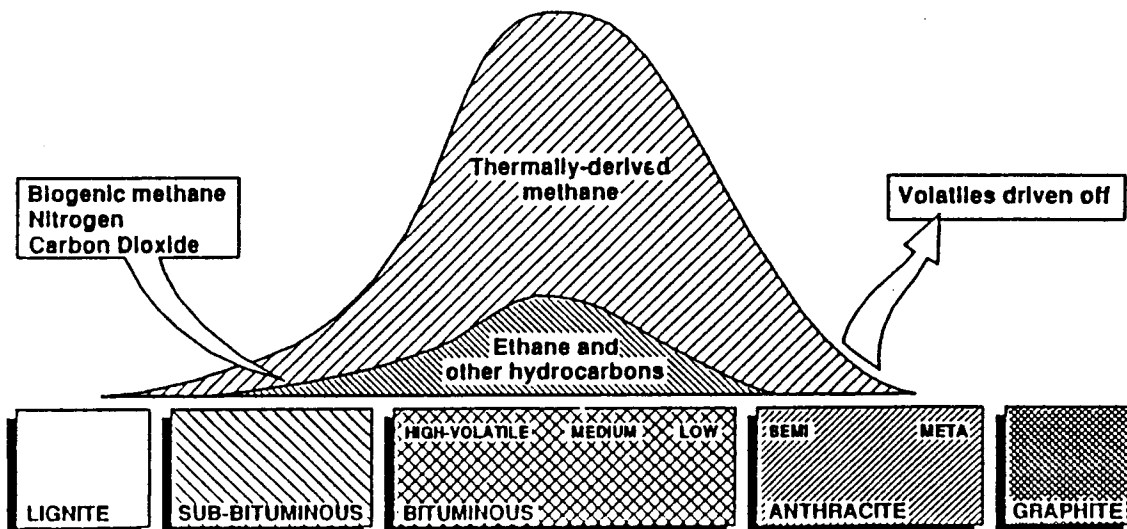
Figure 5. Gas generation in coal.

A lesser amount of methane is retained in macro-pores, which are primarily fractures called cleats. It may be

present as free gas or dissolved in ground-water. Cleats are fractures (also called joints) perpendicular to the coal-bed. Cleat spacing and orientation can influence reservoir flow. There are usually two cleat sets developed nearly perpendicular to each other. Face is the major cleat and may extend great distances. Butt cleat (also called end cleat) is perpendicular to the face cleat. In the Alberta Plains butt cleat is generally parallel to the Rocky Mountain front (figure 6), indicating some relationship to orogenic forces.
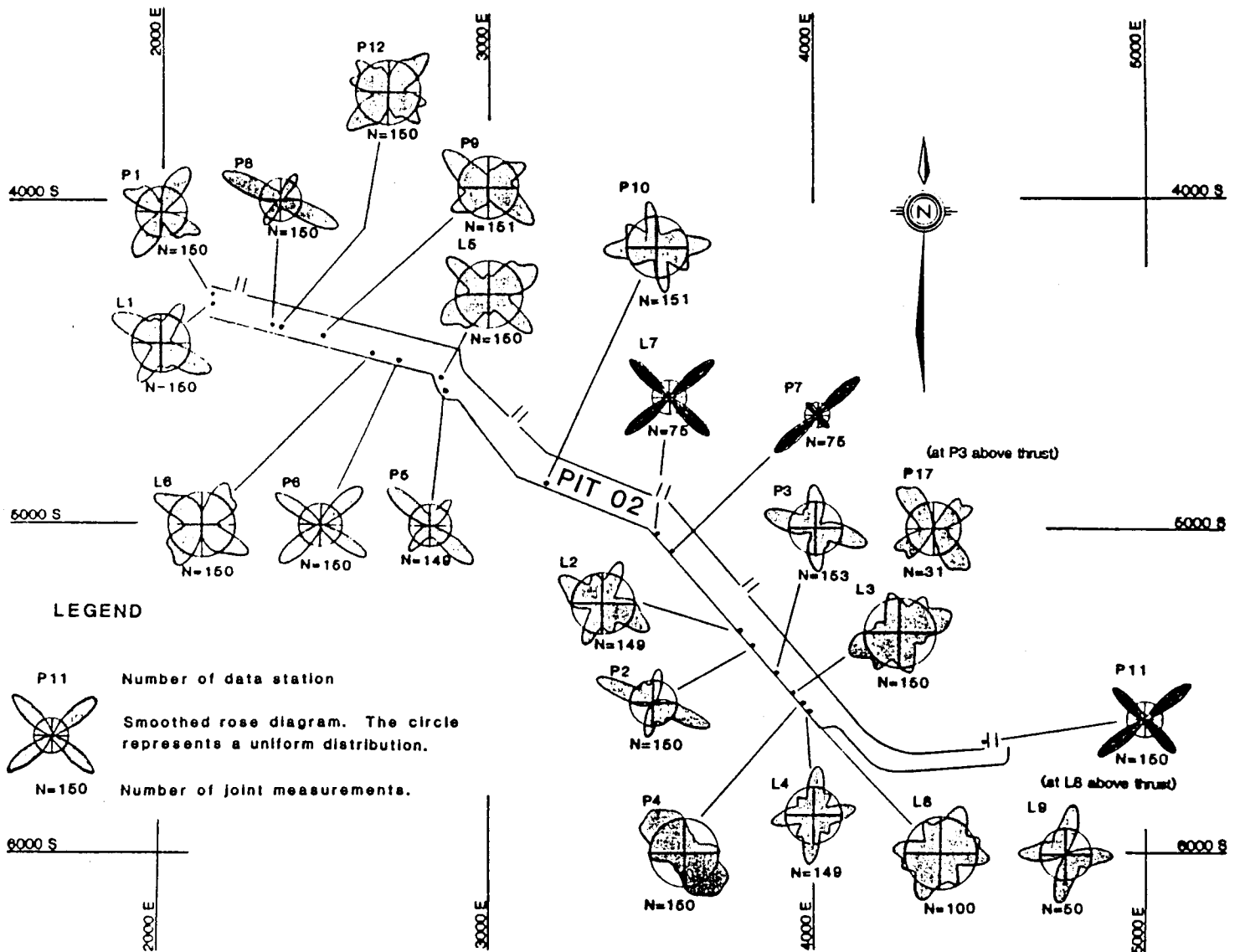
Figure 6. Smoothed rose diagrams of joints and cleats at Pit 2 of the Highvale Mine (near Lake Wabamun). Stations L7, P7 and P11 in coal (cleats); others are joints in clastic sediments (from Moell et al. 1985).

REFERENCES

ASTM (1985): Annual book of ASTM standards. Volume 05.05, Gaseous Fuels; Coal and Coke; American Society for Testing and Materials, Philadelphia.

Bonnel, G.W. and Janke, L.C. (1986): Analysis directory of Canadian commercial coals: supplement No. 6; CANMET Report 85-11E.

Charlesworth, H.A.K. and Gagnon, L.G. (1985): Intercutaneous wedges, the triangle zone and structural thickening of the Mynheer coal seam at Coal Valley in the Rocky Mountain Foothills of central Alberta; Bulletin of Canadian Petroleum Geology, v.33, pp.22-30.

Langenberg, C.W., Kalkreuth, W. and Wrightson, C.B. (1987): Deformed Lower Cretaceous coal-bearing strata of the Grande Cache area, Alberta; Alberta Research Council, Bulletin 56, 54 pages.

Langenberg, C.W., Macdonald, D., Kalkreuth, W., and Strobl, R. (1989): Coal quality variation in the Cadomin-Luscar coalfield; Alberta Research Council, Earth Sciences Report 89-1, 65 pages.

Macdonald, D.E., Langenberg, C.W. and Gentzis, T. (1989): A regional evaluation of coal quality in the Foothills/Mountains region of Alberta; Alberta Research Council, Earth Sciences Report 89-2, 58 pages.

Moell, C., Pawlowicz, J., Trudell, M., Fenton, M., Langenberg, W, Sterenberg, G and Jones, C. (1985): Highwall stability project Highvale Mine - Report of 1984 activities; unpublished report to TransAlta Utilities by Alberta Research Council.

Nurkowski, J.R. (1985): Coal quality and rank variation within upper Cretaceous and Tertiary sediments, Alberta Plains region; Alberta Research Council, Earth Sciences Report 85-1, 39p.

Rightmire, C.T. (1984): Coal-bed methane resource; *in*: Rightmire et al., eds, Coal-bed methane resources of the United States; American association of Petroleum Geologists, Studies in Geology Series, No. 17, pp.1-13.

Strobl, R.S., Wong, R., Krzanowskt, R., Mandryk, G., Chao, D. and Chidambaram, N. (1989): Coal quality in the Ardley coal zone, Plains region of Alberta; Alberta Research Council Open File Report 1989-8.

Ward, C.R. (1984): Coal geology and coal technology; Blackwell Scientific Publishers, 345p.

SEDIMENTARY ENVIRONMENTS OF COAL

Rudy Strobl
Alberta Research Council

Coal seams can be viewed as deposits for mining or as reservoirs for coal bed methane. In both cases, close attention must be paid to measuring the lateral continuity of seams, thickness variation, and aspects of coal quality (including gas content). Understanding the depositional controls on peat formation and the associated clastic successions is a fundamental first step in the exploration process.

Coal deposits can be found in a wide variety of depositional settings, but most coals in the Alberta basin, are associated with alluvial plain and coastal plain settings. Regional exploration models for these two depositional settings are outlined in this paper. Concepts of sequence stratigraphy provides an additional exploration tool. For coal bearing successions associated with coastal plain deposits, periods of coal accumulation may linked to low-stand systems tracts. These aspects of exploration strategies will be expanded upon after a brief introduction to coal facies and conditions necessary for peat (coal) development.

RELATIONSHIP BETWEEN COAL AND CLASTIC SEDIMENTS

Most facies models for coal-bearing strata show peat accumulating close to active clastic depositional environments such as on the floodplain of meandering rivers, coastal mires immediately behind beach barrier systems or in interdistributary bays of deltas. Detailed examination of some of these settings, however, suggests that relatively thick clastic sediment accumulations (primarily muds and silts) are introduced during frequent floods, storm surges or exceptionally high tides. Mires located close to active clastic environments are more likely to produce carbonaceous shales rather than coals (McCabe, 1988).

Thick, low ash peat accumulations are most commonly formed in areas that were removed from active clastic deposition for extended periods of time. As one example, in the Okefenokee, 4 metres of peat required more than 5 000 years to accumulate (Figure 1). Assuming a compaction ratio .of 10:1 for the peat to transform to coal, a 1 m thick coal seam will require uninterrupted peat deposition for tens of thousands of years.

Coal seams have complex internal stratigraphies leading to considerable variation in coal quality both laterally and vertically. Variation in plant types, early alteration of organic material and climate changes are important controlling factors during peat accumulation. In the Okefenokee Swamp (Figure 1), an upward change in peat type from the water lily, Nymphaea peat to the tree and shrub, Ilex-Cyrilla-Lyonia peat is observed (Spackman et al., 1976; McCabe, 1988). Charcoal zones, which develop into fusain layers in coal, indicate that major drought periods also occurred, lowering regional water tables and allowing major fires to sweep across the mire. Similar

variations in the vertical profile of coal seams is observed based on maceral distributions and palynological studies (Hacquebard and Donaldson, 1969; Demchuk and Strobl, 1989). These types of studies suggest that ignoring the coal facies and interpreting the coal simply as "a swamp" may be equivalent to interpreting any carbonate reservoir as "warm shallow marine" (McCabe, 1988). Coal studies, especially coal quality studies, warrant more detailed investigations of the coal facies.

Although some coals and adjacent clastics may have been deposited contemporaneously, in many cases the contact between the two lithologies represents a considerable hiatus in deposition. Peats commonly overlie much older sediments representing a 100,000 year or more hiatus. In modern mires such as the Snuggedy Swamp of South Carolina and the
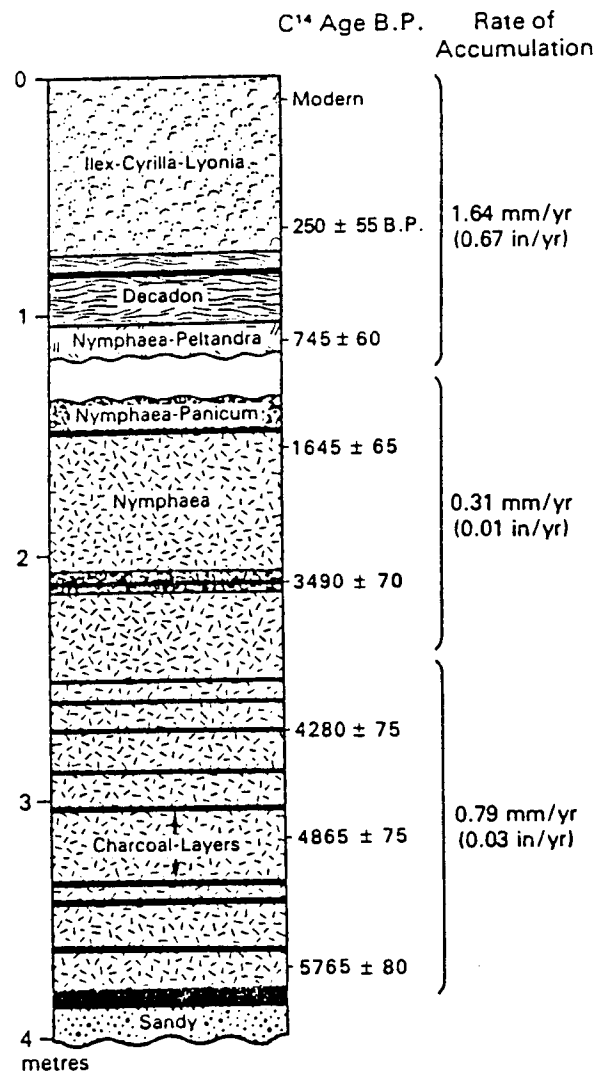
Figure 1.   Core from the Okefenokee Swamp showing variation in peat type and average rates of peat accumulation (after Spackman et al., 1976).

Okefenokee Swamp of Georgia, for example, thick accumulations of peat sit directly on Pleistocene beach ridges 20 to 75 km from the present day shoreline. Well back from the effects of storms and tidal surges, these mires develop extensive, low ash peats unhindered by clastic sources.

Mires can be classified into three types: raised, low-lying and floating (Figure 2). Low-lying mires form in areas of poor drainage. Floating mires develop over lakes until the lake infills with sediment or peat and can later develop into larger low-lying mires. If climatic conditions are favourable, a raised mire can develop. Raised mires occur in areas where annual precipitation is greater that annual evaporation, typically in maritime (ever-wet) environments. Examples of modern raised mires can be found in southeast Asia, northwest Europe and the Fraser River delta in British Columbia. In the modern, most of the world's mires are low-lying, accumulating in cool climates between 50 and 70 degrees North. Interestingly, most tropical rainforests are not sites of peat accumulation because the organic matter rapidly deteriorates.
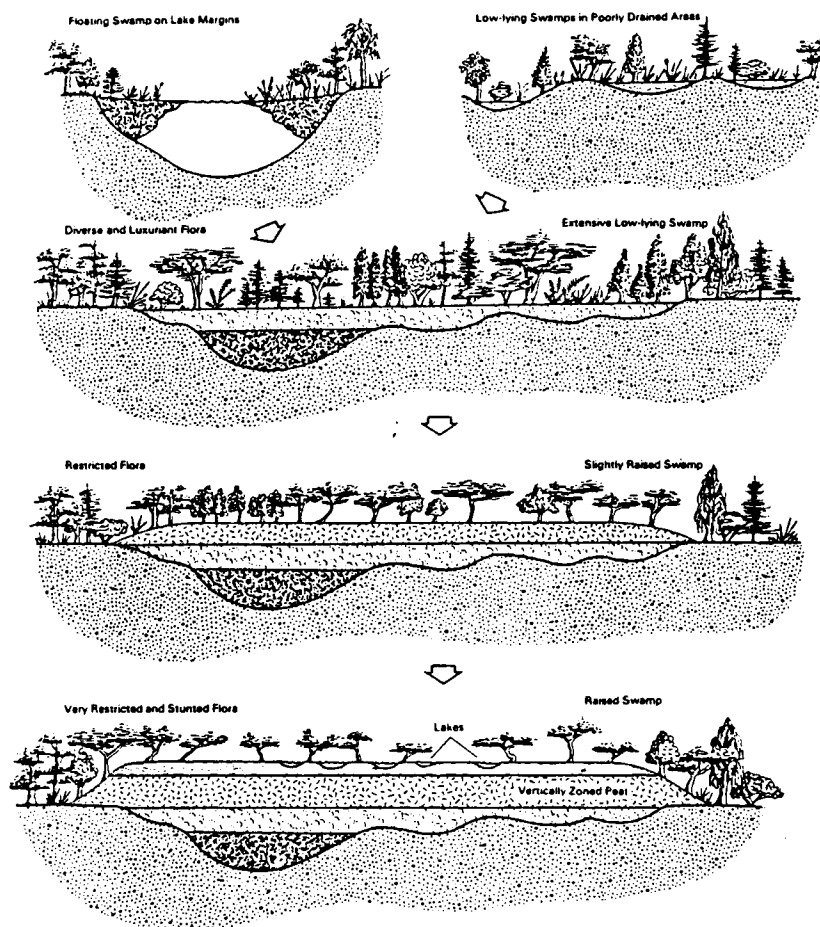
Figure 2. Evolutionary sequence of swamp types (after McCabe, 1984).

ALLUVIAL PLAIN SETTINGS

Coal zones in Alberta which are associated with alluvial plain/fluvial sediments include the Ardley near the base of the Paskapoo Formation (Richardson et al., 1988); the Coalspur in the Saunders Group (Jerzykiewicz, this volume); Carbon-Thompson in the uppermost Horseshoe Canyon Formation (Nurkowski and Rahmani, 1984); the Cutbank and Red Willow Coal Measures of the Wapiti Group (Dawson et al., 1989); and the Obed coal zone in the uppermost Paskapoo Formation (Macdonald et al., 1989).

The alluvial plain environment is characterized by widespread mires and very low gradients. For the Carbon-Thompson coal zone, and portions of the Ardley coal zone, these coals are commonly associated with lacustrine deposits (Nurkowski and Rahmani, 1984; Baofang and Dawson, 1988). For the other study areas, associated sediments appear to be predominantly fluvial in origin. The moderately low ash content, and laterally persistent and relatively thick nature of many of these coal seams suggests the development of widespread mires isolated from clastic deposition for long periods of time.

The Ardley coal zone of the plains region, the equivalent Coalspur in the foothills and the Kakwa coal measures of the Wapiti area are Paleocene in age. These coals generally contain the thickest and most economic of the Alberta coals associated with alluvial plain sediments.

A regional depositional model for the Ardley coal zone is proposed by Richardson et al., 1988) showing the relationship between coal accumulations and the regional tectonic setting (Figure 3). Loading effects of the Laramide orogeny during the Upper Cretaceous and early Tertiary, led to a westward dipping asymmetrical basin. The Ardley coal zone generally thickens towards the western margin of the basin, where relative subsidence was greater than that in the east. The greater amount of coal towards the west is due to higher subsidence rates (Figure 4). With increasing depth, individual seams generally become thicker (up to 4 m), more numerous (up to 15) and cumulative coal increases (up to 24 m). Areas with particularly thick coals (Figure 4) includes the north-south area between Obed and Whitecourt (which includes the Coal Valley mining area) and east-west trending area between from Coalspur to Wabamun (which includes the Highvale, Whitewood and Genessee mining areas).

To illustrate the lateral continuity of individual Ardley coal seams, subsurface studies in the Medicine River and Alix areas were completed (Richardson et al., 1988). In Figure 5, an isopach map of a seam ranging from 1 to 4 m thick is shown blanketing an area of more than 25 townships. Similar lateral continuity of a seam in the Alix area is illustrated in Figure 6. Selected coal seams are remarkably continuous and in many areas can be correlated over 10's of kilometres with a high degree of geologic assurance (Figure 7). On a basin-wide scale, correlations are complicated by seam splits, local thinning and dying out of individual seams (Figure 8). Correlation of the coal zone rather than individual seams, is recommended on a regional scale.

Some alluvial plain coal seams, like seam 100 and 150 (Figure 7) offer potential as reservoirs, if they contain commercial quantities of coal bed methane. The lateral extent of the reservoirs themselves will be enormous. Given the right conditions (coal rank, presence of cleats, gas content and other reservoir parameters), coals like seam 100 and 150 would make attractive exploration targets in deeper parts of the basin. An additional factor to consider is effects of topography created by the underlying strata. Thicker coals should be expected over abandoned channels or lake beds. Anticlinal structures and local drapes of coal seams commonly occur over thick sandy channel successions as a result of differential compaction.

The occurrence of these types of continuous coal seams would suggest that Ardley coal seams and their equivalents in the foothills, are a result of some regional shut down on sedimentation along the eastern flank of the basin. This would allowe extensive peat accumulations with little introduction of clastics. Note the absence of Ardley coals south of Township 30 (Figure 4). One explanation offered is that Ardley equivalent strata in the southern portion of the basin may have experienced semi-arid conditions compared to more humid climates to the north (Jerzykiewicz, 1989).
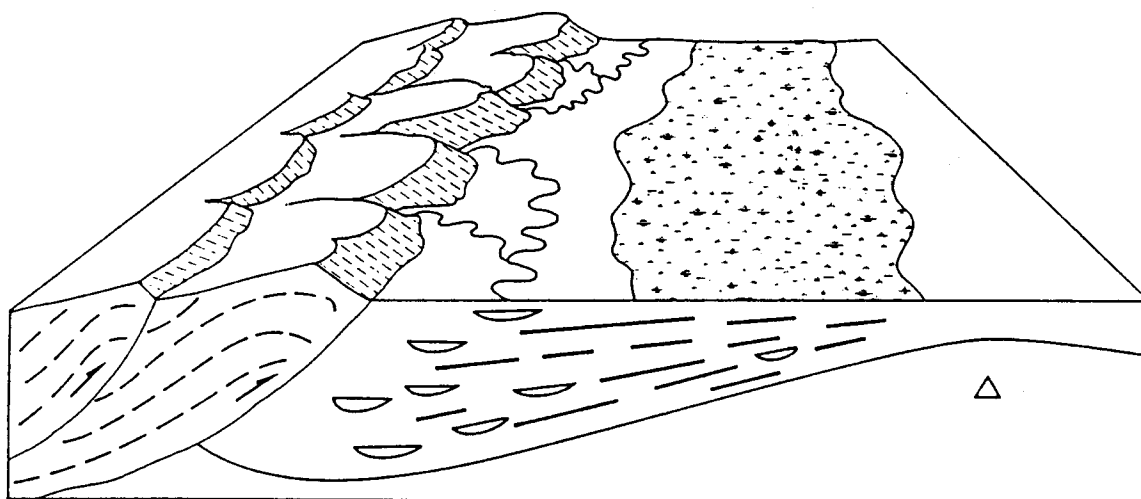
U43

Figure 3.   Schematic sketch showing tectonic controls on coal deposition during the early Tertiary in the Alberta Basin (Richardson et al., 1988).
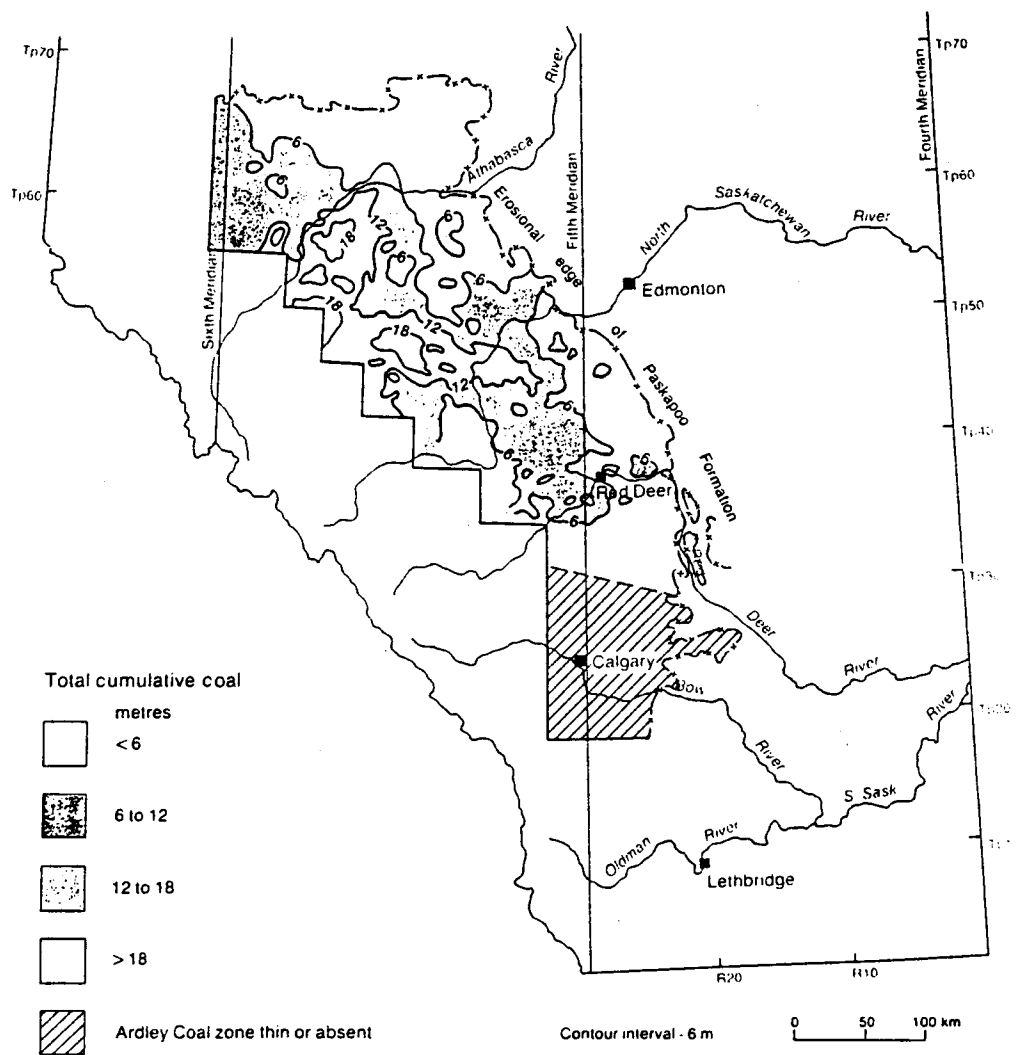
Figure 4. Cumulative coal in the Ardley coal zone, plains region of Alberta (Richardson et al., 1988).
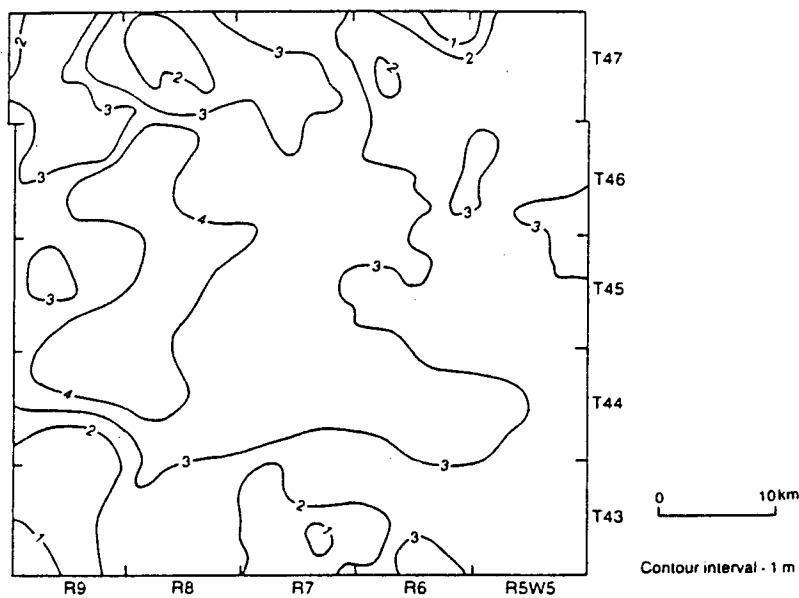
Figure 5. Isopach map showing the variation of seam 100, Medicine River substudy (Richarson et al., 1988).

Figure 6. Isopach map showing the variation of seam 700, Alix substudy (Richardson et al., 1988).

74
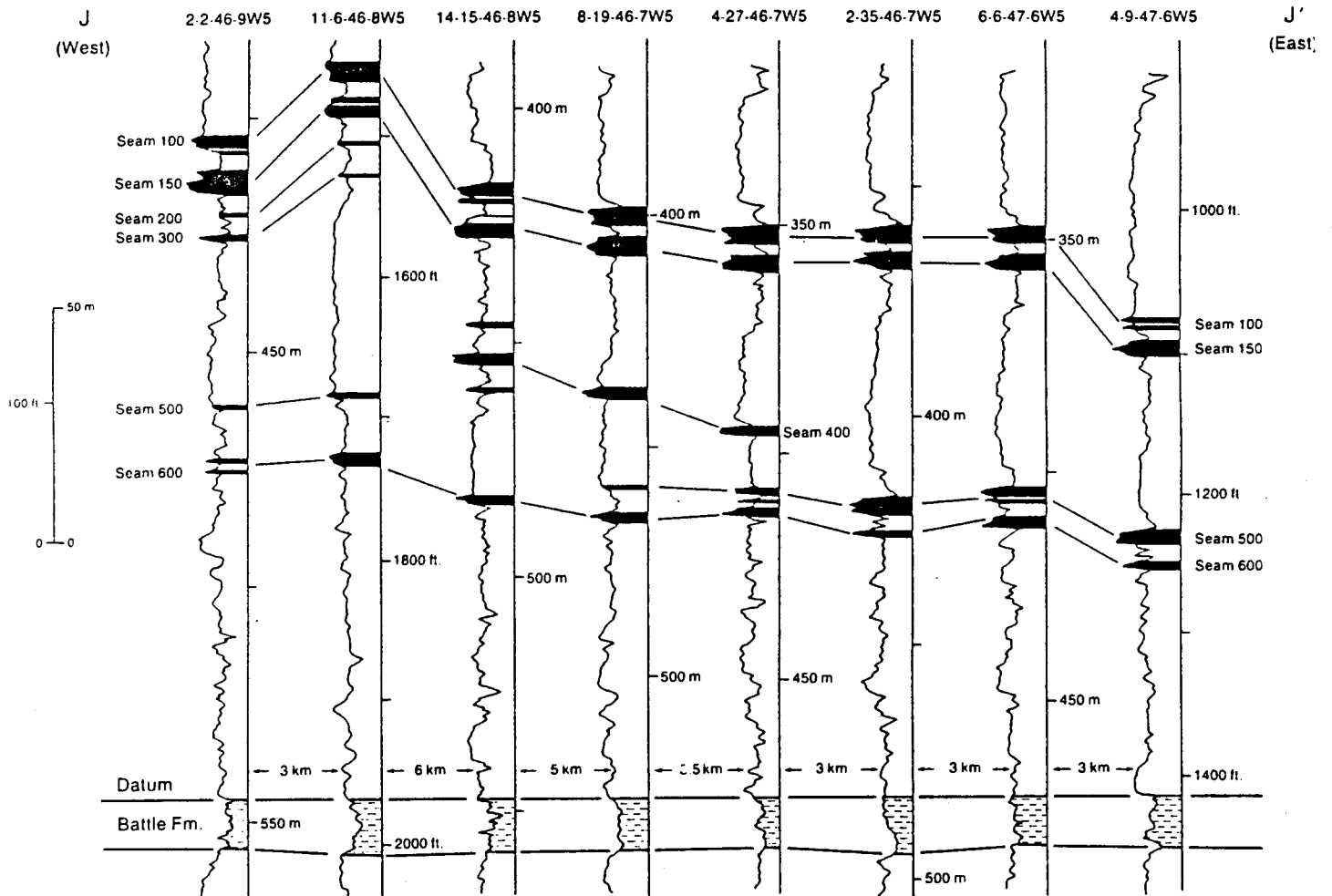
Figure 7.   East-West stratigraphic cross section of Ardley coal seams, based on closely spaced well logs (Richardson et al., 1988).
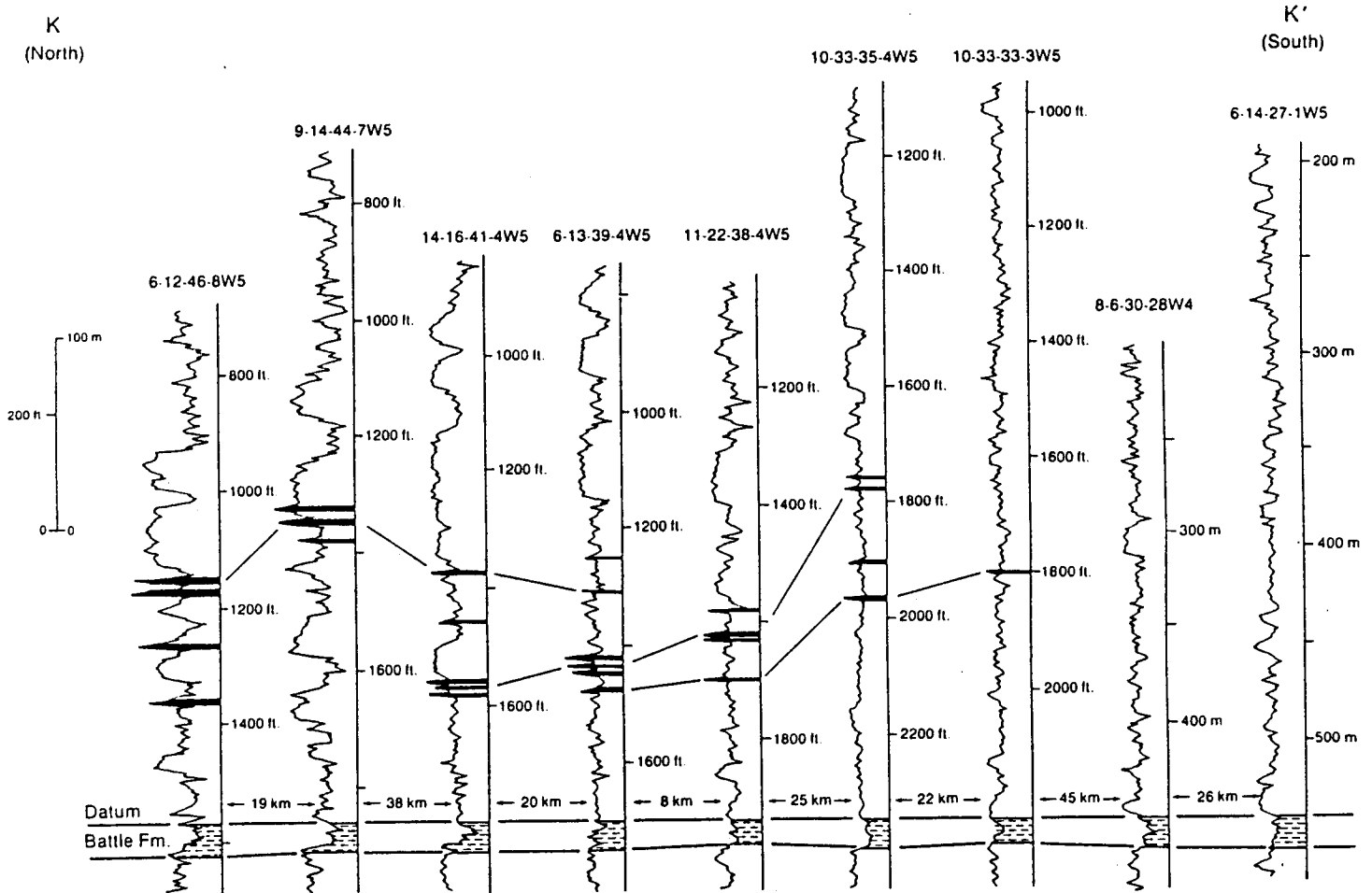
Figure 8. Stratigraphic cross section of the Ardley coal zone on a regional scale. Note the general decrease in the number and thickness of coals towards the south (Richardson et al., 1988).

COASTAL PLAIN SETTINGS

Coal zones in Alberta associated with coastal plain settings include the Upper Mannville coals (Medicine River seam) (Williams and Murphy, 1981); Cadomin-Luscar coals (Jewel Seam) (Langenberg, this volume); lower Horseshoe Canyon Formation coals (Drumheller coal zone) (McCabe et al., 1989); Belly River Formation coals (Lethbridge, Taber and McKay coal zones) (Macdonald et al., 1987) and the St. Mary River Formation coals (Latour, 1961). In virtually all of these coal zones, some of the thickest and most economic coal seams occur as elongate pods, parallel to paleoshorelines. These coals commonly overlie regressive shoreface sandstones, pinching out in a landward direction (Figure 9).

The model presented in Figure 9 by Ryer (1981) for the Cretaceous Ferron coals, show how coal seams extend up to 24 km perpendicular to paleoshorelines and up to 58 km parallel to paleoshoreline trends. The Ferron coals reach their maximum thickness, up to 10 m, about 10 km landward of the landward pinchout of each regressive sequence. Thickness trends observed on isopach maps of individual seams are parallel to paleoshorelines which is consistent with the model proposed. Isopachs can be pod-like due to the effects of fluvial and/or estuarine channel systems flowing perpendicular to the coast. As this example points out, the methods of mapping coals associated with shoreline sequences contrast sharply with those used for alluvial plain coals because of pronounced differences in geometries and depositional controls.

Alberta examples include the coals of the Drumheller coal zone, in the lower Horseshoe Canyon Formation. Spectacular outcrop exposures in the Drumheller and East Coulee areas allows us to model these coals in considerable detail. As predicted by Ryer's model, some of the thickest coals of the Drumheller zone overlie regressive shoreface sandstones (Figure 10). Tying in subsurface drillhole information with the outcrop data, Rahmani (1988), shows the seaward limit of coal deposition and the effects of estuarine channels on coal development (Figure 11).

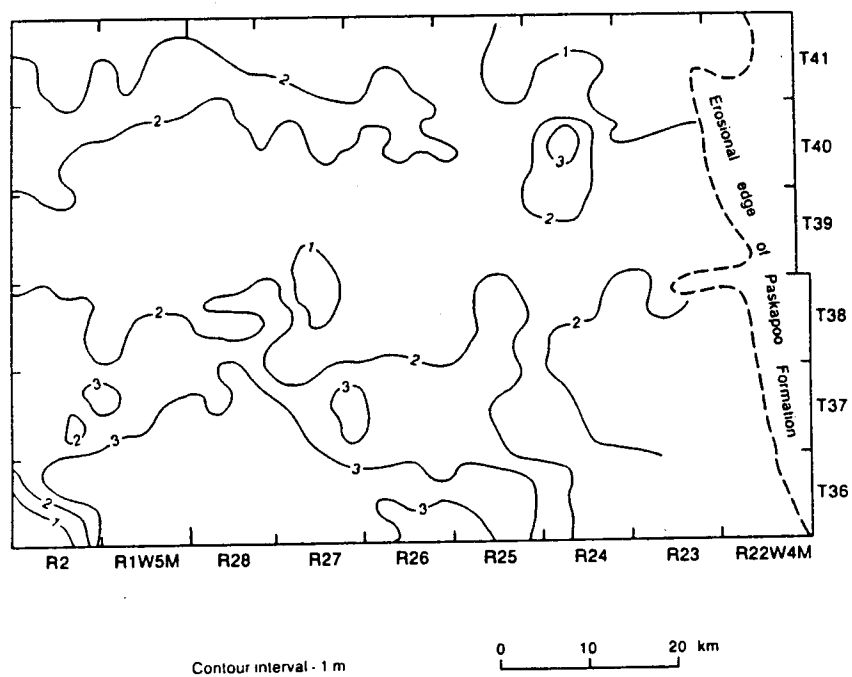In a more regional subsurface study of the lower Horseshoe Canyon coals, similar trends are found to those observed in outcrop (McCabe et al., 1989). Moderately thick coal seams directly overlie shoreface sandstones and pinch out landward (Figure 12). Regional coal seam isopach maps for the lower Horseshoe Canyon Formation show well defined eastern and western limits reflecting controls on mire formation by shoreline position (Figure 13). Coal seams in the lower Horseshoe Formation are commonly less than 2 m thick, but locally can be 4 m or more in thickness. Local thickening can often be tied to the underlying topography at the time of mire development. Thicker coals should be expected, for example, between beach ridges.

The Jewel seam in the Cadomin-Luscar area shows similar trends to those of the Horseshoe Canyon Formation. The Jewel seam is up to 10 m thick sitting directly on the Torrens Sandstone. As mentioned in the introduction, peats accumulating in the Okefenokee Swamp overlie much older Pleistocene beach ridges and shoreface sandtones. Using concepts of sequence stratigraphy, we have an additional exploration tool to
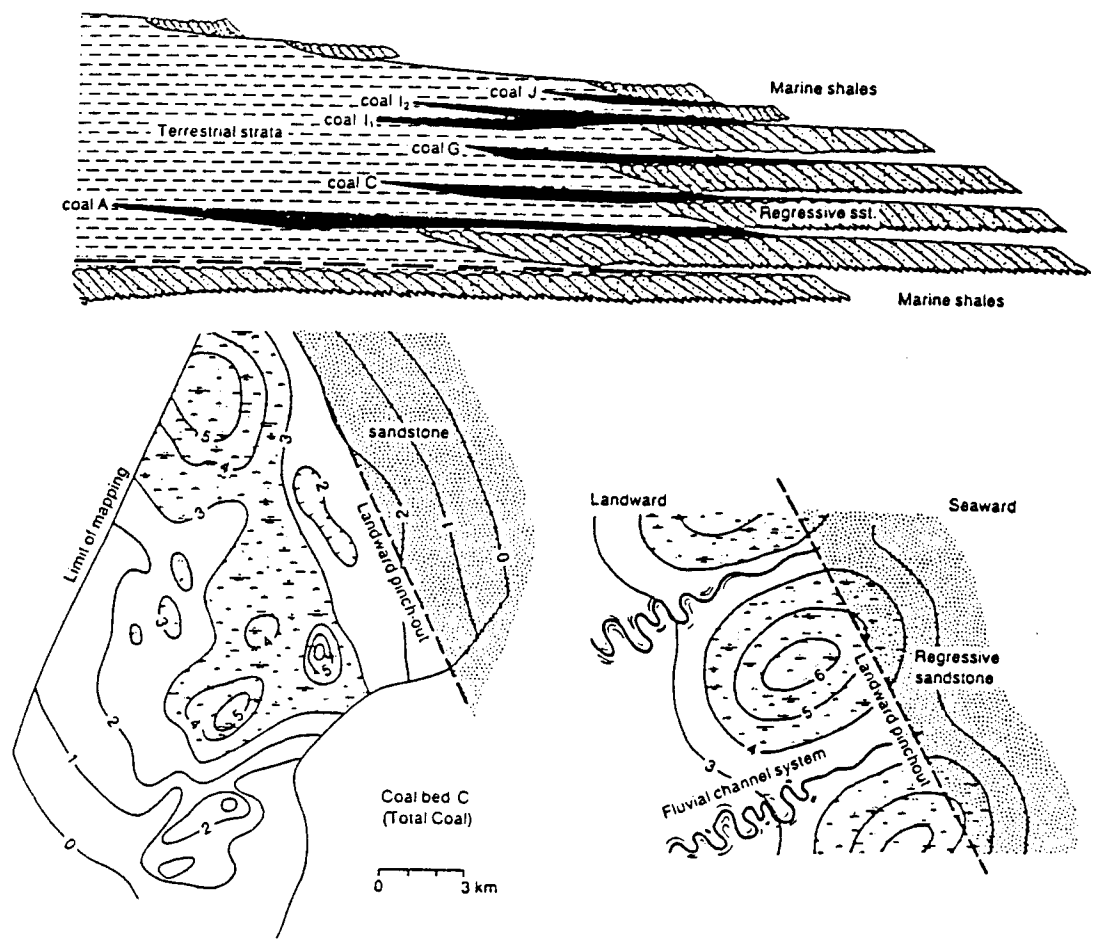
Figure 9. Distribution of coals associated with the Ferron sandstone (after Ryer, 1981). Top: diagrammatic cross section showing coal overlying and thickening landward of regressive units. Lower left: isopach of C coal bed. Lower right: model to explain podlike form of coal seams.
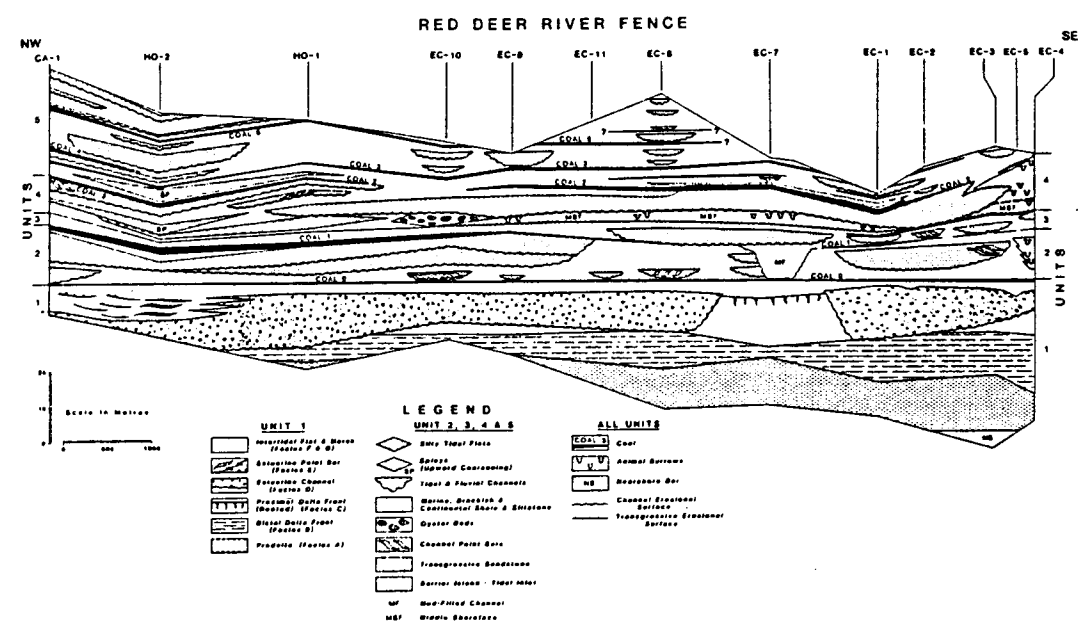
Figure 10. Stratigraphic cross section of the Drumheller coals (lower Horseshoe Canyon Formation) along the Red Deer River (Rahmani, 1988).
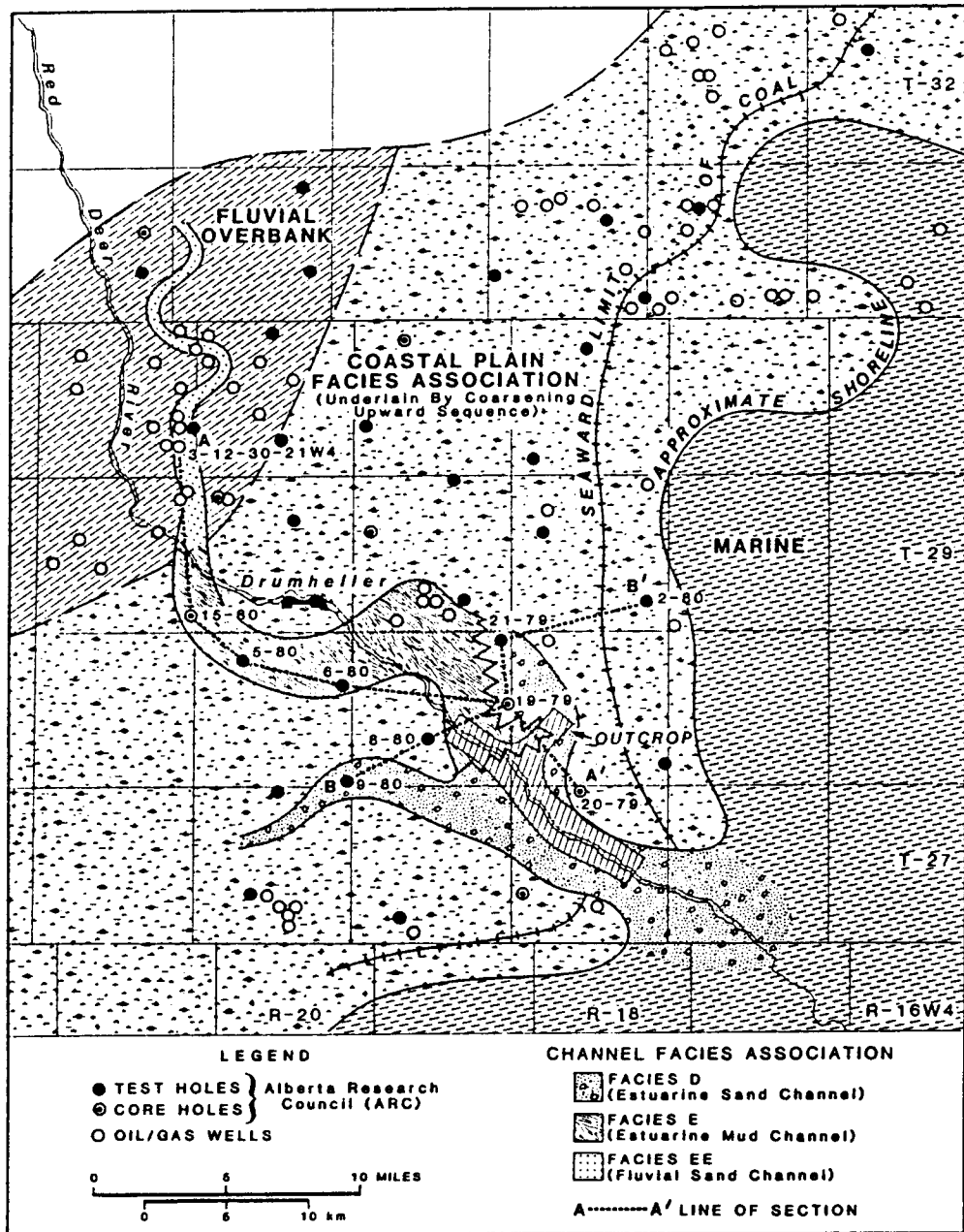
Figure 11. Facies map of the estuarine channel and associated
environments, Drumheller area (Rahmani, 1988).
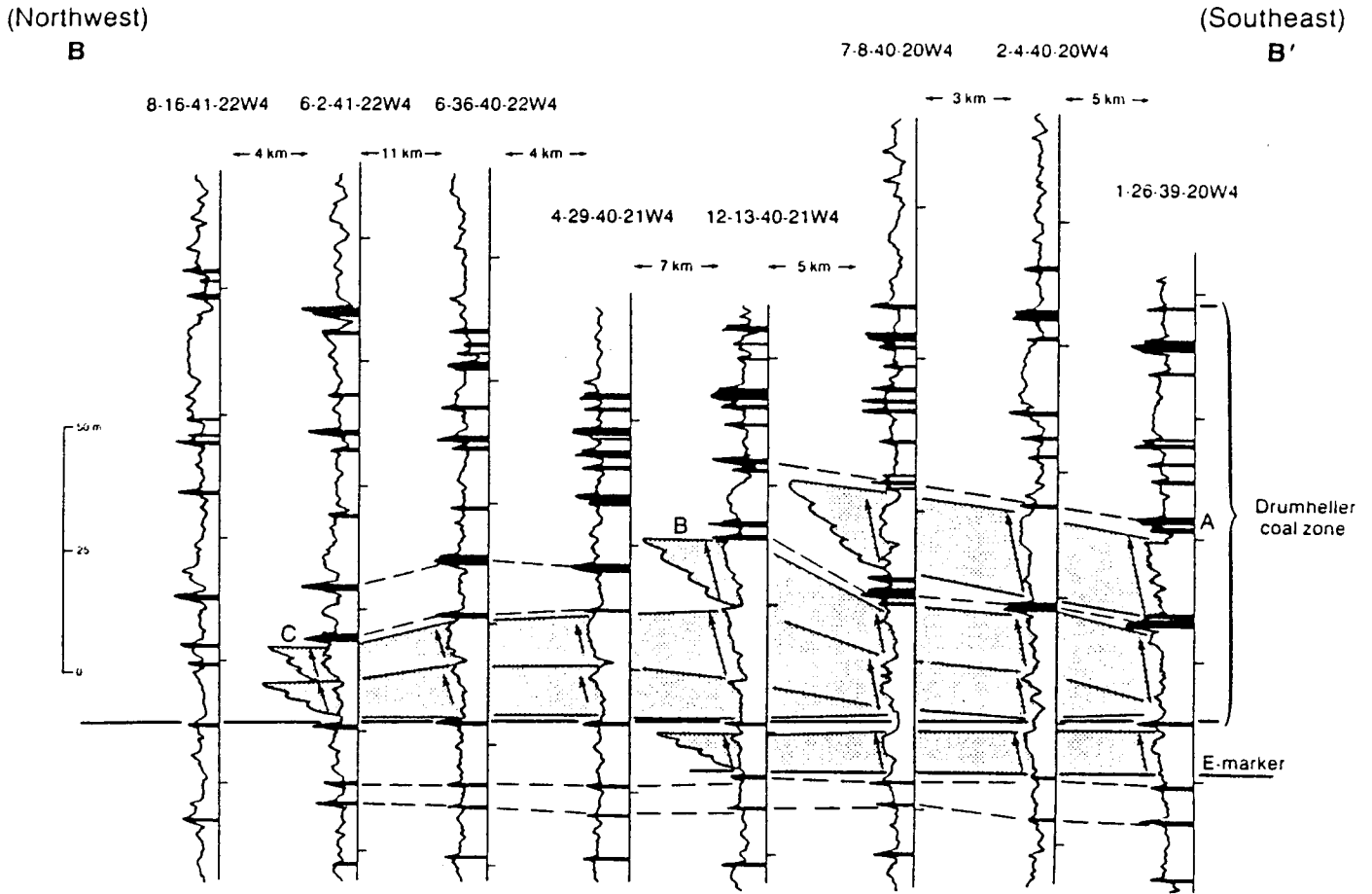
Figure 12. Regional cross section oriented perpendicular to shoreline
trends (near Red Deer) showing correlation of lower
Horseshoe Canyon Formation coals (McCabe et al, 1989).
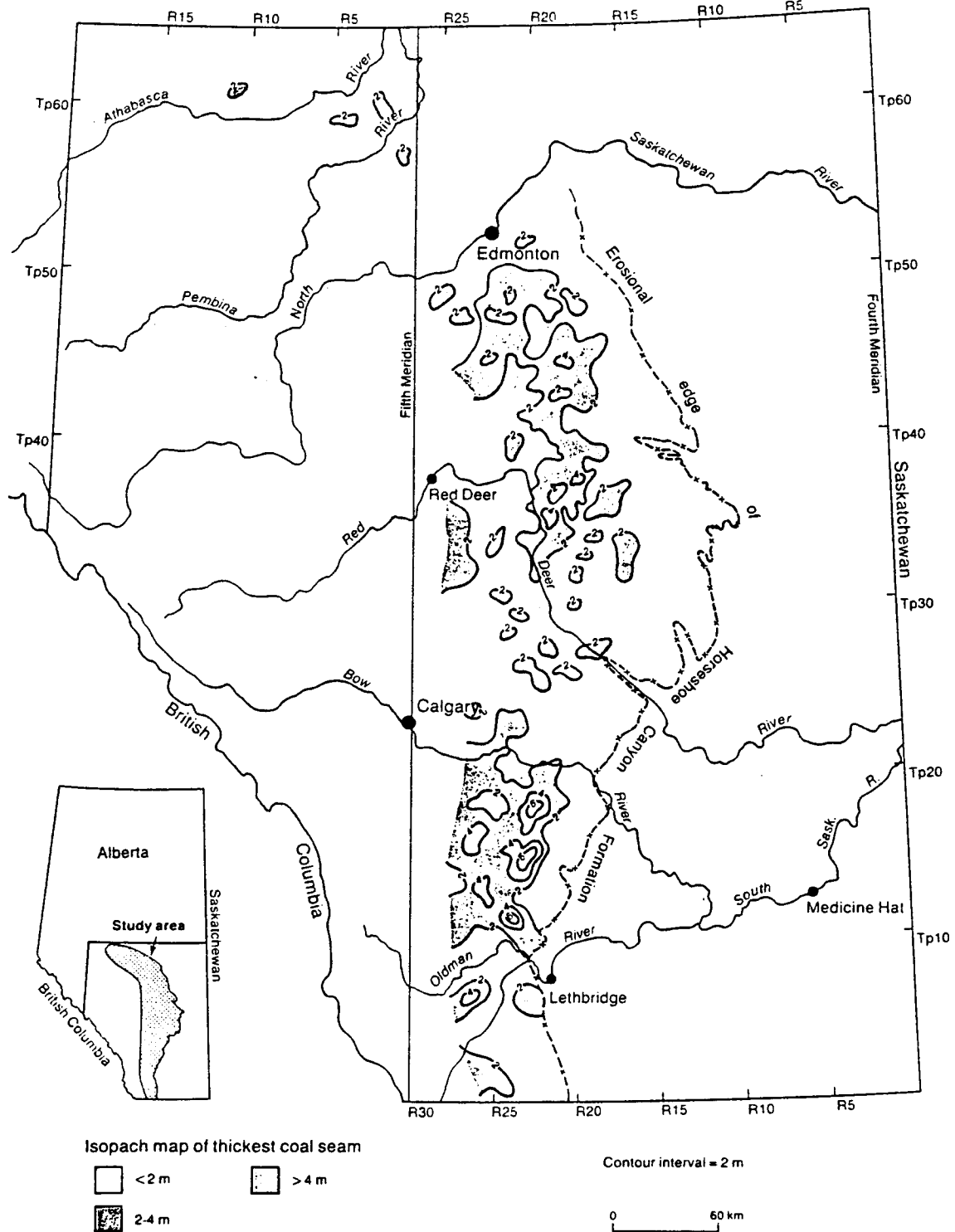
Figure 13. Isopach map of the thickest seam, lower Horseshoe Canyon
Formation. Note that several seams of equal thickness may
occur at any given location (McCabe et al, 1989).
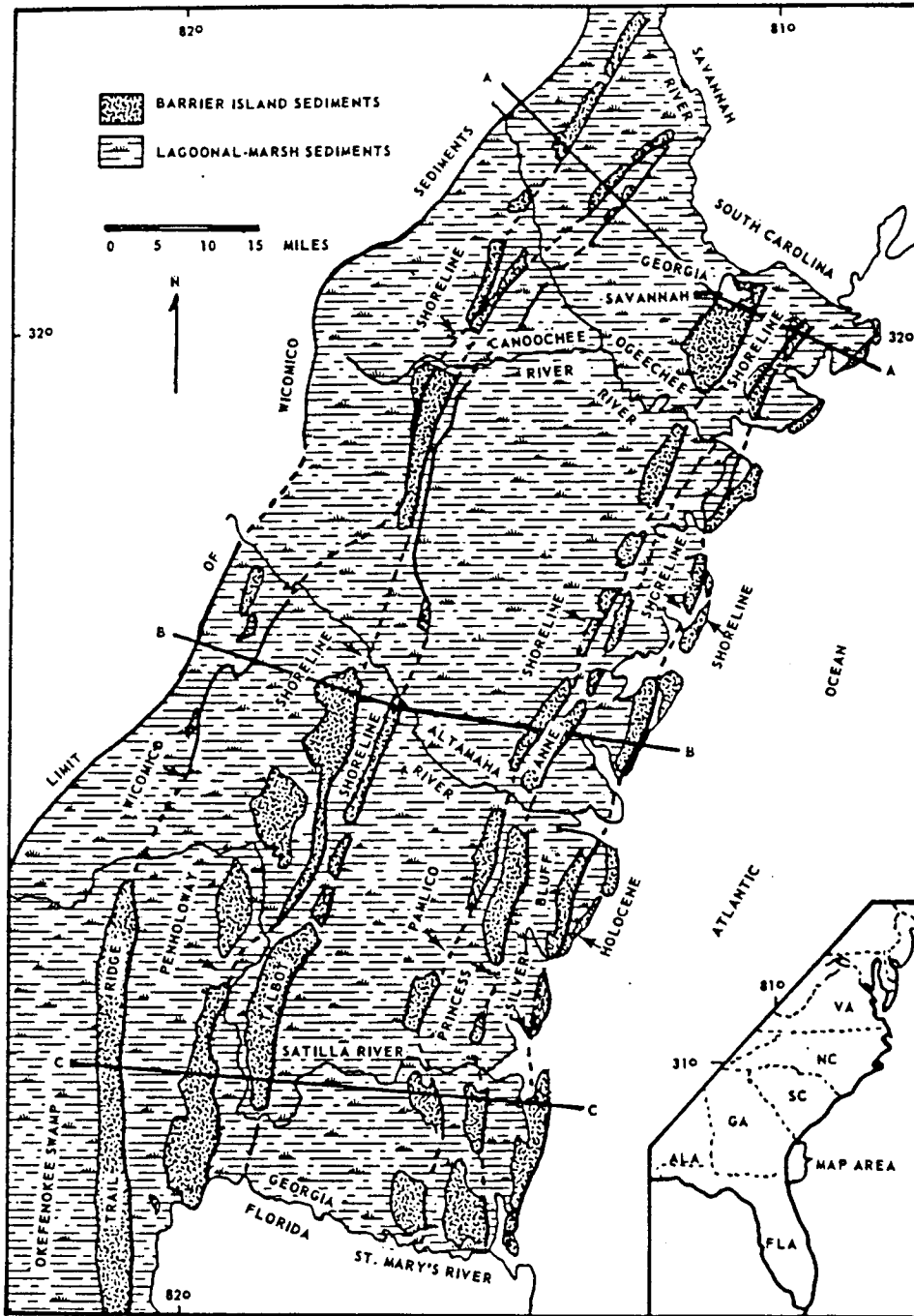
Figure 14. Map of coastal Georgia showing the location of Holocene and Pleistocene shorelines (Hoyt and Hails, 1969).

complement the coal facies model. We recognize that in many sedimentary basins, siliciclastic sequences occur with a 100 000 to 200 000 year frequency and that the lowstand tract is the dominant systems tract preserved (Van Wagoner et al., 1990). Deeply incised valleys extend over the shelf during the lowstands, suggesting that shoreline positions can move seaward considerable distances. This may help explain why anomalously thick and laterally extensive coal seams, such as the Jewel seam of the Cadomin-Luscar area and the Medicine River seam of the central plains area, are developed.

Using the modern Okefenokee Swamp and the Georgia coastline as a model for coals associated with marine depositional settings (Figure 14), we should think in terms of 100 000 to 200 000 year cycles, rather than a relatively short 5 000 to 10 000 year history represented by the Okefenokee and Snuggedy swamps today. Over these longer periods, perhaps peat forming mires grow larger and migrate to fill positions over the former coastal plain. The model predicts thicker peat deposits between beach ridges and elongate thickness trends parallel to paleoshorelines. Many of the Alberta coals associated with marine sediments appear to fit this model.

REFERENCES

Baofang, L. and Dawson, F.M., Stratigraphic framework and depositional setting, Judy Creek coalfield, northern Alberta, in Current Research, Part D, Geological Survey of Canada Paper 88 Id, p. 121-128.

Dawson, F.M., Jerzykiewicz, T. and Sweet, A.R., 1989, A preliminary analysis of the stratigraphy and sedimentology of the coal-bearing Wapiti Group, Northwestern Alberta, in Advances in Western Canada Coal Geoscience - Forum Proceedings, Alberta Research Council Information Series No. 103, p. 1-11.

Demchuk, T. and Strobl, R., 1989, Coal Facies and In-Seam Profiling, Highvale No. 2 Seam, Highvale Alberta, in Advances in Western Canada Coal Geoscience - Forum Proceedings, Alberta Research Council Information Series No. 103, p. 201-211.

Hacquebard and Donaldson, 1969, Geological Society of Americal Special Paper #114, p. 143-191.

Jerzykiewicz, T., 1989, Synopsis, Controls on distribution of coal in the Campanian to Paleocene post-Wapiabi strata of the Rocky Mountain Foothills, Geol Survey of Canada Paper 89-9, p. 41-42.

Jerzykiewicz, T., this volume, Stratigraphy and sedimentary environment of the Coalspur Formation.

Langenberg, W., this volume, The Coal-bearing Luscar Group of Western Alberta.

Latour, B.A., 1961, Coal occurrences along St. Mary River on Blood Indian

Agency, Alberta, Geol. Survey of Canada.

Macdonald, D.E., Ross, T.C., McCabe, P.J. and Bosman, A., 1987, An evaluation of the coal resources of the Belly River Group, to a depth of 400 m in the Alberta plains, Alberta Research Council Open File Report OFR 1987-08, 76 p.

Macdonald, D.E., Langenberg, C.W. and Gentzis,T., 1989, A Regional Evaluation of Coal Quality in the Foothills/Mountains Region of Alberta, Alberta Research Council Earth Sciences Report 89-2, 58 p.

McCabe, P.J., 1984, Depositional Environments of coal and coal-bearing strata, Spec. Publ. Int. Ass. Sediment. Volume 7, p. 13-42.

McCabe, P.J., 1988, Depositional Environments of Coal and Coal-Bearing Strata, Canadian Society of Petroleum Geologists Short Course, 66 p.

McCabe, P.J., Strobl, R.S., Macdonald, D.E., Nurkowski, J.R. and Bosman, A., 1989, An evaluation of the coal resources of the Horseshoe Canyon Formation and laterally equivalent strata, to a depth of 400 m, in the Alberta plains area, Alberta Research Council Open File Report OFR 1989-07, 75 p.

Nurkowski, J.R. and Rahmani, 1984, An Upper Cretaceous fluvio-lacustrine coal-bearing sequence, Red Deer area, Alberta, Canada, Special Publication 7, International Association of Sedimentologists, p. 163-176.

Rahmani, R.A., 1988, Estuarine Tidal Channel and Nearshore Sedimentation of a Late Cretaceous Epicontinental Sea, Drumheller, Alberta, Canada, in P.L. de Boer et al. (eds.), Tide Influenced Sedimentary Environments and Facies, p. 433-471.

Richardson, R.J.H., Strobl, R.S., Macdonald, D.E., Nurkowski, J.R., McCabe P.J., and Bosman, A., 1988, An evaluation of the coal resources of the Ardley coal zone to a depth of 400 m, in the Alberta plains area, Alberta Research Council Open File Report OFR 1988-02, 96 p.

Ryer, T.A., 1981, Deltaic coals of Ferron Sandstone Member of Mancos Shale: predictive model for Cretaceous coal-bearing strata of Western interior, Bull. Am. Ass. Petrol. Geol. Vol. 65, p. 2323-2340.

Spackman et al., 1976, The comparative study of the Okefenokee Swamp and the Everglades mangrove swamp marsh complex of southern Florida, Penn. State Short Course.

Van Wagoner, J.C., R.M. Mitchum, K.M. Campion and V.D. Rahmanian, 1990, Siliclastic Sequence Stratigraphy in Well Logs, Cores and Outcrops, AAPG Methods in Exploration Series, No. 7, 53 p.

Williams, G.D. and Murphy, M.C., 1981, Deep coal resources of the interior plains, estimated from petroleum borehole data, Geological Survey of Canada Paper 81-13, 15 p.

GENERATION, STORAGE AND MIGRATION OF NATURAL GAS IN COAL BED RESERVOIRS

Jeffrey R. Levine
University of Alabama

I. INTRODUCTION

The 4 Requirements for Economic Recovery of Coal Bed Gas

Summary: Four conditions must be met to enable commercial production of coal bed natural gas: 1) Sufficient quantities of gas must have been generated during organic maturation, 2) Sufficient quantities of gas must have been retained in the coal bed reservoir, 3) The gas must be able to migrate through the bed at an acceptable rate, and 4) The reservoir must be large enough to justify the cost of development.

Underground coal seams in Canada and the United States are believed to contain a huge resource of natural gas--estimated at more than 90 TCF. The reservoir behavior of these coals varies widely, however, and it is unclear how much of this vast resource is economically recoverable. Currently, commercial production of coal bed gas in North America is limited mainly to restricted areas of just two basins: the Black Warrior basin (Alabama) and the San Juan basin (Colorado and New Mexico). Commercial production now appears feasible in several other basins as well, including the Raton basin (CO & NM) and the Cahaba basin (AL). Economic production rates have proved elusive in many other regions tested, including large parts of the known producing basins. It is important, therefore, to gain a better understanding of why the coals in some areas are economically productive while other coals are not. Geologists and reservoir engineers must also learn to better **predict** where commercial production may be feasible, based on measurable geologic variables.

Viewed in general terms, the economic recovery of coal bed natural gas is contingent upon **4 conditions** being satisfied: 1) that **sufficient quantities** of free gas **were generated** during organic maturation, 2) that a **sufficient proportion** of these gases **has been retained** in the coal bed, 3) that entrapped gases are **able to migrate through the reservoir at an economically acceptable rate** when fluid pressure is reduced at a well bore, and 4) that the **quantity of producible gas is sufficient** to justify the cost of development. Within this framework, the failure or limited success of coal bed gas production in any given locale can be attributed to a deficiency in one or more of these criteria.

Geologic Factors. A thorough understanding of coal bed gas systems entails an understanding of the many geologic processes influencing each of the aforementioned four requirements for economic production. These can be grouped into three sequential steps, occurring in association with: 1) the sedimentary environments of deposition, 2) the burial/tectonic regime, and 3) the present day geologic conditions, including depth, pressure, temperature, and hydrology.

It is in the sedimentary environment of deposition that organic matter-rich sedimentary layers (peat) are first deposited that will ultimately become coal. The initial composition, thickness, and lateral continuity of the beds are all crucial variables in determining subsequent reservoir behavior in terms of gas generation, gas storage, gas transmission, and reservoir dimensions.

COALBED METHANE RESOURCES OF THE U.S.

Western Washington
24 Tcf

Wind River
2 Tcf

Greater
Green River
30 Tcf

Uinta
5 Tcf

Piceance *
84 Tcf

San Juan*
Fruitland Coal = 50 Tcf
Menefee Coal = 34 Tcf

Powder River
30 Tcf

Illinois
21 Tcf

Northern Appalachian*
61 Tcf

Central
Appalachian*
5 Tcf

Raton Mesa
18 Tcf

Arkoma
4 Tcf

Warrior*
Alabama
20 Tcf
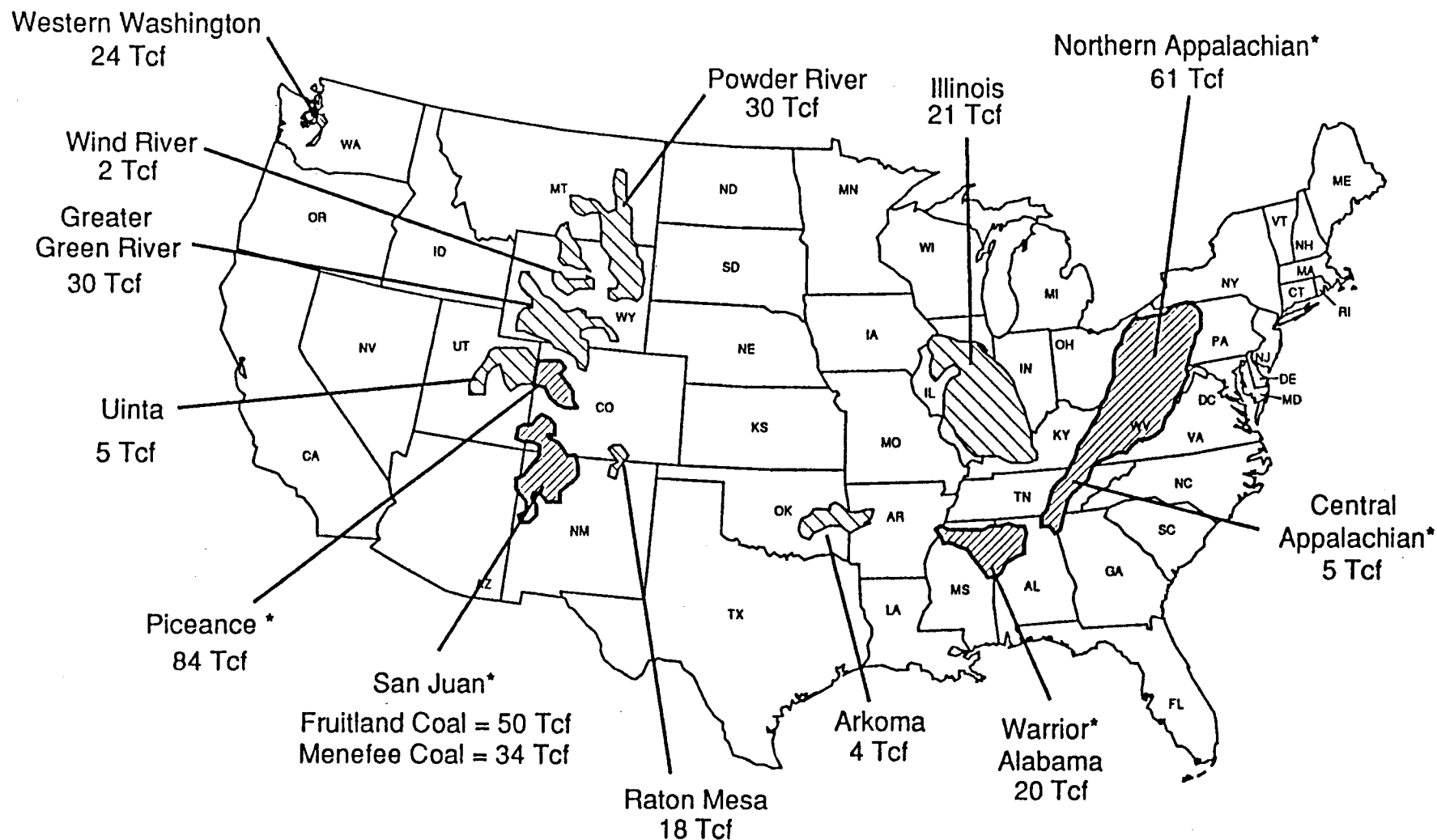
*Detailed Geologic Appraisals Completed by GRI/ICF Resources

From: The Coalbed Methane Resource and the Mechanisms of Gas Production : GRI Topical Report GRI-89/0266

85

It is in the burial/tectonic regime that coal develops its present day composition and form. During the process of "coalification", large quantities of hydrocarbons, notably methane, are generated as by-products. As a reservoir rock, the coal must simultaneously develop the capacity to retain methane and other hydrocarbons under pressure. The optimization of gas generation and gas storage capacity depends on the degree to which coalification has progressed. The transmissibility of gas through the reservoir depends on the development of fractures in the coal (especially "cleat"), which form in coal under the combined influence of coalification and tectonic forces.

Present day geologic conditions provide the most immediate control on reservoir behavior. Coals may be either saturated or undersaturated with respect to their gas storage capacity, and the coal fracture system may be open, or sealed, depending on conditions of confining stress and fluid pressure. Gas diffusion and flow rates also depend upon the temperature and degree of water saturation of the coal bed.

SUMMARY OF 4 REQUIREMENTS FOR ECONOMIC RECOVERY OF COAL BED NATURAL GAS

	Hydrocarbon Generation[1]	Hydrocarbon Retention[2]	Fluid Migration[3]	Reservoir[4] Dimensions
Environment of Deposition	++	+	+	+++
Burial/ Tectonic Regime	+++	++	++	+
Present Geologic Conditions	+	+++	+++	---

[1] Sufficient quantities of gas were generated in the geologic past during organic maturation.

[2] Sufficient quantities of hydrocarbon gases have been retained in coal bed reservoir.

[3] By reducing the fluid pressure, gas is able to migrate through the reservoir at an economically acceptable rate.

[4] The total size of the reservoir is sufficient to justify the cost of development.

```
 + - some influence
 ++ - strong influence
+++ - very strong influence
```

Source Rock/Reservoir Rock Interrelationships:
Conventional Reservoirs vis-à-vis Coal Bed Reservoirs

Summary: The geologic evolution of coal bed reservoirs is essentially similar to that of conventional hydrocarbon reservoirs, but differs in several important respects. The foremost difference involves the mechanism for "entrapment" of reservoired gases. Other important differences relate to source rock/reservoir rock interrelationships and physical properties of the reservoir rock.

The fundamental geologic processes leading to commercial accumulations of oil and gas have been clearly elucidated over the past several decades. While many of the general principles involved can be applied equally to "conventional" reservoirs as well as to **coal bed** reservoirs, there are several important differences. The following section and accompanying table compares and contrasts the main steps in the geologic evolution of source rocks and reservoir rocks in coal bed reservoirs vis-à-vis conventional reservoirs.

In the simplest sense, two conditions must be satisfied to produce any hydrocarbon reservoir: 1) Oil and gas must be formed in the subsurface and 2) Some mechanism must operate to entrap the oil and gas in economic concentrations. To fulfill these conditions requires the more-or-less simultaneous geologic evolution of a good "source rock", from which the oil and gas are generated, and a good "reservoir rock", in which oil and gas can accumulate <u>and</u> from which they can be <u>profitably</u> extracted. Typically, strata having favorable source rock characteristics constitute very poor reservoir rocks and, strata having good reservoir properties tend to be very poor source rocks. One of the unique aspects of coal bed gas systems is that the same stratum (a coal bed) can under favorable conditions serve as both an excellent source and reservoir, especially for methane.

Most conventional oil and gas accumulations are "sourced" by shale beds containing "dispersed" sedimentary organic matter. Typically, the organic matter (OM) concentration in these rocks is only a few weight percent. Coal beds, on the other hand, represent exceptionally thick, rich concentrations of organic source material, containing more than 50 wt-% organic matter and attaining a thickness up to 10s of meters. As a consequence of the large amounts of OM contained within them, coal beds produce prodigious quantities of hydrocarbon gases (predominantly methane) during maturation. A large amount of the hydrocarbons so generated is retained within the coal itself, owing to the high storage capacity of coal. However, large amounts of "excess" methane are apparently released into surrounding strata where they may accumulate in conventional reservoirs.

It can be shown that the amount of methane formed during coalification far exceeds the saturation capacity of the coal. If a coal remains fully saturated throughout most of the process of organic maturation, then no additional "space" would be available in the reservoir to accommodate methane generated outside the coal bed. It could be concluded, therefore, that under these conditions the methane naturally present in the coal seam today was generated from the very same coal bed which now contains it, i.e. the coal bed reservoir has served as its own source rock. There is no reason, however, why a coal which was undersaturated in methane could not become have been charged with gases that were formed outside the bed, as in the case of conventional reservoir rocks.

In order to serve as an effective reservoir for petroleum, a rock must provide a sufficient proportion of accessible "sites" available for storage of oil and gas. In conventional reservoir rocks, this accessibility is provided in the form of open pores, which

are typically on the order of microns to millimeters in dimension and which represent perhaps 5-20% of the rock by volume. Although coal contains some pores in this size range, the porosity of typical reservoir coals is very low--usually less than 5%. Most of the requisite "accessibility" is a consequence of the "open" molecular structure of coal, which provides Angstrom- to nanometer-sized interstices into which small molecules such as methane can penetrate. At this scale, gas molecules exhibit weak attractive forces with the solid coal substrate, which gives the coal a high apparent "surface area" for gas storage. Consequently, coals can accommodate far greater amounts of gas at any given pressure than conventional reservoir rocks.

The other requirement for an good reservoir rock is that it provide satisfactory permeability, so that hydrocarbon fluids are able to flow from the rock matrix, where they are stored, to the well bore and hence to the surface. In coal bed reservoirs (as with many conventional reservoirs) the reservoir "plumbing system" comes in the form of a pervasive fracture system formed during coalification. Coal beds usually have a system of closely spaced joints, termed "cleat", which provides the principal means for fluid transport. Cleat and other fracture development seems to be a crucial variable in determining the reservoir behavior of coal beds.

GEOLOGICAL EVOLUTION OF
CONVENTIONAL HYDROCARBON RESERVOIRS
VS. COAL BED RESERVOIRS

Step	Source Rock Evolution	Reservoir Rock Evolution	
		Conventional	Coal Bed
1 Deposition	Deposition of source bed enriched in primary sedimentary organic matter	Deposition of reservoir precursor, usually a porous sand	Deposition of water-saturated peat deposit
2 Maturation	Organic maturation to form oil & gas in the subsurface	Preservation of primary porosity or development of secondary porosity	Dewatering of coal and augmentation of hydrocarbon "accessibility"
3 Entrapment	Migration of oil & gas away from source rock to conventional reservoir rock or partial or complete retention of oil & gas in coal bed	Fluid trapping usually by impermeable or semi-permeable cap rock to retain oil & gas in reservoir	Maintaining of fluid pressure (water or gas) to retain sorbed gases in the coal bed

FUNDAMENTAL DIFFERENCES BETWEEN
COAL BED AND CONVENTIONAL GAS RESERVOIRS

Reservoir Characteristic	Conventional Reservoirs	Coal Bed Reservoirs
"Pore" Size	1μ to >1 mm (approx.)	<5 Å to 50 Å (approx.)
Physical State of Gas	Free gas, condensate, or dissolved	Adsorbed or "Absorbed"
Source Bed/ Reservoir Relationship	Source beds are distinct from reservoir	Coal reservoir can be its own source rock
Gas Composition	Primarily CH_4, but commonly incl. 5% higher hydrocarbons	Usually CH_4 & CO_2; usually little hhc

TOPICS TO BE ADDRESSED ON COAL BED GAS RESERVOIRS

```
┌─────────────────────┐
│ Generation, Storage │
│    and Migration    │
│   of Naturals Gas   │
│     in Coal Bed     │
│     Reservoirs      │
└─────────────────────┘
```

```
┌──────────────┐          ┌──────────────────┐
│   Part I:    │          │    Part II:      │
│  Coal as a   │          │   Coal as a      │
│ "Source Rock"│          │ "Reservoir Rock" │
└──────────────┘          └──────────────────┘
```

```
┌──────────────┐          ┌──────────────────┐
│ Fluid Storage│          │ Fluid Migration  │
│   in Coal    │          │  through Coal    │
└──────────────┘          └──────────────────┘
```
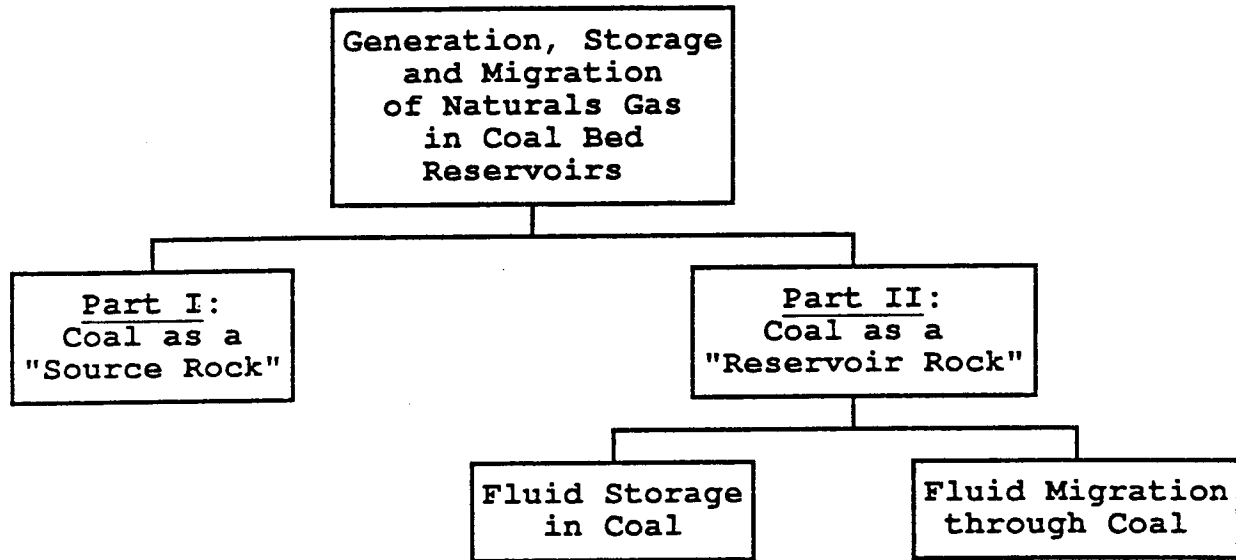
Coal as a "Source Rock":

- What quantities of oil and gas are generated by coal during coalification?

- What is the influence of coal composition on the quantity and type of volatile products formed during coalification?

Coal as a "Storehouse" for Natural Gas:

- In what physical "state" is methane stored in coal bed reservoirs?

- How is the gas content and storage capacity of coal measured?

- How is the gas storage capacity of coal influenced by coal composition? What is the influence of:
  - organic maturation (rank)?
  - mineral matter content (grade)?
  - petrographic composition (type)?
    - moisture saturation?

Coal as a Gas "Pay" Zone:

- What are the mechanisms of gas transport through coal?

- What is the influence of free water on the transport of gas through coal?

- What is the nature and origin of the fracture system in coal through which most of the gas flows during production?

II. REVIEW OF COAL COMPOSITION
AS APPLIED TO THE STUDY OF COAL BED GAS RESERVOIRS

Different Ways of Classifying the "Components" of Coal

Summary: The term "coal" can be defined in a variety of ways, stratigraphically, petrographically, geochemically, or otherwise, depending on the context in which it is being studied. Although coal has conventionally been regarded as a "solid" fuel, a modern understanding of coal structure and chemical composition demands a broader definition, encompassing all those materials naturally occurring within the coal seam, including entrapped volatile species such as water, oil, and methane.

The '3-axis diagram' to Represent Coal Composition

The 3-axis diagram represents a traditional "petrographic" approach to coal composition. The concept is to provide a comprehensive scheme by which all coals and/or organic matter-bearing sediments can be compositionally classified. This diagram also provides a organizational framework to understand the many methods of analyzing and characterizing coal and other sedimentary organic matter (OM).

In accordance with the definition of coal from the AGI Glossary of Geologic Terms, coal can be classified according to three distinct, but interrelated criteria: grade, type and rank. On the 3-axis diagram, these are plotted on 3 orthogonal axes.

A variety of variables may be used for classification purposes along each of the three axes. For example, rank can be determined according fixed carbon yield (d,mmf) or vitrinite reflectance, or any number of other rank-dependent variables. Type designation is usually based on visual classification of the microscopic constituents of coal (the "macerals") by a trained petrographer, hence is somewhat subjective. Grade classification is normally based upon the weight percentage of organic matter present.

As indicated on the diagram, the grade and type of OM are initially established in the sedimentary environment of deposition. The projection of the grade and type axes into the third dimension (rank) represents compositional changes occurring during coalification in the subsurface (burial) environment. Different OM types become compositionally more homogeneous during organic metamorphism, hence converge upon one another along the rank axis. Theoretically, the grade also changes during maturation, as a certain proportion of the OM originally present will be lost as volatile products such as methane, water, and in some cases oil. It is virtually impossible, however, to actually document such changes in grade in nature, since the original proportion of OM present is indeterminate.
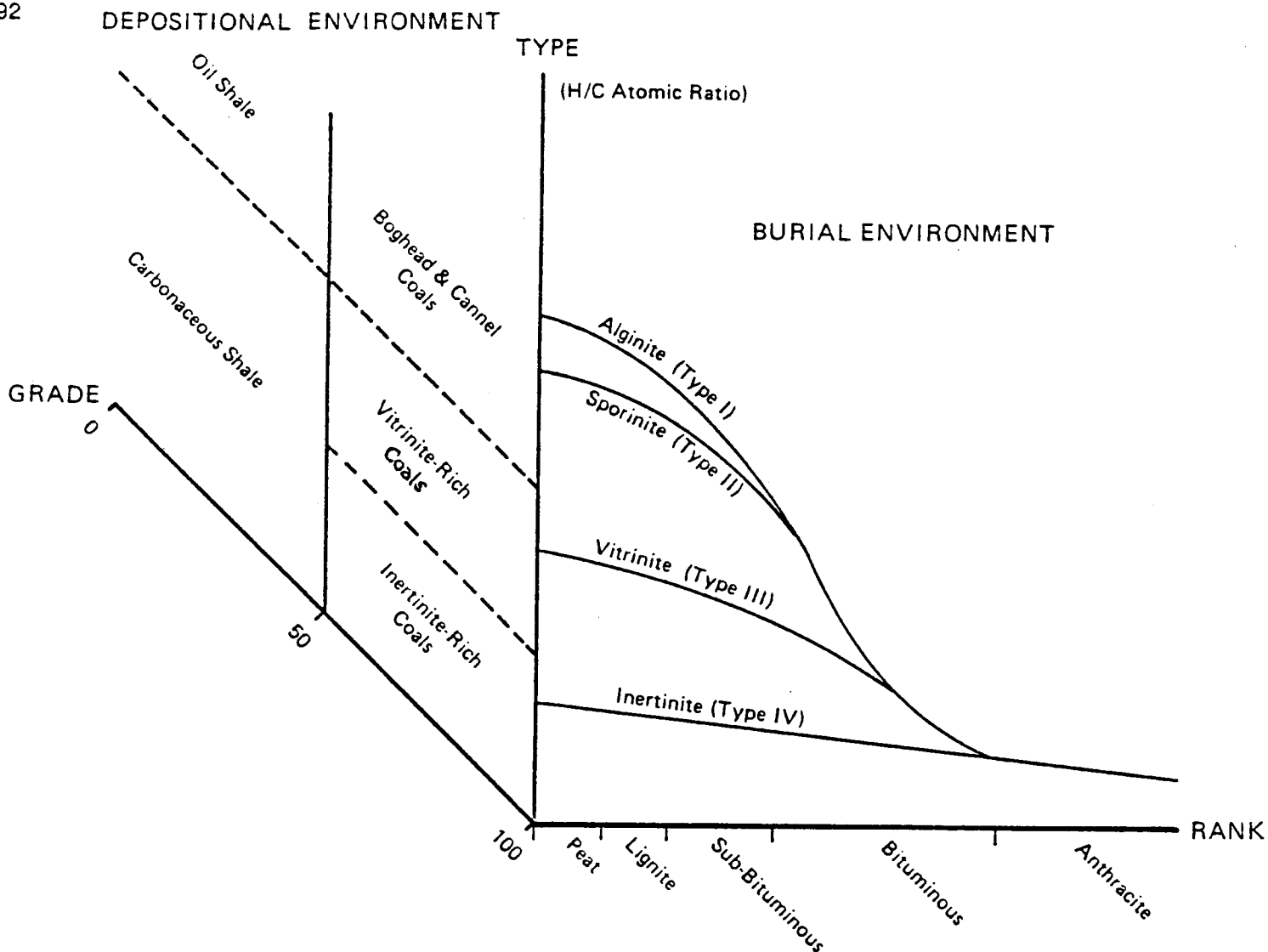
INFLUENCE OF COAL COMPOSITION ON THE
CRITICAL ATTRIBUTES OF COAL BED GAS RESERVOIRS

Coal Compositional Parameter	Imparted During:		Critical Attributes For Economic Production of Coal Bed Reservoir Gas:			
	Sediment Deposition	Burial/ Coalification	1. Gas Generation	2. Gas Retention	3a. Gas Diffusion	3b. Gas Migration
A. Grade	+++	+	+++	+++	++	++
B. Type	+++	(+++)	++	++ ?	+	+
C. Rank	---	+++	+++	++	++	+++

```
    + - some influence
   ++ - strong influence
  +++ - very strong influence
```

CLASSIFICATION OF COAL CONSTITUENTS
FROM THE STANDPOINT OF RESERVOIR BEHAVIOR

To better understand coal from the standpoint of reservoir behavior, it is instructive to regard coal composition from a more "geochemical" orientation, reflecting the physical/chemical "state" of the components of the coal bed, as depicted on the accompanying diagram.

According to this scheme, the materials comprising a coal bed, fall broadly into two categories: 1) a "volatile" fraction, comprised of those materials which can be readily separated from the rest of the coal by mild heating (<150°C) or by mild solvent extraction. These separation procedures serve merely to liberate "entrapped" molecular species from the coal, but are not strong enough to cause the breakage of molecular bonds; 2) the "non-volatile" fraction, which remains fixed in a "solid" mass after mild heating or extraction.

Both the volatile and non-volatile fractions of coal can be further subdivided into "organic" and "inorganic" components, as depicted below:

```
                        ┌─────────┐
                        │ Whole   │
                        │ Coal    │
                        └─────────┘
                             │
          ┌──────────────────┴──────────────────┐
     ┌─────────┐                           ┌──────────────┐
     │Volatile │                           │ Non-volatile │
     │Fraction │                           │ Fraction     │
     └─────────┘                           └──────────────┘
          │                                      │
   Inorganic │ Organic                  Organic │ Inorganic
      ┌──────┴──────┐                     ┌──────┴──────┐
 ┌──────────┐ ┌──────────┐         ┌───────────┐ ┌──────────┐
 │ Moisture │ │ "Mobile  │         │"Framework │ │ "Mineral │
 │and other │ │ Phase",  │         │ Phase"    │ │ Matter"  │
 │  inert   │ │including │         └───────────┘ └──────────┘
 │components │ │methane & │
 └──────────┘ │other weak-│
              │ly bonded │
              │components │
              └──────────┘
```
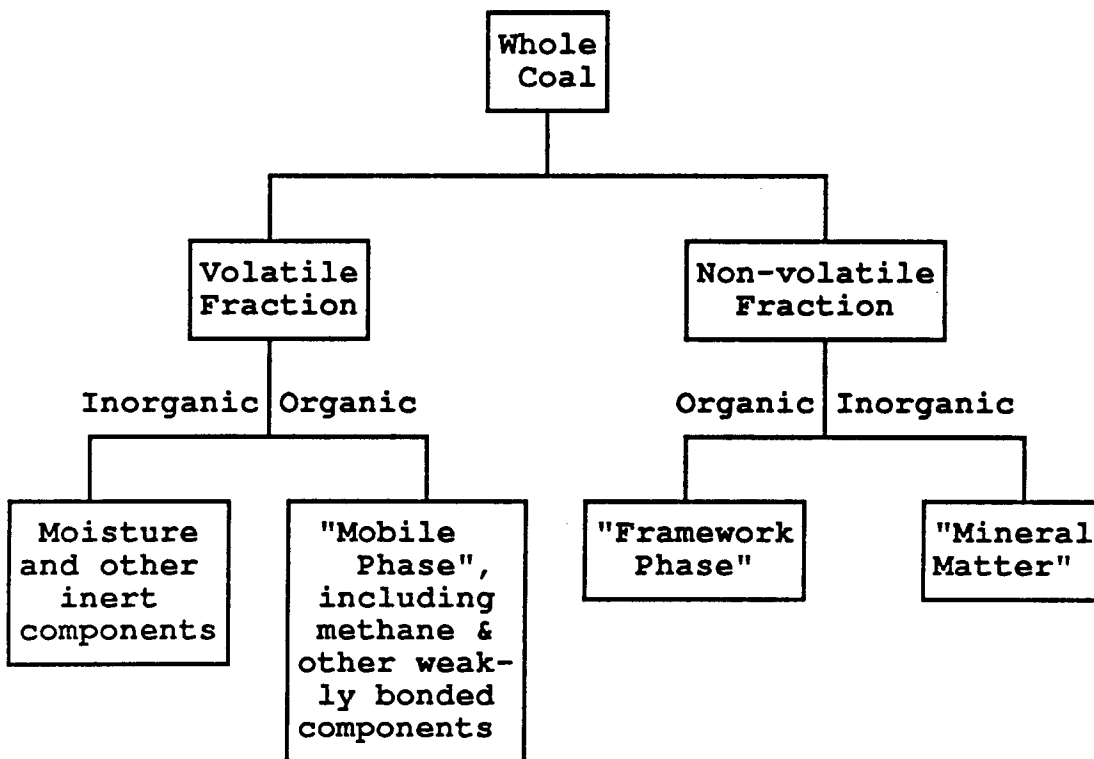
THE INFLUENCE OF MOISTURE CONTENT OF COAL
ON RESERVOIR PROPERTIES

Summary: The moisture content of coal seams is commonly misunderstood and mismeasured; yet an understanding of the moisture content of coal is central to the understanding of the coal bed reservoir system. Moisture content is a rank-related variable that directly influences the gas storage capacity of coal beds. Moreover, the presence of free water in the reservoir can effectively inhibit the free flow of gas through the reservoir fracture system. The following sections will discuss some of the methods by which moisture content of coal is measured.

The Mode of Occurrence of Moisture in Coal

In the simplest terms, water is considered to occur in 4 different states in coal, as described by Krumin (1963, p. 2):

1) **"adherent moisture"** - mechanically retained on the surface of the coal or in cracks and internal cavities too large to be considered part of the structure of the coal substance, and possessing normal vapor pressure. Synonymous or similar terms include "free moisture", "bulk water", "superficial water".

2) **"inherent moisture"** - condensed or physically sorbed in the capillaries and micro pores of the coal substance, distinguished by subnormal vapor pressure. Similar or synonymous terms include: "true bed moisture", "(natural) bed moisture", or "capacity moisture".

3) **"chemically combined water"** - bound into the molecular structure of the coal and released only by the breaking of molecular bonds. This can occur either naturally during coalification or artificially during pyrolysis.

4) **moisture of hydration** of inorganic constituents in the coal, especially clay minerals.

Only moisture of forms 1 & 2 are of importance in conventional laboratory moisture determinations. The low temperatures used (ca. $107^\circ C$) are insufficient to liberate moisture of forms 3 & 4.

Methods of Moisture Determination

The moisture content of any given coal sample is variable, and may range from near zero up to (or exceeding) a maximum "capacity" moisture content, which is reflective of the coal's rank and composition. Coals underground are generally considered to be fully saturated with water, although evidence from some Western North American basins suggests that this may not always be so. In any case, once a coal sample is removed from the ground, its moisture content is subject to change, and will re-equilibrate to the ambient conditions of temperature and relative humidity. In most cases, this involves a loss of moisture from the coal. The various methods of measuring the moisture content of coal are reflective of this variable degree of moisture loss.

Most methods of moisture determination culminate by measuring the percentage weight loss of finely ground coal (typically <60 mesh) after heating for 1 hour at $107 +/- 4^\circ C$ (just above the boiling point of water) in a vacuum or in an inert environment (typically nitrogen).

Moisture contents are reported on different "bases", depending on how the sample was processed and prepared prior to analysis. These results can vary substantially. Therefore, it is important that the sample be handled carefully and that the basis of measurement be specified.

Three moisture bases are important and commonly reported in the coal literature: "as received", "as determined", and "equilibrium".

"As received moisture content" - refers to the total moisture content of a coal sample as it arrived in the laboratory for analysis, and before any processing and conditioning.

"As received moisture" may include "inherent moisture" plus "adherent moisture" (as defined above). In cases where the coal includes excessive amounts of surficial moisture, the "as received" moisture can exceed the "capacity moisture". If a coal sample is carefully collected and maintained in a tightly sealed container, the "as received" moisture content is generally very close to the "equilibrium moisture" content (Rees et al., 1939).

For most industrial applications, the "as received" moisture content of coal is the measurement basis of greatest interest and significance, irrespective of whether or not this value reflects the true "capacity moisture" or its "bed moisture". Moreover, the determination of "equilibrium moisture" is a time-consuming and relatively difficult procedure. Hence, the "as received" basis is the value most commonly reported in the literature. Persons using "as received" moisture data must be warned that more often than not coal samples are handled with little regard to maintaining the moisture content and, therefore, the as received moisture content may vary significantly from the true in situ moisture content.

"As determined" moisture content refers to the moisture content of the sample after conditioning and preparation for analysis, and reflects the particular moisture level at the time of analysis.

"Equilibrium Moisture" pertains to the total moisture in equilibrium with a coal sample at $30^{o}C$ and at 96-97% relative humidity, as measured according to procedures described in ASTM Method D-1412.

The equilibrium moisture content is an excellent means of determining the "inherent" or "capacity" moisture content of coal. Coals which have dried out prior to analysis can be effectively resaturated with water using this method (Selvig and Ode, 1953), provided that sufficient time is allowed for re-equilibration. Coals below the rank of high volatile bituminous C suffer irreversable changes in drying and cannot be accurately re-equilibrated. The relative humidity is kept slightly below 100% to prevent the condensation of free water and to allow the evaporation of adherent water.

Relationship of Moisture Content to Rank

The capacity moisture content of coal decreases progressively with rank, from over 50% in freshly deposited peat to around 1-2% in low volatile bituminous coals. Moisture content of coal is a particularly sensitive rank parameter at low rank. In fact, some international standards, both established and proposed, use "capacity moisture" as a fundamental rank indicator for low rank coals. Moreover, BTU yield (measured on a moist, mineral matter-free basis, which is the ASTM North American standard rank parameter for low rank coals) essentially provides an alternative measure of moisture content as well.
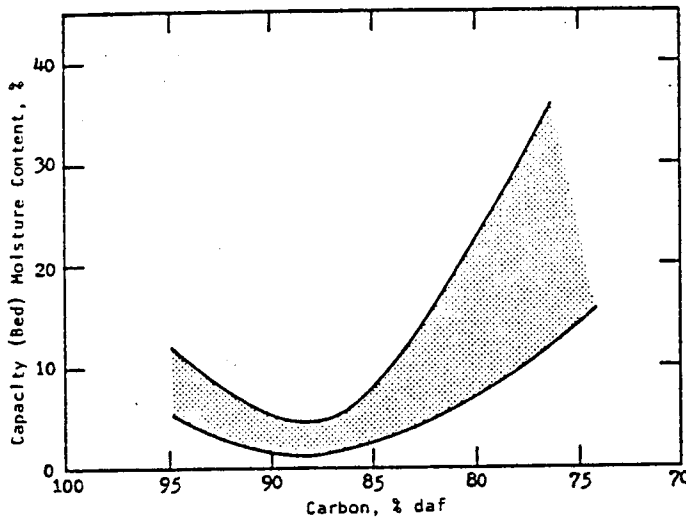
(from Berkowitz, 1979)

Generalized variation of capacity (or bed) moisture contents with rank.
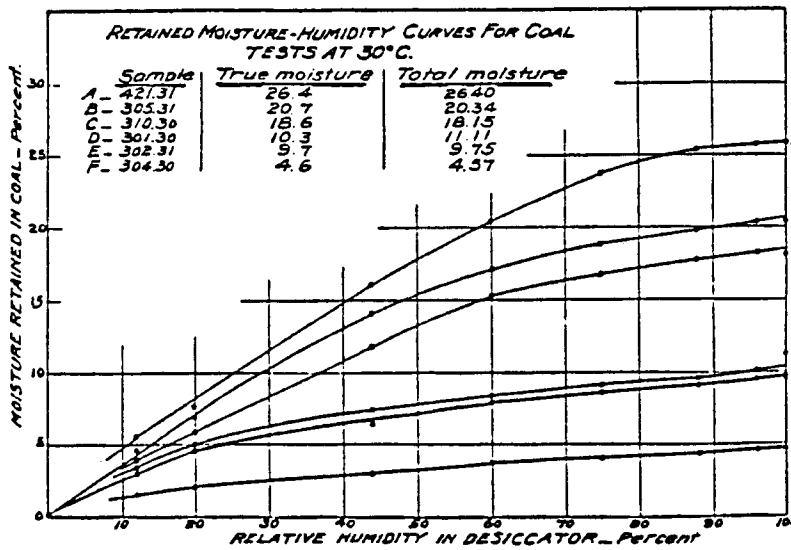
(Stansfield and Gilbart, 1932)

(from Law et al., 1983)

Coal and Sandstone Values Used in Determination of Coal Dewatering

Coal Rank	Sandstone* Thickness (ft)	Sandstone* Porosity (%)	Sandstone* Pore Volume (ft³/acre)	Coal Thickness (ft)	Coal Peat:Coal	Coal Moisture (%)	Coal Moisture Volume (ft³/acre)	ΔMoisture	ΔMoisture/Sandstone Pore Volume
Early Peat	10.0	40.0	174,240	10.0	1:1	90	525,938		
Peat	9.2	31.5	124,834	5.0	2:1	60	175,313	350,625	2.81
Lignite	7.9	19.0	65,384	3.3	3:1	43	82,923	92,390	1.41
Sub-C	7.4	14.0	45,128	2.5	4:1	30	44,329	38,594	0.86
Sub-B	7.3	12.7	40,384	2.0	5:1	24	28,371	15,958	0.40
Sub-A, hvCb	7.1	11.4	35,257	2.0	5:1	17	20,096	8,275	0.23
hvBb	7.1	9.8	30,309	1.7	6:1	7	7,153	12,943	0.43
hvAb	7.1	7.7	23,814	1.7	6:1	6	6,131	1,022	0.04
mvb	7.1	5.5	17,010	1.4	7:1	6.5	5,470	664	0.04
lvb	7.1	3.6	11,134	1.4	7:1	5	4,208	1,262	0.11
Semianthracite	7.1	2.8	8,660	1.3	8:1	3.5	3,039	1,169	0.13

*Sandstone parameters for peat and higher coal ranks represent average values.
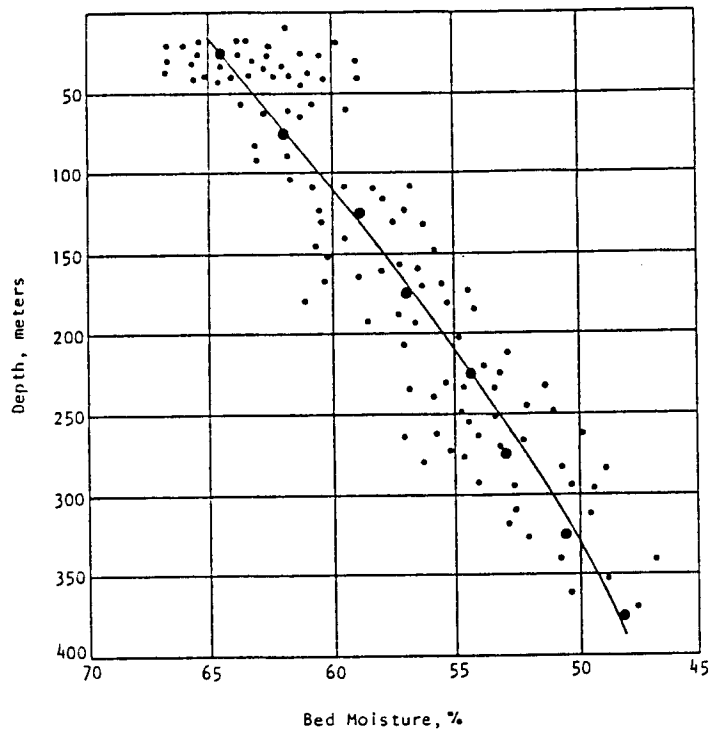
The variation of bed moisture contents of soft brown coals (or unconsolidated lignites) with depth of burial: Cologne region. West Germany. Large points show statistically weighted averages for each 50-m depth interval. (After Kutzner [59]; by permission of M. and R. Teichmüller.)

(from Berkowitz, 1979)
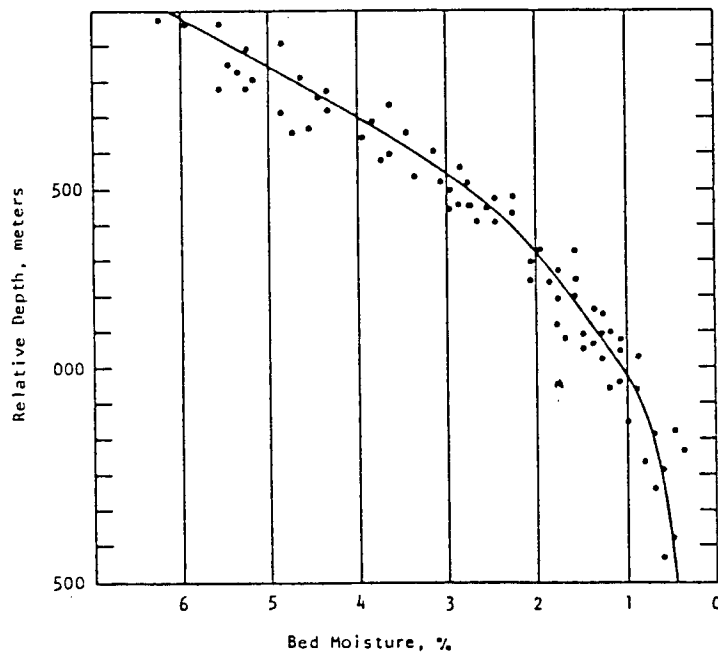
The variation of bed moisture contents of high-rank coals with depth of burial: Saar region, West Germany. Data relate to 10 boreholes. (After Damberger et al. [60]: by permission of M. and R. Teichmüller.)

Influence of Water in Coal Seams on Reservoir Behavior

The presence of water in coal seams underground has a very strong influence on the reservoir behavior of the coal in two fundamental respects: 1) The presence of "inherent water" in the coal suppresses its methane sorption capacity. This effect can be very significant, especially for low rank coals; and 2) the presence of free "adherent water" in the coal bed reservoir fracture system suppresses the permeability to gas flow. It is for this reason that water must be pumped from coal bed gas wells in order to allow the ready flow of gas. These topics will be explored in greater detail in subsequent sections.

Literature References on Moisture Content of Coal

Allardice, D.J. and Evans, D.G., 1978, Moisture in coal, in Karr, C., Jr., ed., Analytical methods for coal and coal products, v.1: New York, Academic Press, p. 247-262.

ASTM, 1981, 1981, Annual Book of Standards, pt. 26- gaseous fuels; coals and coke; atmospheric analysis: Philadelphia, American Society for Testing and Materials, 920 p.

Edwards, A.H., 1968, The determination of the moisture-holding capacity of bituminous coals: Fuel, v. 47, p. 29-49.

Fuller, E.L., Jr., 1981, Physical and chemical structure of coals: sorption studies, in Gorbaty, M.L. and K. Ouchi, eds., Coal Structure: Advances in Chemistry Series 192, Washington, D.C., American Chemical Society, p. 293-309.

Gauger, A.W., 1932, Condition of water in coals of various ranks: AIME Transactions, v. 101, p. 148-164.

Joubert, J.I, Grein, C.T., and Bienstock, D., 1974, Effect of moisture on the methane capacity of American coals: Fuel, v. 53, p. 186-191.

Krumin, P.O., 1963, The determination of forms of moisture in coal: Ohio State Engineering Experimental Station Bulletin 195, 78 p.

Law, B.E., Hatch, J.R., Kukal, G.C., and Keighin, C.W., 1983, Geologic implications of coal dewatering: American Association of Petroleum Geologists Bulletin, v. 67, p. 2255-2260.

Rees, O.W., F.H. Reed and G.W. Land, 1939, A study of the equilibrium method of detemining moisture in coal for classification by rank: Illinois State Geological Survey, Report of Investigations 58, 34 p.

Selvig, W.A., and W.H. Ode, 1953, Determination of Moisture-holding capacity (bed-moisture) of coal for classification by rank: U.S. Bureau of Mines Report of Investigations 4968, 10 p.

Stansfield, E., and K.C. Gilbart, 1932, Moisture determination for coal classification: AIME Transactions, v. 101, p. 125-43.

Thomas, J., Jr., and H.H. Damberger, 1976, Internal surface area, moisture content, and porosity of Illinois coals: variations with coal rank: Illinois State Geological Survey Circular 493, 38 p.
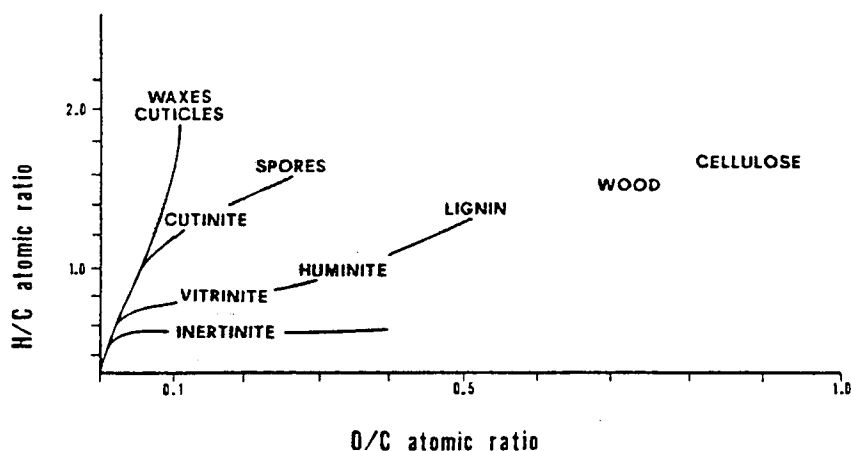
Elemental Composition of Coal

The organic fraction of coal is comprised almost entirely of just 5 elements: carbon, hydrogen, oxygen, nitrogen, and sulfur. The measurement of these five elements comprises the so-called "ultimate analysis" of coal. Results of ultimate analysis are usually reported on a weight-% basis for each element. Note that in some cases, data are converted from weight-% to atomic-%, especially when considering H/C and O/C (atomic) ratios. Where unspecified, data are usually on a weight-% basis.
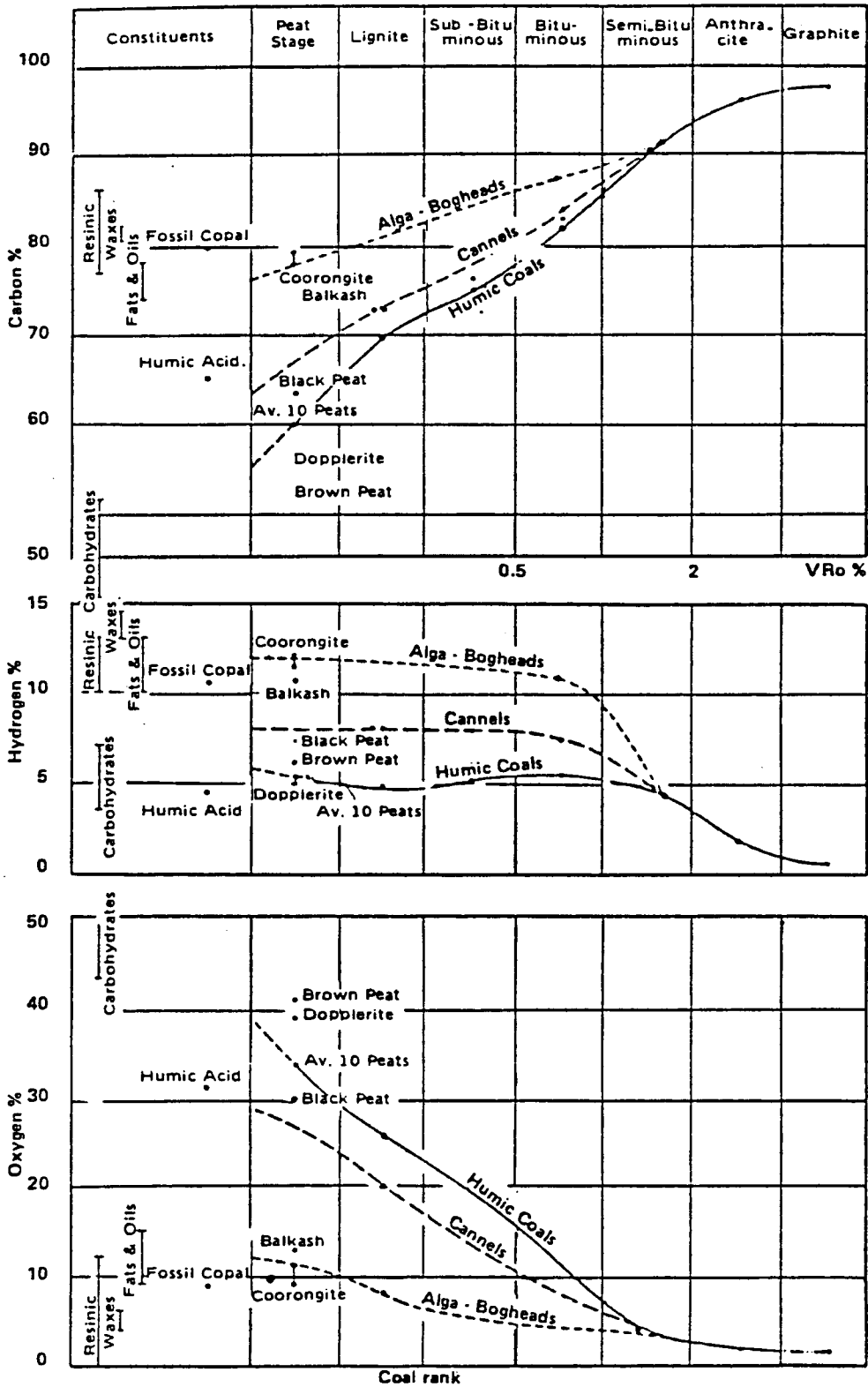
Direct measurement methods are specified by ASTM for C,H,N, and S. Oxygen is normally calculated "by difference". The presence of mineral matter in coal can significantly influence elemental analyses. For example, CO_2 liberated from carbonate minerals, or sulfur liberated from pyrite can strongly influence analytical results. These differences accumulate in the estimate of oxygen content, which can vary by a factor of 2 or more when mineral matter composition is taken into account. See Given and Yarzab (1978) for in depth discussion of these problems.

The figure on the following page depicts the changing weight percentages of C, H, & O for several different "types" of coal, with increasing coal rank. With respect to gas generation, several trends are important here: 1) For all coal types, the carbon content progressively increases as the hydrogen and oxygen contents progressively decrease. Initially carbon contents are around 70 % by weight, but increase to nearly 100% as the coal becomes "graphitized". 2) Different coal types start out with different weight percentages of C, H, and O. Humic coals are initially rich in oxygen and relatively poor in hydrogen. Boghead coals are rich in hydrogen and poor in oxygen, and cannel coals are intermediate between the other two. 3) In spite of these initial differences, the various coal types become increasingly homogeneous with increasing rank, gradually becoming indistinguishable at anthracite rank.

A more common and instructive means of depicting the changing elemental composition of coals and coal constituents is by means of the "van Krevelen diagram" wherein the hydrogen to carbon atomic ratio is plotted along the "Y" axis and the oxygen to carbon atomic ratio is plotted along the "X" axis. Progressive enrichment of the coal in elemental carbon during coalification is reflected in the decreasing H/C and O/C ratios. On this diagram, the maturation pathway labeled "Type I" corresponds to alginite in the previous figure. "Type II" corresponds to "cannel coal", and "Type III" corresponds to "humic coals". Once again, the maturation pathways of the various coal constituents converge upon one another as they progress toward the origin, which represents pure carbon.

(from Tissot and Welte, 1984)

Constituents	Peat Stage	Lignite	Sub-Bitu-minous	Bitu-minous	Semi-Bitu-minous	Anthra-cite	Graphite

(from Robert, 1988, after White, 1933)
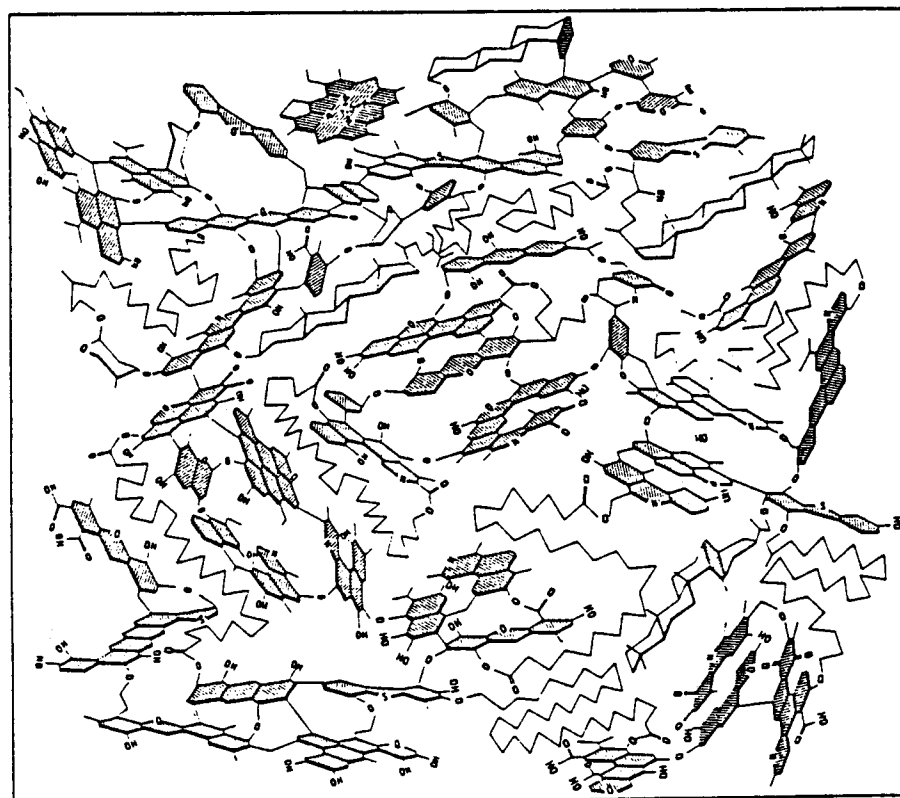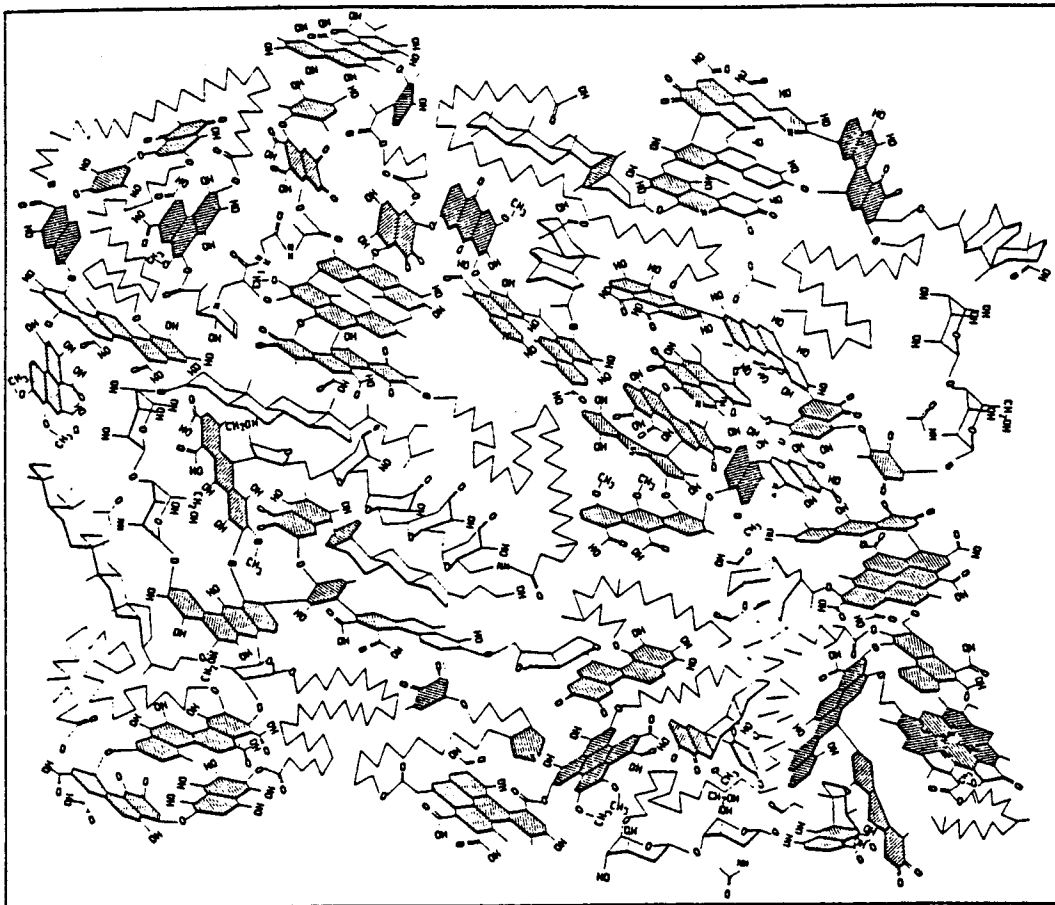
Behar and VanderBroucke, 1987
Organic Geochemistry, Vol. 11, p. 15-24

III. COAL AS A SOURCE ROCK

C O A L I F I C A T I O N &
H Y D R O C A R B O N   G E N E R A T I O N

Starting Material: **Products Materials:**

| | Residual coal enriched in carbon: | Volatile products enriched in hydrogen & oxygen |

```
┌─────────────┐              ┌──────────┐        Methane
│             │              │          │      + Carbon Dioxide
│   Coal 1    │  ──────────▶ │  Coal 2  │      + Water
│             │              │          │      + Etc. ?
└─────────────┘              └──────────┘
```


(Tissot & Welte, 1984)
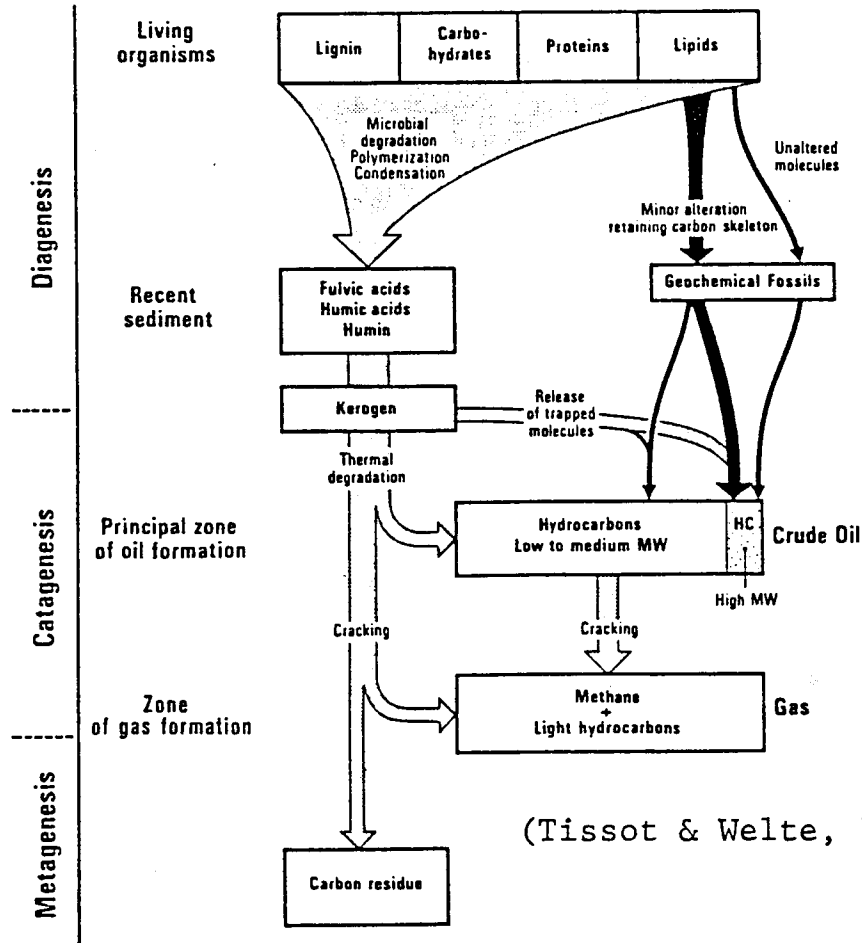
Generation of Hydrocarbon Gases During Peat Formation

Anaerobic fermentation in the swamp environment can result in the formation of gases (marsh gas), which can include low molecular weight hydrocarbons, notably methane. Laboratory experiments carried out on fatty acids, carbohydrates, and natural muds show that methane is the single hydrocarbon produced in major quantities, with ethane, propane, and butane present in only very low concentrations (10^{-5}-10^{-6}) (Davis and Squires, 1953; Bokova, 1959). Kim and Douglas (1972) derived similar results from studies of simulated swamp environments and conclude that the low but significant levels of higher hydrocarbons present in coal bed gas at higher rank (Kim 1978) are produced during subsequent stages of coalification.

The conditions of temperature and pressure in the coal-forming swamp provide no mechanism for retention of the gases generated during peat formation. Therefore, these gases are nearly completely lost from the system. At much higher coal ranks, however, and at elevated fluid pressure in the burial environment, coals do have the capacity to retain gases generated during coalification. These relationships will be explored subsequently.

Coal as a Source Rock for Oil? - Implications for Coal Bed Gas Generation and Storage

Over the past several years, considerable debate and interest has focused on the question of whether or not coals can serve as source beds for oil, as opposed to producing only natural gas during coalification. The former paradigm had been that coal beds, being compositionally dominated by "humic" or "terrestrial" or "Type III" organic matter was "gas prone" and was essentially devoid of oil generation. On the other hand, geologic and geochemical evidence from a variety of field localities, especially in Australia and nearby regions of southeast Asia, point strongly to coal beds as having been the source for significant oil deposits (Saxby and Shibaoka, 1986).

There is little dispute about whether liquid hydrocarbons are actually formed in coals during coalification. The evidence for this is now overwhelming--in the appearance of fluorescent "secondary" liptinite macerals visible in the optical microscope (Teichmuller, 1986), the development of fluorescence and "suppressed" reflectance in vitrinite (Lin et al., 1987), the progressive increase and changing composition of the so-called "mobile phase" component of coal (Derbyshire et al., 1989), and the results of artificial coalification experiments which show experimental evidence of oil generation and expulsion (Saxby et al., 1986). The controversy, such as it still exists, centers around the degree to which liquid petroleum products are released from the coal into surrounding strata. The more traditional view is most liquid hydrocarbon products remain physically entrapped or weakly bonded to the coal, hence are not free to migrate into surrounding strata in natural settings. More liberal interpretations suggest that coal is a good generator of oil (Cook and Struckmeyer, 1986).

This debate has two important implications with respect to coal bed gas reservoirs. Firstly, the generation of oil as oppposed to merely gas, during coalification will significantly limit cumulative production of gas. For example, in the artificial coalification experiments conducted by Saxby et al. (1986) in Australia, a large proportion of the volatile byproducts of coalification were hydrocarbon gases C_2 through C_5, plus a significant amount of solvent extractable oils and asphaltenes. As a result, molar production of methane was rather modest--around 9 cm^3 (STP) per gram of solid product. In contrast, if methane were the only hydrocarbon released by the coal, cumulative production would have been closer to 60 cm^3 (STP) per gram (by estimation method discussed subsequently). The difference in these figures is crucial, in that the smaller amount would probably have been insufficient to fully saturate the reservoir with methane.

The second implication of oil generation from coal pertains to the natural gas storage capacity of coal, which appears to be diminished by the presence of entrapped oils "plugging" the pore structure of the coal. Hypothetically, the oil molecules occupy molecular storage sites in the coal structure that would be otherwise be accessible to methane, thus decreasing the methane sorption capacity. This circumstance would be analogous to the comparatively well-documented decrease in methane sorption capacity due to the variable presence of water.

Although hard data is lacking, experimental and field evidence both suggest that the methane sorption capacity of coal is diminished by the presence of entrapped oils. Thomas and Damberger (1976) demonstrated that the N_2 and CO_2 surface areas of bituminous coals in Illinois decrease (on a dry basis) as the coal rank increases from high volatile C bituminous to high volatile A bituminous. This rank range coincides with the entry of the coal into the oil generation "window". N_2 and CO_2 surface areas of high volatile A coals were shown to increase significantly, however, when pores were "deplugged" by mild heating and attendant devolatilization. A variety of other recent laboratory and field evidence also supports this hypothesis.
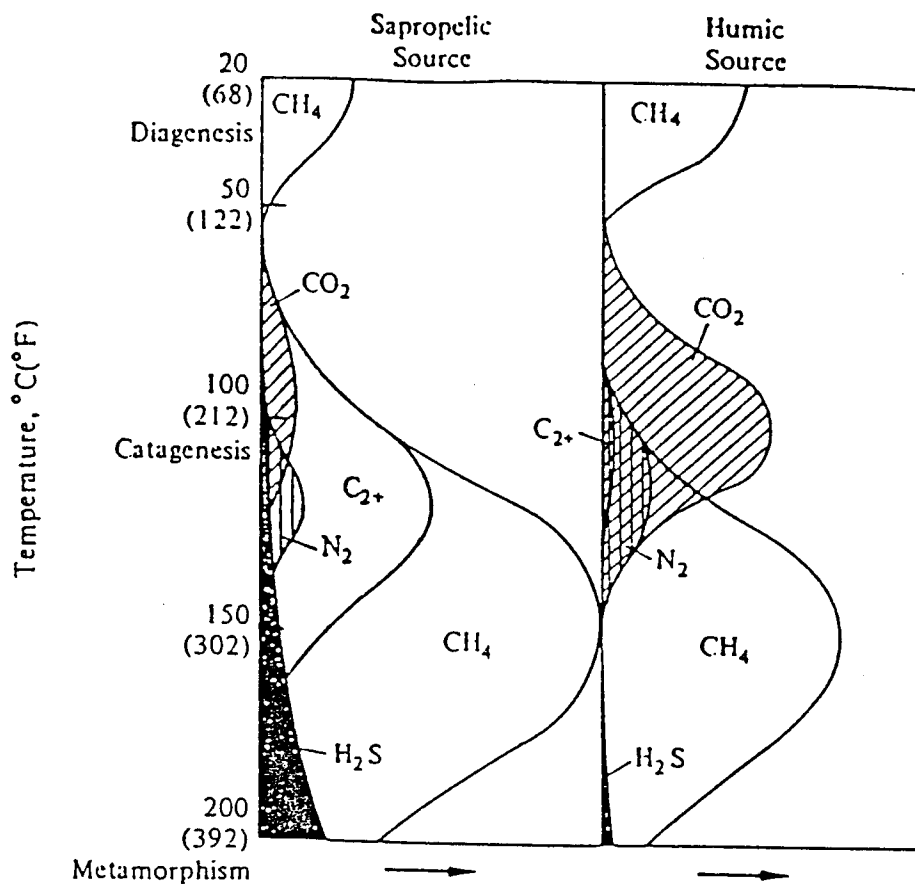
Relative Yield of Gas from
Organic Matter in Fine-Grained Sediments
(Hunt, 1979)

Volatile Evolution During Coalification

Throughout the whole period of its geochemical history, from peat formation through graphitization, fossilized organic matter undergoes a continuous loss of mass accompanied by the evolution of volatile products. This process results in a progressive enrichment of elemental carbon in the solid coal, due to the relative loss of hydrogen and oxygen in the "volatile" products. As a consequence, the H/C and O/C atomic ratios of the product coal progressively decrease. Since the three principal maceral groups (vitrinite, liptinite, and inertinite) differ substantially in their initial H/C and O/C ratios, they also differ in the quantity and type of volatile products formed during coalification.

In natural settings, coalification occurs over millions of years. Consequently, we are constrained to examinining only the end product, inferring as best we can the processes that led up to it. Inasmuch as the volatile products of coalification are free to migrate out of the coal, their original abundance and composition are largely problematical. If a number of reasonable assumptions are made, however, then the quantities of CH_4, CO_2, and H_2O liberated can be precisely estimated on the basis of changes in the major element (C-H-O) composition. The model presented here assumes:

<u>3 Assumptions of Model:</u>

1) coal macerals evolve compositionally along the four generalized maturation

    pathways depicted in Figure 1

2) CH_4, CO_2, and H_2O represent the only forms in which carbon, hydrogen, and

    oxygen can escape from the coal bed, and

3) once they are formed, free CH_4, CO_2, and H_2O cannot recombine with the solid

    coal.

Devolatilization Paths Plotted on the van Krevelen Diagram

Elemental compositions of coalification products and reactants can be plotted on a van Krevelen diagram (Figure 1), which depicts the H/C vs O/C atomic ratios. Coalification paths for the 4 principal kerogen types are plotted (Type I and Type II = Liptinite; Type III = Vitrinite; and Type IV = Inertinite). At low rank, the maceral groups differ substantially in composition, but the pathways progressively converge upon one another at higher rank.

A vector connecting any pair of starting and end points on the diagram can be used to represent the compositional evolution of a particular coal or coal constituent. This vector can be resolved into 1, 2, or 3 components, parallel to the dehydration, decarboxylation, and/or demethanation pathways on the diagram (dotted, solid, and broken lines, respectively, on Figure 1). These devolatilization paths represent the change in composition brought about by the progressive removal of H_2O, CO_2, and CH_4, respectively.

Applying the constraints of the model, it is possible to reach a particular end point by a variety of pathways--but only within a limited range of possibilities--or else condition 3 (above) will be violated. For example, if a liptinite maceral of initial composition A is coalified to composition C, the two limiting coalification pathways are represented as paths A-A'-C and A-A"-C. The first case involves the production of only CH_4 and CO_2 while the second involves only CH_4 and H_2O. Compositional changes associated with the CH_4-CO_2 path can be represented by a decarboxylation vector (A-A'), linked with a demethanation vector (A'-C). In the other end member case, the dehydration vector intersects the demethanation path at A".

By comparing the relative lengths of vectors A'-C and A"-C, it is appears qualitatively that the decarboxylation-demethanation path will result in a larger production of methane than the dehydration-demethanation path.

Mass Balance of Products & Reactants

Quantification of the Model. To quantify this model and determine the precise composition and quantities of gases formed on each path, a set of equations is formulated whereby the total number of atoms of C, H, and O are equated between reactants and products, and the H/C - O/C ratios of the reactants and products must be adhered to:

$$C_p = C_r - CH_4 - CO_2 \tag{1}$$

$$H_p = H_r - 4*CH_4 \qquad - 2*H_2O \tag{2}$$

$$O_p = O_r - \qquad 2*CO_2 \qquad - H_2O \tag{3}$$

where C_p, H_p, and O_p are the number of atoms or moles of carbon, hydrogen, and oxygen per unit of the product. C_r, H_r, and O_r are the number of atoms or moles of carbon, hydrogen, and oxygen in the starting (reactant) mixture; and CH_4, CO_2, and H_2O are the number of molecules or moles of methane, carbon dioxide, and water formed from the reactants during coalification.

The H/C and O/C ratios of the products and reactants are known:

$$H_p/C_p = 0.50 \tag{4}$$

$$O_p/C_p = 0.06 \tag{5}$$

$$H_r/C_r = 1.25 \tag{6}$$

$$O_r/C_r = 0.07 \tag{7}$$

The system can be further constrained by envisioning an "imaginary" molecule of coal, comprised of 1000 atoms, forming the starting material:

$$C_r + H_r + O_r = 1000 \tag{8}$$

In subsequent calculations, these 1000 atoms will be partitioned between the coal and the various volatile products.

Equations (6), (7), and (8) together constitute three equations with three unknowns, yielding a unique solution:

$$C_r = 431 \qquad (9)$$

$$H_r = 539 \qquad (10)$$

$$O_r = 30 \qquad (11)$$

Substituting equations (9), (10), and (11) into equations (1) - (5), we are left with 5 equations and 6 unknowns. In order to derive a unique solution, one additional relationship must be defined. For end member case A-A'-C, $H_2O = 0$; and for case A-A"-C, $CO_2 = 0$. For intermediate pathways, some ratio of CO_2 to H_2O generation must be specified.

## Other Methods of Estimating Volatile Yields

Numerous alternative schemes have been utilized to estimate the quantity of hydrocarbons generated during maturation. These fall broadly into two categories: a) pyrolysis or artificial coalification experiments and b) empirical estimation procedures, based upon the composition of the solid residues. The method utilized in the present investigation falls into the second category, but differs in some details from previous methods. For example, Juntgen and Karweil (1966) estimated volatile generation by assuming, as in the present paper, that CH_4, CO_2, and H_2O are the only volatile products. Juntgen and Karweil speculated that the proximate analysis volatile matter content (measured by pyrolysis at 950o) could be used as an estimate of the total weight of material evolved as volatile products during coalification. However, this assumption is unwarranted and thermodynamically unsound. Moreover, by requiring that their coals expulse such a large volume of volatiles, Juntgen and Karweil's equations yielded negative values for water production--In other words, their calculations required that water be added to the coal structure in order to "balance" their. Thus, the widely-cited estimates of gas production volumes based on this model must be called into question.

Depending on the path chosen, the relative proportions and total weight percentages of the volatile products vary considerably. Table 1 lists the yields of CH_4, CO_2, and H_2O and volatile matter produced along the various maturation pathways depicted in Figure 1. For example, as coal increases from Ro(vit) = 0.5 to Ro = 2.0, vitrinite can evolve anywhere from 24 to 173 cm3/g coal, depending upon whether B-B'-C or B-B"-C is followed. Assuming a reasonable ratio of 4:1 H_2O:CO_2 production, vitrinite will generate around 30 cm3/g, far less than previously published estimates. Over this same rank range, and within the constraints of the model, liptinite macerals generate between 421 and 466 cm3/g; however, in reality, liptinites probably lose a significant proportion of their hydrogen as longer chain hydrocarbons.

Although coals are known to produce small amounts of higher hydrocarbons during coalification, there is controversy regarding how much of these substances are actually released into the surrounding strata (Tissot and Welte, 1975, p. 224). Petrographic evidence shows that a significant proportion of these oil-like products remain in the coal-- impregnating void spaces and penetrating into the molecular structure of the vitrinite. Hence, elemental analyses of whole coals containing these oil-like products would include contributions from both the solid coal plus any entrapped hydrogen-rich "volatiles" substances.
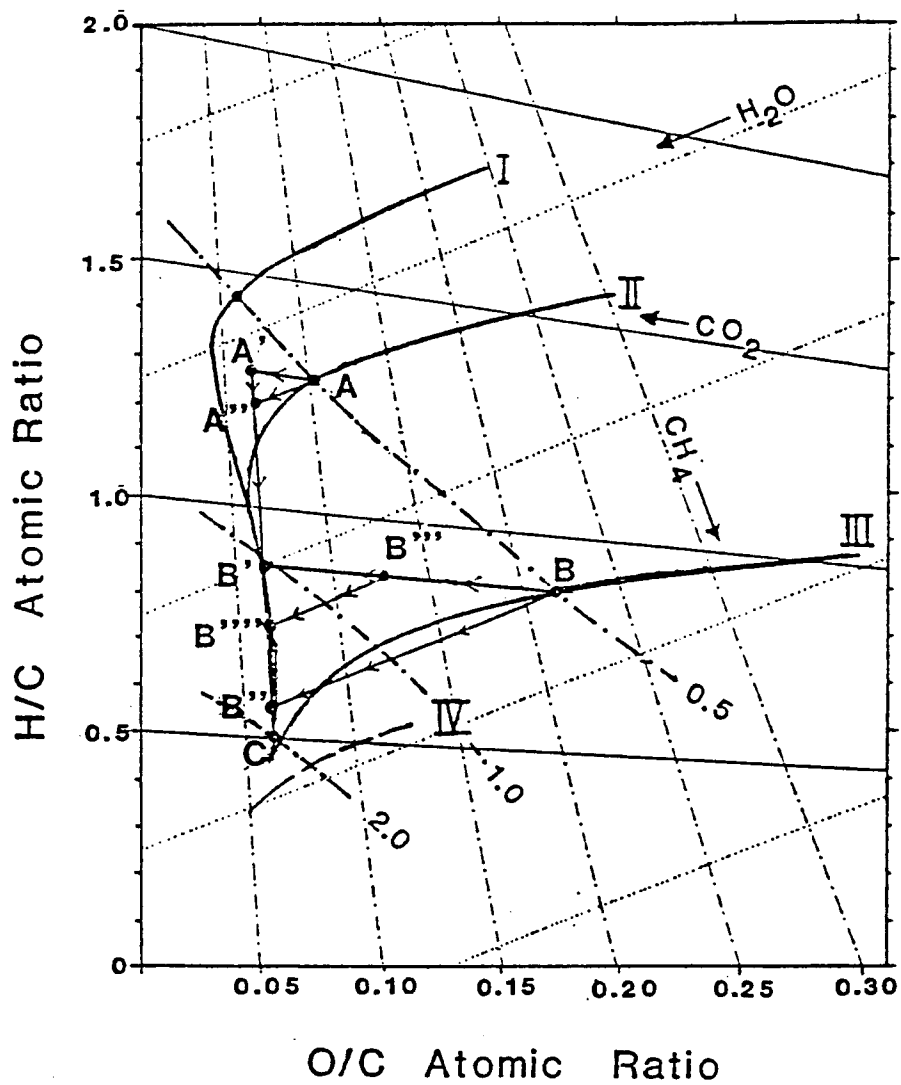
Coalification from $R_o(vit) = 0.5$ to $R_o(vit) = 2.0$		Cumulative Grams of Volatiles per Gram of Coal			% of Original Weight Lost as Volatiles	Volume of CH_4 (stp) per Gram of Solid Coal
Path	Description	CH_4	CO_2	H_2O		
A–A'–C	Max. CH_4, Max. CO_2, Min. H_2O	0.333	0.049	0	27.6	466.
A–A"–C	Min. CH_4, Min. CO_2, Max. H_2O	0.301	0	0.036	25.2	421.
B–B'–C	Max. CH_4, Max. CO_2, Min. H_2O	0.124	0.236	0	26.5	173.
B–B"–C	Min. CH_4, Min. CO_2, Max. H_2O	0.017	0	0.156	14.7	24.
B–B"'– B""–C	Interme- diate Path: $H_2O = CO_2$	0.083	0.146	0.059	22.4	116.

GAS GENERATION
for
$m_{CO_2} = m_{H_2O}$
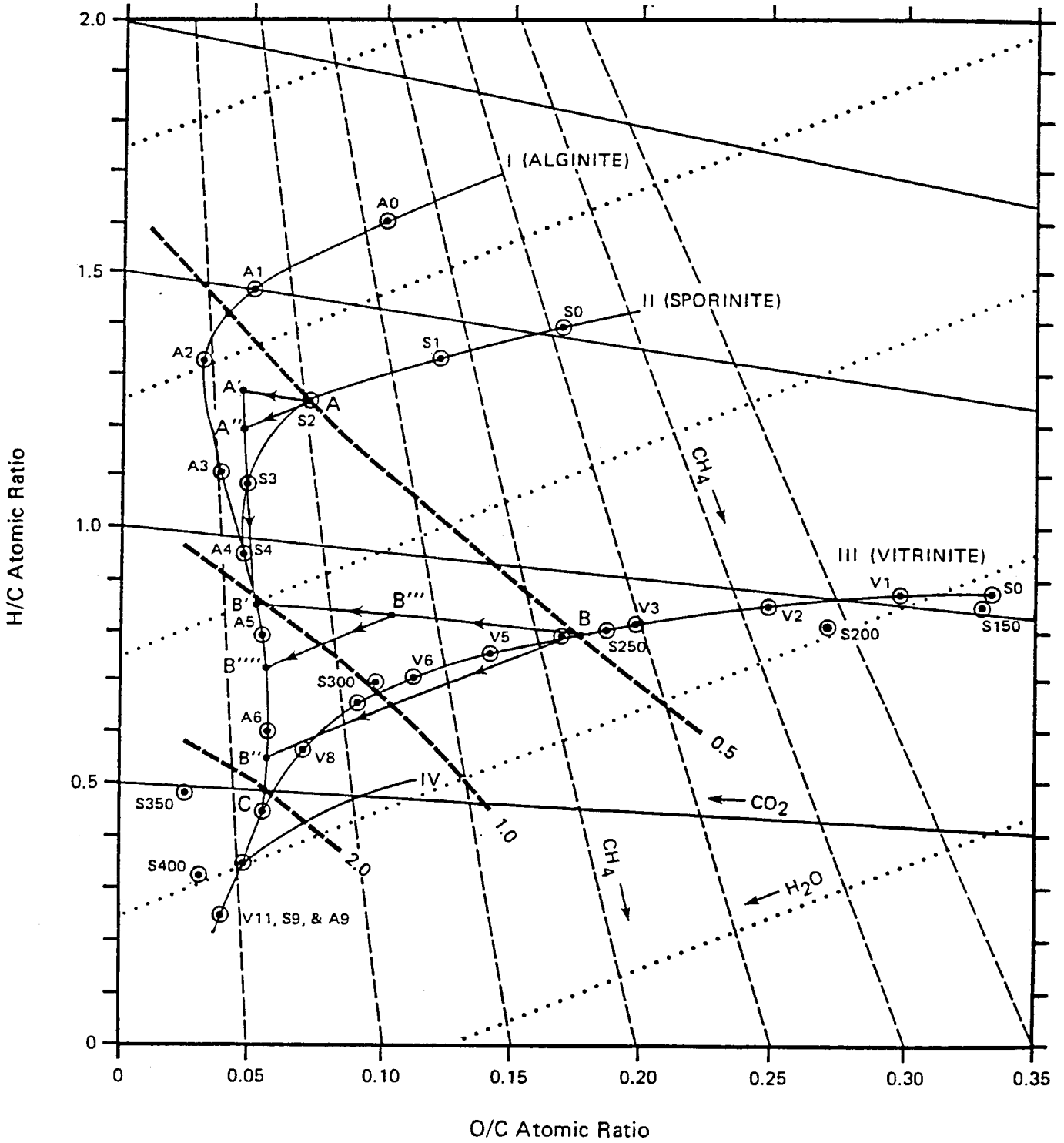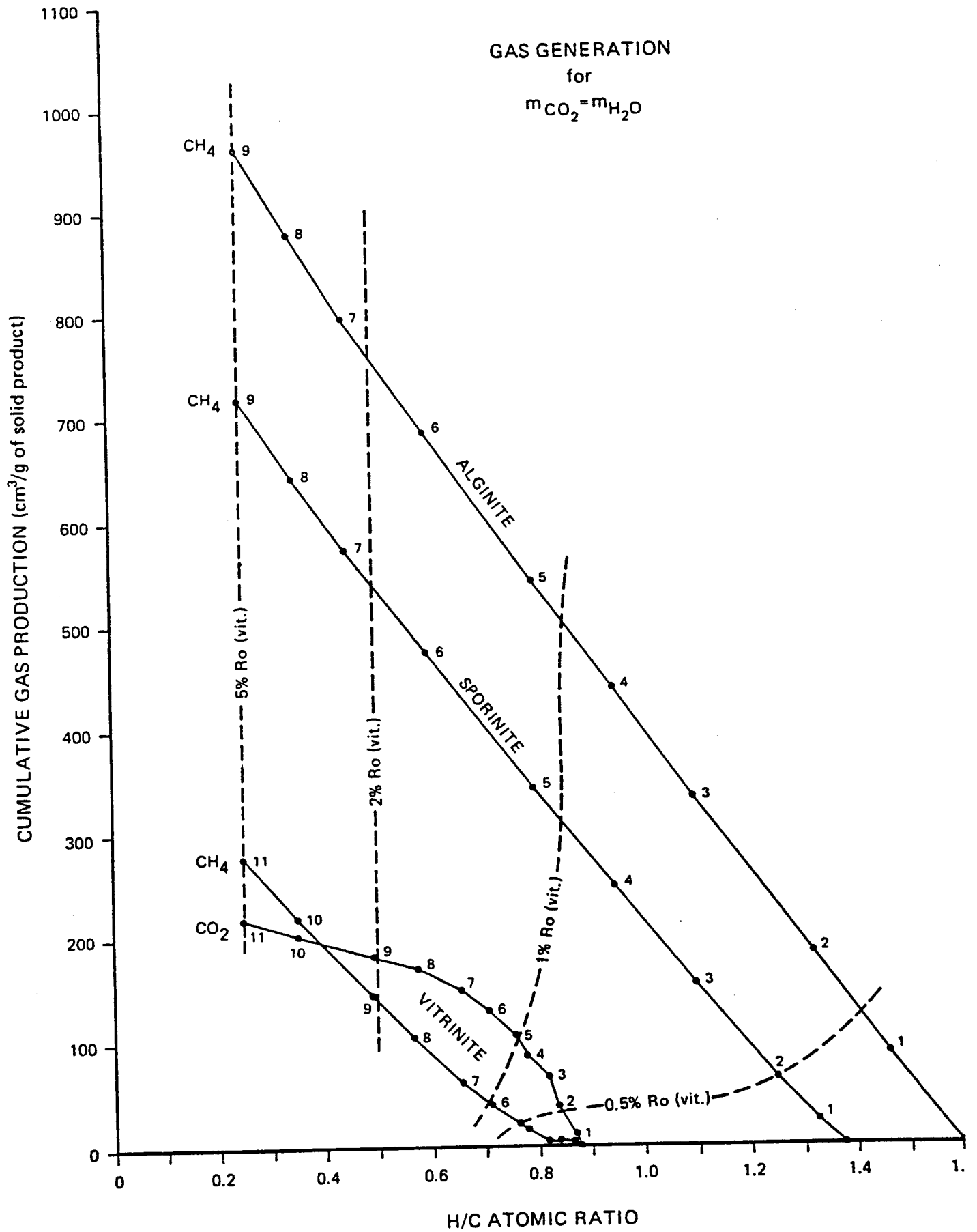
IV. COAL AS A RESERVOIR ROCK

Introduction

As noted in the previous sections, coal beds generate large quantities of hydrocarbons--especially dry gas--as a byproduct of coalification (e.g. Welte et al., 1984; Meissner, 1984; Teichmuller, 1986). Of particular interest in the following sections, however, is the potential role of coal as a reservoir rock for natural gas. Two aspects of the coal bed are of interest in this regard: 1) the coal's capacity to "soak up" large volumes of gas under pressure and 2) the coal's capacity to allow flow of gas through the reservoir.

Gas storage capacities are widely variable for different coals, depending on fluid pressure, temperature, coal rank, mineral matter content, and degree of water saturation. Coal beds also vary significantly in their permeability to gas flow, although the relationships here are more problematical. In some cases coals have very high gas contents but unsuitably low permeabilities, whereas in other cases the permeabilities may be acceptable while the gas contents are too low. Both variables must be optimized in tandem to maximize production characteristics.

Of additional interest in this section are the methods for determining the concentration of gas in the reservoir and the total in-place gas resource.

Nature of Gas Storage in Coal

Natural gas can be stored in coal in both an adsorbed state (physically attached to internal "surfaces" in the coal) and as a free gas in "open" pores and fractures. Since the relative proportion of these two states is unknown, and since the true nature of the "adsorption" is not well understood, the term "sorption" without a prefix is most appropriate to describe this system.

The gas sorption capacity of coal is a function of its physical structure and the strength of the molecular interactions between the coal substrate and the sorbate gas. For any single coal, sorption capacity decreases with increasing temperature, increases with increasing partial pressure of the sorbate, and decreases due to the presence of other guest species (notably water), which can apparently displace gas from sorption sites that it would otherwise occupy (Joubert et al., 1973; 1974).

Sorption capacity is known to vary significantly from coal to coal, but the controlling factors are inadequately understood. Rank-related differences in the composition and structure are important influences (Kim, 1977). Pore volume and average pore size decrease with rank (Mahajan and Walker, 1978). Inherent moisture content decreases with rank-- reflecting both the loss in porosity and the loss of hydrophyllic functional groups. There may also be a concurrent increase in the concentration of methane surface-active sites with rank. As a combined consequence of these differences, the accessibility of methane to storage sites in the coal structure progressively increases with rank.

Influence of Petrographic Composition on Sorption Capacities of Coal

Several studies in the Russian literature report that the gas-holding capacity of coals can be influenced by coal "type" - particularly by the lithotypes present. Gas content appears to increase with increasing fusain content, and decrease with increase in concentration of [some types of?] vitrain (Ettinger, I.L., 1966). Zabigaylo et al. (1972) indicate that, with rare exceptions, higher concentrations of structured gelified vitrain components improve the
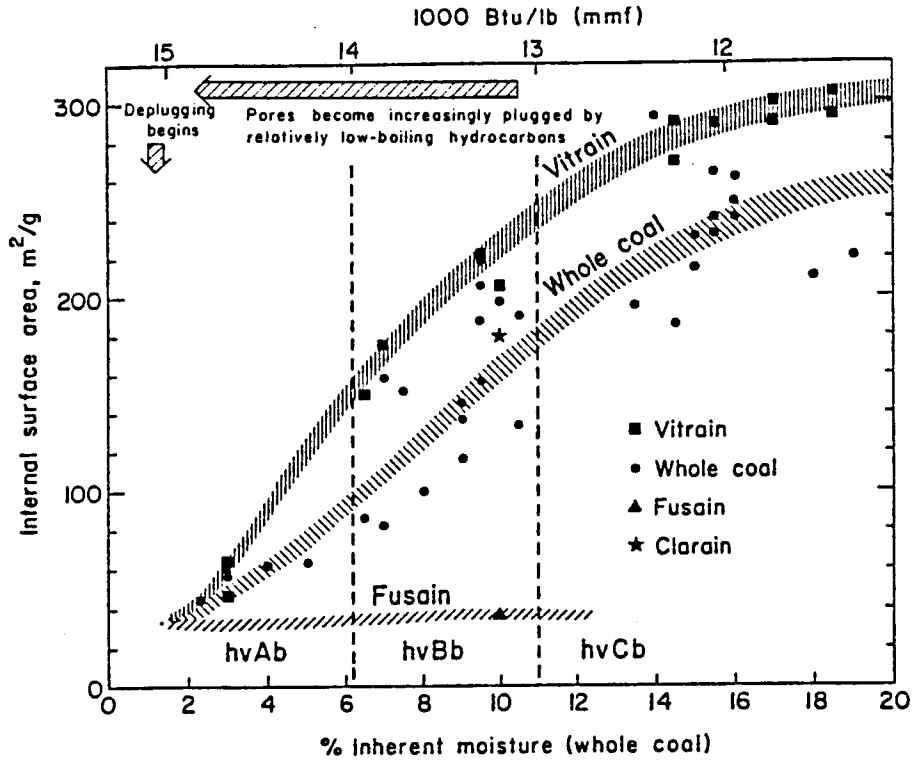
(Thomas and Damberger, 1976)

(from Berkowitz, 1979)

(Meissner, 1984)
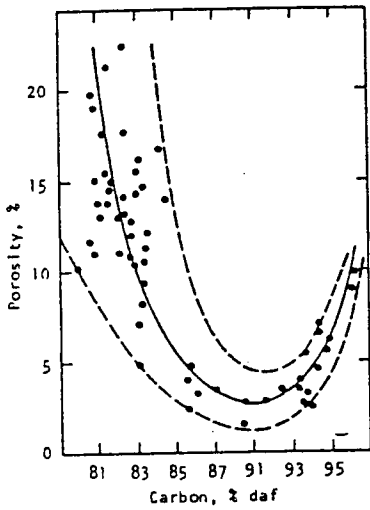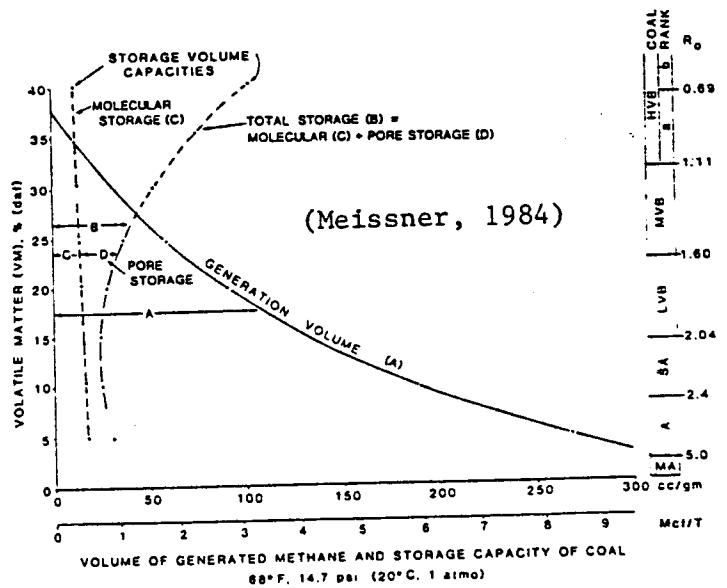
sorptive capacities of coal, as does an increase in the proportion of fusain. However, an increase in the concentration of homogeneous matrix [durain?] decreases sorption capacity. Consistent with these studies, Levine (1987) reports a weak positive correlation between intertinite content and gas content in coals from the Cahaba basin, Alabama. Creedy (1989) and Ulery (1988) have also investigated the relationship of petrographic composition on natural gas contents, but found very little influence, perhaps reflecting the low variability in petrographic composition of their sample sets.

- -

Influence of P, T, & Sorbate Composition on Sorption Capacity
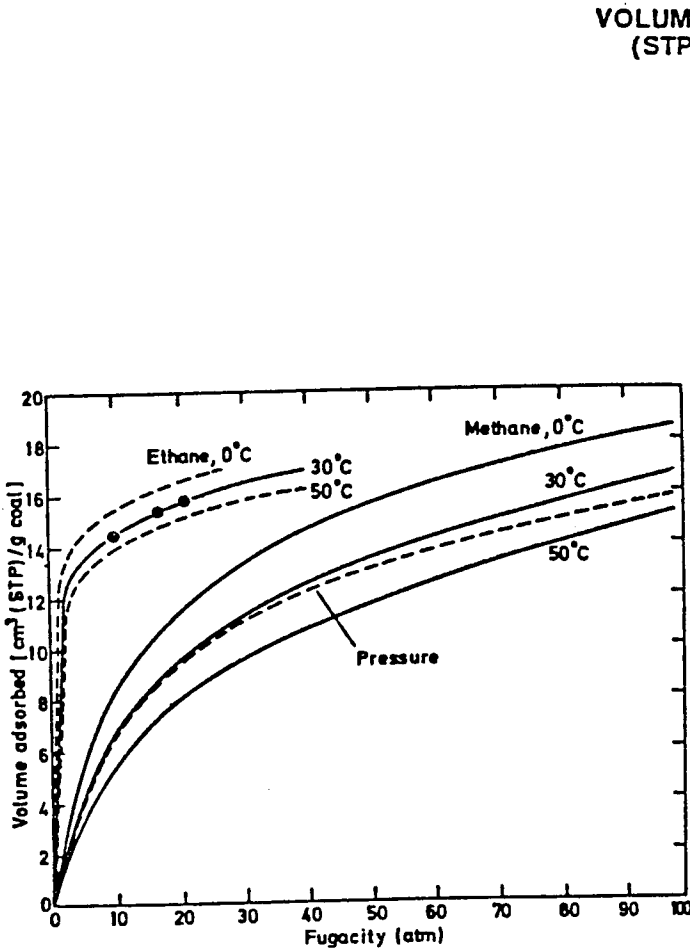
Figure 4 Equilibrium adsorption isotherms for methane and ethane on dry high-volatile 'A' bituminous coal

(Ruppel, Grein, and Bienstock, 1972)

	ΔP,atm	% GAS DESORBED
A	0	INITIAL GAS CONTENT
A to B	10	11
A to C	20	33
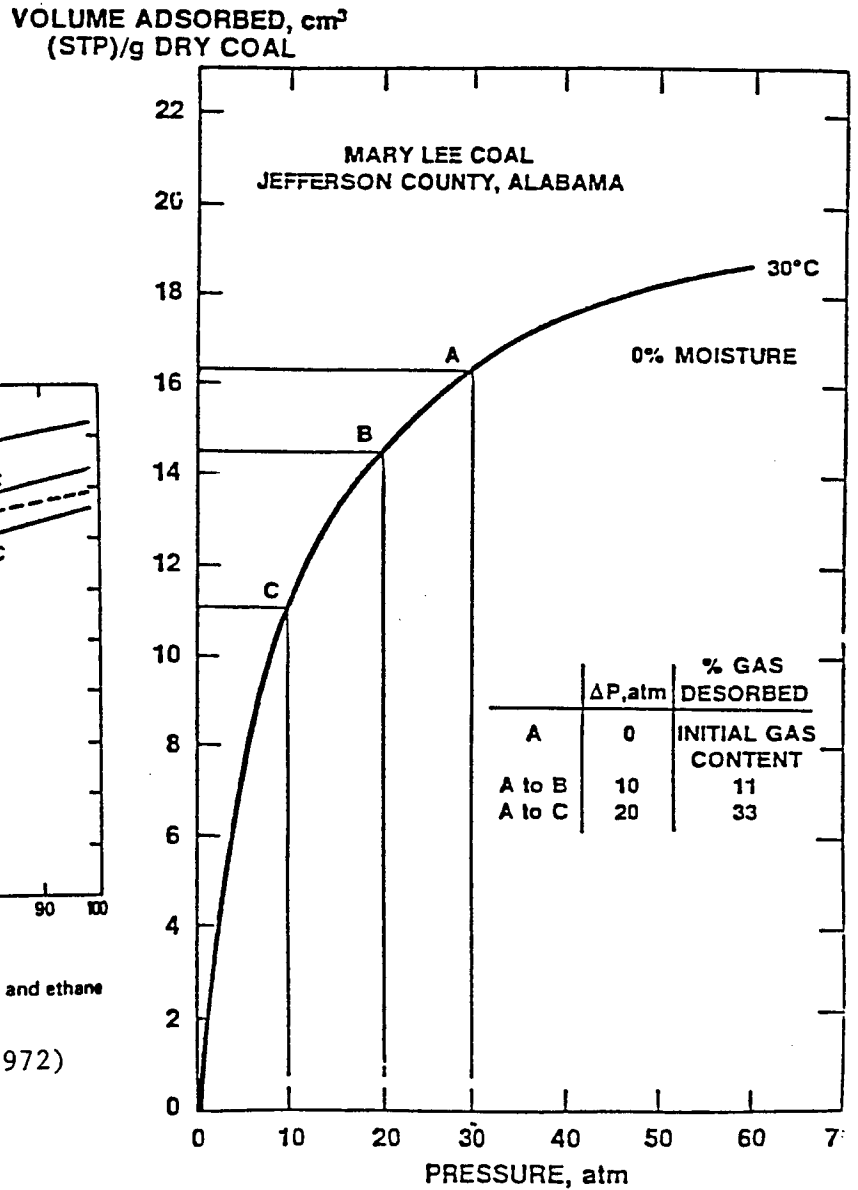
(Lambert, Trevits, and Steidl, 1980)

Influence of Rank and Depth on Sorption Capacity

Joubert et al., 1974
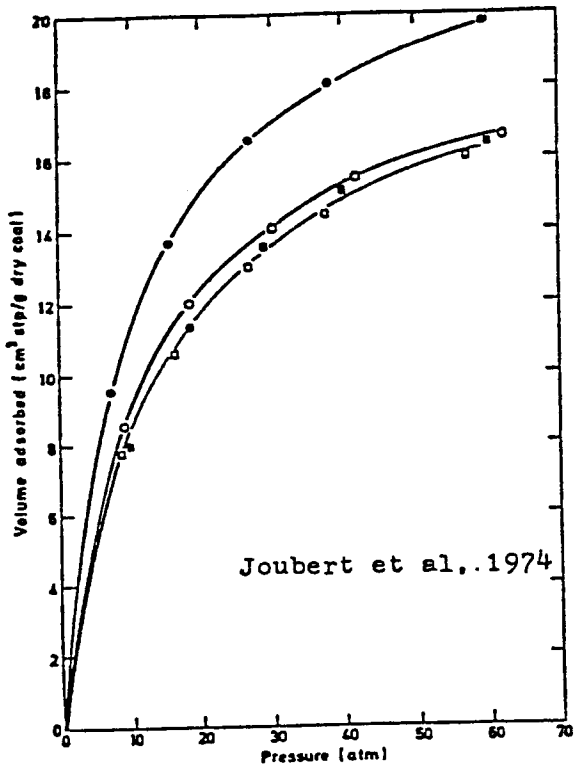
Methane adsorption isotherms for Lower Kittanning coal at 30°C
Moisture content: ● zero, O 1-28%, ■ 3-48%, □ 4-77%

Joubert et al., 1974
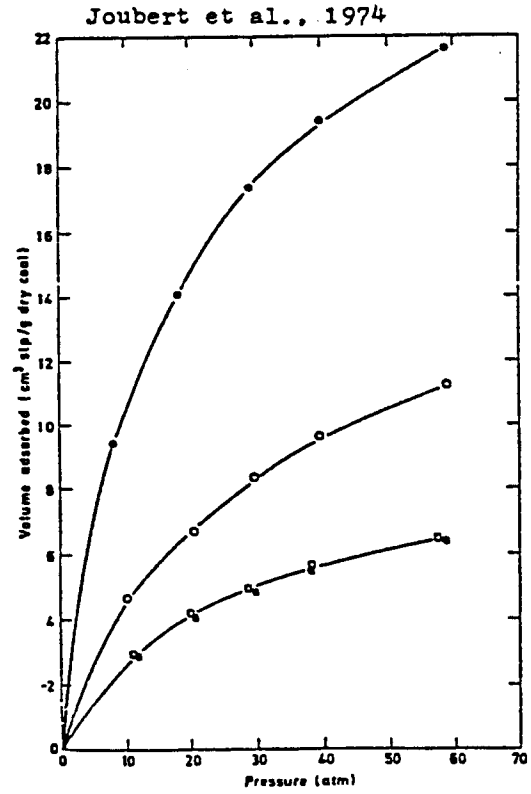
Methane adsorption isotherms for Illinois No.6 coal at 30°C
Moisture content: ● zero, O 5-44%, ■ 10-70%, □ 14-28%

KEY
Anthracite
Low-volatile bituminous
Medium-volatile bituminous
High-volatile bituminous
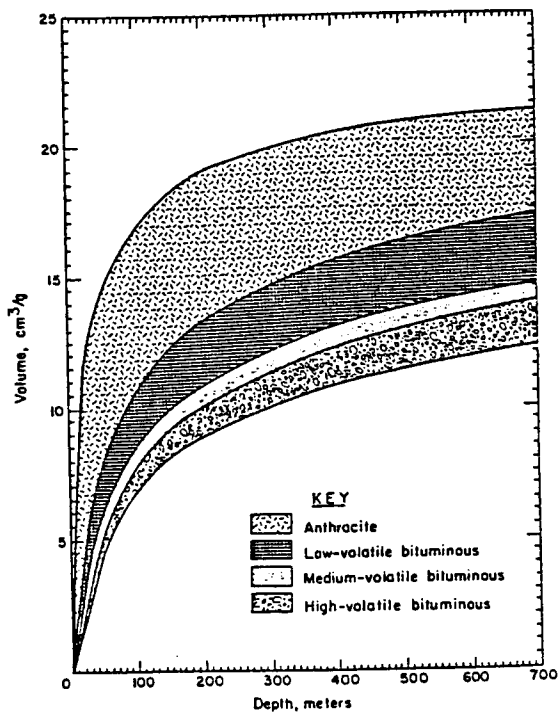
Adsorption capacity as a function of depth.

(Deul and Kim, 1986)

Temperature 30° C

| KEY | |
Coalseam	Moisture, pct
Hartshorne	L3
Pocahontas No.3	0.7
Pocahontas No.3	1.1
Pittsburgh	1.4
Castlegate (subseam No.3)	2.2
Illinois No.6	8.0

FIGURE - Equilibrium adsorption isotherms. Coal type and moisture levels selected to correspond to the cores extracted from the vertical boreholes.

(Kissell, McCulloch, and Elder, 1973)
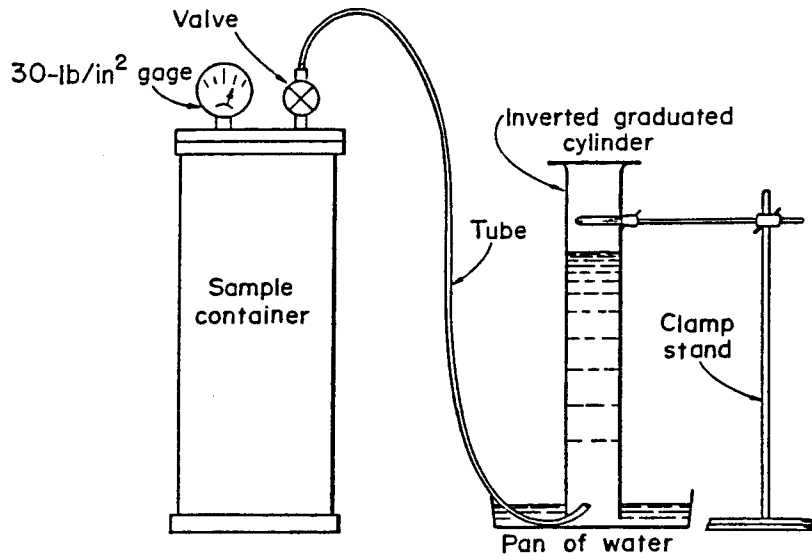
Equipment for direct method test.
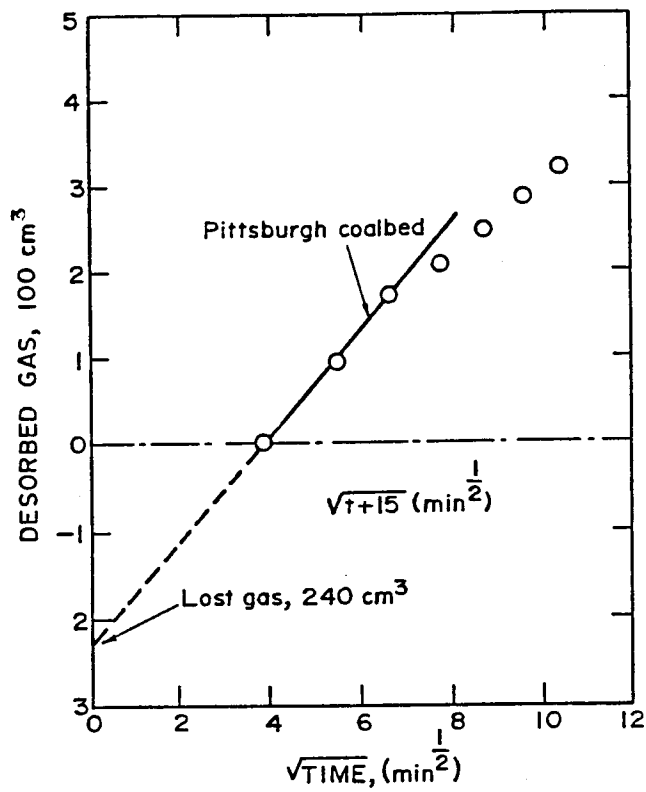
(Deul and Kim , 1986)

Data for "lost" gas graph for direct method test.

(Deul and Kim, 1986)

Gas Content vs. Depth: Warrior Basin

High Volatile A Bituminous
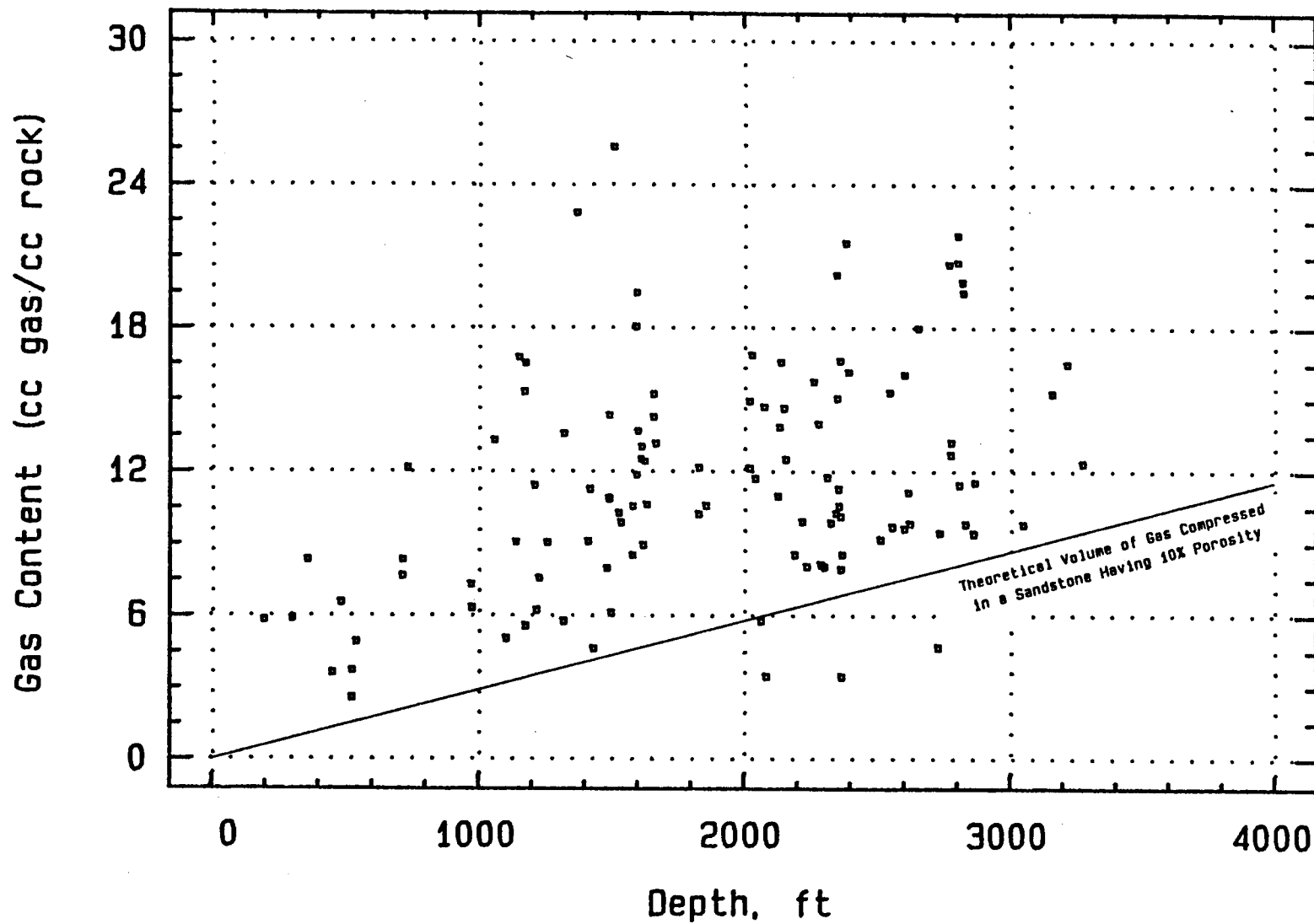
The Composition of Coal Bed Natural Gas

Compositionally, there are many varieties of coal bed gas. It is potentially misleading, therefore, to make generalizations regarding its composition. Nevertheless, most natural gas from coal beds is comprised primarily of methane--usually in excess of 90%--as is also the case with most "conventional" natural gas. The unfortunate and misleading term "coalbed methane" was derived from the coal mining industry via the U.S. Bureau of Mines, in reference to the potentially explosive gas (a.k.a "firedamp") that is liberated into the underground mine atmosphere during and after mining. Other components of coal bed gas normally include CO_2, N_2 and a variable percentage of higher hydrocarbons.

Some coal bed gas is extremely "dry", being comprised of over 98% methane; but coal bed gas can contain in excess of 10% ethane plus higher hydrocarbons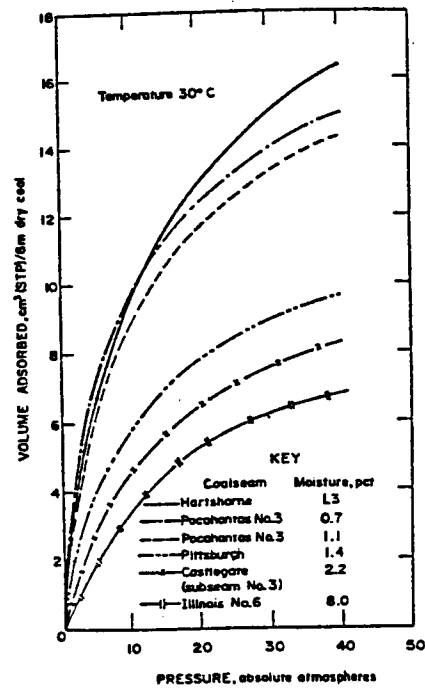 in some localities, especially in Western coal basins. Some coal bed gas wells in the San Juan basin are quite "wet"--precipitating a waxy condensate at the surface. In other areas of the San Juan Basin CO_2 content of coal bed gas can be greater than 50%, having a very low BTU value. In general, though, the BTU yield of most coal bed gas is of pipeline quality, yielding more than 1000 BTU/cf (see Table below). Normally, no processing or cleaning is required aside from water separation.

Another complicating factor is that coal has variable affinity for different occluded gases. Therefore, the composition of the gases released changes during desorption due to this "chromatographic effect". Methane is liberated relatively readily, while higher hydrocarbons tend to be preferentially retained.
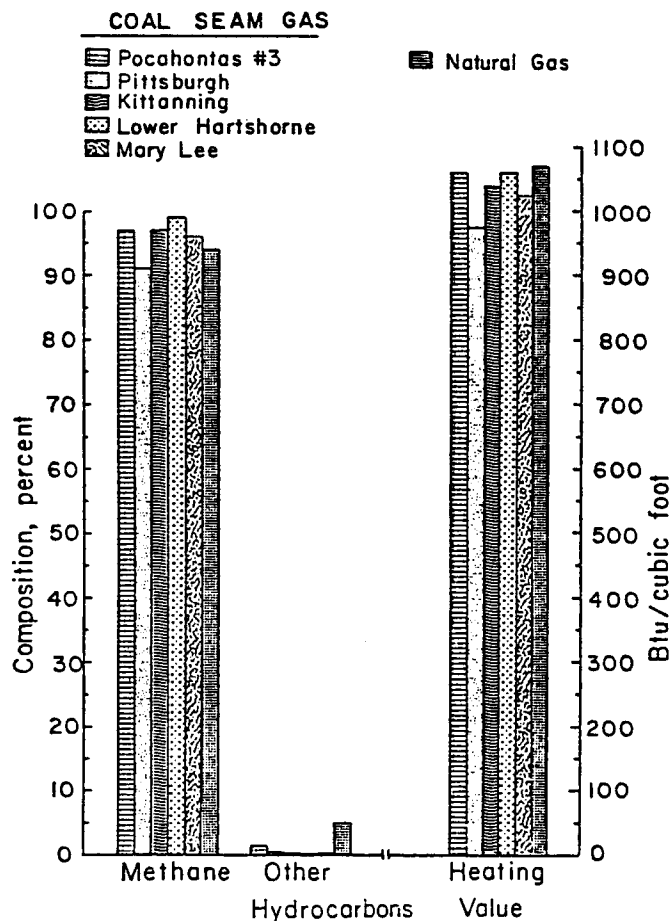
Comparison of gas from coalbeds and natural gas.

(Deul and Kim, 1986)

Estimation of Gas-in-Place for High-Ash Coals

Coalbeds potentially provide attractive target horizons for gas production because they commonly contain much higher concentrations of gas at any given depth than "conventional" gas reservoirs. Therefore, the crux of any "coalbed methane" exploration program is to estimate the total amount of gas present as well as identify the stratigraphic intervals in which gas is most highly concentrated. These data should be presented in a manner which will aid in identifying target zones for production.

To estimate resources of coalbed gas in place, most previous studies (e.g. McFall et al., 1986, Thompson 1983) have used a calculation procedure similar to:

$$GIP = GC \times h \times A \times d$$

where:

GIP	=	gas in place, measured in units of volume (STP)
GC	=	gas content of the coal, measured in units of volume of gas (STP) per unit weight of coal
h	=	total coal thickness
A	=	area under consideration
d	=	specific gravity of coal, in weight per unit volume

In order for this calculation to yield meaningful results, a self-consistent set of measurement units must be used. For example, to calculate GIP in cubic feet, area can be measured in acres, thickness in feet, gas content in cubic feet per ton, and density in tons per acre-foot. Even if these units are used, however, errors may arise if the coal is not consistently measured on the same basis. For example, in estimating GIP for the Black Warrior basin, McFall et al. (1986, p. 53) calculated gas content and specific gravity[*] on an ash-free basis, but calculated coal thickness on an as-determined basis. (That is, they used the full thickness of the coal in place, irrespective of mineral matter content or partings). The implication of this procedure is that the coalbed is composed entirely of organic matter, which is not true. Ash yields for the coalbeds analyzed typically range between 10% to 30% and are sometimes higher (McFall et al., 1986, Table 4). Thus, the estimated tonnages of "clean coal" based on these thicknesses are exaggerated. The resulting error in GIP might be acceptably small for coals low in ash yield; however, large overestimates would result for high ash coals.

Three methods could be used to improve the accuracy of GIP calculations. One alternative would be to use a "modified" bed thickness rather than the true bed thickness to calculate the volume of coal present. In this case the adjusted thickness would represent only the portion of the bed comprised of "clean" mineral matter-free coal. A second alternative would be to do all GIP calculations on an "as-determined" basis, rather than an ash-free basis, in which case the true bed thickness would be used, but the specific gravity would be recalculated so as to reflect the actual mineral matter content of the coal. The third option is to calculate the gas content of coal per unit volume of reservoir. To estimate GIP, simply multiply this figure by the total volume of reservoir rock present.

---

[*] For their GIP calculations, McFall et al. (1986) used estimates of 1800 tons/acre-foot for high volatile bituminous coal, 1850 tons/acre-foot for medium volatile bituminous coal, and 1900 tons/acre-foot for low volatile bituminous coal. These figures were attributed to Averitt (1975) and apparently refer to mineral matter-free coal. However, Averitt's report actually includes only a single estimate of 1800 tons/acre-foot (1.32 g/cm^3) for all bituminous coals and an estimate of 2000 tons/acre-foot (1.47 g/cm^3) for anthracite and semianthracite. The higher specific gravities used by McFall et al. (1986) apparently constitute an interpolation between Averitt's bituminous and anthracite values. However, the density of coal actually decreases through low volatile bituminous before increasing quickly in the anthracites (see Berkowitz, 1979). Therefore, McFall et al.'s modifications of Averitt's original estimate for bituminous coals may have introduced an additional inaccuracy in their calculations.

Gas contents can be calculated on several different bases to enable resource evaluation:

Abbreviation:	Full description:	Units:
GC_{ad}	Volume of gas (STP) per unit weight of coal in the reservoir	cm^3 of gas (STP)/* g of coal (as-det'd)
GC_{af}	Volume of gas (STP) per unit weight of ash-free coal	cm^3 of gas (STP)/* g of coal (af)
GC_{ua}	Volume of gas (STP) per unit area of selected reservoir bed(s)	cm^2 of gas (STP)/ cm^2 of reservoir
GC_{uv}	Volume of gas (STP) per unit volume of selected reservoir bed(s)	cm^3 of gas (STP)/ cm^3 of reservoir

*Commonly converted to cubic feet per ton.

Each basis has its own particular utility. GC_{uv} is a particularly useful measure for several reasons. Firstly, it provides the most direct means of calculating the gas resource in place, by simply multiplying by the volume of coal present (irrespective of mineral matter content or specific gravity). Secondly, it can be used as a parameter to evaluate the quality of a gas reservoir (The higher the GC_{uv}, the better the reservoir). Thirdly, when calculated as cm^3 of gas (STP) per cm^3 of reservoir, GC_{uv} can be thought of as representing the Gas Concentration Factor (or GCF), which is the ratio of the number of volume units of desorbed gas (at STP) per equivalent volume unit of reservoir rock. Since GCF is a simple ratio, any desired units can be substituted (e.g. ft^3 of gas (STP) per ft^3 of reservoir).

References on Measurement and Estimation of the Gas Content of Coal

Banerjee, B.D., 1987, A new approach to the determination of methane content in coal seams: International Journal of Mining and Geolgical Engineering, v. 5, p. 369-376.

Joubert, J.I., Grein, C.T., and Bienstock, D., 1973, Sorption of methane in moist coal: Fuel, v. 52, p. 181-185.

Joubert, J.I., Grein, C.T., and Bienstock, D., 1974, Effect of moisture on the methane capacity of American coals: Fuel, v. 54, p. 186-191.

Kim, A.G., 1977, Estimating the methane content of bituminous coalbeds from adsorption data: U.S. Bureau of Mines Report of Investigations 8317, 18 p.

Kissell, F.N., McCulloch, C.M., and Elder, C.H., 1973, The direct method of determining the methane content of coalbeds for ventilation design: U.S. Bureau of Mines Report of Investigations 7767, 17 p.

McCulloch, C.M., Levine, J.R., Kissell, F.N., and Deul, M., 1975, Measuring the methane content of bituminous coalbeds: U.S. Bureau of Mines Report of Investigations 8043, 22 p.

Smith, D.M. and Williams, F.L., 1984, Direct method of determining the methane content of coal a modification: Fuel, v. 63, p. 425-426.

Smith, D.M. and Williams, F.L., 1984, Diffusion models for gas production from coals-- application to methane content determination: Fuel, v. 63, p. 251-255.

GAS CONTENT DATA: BLACK CREEK INTERVAL
Duncanville Core Hole

Rock Type	Thickness in feet: Coal	Shale	Coal Sample ID	Ash (wt-%)	GC_{ad} (cm^3/g)	GC_{af} (cm^3/g)	GC_{ua} (cm^3/cm^2)	GC_{uv} (cm^3/cm^3)
	1.1		152	20.5	8.6	10.9	419.	12.5
		1.0						
	0.3		153	60.2	3.2	8.0	55.	6.0
		0.2						
	0.1		153	60.2	3.2	8.0	18.	6.0
		0.5						
	0.3		153	60.2	3.2	8.0	55.	6.0
		1.0						
	0.1		153	60.2	3.2	8.0	18.	6.0
		1.1						
	1.7		154	8.0	10.8	11.7	737.	14.7
Complete Interval:	3.6	3.8		74.8	2.7	10.6	1302.	5.8

Total Natural Gas In Place— Target Coal Groups

~5~ Gas In-Place Contour
Contour Interval: 2 Bcf/Square Mile

Warrior Basin, Alabama

Prepared by:
Lewin and Associates, Inc.
1986 McFall et al., 1986
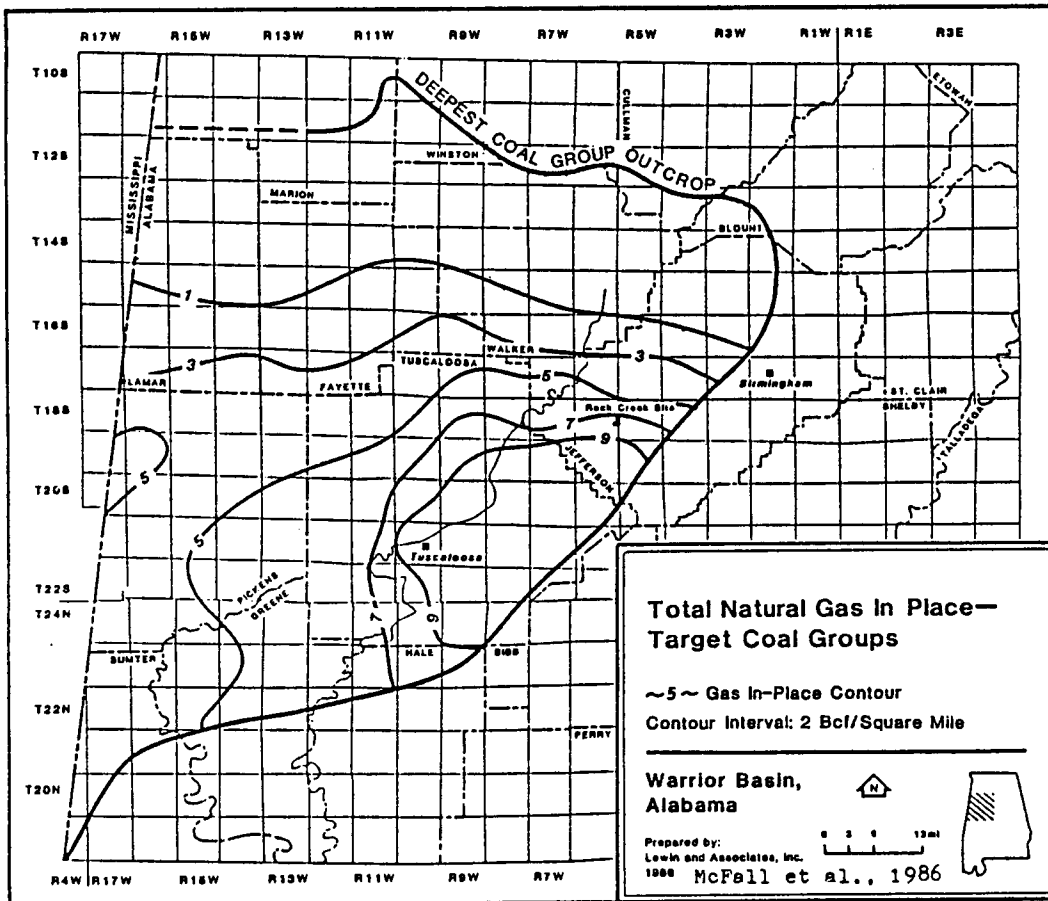
CLEAT

Cleat is a miners' term used to describe a natural system of joints occuring in most coals[*]. Classically the cleat system in coal comprises 2 or more sets of subparallel fractures, both of which are (usually) oriented roughly perpendicular to bedding. One set of fractures, called the "face cleat" is usually dominant, with individual planes being relatively straight and persistant. The "butt cleat" is normally sub-perpendicular to the face cleat, but the fractures are relatively discontinuous, curved, and often terminate against face cleat surfaces.

Several sets of face and butt cleat may be present at any single locality, apparently representing the "overprinting" of more than one structural fabric (Nickelsen and Hough, 1967; Levine and Davis, in press).

The spacing of these fractures can vary from millimeters scale up to 10s of centimeters, and is apparently related to coal rank, bed thickness, and composition. Cleat is barely developed in low rank coals, but becomes progressively better developed through the bituminous rank series. The closest cleat spacings are typically observed in coals around low volatile bituminous rank. The hardness and non-fractured nature of higher rank (semianthracite and anthracite) coals indicate that former cleat surfaces have become resealed, perhaps by cross-linking of the coal molecules. In most anthracites, cleat planes can be discerned, but the coal does not readily break across them.

At any given coal rank, the cleat spacing is primarily a function of composition (McCulloch et al., 1974). Macrae and Lawson (1954) report that in the Yorkshire coal field durain bands thicker than 6 inches had fewer than 5 fractures per foot, while bright coal (vitrain & clarain(?)) had as many as 70 fractures per foot. Likewise, dirty (clay rich) layers in coal seams are obviously less cleated than clean layers. Decker et al. (1989) report that cleat spacing is inversely proportional to ash yield (although the correlation is very poor) in coals from the Cedar Hill field, San Juan Basin.

In the underground environment, cleat may be filled with fluids (gas or water) or mineral fillings. In some beds, mineral fillings in cleat can constitute a large proportion of the total mineral matter (J. Ferm, in Ward, 1984, p. 157).

Coal breaks apart readily on cleat planes, and this property has influenced both the mining and processing of coal. Coal with well developed cleat is more friable and breaks into smaller pieces during handling. Prior to mechanical mining of coal, most mines were laid out parallel to the cleat directions, with the working face, oriented parallel to the face cleat direction.

In coal bed gas reservoirs, cleat spacing and oriention can influence reservoir flow characteristics in a manner to be discussed subsequently.

The origin of cleat is obscure, and there have been remarkably few studies of its origin and occurrence. Where butt cleats terminate against face cleats, as is often the case, one can conclude that the face cleat is the first formed. However, it seems unlikely that all the butt cleat post-date all the face cleat. Face cleat apparently forms parallel to the direction

[*] a "joint" is a fracture across which no appreciable displacement has occurred. This implies that the shear stress across the joint plane was zero when the joint formed, a condition which is satisfied only in the three "principal" stress planes. In fact, joints are interpreted to form perpendicular to the minimum principal axis of compressive stress--parallel to the direction of maximum principal compressive stress. In this manner, joints in rocks (including cleat in coal) have been used as indicators of the trajectories of maximum compression during joint (cleat) formation (e.g. Engelder and Geiser, 1979)

of maximum compressive stress, and may represent a natural hydraulic fracture in the coal. Butt cleat often forms parallel to fold axes and may, in part, be related to strains during folding. Nickelsen and Hough (1967) have suggested that the butt cleats from unloading of overburden during uplift and erosion of the sedimentary pile containing the coal. However, in tectonically folded strata, such as in the Anthracite region, in eastern Pennsylvania, cleat planes are folded along with bedding indicating that they predate the folding and probably formed while the beds were still flat-lying (Nickelsen, 1979).

Literature References on Cleat

Condon, S.M., Joint patterns on the northwest side of the San Juan basin (Southern Ute Indian Reservation), southwest Colorado, in Fassett, J.E., ed., Geology and coal-bed methane resources of the northern San Juan basin, Colorado and New Mexico: Denver, CO, Rocky Mountain Association of Geologists, p. 61-68.

Engelder, T. and Geiser, P., 1980, On the use of regional joint sets as trajectories of paleostress fields during development of the Appalachian Plateau, New York: Journal of Geophysical Research, Section B, v. 85, p. 6319-6341.

Macrae, J.C. and Lawson, W., 1954, The incidence of cleat fracture in some Yorkshire coal seams: Transactions of the Leeds Geol. Assoc., v. 6, p. 224-227.

McCulloch, C.M., Deul, M., and Jeran, P.W., 1974, Cleat in bituminous coalbeds: U.S. Bureau of Mines Report of Investigations 7910, 25 p.

McCulloch, C.M., Lambert, S.W., and White, J.R., 1976, Determining cleat orientation of deeper coalbeds from overlying coals: U.S. Bureau of Mines Report of Investigations 8116, 19 p.

Nickelsen, R.P., 1979, Sequence of structural stages of the Alleghany orogeny at the Bear Valley strip mine, Shamokin, Pennsylvania: American Journal of Science, v. 279, p. 225-271.

Nickelsen, R.P. and Hough, V.D., 1967, Jointing in the Appalachian Plateau of Pennsylvania: Geological Society of America Bulletin, v. 78, p. 609-630.

Ward, W.E., II, Drahovzal, J.A., and Evans, F.A., Jr., 1984, Fracture analysis in a selected area of the Warrior coal basin, Alabama: Geological Survey of Alabama Circular 111, 78 p.
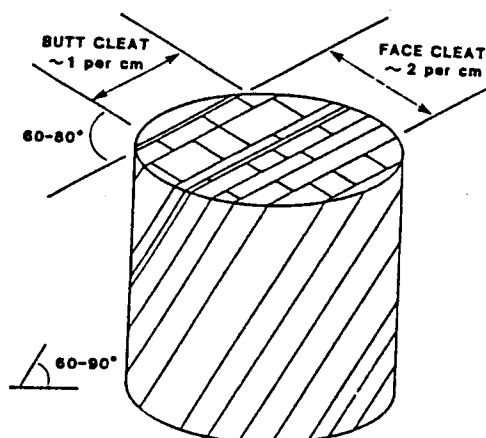
Cleat system determined for coal seam in the Fruitland formation, San Juan Basin.
Source: Jones et al., 1985a

(Nickelsen & Hough, 1967)
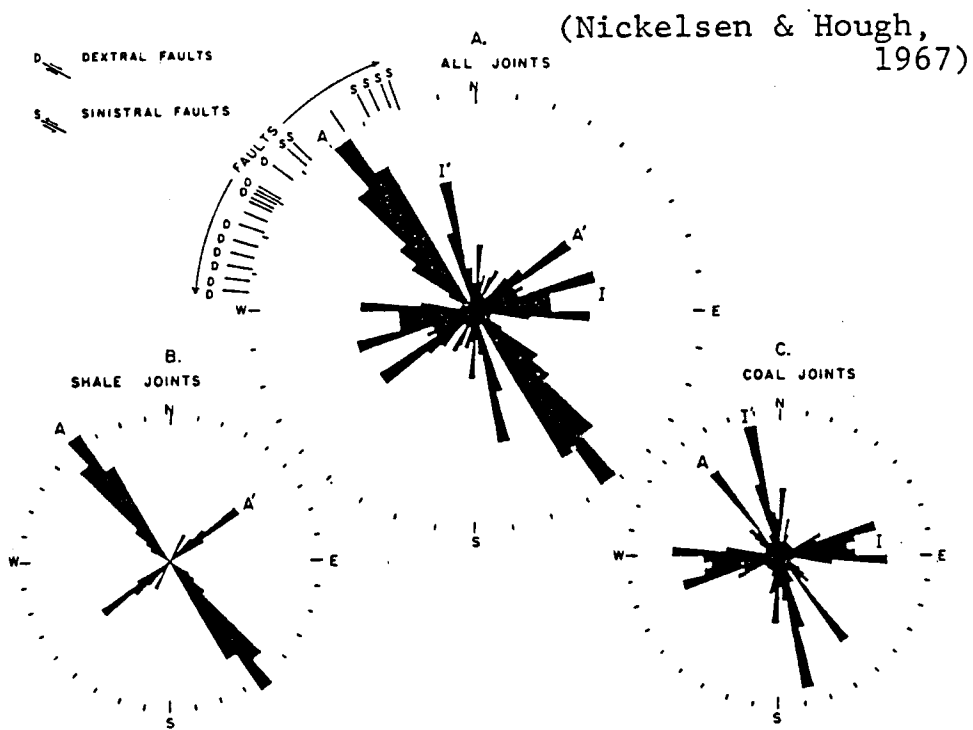
Histograms of Houtzdale quadrangle faults and joints in coal and shale. Redrawn *from* Nickelsen and Williams (1955)

(from Decker et al., 1989)

Face Cleats
Cedar Hill Field, Hamilton #3

LEGEND

/ Systematic shale joints (Sets, A, B, C, D, E)

/ Systematic coal joints (Sets I, II, III, IV)

Anticlinal axial trace

(III) Set III joints of Parker (1942, Pl. IX)

Regional dip from Parker

Systematic and nonsystematic coal joints from Ver Steeg (1944, Fig I)

scale 1 0 1 0 R miles

(Nickelsen & Hough, 1967)
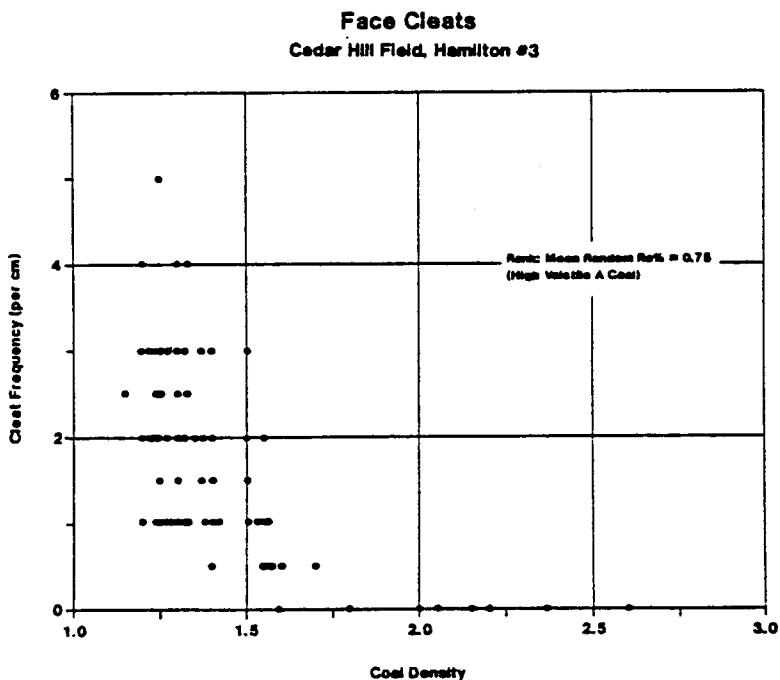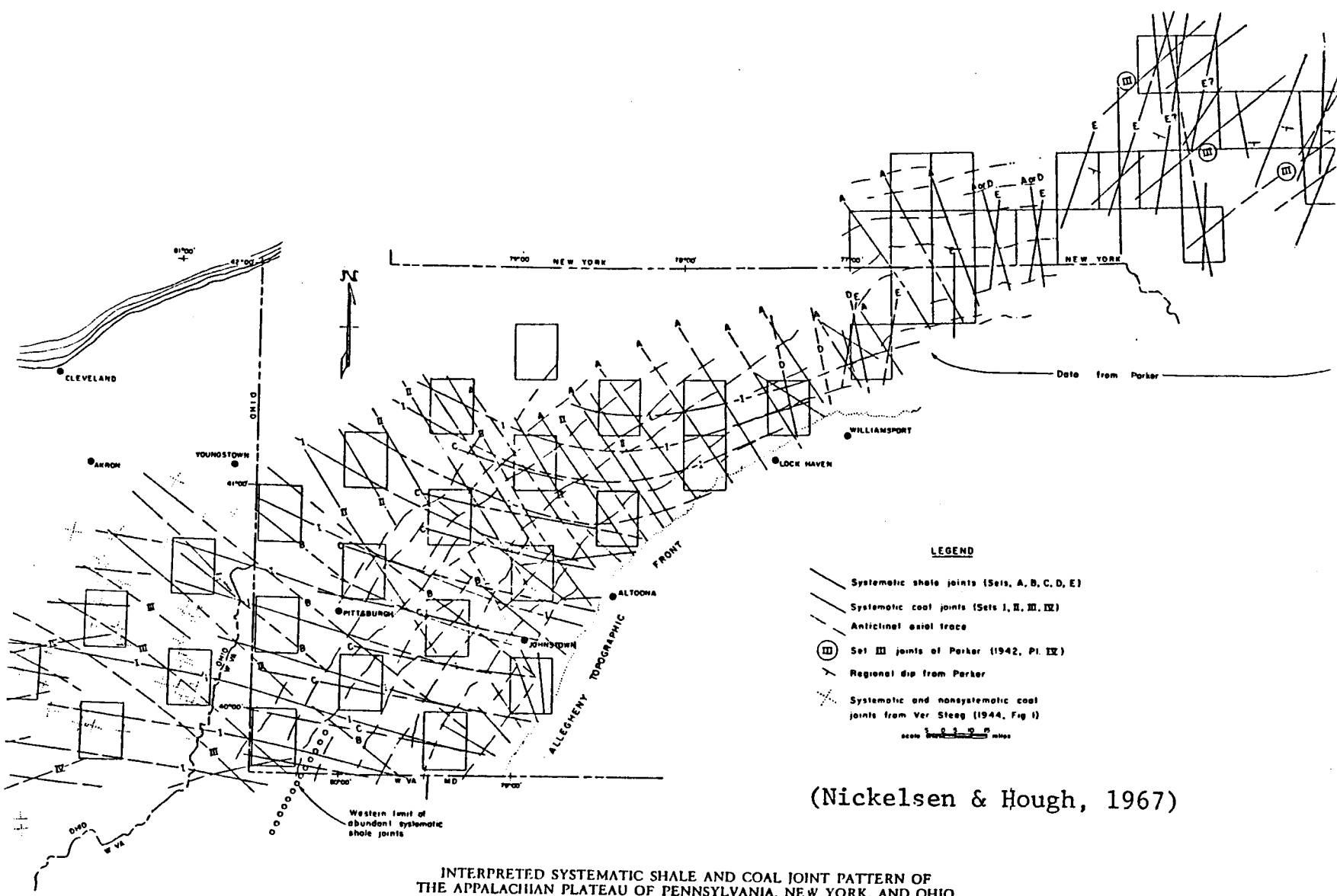
INTERPRETED SYSTEMATIC SHALE AND COAL JOINT PATTERN OF
THE APPALACHIAN PLATEAU OF PENNSYLVANIA, NEW YORK, AND OHIO

Mechanisms of Fluid Transport in Coal Beds

Most coal beds are characterized by high water saturations underground. This is particularly true for coals in the eastern United States. Some western coal basins are known to contain areas where the cleat system is filled with gas rather than water. It is not known whether these coals are also undersaturated with respect to their "inherent moisture" capacity. In any case, water saturated coal beds must first be dewatered before gas flow can commence. Dewatering has two major effects on the reservoir. It reduces the hydrostatic fluid pressure that holds the methane (and other hydrocarbons) in their sorbed state, and it "opens up" the fracture system to allow a more ready flow of gas.

The process of gas transport has been modeled as proceeding in two successive stages: 1) a desorption/activated diffusion step, which is limited by the diffusion rates of gas from the coal matrix into the fracture system, and 2) Darcian flow through the fractures to the well bore. As water is removed from the coal bed by pumping, gas begins to desorb from the coal into the fracture and hence to the well bore.

Koenig and Bell (1985) have modeled the fracture flow through coal as proceeding in three main stages: 1) single phase flow, where only water is produced and the reservoir pressure drop is small, 2) unsaturated single-phase flow where both water and gas are present as distinct phases, but the gas is immobile, and finally 3) two-phase flow, where both gas and water are free to move through the fractures down pressure gradient. The relative permeability of water and gas is dependent on coal composition, fracturing, and degree of water saturation. An example relative permeability curve is reproduced in the diagrams accompanying this section.

Owing to the increasing relative permeability of gas with dewatering, the production rate of coal bed gas wells typically improves with time until the reservoir begins to be depleted. Continuous recharge of the fracture-gas with desorbed gas, however, gives rise to very long production lives for typical coal bed gas wells, with very little pressure drop with time.

In most cases, coal bed gas wells are hydraulically stimulated prior to initial production in an effort to augment the natural permeability of the formation. It is hotly debated, however, how much impact hydraulic stimulation has on ultimate production or the best methods to use. It is clear that a certain minimum level of formation permeability is a necessary precondition for good productivity irrespective of the gas contents or completion method used.

Desorption Kinetics

The rate at which sorbed gases are released from coal is not well understood from the standpoint of coal composition (Malone et al, 1989). A few interrelationships are apparent in a qualitative sense, however. Low rank, blocky coals desorb gas more slowly and tend to retain more of their entrapped gas than do higher rank, more friable coals (McCulloch et al., 1975). The difference is at least partly due to the cleat spacing being closer for the higher rank coals high rank (Bielicki et al., 1972; Banerjee, 1988). Qualitatively, the same relationship would also be expected for high ash coals vs. clean coals or vitrain-rich coals vs. durain-rich coals. In each case, the former would be expected to have a closer-spaced, better developed cleat system.

The process of diffusion of gases through the coal matrix are complex and not well understood. Diffusion appear to be influenced by the pore structure, including pore size distribution, throat diameter, and pore interconnectedness (Olague and Smith, 1989), each of

which is related in part to coal composition and rank. Increasing temperature also increases the rate at which gases diffuse through coal (Hofer et al., 1965)

<div align="center">

Geologic Factors Affecting
Fracture Openness and Relative Permeability

</div>

Fluid permeability through coal relies largely on flow through the pervasive cleat fracture system, augmented by flow through other tectonically induced fractures. The absolute permeability of the cleat system is dependent on the openness of the fractures, which in turn depends upon the effective stress (equal to the total stress minus the hydrostatic stress) and the strength of the coal. Effective stress is partly a function of depth of burial. Not surprisingly, the absolute permeability of coal decreases by several orders of magnitude as overburden depth increases, as shown on the accompanying diagram.

Coal strength is difficult to determine, but varies as a function of coal rank, petrographic composition, and mineral matter content . High mineral coals are comparatively strong, as are coals with a predominance of dull lithotypes. Coal strength also decreases with increasing coal rank through low volatile bituminous, whereupon the strength increases through anthracite rank (see attached diagram from Jones et al.,1988).

Tectonic activity during burial can potentially have a signifcant impact on formation permeability. Tectonic stress probably induces a more closely spaced, better oriented cleat system in the coal. Tectonic fractures other than cleat can also significantly enhance formation permeability, including various classes of faults and shear zones. A considerable amount of effort has been extended to identify fracture zones in the coal seam for the purpose of siting drill holes. Zones of bedding curvature may also be associated with more open, permeable fractures (Decker et al., 1989).
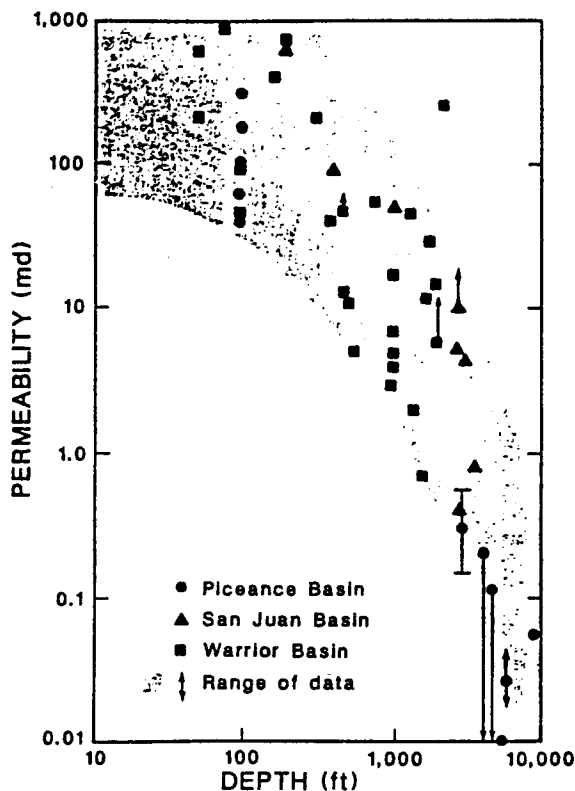
(from McKee et al., 1986)

Summary plot showing permeability vs. depth field for coal seams in the San Juan, Piceance, and Warrior basins.
Source: McKee, Bumb, and bell, 1986
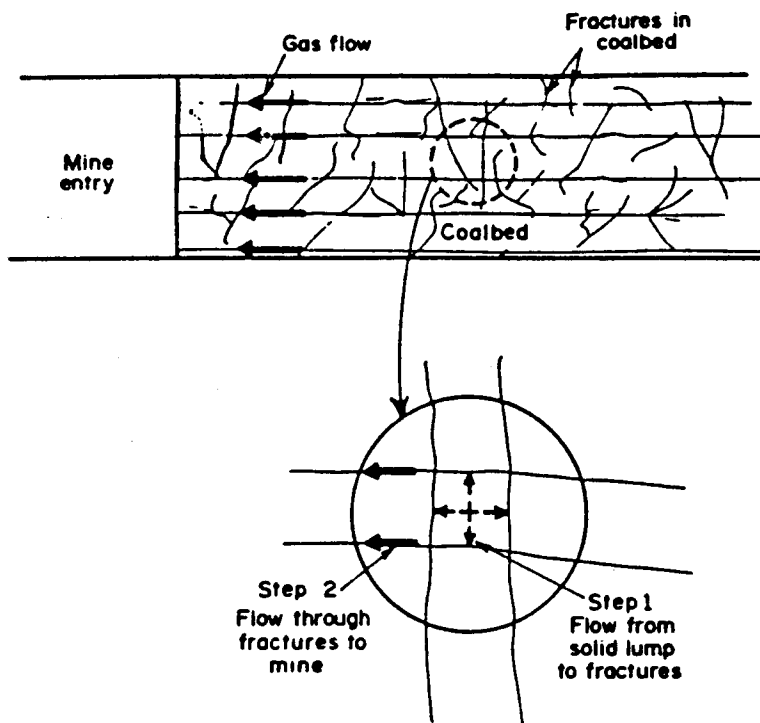
Two-step gas flow from coal.

(Deul and Kim, 1986)

Diagram representing three stages of methane flow in coalbed reservoirs.
Source: Koenig and Bell, 1985

Comparison of unconfined compressive strength with volatile matter content (modified from Pomeroy and Foote, 1960).

(from Jones et al., 1988)

V. SUPPLEMENTARY REFERENCES

Averitt, P., 1975, Coal resources of the United States, January 1, 1974: U.S. Geological Survey Bulletin 1412, 131 p.

Banerjee, B.D., 1988, Spacing of fissuring network and rate of desorption of methane from coals: Fuel, v. 67, p. 1584-1586.
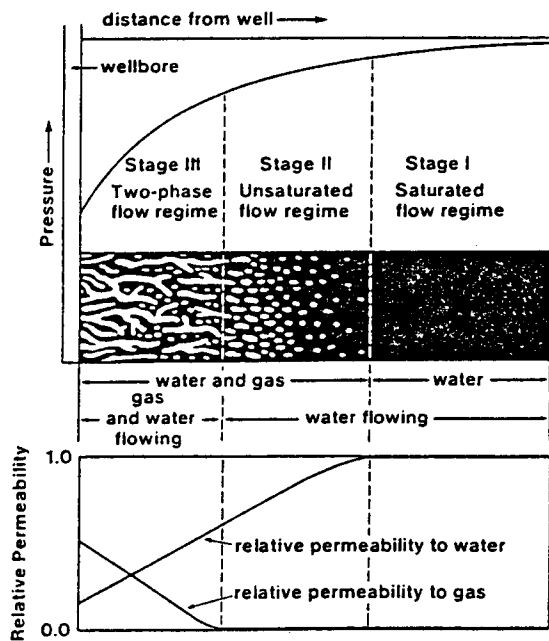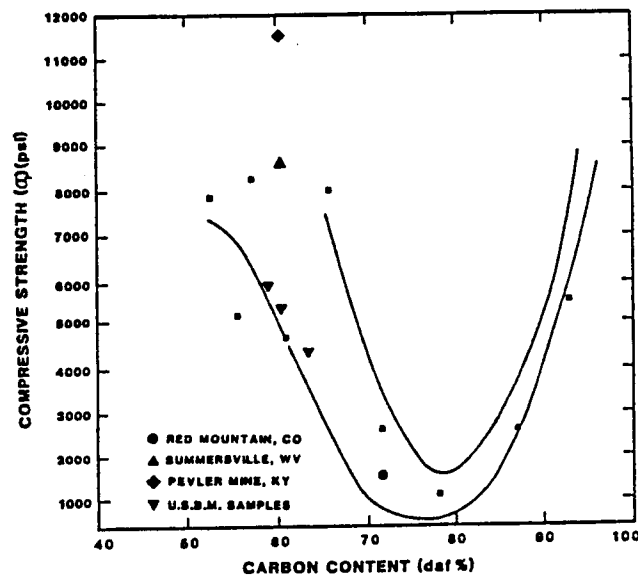
Behar, F. and Vandenbrouke, M., 1987, Chemical modelling of kerogens: Organic Geochemistry, v. 11, p. 15-24.

Bielicki, R.J., Perkins, J.H., and Kissell, F.N., 1972, Methane diffusion parameters for sized coal particles: U.S. Bureau of Mines Report of Investigations 7697, 12 p.

Bokova, E.N., 1959, Formation of heavy hydrocarbons during anaerobic decomposition of organic matter: Geol. Nefti i Gaza, v. 3, p. 44-47.

Cook, A. and Struckmeyer, H., 1986, The role of coal as a source rock for oil, in Glennie, R.C., ed., Second Southeastern Australia Oil Exploration Symposium: Petroleum Exploration Society of Australia, Melbourne, p. 419-432.

Creedy, D.P., 1979, A study of variations in gas content of coal seams in relation to petrographic and stratigraphic variations [MSc Thesis]: Cardiff, U.K., University of Wales, 485 p.

Davis, J.B., and Squires, R.M., 1953, Detection of microbially produced hydrocarbons other than methane: Science, v. 119, p. 381-383.

Decker, A.D., Close, J., and McBane, R.A., 1989, The use of remote sensing, curvature analysis, and coal petrology as indicators of higher coal reservoir permeability: Proceedings of the 1989 Coalbed Methane Symposium, The University of Alabama, Tuscaloosa, AL (April 17-20, 1989), p. 325-340.

Derbyshire, F. et al., 1989, Molecular structure of coal: a debate: Fuel, v. 68, p. 1091-1106.

Deul, M. and Kim, A., 1986, Methane Control Research - Summary of Results 1964-80: U.S. Bureau of Mines Bulletin 687, 174 p.

Ettinger, I.L., 1966, Gasoyemkost' iskopayemykh ugley (Gas Capacity of Coals): Moscow (cited in Zabigaylo et al., 1972)

Given, P.H. and Yarzab, R.F., Analysis of the organic substance of coals: Problems posed by the presence of mineral matter: in Karr, C., Jr., Analytical methods form coal and coal products (Volume II): New York' Academic Press, p. 3-41.

Hofer, L.J.E., Bayer, J., and Anderson, R.B., 1965, Rates of adsorption of methane on Pocohontas and Pittsburgh seam coals: U.S. Bureau of Mines Report of Investigations 6750, 13 p.

Hunt, J.M., 1979, Petroleum Geochemistry and Geology: W.H. Freeman and Co., 617 p.

Jones, A.H, Bell, G.J., and Schraufnagel, R.A., 1988, A review of the physical and mechanical properties of coal with implications for coal-bed methane well completion and production, in Fassett, J.E., ed., Geology and coal-bed methane resources of the northern San Juan basin, Colorado and New Mexico: Denver, CO, Rocky Mountain Association of Geologists, p. 169-181.

Joubert, J.I., Grein, C.T., and Bienstock, D., 1973, Sorption of methane in moist coal: Fuel, v. 52, p. 181-185.

Joubert. J.I., Grein, C.T., and Bienstock, D., 1974, Effect of moisture on the methane capacity of American coals: Fuel, v. 53, p. 186- 191.

Kim, A.G., 1978, Experimental studies on the origin and accumulation of coalbed gas: US BuMines Report of Investigations 8317, 18 p.

Kim, A.G. and Douglas, L.J., 1972, Hydrocarbon gases produced in a simulated swamp environment: U.S. BuMines Report of Investigations 7690, 15 p.

Koenig, R.A. and Bell, G.J., 1985, Design of single phase flow tests for water saturated coalbed methane reservoirs: Quarterly Review of Methane from Coal Seams Technology, v. 3, p. 17-22.

Lambert, S.W., Trevits, M.A., and Steidl, P.F., 1980, Vertical Borehole Design and Completion Practices to Remove Methane Gas from Mineable Coalbeds. Report of Investigations DOE/CMTC/TR-80/2. U.S. Dept. Energy, 163 p.

Levine, J.R., 1987, Influence of coal composition on the generation and retention of coalbed natural gas: Proceedings of the 1987 Coalbed Methane Symposium, Tuscaloosa, Alabama (Nov. 16-19, 1987), p. 15-18.

Levine, J.R. and Davis, A., 1989, The relationship of coal optical fabrics to Alleghanian tectonic deformation in the central Appalachian fold-and-thrust belt, Pennsylvania: Geological Society of America Bulletin, v. 101, p. 1333-1347.

Levine, J.R., Thompson, D.A., Telle, W.R., and Thomas, J.N., 1989, A coalbed methane resource evaluation in southern Tuscaloosa County, Alabama: Research Report 89-1, School of Mines and Energy Development, The University of Alabama, Tuscaloosa, AL, 90 p.

Lin, R., Davis, A., Bensley, D.F., and Derbyshire, F., 1987, The chemistry of vitrinite fluorescence: Organic Geochemistry, v. 11, p. 393-399.

Mahajan, O.P. and Walker, P.L., Jr., 1978, Porosity of coal and coal products: The Pennsylvania State University, Research Report PSU-TR-7, 54 p.

Malone, P.G., Lottman, L.K., Camp, B.S., and Smith, J.L., 1989, An investigation of parameters affecting desorption rates of Warrior Basin coals: Proceedings of the 1989 Coalbed Methane Symposium, The University of Alabama, Tuscaloosa, AL (April 17-20, 1989), p. 35.

McCulloch, C.M., Levine, J.R., Kissell, F.N., and Deul, M., 1975, Measuring the methane content of bituminous coalbeds: U.S. Bureau of Mines Report of Investigations 8043, 22 p.

McFall, K.S., Wicks, D.E., and Kuuskraa, V.A., 1986, A geologic assessment of natural gas from coal seams in the Warrior Basin, Alabama: Topical Report (September, 1985-September, 1986): Chicago, IL, Gas Research Institute, 84 p.

McKee, C.R., Bumb, A.C., and Bell, G.J., 1984, Effects of stress-dependent permeability on methane production frm deep coal seams: SPE/DOE/GRI Paper #12858 (presented at Unconventional Gas Recovery Symposium, Pittsburgh, May, 1984).

Meissner, F.F., 1984, Cretaceous and Tertiary coals as sources for gas accumulations in the Rocky Mountain area, in Hydrocarbon source rocks of the greater Rocky Mountain region: Denver, CO, Rocky Mountain Association of Geologists, p. 401-432.

Olague, N.E. and Smith, D.M., 1989, Diffusion of gases in American coals: Fuel, v. 68, p. 1381-1387.

Robert, P., 1988, Organic metamorphism and geothermal history: Dordrecht, Holland, D. Reidel (English Edition), 311 p.

Ruppel, T.C., Grein, C.T., and Bienstock, D., 1972, Adsorption of methane/ethane mixtures on dry coal at elevated pressure: Fuel, v. 51, p. 297-303

Saxby, J.D. and Shibaoka, M., 1986, Coal and coal macerals as source rocks for oil and gas: Applied Geochemistry, v. 1, p. 25-36.

Saxby, J.D., Bennett, A.J.R., Corcoran, J.F., Lambert, D.E., and Riley, K.W., 1986, Petroleum generation: Simulation over six years of hydrocarbon formation from torbanite and brown coal in a subsiding basin: Organic Geochemistry, v. 9, p. 69-81.

Teichmuller, M., 1986a, Organic petrology of source rocks, history, and state of the art: Organic Geochemistry, v. 10, p. 581-599.

Teichmuller, M., 1986b, Coalification and natural gas deposits in northwestern Germany, in Brooks, J., Goff, J.C. and van Hoorn, B., eds., Habitat of Palaeozoic Gas in N.W. Europe: Geological Society Special Publication 23, p. 101-112.

Thomas, J., Jr., and H.H. Damberger, 1976, Internal surface area, moisture content, and porosity in Illinois coals: variations with coal rank: Illinois State Geological Survey Circular 493, 38 p.

Thompson, D.A., Coalbed methane potential of "J" group coals in the vicinity of Tuscaloosa: School of Mines and Energy Development, The University of Alabama, Research Report, 71 p.

Tissot, B.P., and Welte, D.H., 1984, Petroleum Formation and Occurrence. 2nd Edition, Springer & Verlag, 1984, 699 p.

Ulery, J.P., 1988, Geologic factors influence the gas content of coalbeds in southwestern Pennsylvania: U.S. Bureau of Mines Report of Investigations 9195, 26 p.

Ward, C.R., ed., 1984, Coal geology and coal technology: Oxford, Blackwell Scientific Publications, 345 p.

Welte, D.H., Stoessinger, W., Schaefer, R.G., and Radke, M., 1984, Gas generation and migration in the Deep Basin of Western Canada, in Masters, J.A., ed., Elmworth--a case study of a deep basin gas field: American Association of Petroleum Geologists Memoir 38, p. 35-47.

Zabigaylo, V.E., Shirokov, A.Z., and Shul'man, N.V., 1972, Variation of methane content in coal as a function of thickness of coal beds (Translated by AGI from: Izmeneniye metanoyemkosti ugley po moshchnosti ugol'nykh plastov): Doklady Akakemii Nauk SSSR, v. 206, p. 456-458.

GEOPHYSICAL LOG INTERPRETATION

Georgia L. Hoffman
Consultant

The single greatest difference between geophysical logging practices in the oil industry and in coal mining is the emphasis on thin-bed resolution in coal. Thin beds can be very significant for both coal and oilsands mine operators (a 2cm-thick clay layer dipping toward an open pit can cause a very expensive highwall failure, for example), and they have been demanding the highest possible resolution from logging equipment. The tools are therefore designed to emphasize this, and to operate in smaller-diameter drillholes, but the basic types and principles of the logging tools are the same as in the oil industry. To obtain the best possible resolution, very slow logging speeds are used over the zones of interest (as low as 3m/min), with very high rates of data sampling (as often as once per centimetre).

Since coal drillholes are usually very shallow (almost always less than 500m), there are also differences in drilling conditions and the drillhole environment. If the drillers are careful, hole roughness and caving can be minimized, even within the coal zones. Exotic drilling muds are seldom needed (many holes are drilled with ordinary water), and pump pressures are low so formation damage, mud cake, and invasion are minimal. This can simplify log interpretation, and often eliminates the need for deep-reading tools with poor vertical resolution. The salinity of the drilling fluid and formation water are low, which produces poor SP logs, however. Sonic logs are strongly influenced by the geotechnical weakness of shallow strata, as well as by porosity and lithology, which limits their usefulness for the latter two applications in shallow holes.

The most commonly used logs in the coal industry are caliper, high-resolution density, high-resolution focused resistivity, and natural gamma. Neutron-neutron logs are often used, but neutron "porosity" values are misleading, as will be discussed below. Sonic logs are often used if geotechnical factors are of interest, and SP logs are usually omitted. Dipmeter logs are often useful; they have particularly good vertical resolution and sometimes respond to fractures.

Comparison of geophysical logs with coal core during the coal frenzy of the late 1970s demonstrated a strong relationship between the observed characteristics of a seam (coal lithotypes, rock bands), and high-resolution focused resistivity and density logs. It became a common practice in many companies to use those logs to determine the thicknesses of the coal layers and rock bands, and to identify zones of core loss. A visual description of the coal in terms of its general "degree of brightness" (i.e., percentage of vitrain content) was made on site and plotted as a histogram, and its peaks and valleys could be matched to those of the logs, as shown by the attached example of a coal data

sheet. The geologist would then use that data sheet to plan the core sampling intervals, and when the analytical results were returned by the laboratory they were added to the data sheet, which was retained as the permanent record of that coal intersection. Similar practices may prove useful in CBM evaluation.

In order to make more quantitative use of the logs, it is necessary to give some thought to the nature of a coal seam in situ, how its individual components affect log response, and how they are treated by log interpretation models. In the oil industry, the basic model usually involves a matrix of sand grains, with water, shale, and hydrocarbons (oil or gas) in the pore spaces. In coal the matrix is the hydrocarbon, with water and adsorbed methane in the fine, inherent porosity; water in the fracture porosity; and clays and other ash-forming minerals both in discrete layers and finely disseminated through the hydrocarbon.

In the coal industry, we are interested in determining the ash, moisture and heat content of the coal, and the thicknesses of the coal plies and rock bands. For CBM applications, we are also interested in gas content, which is a function of the inherent porosity of the coal; and in the permeability, which is a function of the fracturing.

One common practice in coal applications is to estimate ash content from the density log, assuming a linear relationship. Where moisture content (in both fracture porosity and inherent porosity) and ash mineralogy are fairly constant, there is a fairly good correlation between bulk density, ash content, and heat content; where they vary the correlation becomes weaker. The natural gamma log can also be used this way but the correlation is much poorer.

More sophisticated models define coal as a combination of three phases: hydrocarbon (pure coal), moisture, and mineral matter. To solve for the three unknowns, three equations are used: two equations based on log response, and one based on the fact that the total of the phases is equal to 100%. In practice this approach seldom provides the degree of accuracy needed for coal applications. This arises in part from the fact that the answers cannot be compared directly with laboratory data. The logs respond to the coal in situ on a volume basis. The laboratory data are determined on a weight basis and do not represent the in situ state. The mineral matter is altered in the ashing process (calcite in situ, for example, becomes CaO in the laboratory ash, and similar changes occur for clays, pyrite and other ash-forming minerals), and some of the moisture and gas is usually lost in the coring and sampling process. Further, the fracture porosity cannot be fully evaluated from core samples; the core and drillhole diameter are too small to provide a representative look at fracture frequency, distribution and volume (this also applies to fracture evaluation with acoustic televiewers and dipmeter tools).

A more fundamental problem is that we are really interested in more than three variables (particularly for CBM applications), and that each type of log responds to a combination of them. To solve for all of the the variables using the few types of logs that are applicable requires a number of assumptions and estimates, and the fact that most of the variables are interrelated can be both a help and a hinderance.

For CBM purposes, the porosity of the coal is of primary importance, and there are two types of porosity. The very small pores within the coal matrix contain the methane and water, and have a very low permeability. The fracture porosity (cleat) contains mainly water, but has a much greater permeability and allows the methane to travel to the well bore when it is released from the fine pores. Unfortunately, the traditional "porosity" logs of the oil industry won't automatically tell you either type of porosity in coal. Neutron porosities assume that all hydrogen within the coal seam represents water, including the hydrogen in the hydrocarbons and clays, and thus it gives impossibly high porosity values in coal seams. The sonic log has better potential, but for shallow holes it is strongly affected by geotechnical weakness which can obscure its response to porosity. Even the density log, which is the most promising, has a number of problems.

The bulk density log responds to a combination of the total content of ash-forming minerals and their individual densities (the ash mineral assemblage can change dramatically over short distances), total water content in both the fracture porosity and the inherent porosity, total gas content, and the coal content and its rank (thermal maturation). The inherent porosity and the rank are related, and since the latter can be determined by vitrinite reflectance (which can be measured from a very small sample of coal cuttings), this should be done to help reduce the number of variables.

The focused resistivity log also deserves serious consideration. Pure coal has a high resistivity which is lowered according to the water and clay content. Further, focused resistivity logs may be capable of differentiating between the coal lithotypes (as can be seen on the attached coal data sheet) and this would be significant for CBM applications.

Since the interpretation of downhole logs for CBM is a fairly new endeavor, the details of the relationships and the constants for the equations (which are site specific) will have to be determined as work progresses. To facilitate this, a broad suite of high-quality, high-resolution logs should be obtained from the beginning of any drilling and testing program. Run all the types of logs that could be applicable, as discussed above. Use slow logging speeds and high data sampling rates over the coal zones. Make sure that all of the parameters that are needed for use with the log data are recorded (drilling fluid density, resistivity, temperature, etc.). The extra time, effort and cost that is required will be justified by the higher quality of the log data.
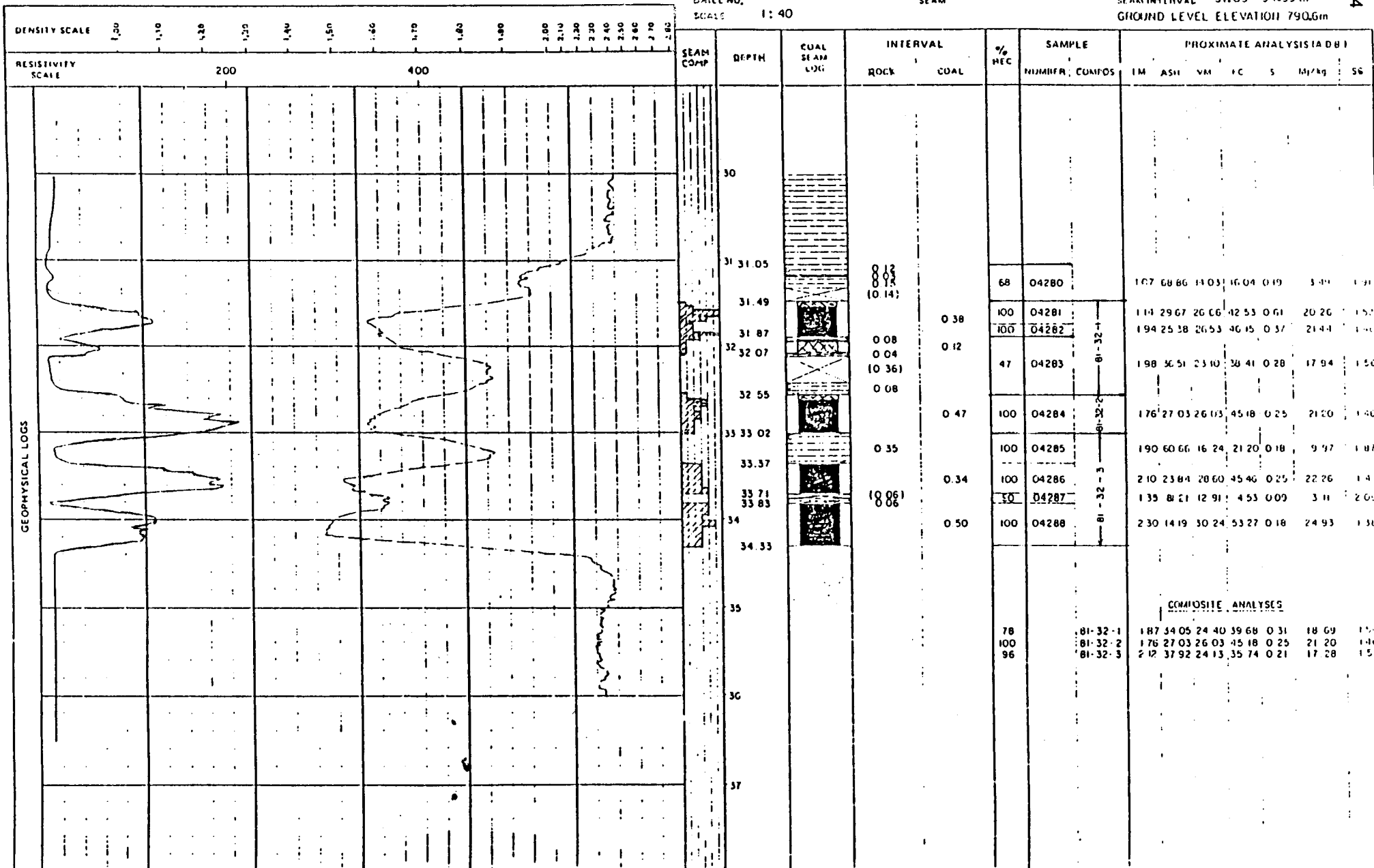
COAL SEAM DATA SHEET

DENSITY —— RESISTIVITY ——

DENSITY SCALE

RESISTIVITY SCALE   200   400

DRILL NO.   SEAM   SEAM INTERVAL 31.05 - 34.33 m
SCALE 1:40   GROUND LEVEL ELEVATION 790.6m

GEOPHYSICAL LOGS

SEAM COMP	DEPTH	COAL SEAM LOG	INTERVAL		% REC	SAMPLE		PROXIMATE ANALYSIS (AD8)						
			ROCK	COAL		NUMBER	COMPOS	IM	ASH	VM	FC	S	MJ/kg	SG
	30													
	31 31.05		0.12 0.15 (0.14)		68	04280		1.67 68.86 14.03 16.04 0.19					3.44	1.91
	31.49			0.38	100	04281	81-32-1	1.14 29.67 26.06 42.53 0.61					20.26	1.52
	31.87				100	04282		1.94 25.38 26.53 46.15 0.57					21.44	1.46
	32 32.07		0.08 0.04 (0.36)	0.12	47	04283		1.98 36.51 23.10 38.41 0.28					17.94	1.56
	32.55		0.08				81-32-2							
				0.47	100	04284		1.76 27.03 26.03 45.18 0.25					21.20	1.46
	33 33.02													
	33.37			0.35	100	04285		1.90 60.66 16.24 21.20 0.18					9.97	1.87
				0.34	100	04286	81-32-3	2.10 23.84 20.60 45.46 0.25					22.26	1.43
	33.71 33.83		(0.06) 0.06		50	04287		1.35 81.21 12.91 4.53 0.09					3.11	2.09
	34			0.50	100	04288		2.30 14.19 30.24 53.27 0.18					24.93	1.38
	34.33													
	35						COMPOSITE ANALYSES							
					78	81-32-1		1.87 34.05 24.40 39.68 0.31					18.69	1.53
					100	81-32-2		1.76 27.03 26.03 45.18 0.25					21.20	1.46
					96	81-32-3		2.12 37.92 24.13 35.74 0.21					17.28	1.57
	36													
	37													

THE ARDLEY COAL ZONE
OF CENTRAL ALBERTA

Thomas D. Demchuk, Department of Geology and Geophysics
The University of Calgary, Calgary, Alberta T2N 1N4

INTRODUCTION

The Ardley coal zone of the central Alberta Plains, stratigraphically occurs within the upper portion of the Scollard Formation, the uppermost formation of the Edmonton Group in the central and south-central Alberta Plains (Fig. 1) (Gibson, 1977). Strata of this coal zone outcrop extensively in the Red Deer River Valley, and these strata extend from Three Hills in the south, to Fox Creek in the north. Correlative coal-bearing strata also outcrop in the central Alberta Foothills (the Coalspur Formation). The majority of Alberta's thermal coal (approximately 80 percent) is derived from the Ardley coal zone, with the Highvale mine at Wabamun accounting for a large percentage of this total (Dawson *et al.*, 1985).

TECTONOSTRATIGRAPHY

Deposition of coal-bearing strata of the Ardley coal zone is associated with the late stages of infilling of the Western Canadian Sedimentary Basin, during the last episodes of the Laramide Orogeny (Fig. 2). The coals of the Ardley were deposited in the Basin during a period of tectonic quiescence in the Cordillera (renewed tectonic activity in the Cordillera is represented by the conglomeratic sandstones of the lower Paskapoo Formation which overlie the Ardley coals) (McLean and Jerzykiewicz, 1978). Major fluvial channels were few, as indicated by the relatively minor number of

channel sandstones dissecting Ardley coals. These coals have wide geographic extent, thus major channels likely were not prevelant and the basin environments were conducive for thick coal accumulation. Further, the majority of fluvial activity may have been confined to a narrow geographic area which paralleled the rising Cordillera. This area may have acted as a "sediment trap", diverting clastic material to the south, allowing Ardley coals to form distal (to the east) of any major fluvial activity (Richardson *et al.*, 1988).

During Ardley time, there is no indication of marine influence. The last transgression northwards from the Gulf of Mexico, extended as far as North Dakota and Wyoming. A lack of marine influence may also be deduced from the fact that Ardley coals display extremely low sulfur contents.

STRATIGRAPHY AND NOMENCLATURE

The Ardley coals in the Alberta Plains are lower Paleocene in age (Demchuk, 1990). The lowermost of the Ardley coals is usually associated with the Cretaceous-Tertiary boundary, as defined paleontologically and geochemically (Lerbekmo *et al.*, 1987) (Fig. 3).

The Ardley coal zone occurs within the upper portion of the Scollard Formation. The Scollard is underlain by the Battle Formation (Fig. 1) a most distinctive stratigraphic marker in the central Plains (Irish and Havard, 1968). In outcrop, the Battle Formation weathers a characteristic purple-grey color, a sharp contrast to the underlying white sandstones of the Whitemud Formation (upper Horseshoe Canyon Formation) and the olive-green siltstones and sandstones of the overlying Scollard. In the subsurface, the Battle Formation is

distinguished as an unusually low resistivity "kick" on geophysical logs, again in contrast to the higher resistivity characteristics of the sandstones of the underlying Whitemud Formation.

The Ardley coal zone (and hence Scollard Formation) is overlain disconformably (?) by the conglomeratic sandstones of the lowermost Paskapoo Formation (Fig. 1). In outcrop, these thick Paskapoo sandstones weather a distinctive yellow, and are prominent cliff-formers along the walls of the Red Deer River Valley, compared to the easily erodable shales of the underlying Scollard.

In the past, various names have been used in describing the coal seams of the Ardley. However, none have met with much success. This is due to the fact that over any appreciable distance, it becomes exceedingly difficult to correlate individual Ardley coal seams (Richardson et al., 1988). This is especially true in the subsurface where the rapid lateral and vertical facies changes characteristic of the Scollard Formation, are compounded by problems of well-spacing. In contrast, the coal zone as a whole, is readily identifiable in the subsurface and can be correlated with a high degree of accuracy through to the Foothills. Close to the outcrop edge however, the coal zone is usually hidden behind surface casing.

In the Red Deer River Valley, two prominent seams have been informally referred to as the No. 13 Nevis seam (stratigraphically lower) and the No. 14 Ardley seam (stratigraphically higher) (Fig. 3) (Allan and Sanderson, 1945). At certain localities along the river valley (eg. at Ardley Bend) the No. 14 seam may reach thicknesses of two to three meters and thus, this seam has been mined extensively

in the river valley. Overlying the No. 14 seam occur a number of thinner coal seams which collectively, are informally referred to as the upper Ardley coal zone (Gibson, 1977) (Fig. 3). In the Red Deer River Valley, the entire Ardley coal zone attains a thickness of approximately 30 to 35 m.

To the north and west at Wabamun (Fig. 4), the Ardley coal zone thins stratigraphically, but the coals become thicker. Six seams are limited to a stratigraphic interval of approximately 15 m (Fig. 5). At this locality, it is the upper coal seams which are economic to mine, individually reaching three to four meters in thickness (upper Ardley coal zone stratigraphic equivalent) and the lower seams which are relatively thinner (No. 13 and 14 stratigraphic equivalent). All six seams are mined at the Highvale and Whitewood mines.

Towards the Foothills into the subsurface, the stratigraphic package containing of the Ardley coal zone thickens dramatically. This is accompanied by an increase in the actual number of coal seams, as well as an increase in cumulative coal thickness (Richardson *et al.*, 1988).

DEPOSITIONAL ENVIRONMENTS AND PALEOECOLOGY

The coals of the Ardley coal zone were deposited on a broad alluvial plain which extended eastwards from the rising Cordillera. This alluvial plain was dissected by few major fluvial channels. Deposition of clastics was minimal owing to the lateral extent of the coal zone, and the thicknesses that some coal seams may attain.

Paleoecologically, the coal mires (swamps) that formed the Ardley coals were dominated by Cypress vegetation (Demchuk and

Strobl, 1989). This means that the Ardley coal swamps may have been similar to the present-day Okefenokee Swamp and northern Everglades of the southeastern United States. Localized abundances of Pine pollen, fern spores and the spores of *Sphagnum* moss within certain coals at Highvale indicate that at times during their existence (especially the latter stages of succession within individual coal seams) Ardley mires dried out and the water table was relatively low. This is confirmed by coal petrographic studies in which anomalous abundances of oxidized plant remains (inertinite maceral) are present. Combined palynology and petrography provide evidence for a <u>relative</u> raising of the mire surface above the influence of the water table. Although not necessary for the formation of thick clean coal, this scenario of a relative raised mire surface is only one model which may be used to explain the Ardley coals at Highvale. Further paleoecologic details are covered by Demchuk and Strobl (1989).

REFERENCES CITED

Allan, J.A. and Sanderson, J.O.G. 1945 Geology of the Red Deer and Rosebud map-sheets: Alberta Research Council Report No. 13, 109p.

Dawson, F.M., McCandlish, K., Godfrey, T., Nikols, D. and Fenton, M. 1985 The Ardley Coal Zone: Canadian Society of Petroleum Geologists Coal Division Fieldtrip No. 1.

Demchuk T.D. 1990 (in press) Palynostratigraphic zonation of the Paleocene strata in the central and south-central Alberta Plains: Canadian Journal of Earth Sciences.

Demchuk, T.D. and Strobl, R.S. 1989 Coal facies and in-seam profiling, Highvale No. 2 seam, Highvale, Alberta *in* Proceedings, Western Canadian Coal Geoscience Forum *compiled*

by W. Langenberg. Alberta Research Council Information Series No. 103, pp. 201-211.

Gibson, D.W.   1977   Upper Cretaceous and Tertiary coal-bearing strata in the Drumheller-Ardley region, Red Deer River Valley, Alberta: Geological Survey of Canada Paper 76-35, 41p.

Horacek, Y. 1986   Geology of Alberta Coal *in* Coal in Canada *edited by* T.H. Patching: Canadian Institute of Mining and Metallurgy Special Volume 31, pp. 115-133.

Irish E.J.W. and Havard, C.J.   1968   The Whitemud and Battle formations (Kneehills Tuff Zone), a stratigraphic marker: Geological Survey of Canada Paper 67-63, 51p.

Lerbekmo, J.F., Sweet, A.R. and St. Louis, R.M.   1987   The relationship between the iridium anomaly and palynological floral events at three Cretaceous-Tertiary localities in western Canada: Geological Society of America Bulletin, v. 99, pp.

McLean J.R. and Jerzykiewicz, T.   1978   Cyclicity, tectonics and coal: some aspects of fluvial sedimentology in the Brazeau-Paskapoo formations, Coal Valley area, Alberta, Canada *in* Fluvial Sedimentology *edited by* A.D. Miall.   Canadian Society of Petroleum Geologists Memoir 5, pp. 441-468.

Richardson, R.J.H., Strobl, R.S., MacDonald, D.E., Nurkowski, J.R., McCabe, P.J. and Bosman, A.   1988   An evaluation of the coal resources of the Ardley coal zone to a depth of 400 m in the Alberta Plains area, Volume I: Alberta Research Council Open File Report 1988-02, 96p.

Taylor, J.   1986   Highvale Mine *in* Coal in Canada *editedy by* T.H. Patching: Canadian Institute of Mining and Metallurgy Special Volume 31, pp. 164-167.
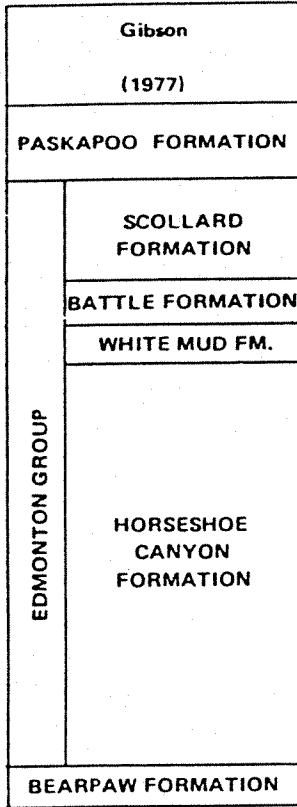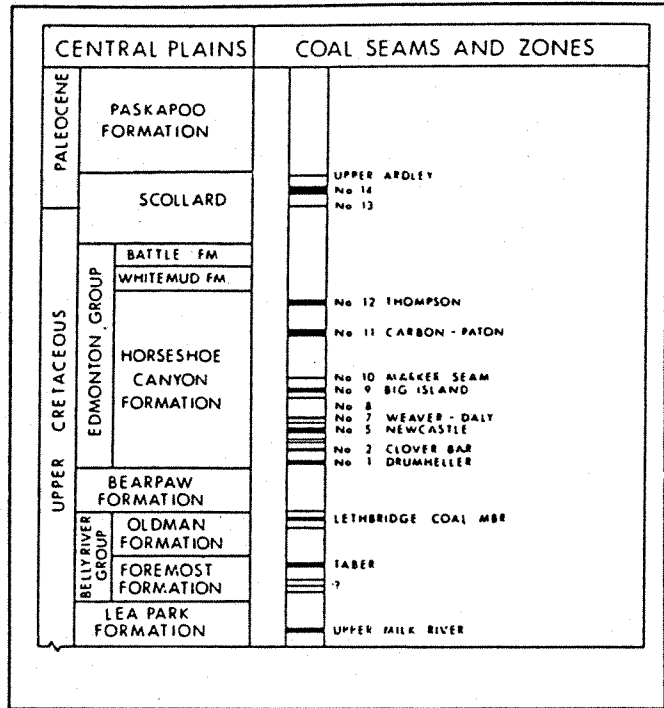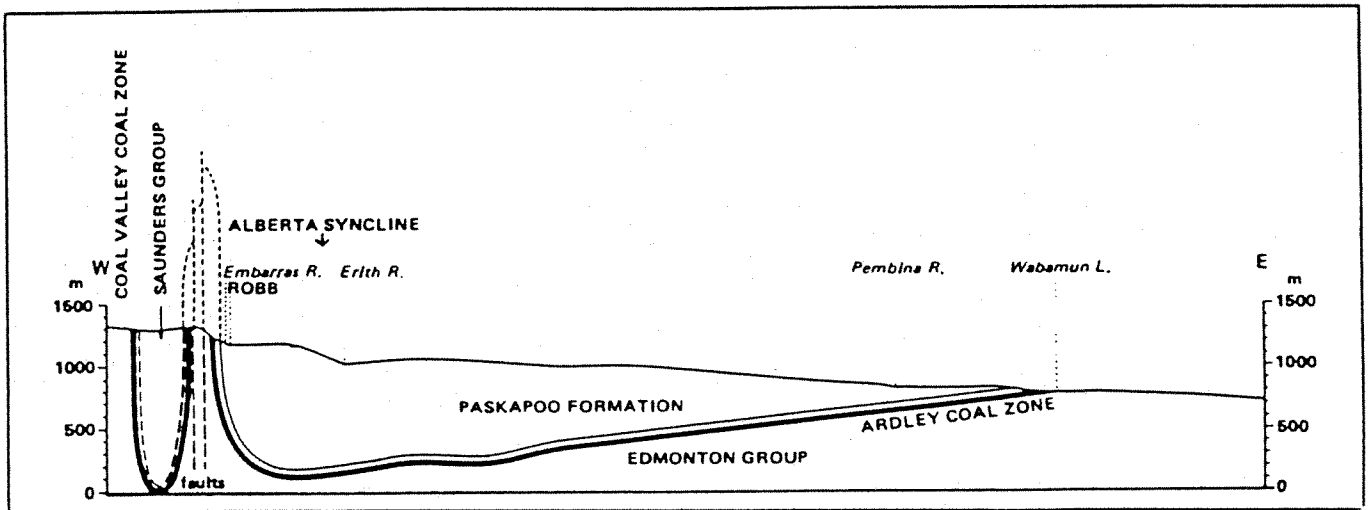
Figure 1

	Gibson (1977)
	PASKAPOO FORMATION
EDMONTON GROUP	SCOLLARD FORMATION
	BATTLE FORMATION
	WHITE MUD FM.
	HORSESHOE CANYON FORMATION
	BEARPAW FORMATION

Figure 1.

Figure 3

	CENTRAL PLAINS		COAL SEAMS AND ZONES
PALEOCENE	PASKAPOO FORMATION		
UPPER CRETACEOUS	SCOLLARD		UPPER ARDLEY No 14 No 13
	EDMONTON GROUP	BATTLE FM	
		WHITEMUD FM	
		HORSESHOE CANYON FORMATION	No 12 THOMPSON No 11 CARBON - PATON No 10 MARKER SEAM No 9 BIG ISLAND No 8 No 7 WEAVER - DALY No 5 NEWCASTLE No 2 CLOVER BAR No 1 DRUMHELLER
		BEARPAW FORMATION	
	BELLYRIVER GROUP	OLDMAN FORMATION	LETHBRIDGE COAL MBR
		FOREMOST FORMATION	TABER ?
	LEA PARK FORMATION		UPPER MILK RIVER

Figure 3. From Horacek, 1986.

Figure 2. From Horacek, 1986.
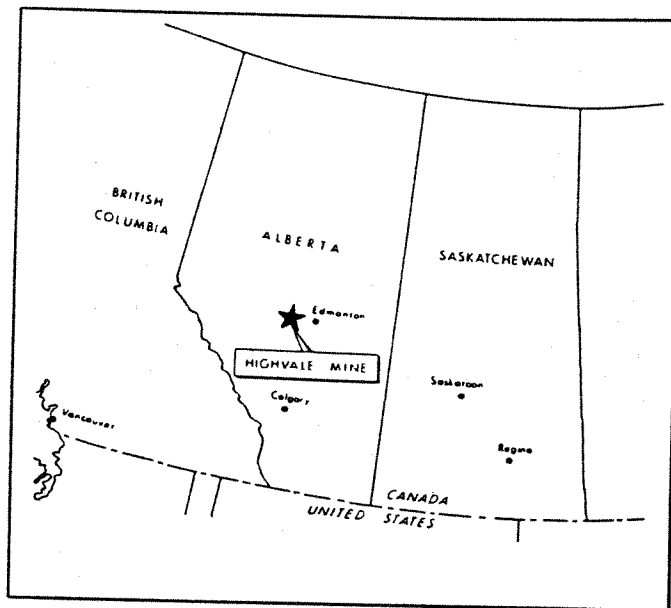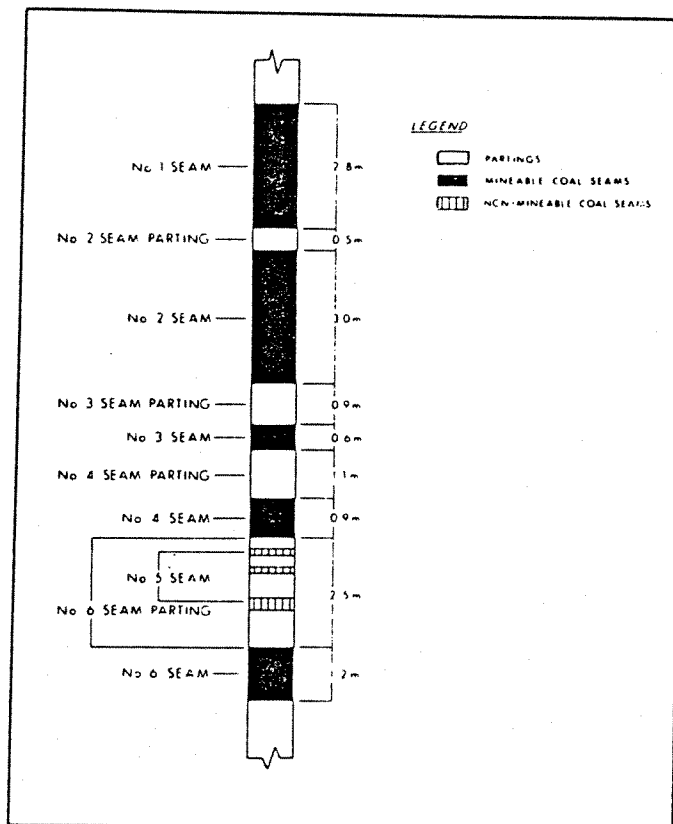
Figure 4. From Taylor, 1986.

Figure 5. From Taylor, 1986.

Stratigraphy and sedimentary environment of the Coalspur Formation

Tomasz Jerzykiewicz
Geological Survey of Canada, Calgary

The Coalspur Formation is a continental succession of interbedded mudstone, siltsone and fine grained sandstone with subordinate coarser grained sandstone layers and channel lag deposits. Chert-pebble conglomerate (the Entrance conglomerate)
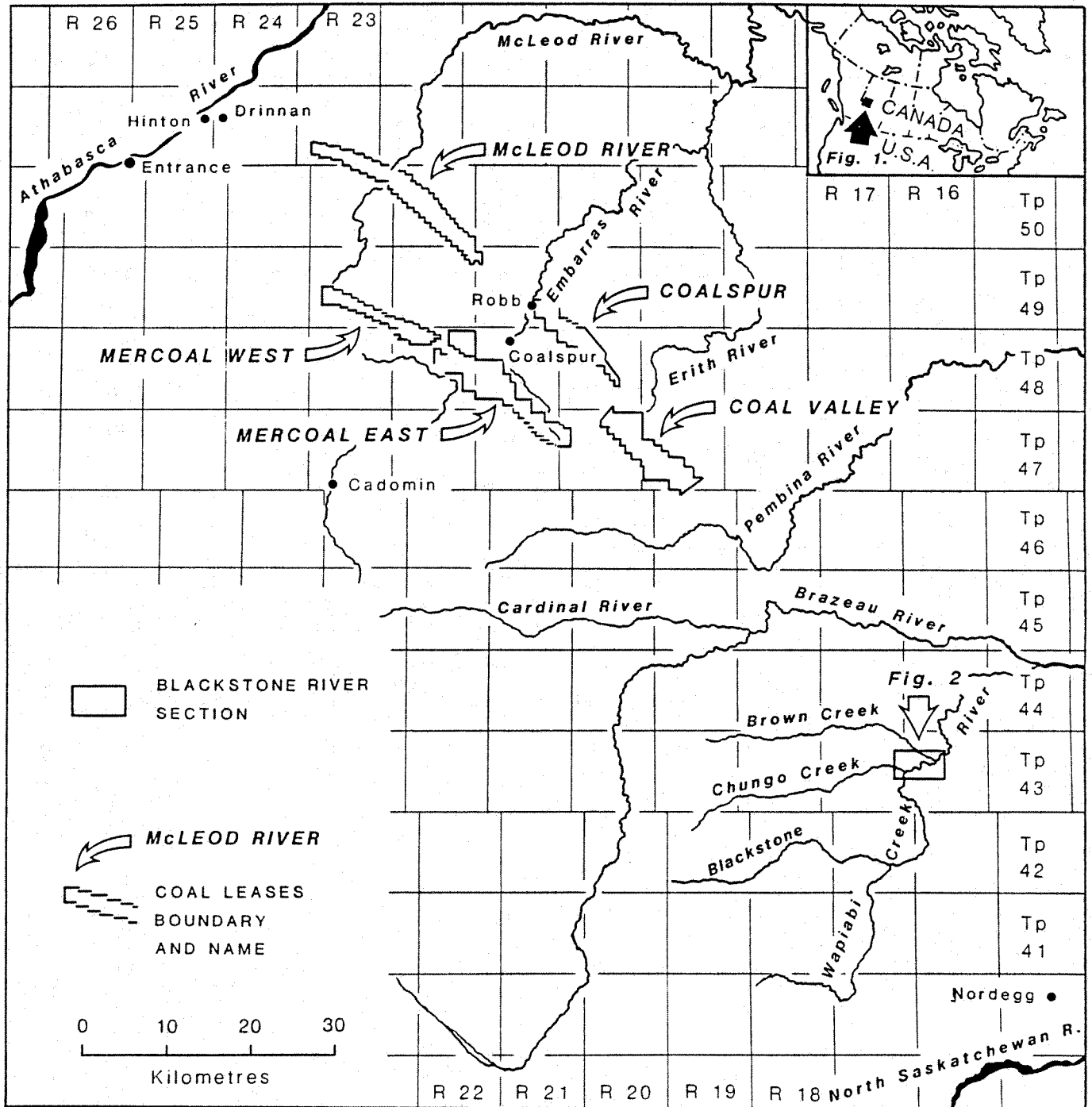

Figure 1. Location map.

occurs at the base of the formation, and coal beds interbedded with coaly shale and numerous thin bentonites occur in the upper part of the formation.

An economically significant amount of high-quality thermal coal occurs within the upper, Paleocene part of the formation named the Coalspur coal zone. Coal from this zone, also known as the Coal Valley coal zone (Energy Resources Conservation Board, Reserves of Coal, unpublished report, 1983) is being exploited in the Coal Valley Mine (Fig. 1).

The Coalspur coal zone has been described from numerous drillholes, test pits and other surface sections in the area between Hinton and Coal Valley (McAndrew, 1931; Jerzykiewicz and McLean, 1980; Manalta Coal Ltd., Mercoal and McLeod Projects, unpublished report, 1981; Denthrem Resources Ltd., Coalspur Project, unpublished report, 1982; Jerzykiewicz and Langenberg, 1983; Engler, 1986).
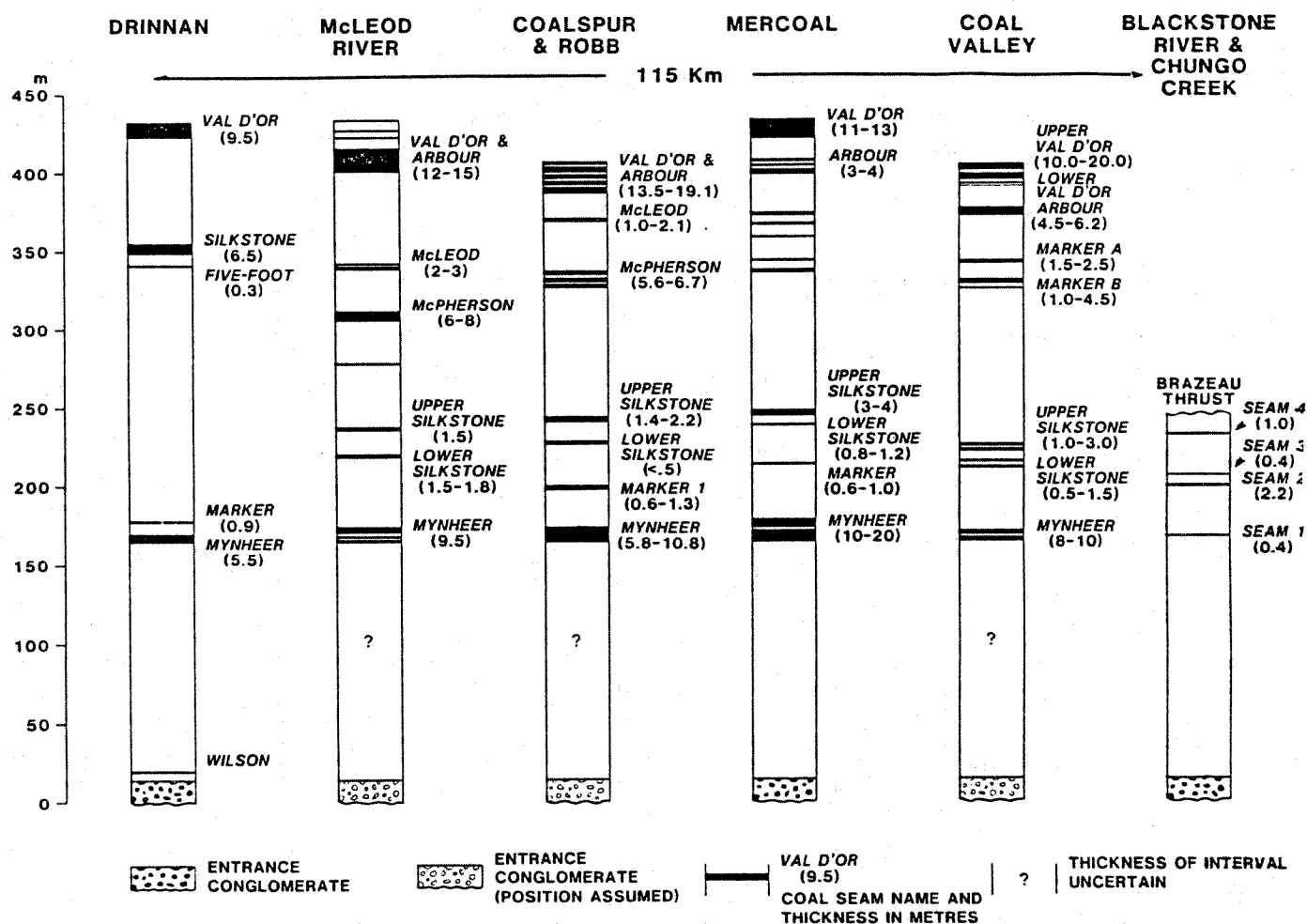

Figure 2. Nomenclature and correlation of coal seams within the Coalspur coal zone between Athabasca and Blackstone rivers.

Figure 2 shows the position of the coal beds within the Coalspur coal zone. Despite some local variation and change in coal seam nomenclature, the uppermost Val d'Or and the lowermost Mynheer coal seams are recognizable in the whole area between Hinton and Coal Valley over a distance of about 70 km.

Although the Coalspur coal zone is nowhere exposed in its entirety, superpositional relationships between the major coal seams can be compiled from subsurface borehole data (Jerzykiewicz, 1985; Engler, 1986; Figs 2 and 3A). The upper part of the Coalspur coal zone from the McPherson through Arbour and Val d'Or coal seams up to the contact with the overlying Paskapoo Formation is well exposed at Coalspur (Fig. 3, B and C). The lower part of the Coalspur coal zone from the Silkstone coal down to the Mynheer seam, and the remaining part of the Coalspur Formation down to its lower boundary at the base of the Entrance conglomerate is just fragmentary, exposed in numerous outcrops between Athabasca River and North Sasaktchewan River and in one almost continuous section along Blackstone River and Chungo Creek (Jerzykiewicz, 1985; Fig. 1).

The Coalspur Formation (previously named the Coalspur beds by Mackay, 1949) was formalized on the basis of the above mentioned surface sections in Coalspur and along Blackstone River – Chungo Creek supplemented with the continuous subsurface section of the Coalspur coal zone from the Denthrem Resources Ltd., drillhole CRD 8137 (Jerzykiewicz, 1985; Fig. 3). The Coalspur Formation has well defined boundaries. The lower one is drawn at the base of the Entrance conglomerate, and the upper one is set at the base of the lowest prominent sandstone layer above the highest thick coal seam (Val d'Or) of the Coalspur coal zone. The formation is recognized as being about 450 m thick from the vicinity of Hinton southeast to the Nordegg area.

The lower part of the Coalspur coal zone containing the Mynheer coal seam was the subject of a detailed stratigraphic and palynological study (Jerzykiewicz and Sweet, 1986; Sweet, 1986) to determine the Cretaceous-Tertiary boundary. Using palynological evidence, the Cretaceous-Tertiary boundary was found for the first time in the Western Canada Sedimentary Basin in two cored boreholes drilled by Luscar Sterco (1977) Ltd. for the Geological Survey of Canada over Pit #42-2 in the Coal Valley mine site (Jerzykiewicz and Sweet, 1986). Analysis of the boundary claystone lamina for iridium from these boreholes showed an anomaly reaching a maximum of approximately 6 ppb (Jerzykiewicz et al., 1984).

Subsequent definition of the Cretaceous-Tertaiary boundary in several other localities in the Foothills and Plains allowed for the precise stratigraphic correlation of the Coalspur Formation with other formations within the Alberta Foreland Basin (Fig. 4; Jerzykiewicz and Sweet, 1988).
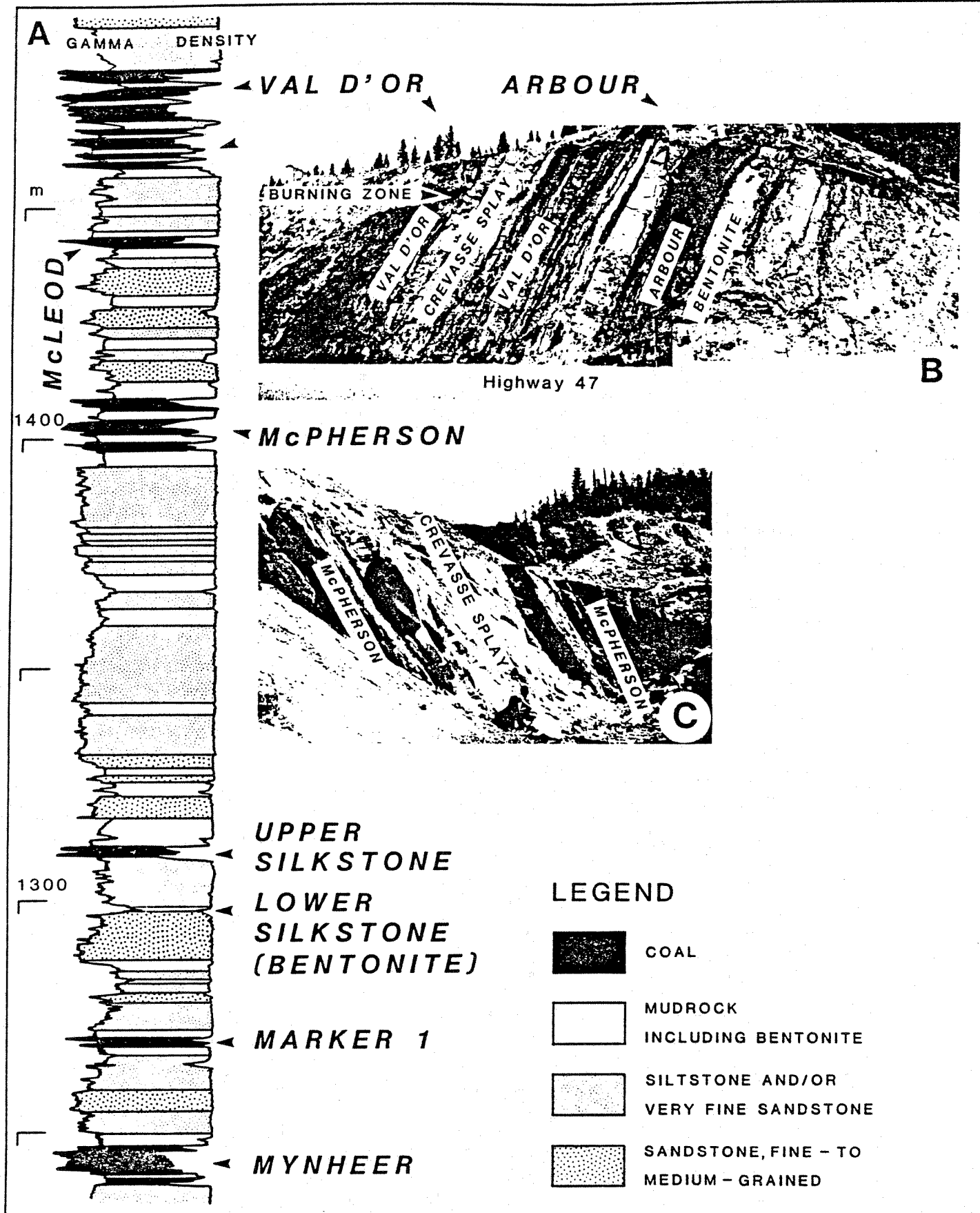
146

Figure 3. Coal seams of the Coalspur coal zone in the vicinity of
Coalspur. A. Dentherm Resources Ltd., drillhole CRD 8137; B. Road
cut section in Coalspur; C. Abandoned open pit on hill about 800
m southeast of Highway 47 in Coalspur.

AGE	CENTRAL FOOTHILLS				SOUTHERN FOOTHILLS	CENTRAL PLAINS	NORTHWEST-CENTRAL PLAINS
	Allan and Rutherford, 1923	Douglas, 1958	Jerzykiewicz, 1985 CYCLOTHEMS FORMATIONS		Carrigy, 1971	Gibson, 1977 McLean, 1971	Kramers and Mellon, 1972
TERTIARY	SAUNDERS GROUP — UPPER SAUNDERS	PASKAPOO FM — UPPER	High Divide Ridge congl PASKAPOO FM	VI a	PORCUPINE HILLS FM	PASKAPOO	"PASKAPOO" FM
	COAL-BEARING SAUNDERS	LOWER	VAL D'OR — COALSPUR — MYNHEER — FM Entrance congl.	b / V / a	WILLOW CREEK FM	EDMONTON GROUP — ARDLEY — SCOLLARD — NEVIS — FM	WAPITI GROUP — ARDLEY "ZONE"
CRETACEOUS	LOWER SAUNDERS	BRAZEAU FM — UPPER	BRAZEAU FM	IV b/a	KNEEHILLS TUFF	BATTLE FM / WHITEMUD FM	UPPER KNEEHILLS TUFF
		MIDDLE		III b/a	ST. MARY RIVER FM	HORSESHOE CANYON FM	MIDDLE
				II a			
				b	BEARPAW FM		
		LOWER		I a	BELLY RIVER FM	JUDITH RIVER FM	LOWER
	WAPIABI FORMATION					LEA PARK FM	SMOKY GROUP

Figure 4. Lithostratigraphic correlation chart.

Sedimentological features of the Coalspur Formation suggest a nonmarine, fluvially dominated environment of deposition. The fluvial channels were part of a large longitutidal drainage system composed of meandering rivers and extensive floodplains (Jerzykiewicz, 1989, fig. 1, IV). The rivers emptied into large inland lakes. Coal-forming swamps developed in the floodplains of the rivers (abandoned channels and backswamps behind levees of active channels) and in the delta plains of the large inland lakes.

References

Allan, J.A. and Rutherford, R.L.
1923: Saunders Creek and Nordegg coal basins, Alberta, Canada; Scientific and Industrial Research Council of Alberta, Geology Division Report 6.

Carrigy, M.A.
1971: Lithostratigraphy of the uppermost Cretaceous (Lance) and Paleocene strata of the Alberta Plains; Research Council of Alberta, Bulletin 27, 161 p.

Douglas, R.J.W.
1958: Chungo Creek map-area, Alberta (83 C/9); Geological Survey of Canada, Paper 58-3.

Engler, R.F.
1986: The Coalspur Beds: regional variations and correlations; CIM Bulletin, 61-66.

Gibson. D.W.
   1977: Upper Cretaceous and Tertiary coal-bearing strata in the Drumheller-Ardley region, Red Deer River Valley, Alberta; Geological Survey of Canada, Paper 76-35.

Jerzykiewicz, T.
   1985: Stratigraphy of the Saunders Group in the central Alberta Foothills - a progress report; Geological Survey of Canada, Paper 85-1B, p. 247-258.

   1989: Synopsis: "Controls on the distribution of coal in the Campanian to Paleocene post-Wapiabi strata of the Rocky Mountain Foothills (Canada)"; Geological Survey of Canada Paper 89-8, p. 41-42.

Jerzykiewicz, T. and Langenberg, W.
   1983: Structure, stratigraphy and sedimentary facies of the Paleocene and Lower Cretaceous coal-bearing strata in the Coalspur and Grande Cache areas, Alberta; The Canadian Society of Petroleum Geologists Conference, The Mosozoic of Middle North America, Field Trip Guidebook No. 9, 63 p.

Jerzykiewicz, T. and McLean, J.R.
   1980: Lithostratigraphical and sedimentological framework of coal-bearing Upper Cretaceous and Lower Tertiary strata, Coal Valley area, central Alberta Foothills; Geological Survey of Canada, Paper 79-12, 47 p.

Jerzykiewicz, T., Lerbekmo, J.F. and Sweet, A.R.
   1984: The Cretaceous-Tertiary boundary, central Alberta Foothills; 1984 Canadian Paleontology and Biostratigraphy Seminar, Programme with Abstracts, p. 4.

Jerzykiewicz, T. and Sweet, A.R.
   1986: The Cretaceous-Tertiary boundary in the central Alberta Foothills. I: Stratigraphy; Canadian Journal of Earth Sciences, 23, p. 1356-1374.

   1988: Sedimentological and palynological evidence of regional climatic changes in the Campanian to Paleocene sediments of the Rocky Mountain Foothills, Canada; Sedimentary Geology, 59, p. 29-76.

Kramers, J.W. and Mellon, G.B.
   1972: Upper Cretceous-Paleocene coal-bearing strata, northwest-central Alberta Plains; in Proceedings of the First Geological Conference on Western Canadian Coal, ed. G.B. Mellon, J.W. Kramers and E.J. Seagel; Research Council of Alberta, Information Series 60, p. 109-124.

MacKay, B.R.
   1949: Coal areas of Alberta; Geological Survey of Canada Atlas, to accompany estimate of coal reserves prepared for the Royal Commission on Coal, 1949.

McAndrew, R.T.
    1931: Coal Mining at Drinnan, Alberta; The Canadian Mining and
    Metallurgical Bulletin N. 236, p. 1375-1395.

McLean, J.R.
    1971: Stratigraphy of the Upper Cretaceous Judith River
    Formation in the Canadian Great Plains; Saskatchewan Research
    Council, Geology Division Report 11, 96 p.

Sweet, A.R.
    1986: The Cretaceous-Tertiary boundary in the central Alberta
    Foothills. II: Miospore and pollen taxonomy. Canadian Journal
    of Earth Sciences, 23, 1375-1388.

THE COAL-BEARING LUSCAR GROUP OF WESTERN ALBERTA

Willem Langenberg
Alberta Research Council

The outcrop area of the Luscar Group in Alberta is shown in figure 1. The largely Albian Luscar Group consists of the Cadomin, Gladstone, Moosebar and Gates formations (Langenberg and McMechan, 1985). This group, which is equivalent to the Mannville Group of central Alberta (figure 2), shows both marine and non-marine sedimentary environments. In the Deep Basin (north of the Cadomin area), as many as eight marine cycles of marine sedimentation have been recognized in correlative strata of the Spirit River Formation (Cant, 1983; Smith et al; 1984). These include the Wilrich A and B cycles, the Falher A through G cycles and the Notikewin (figure 3). In the Cadomin area, the Gates Formation is mostly nonmarine and it is not possible to recognize all of the Falher Member cycles.
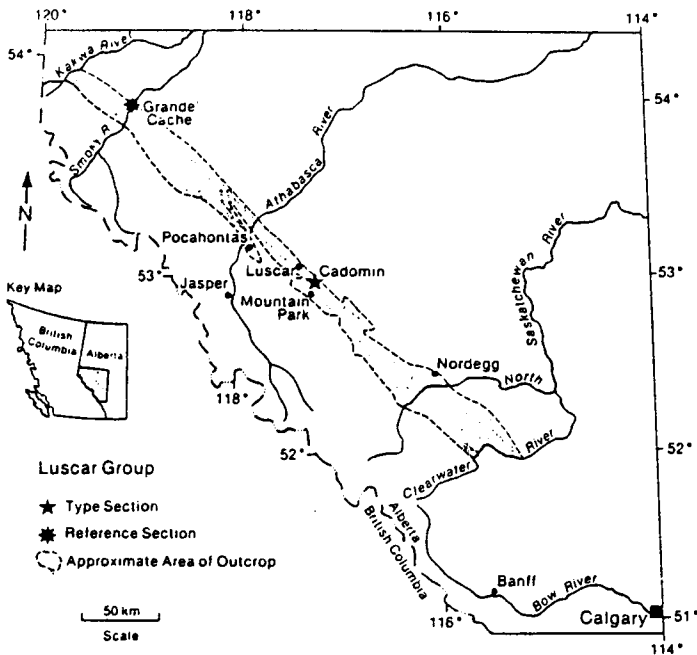

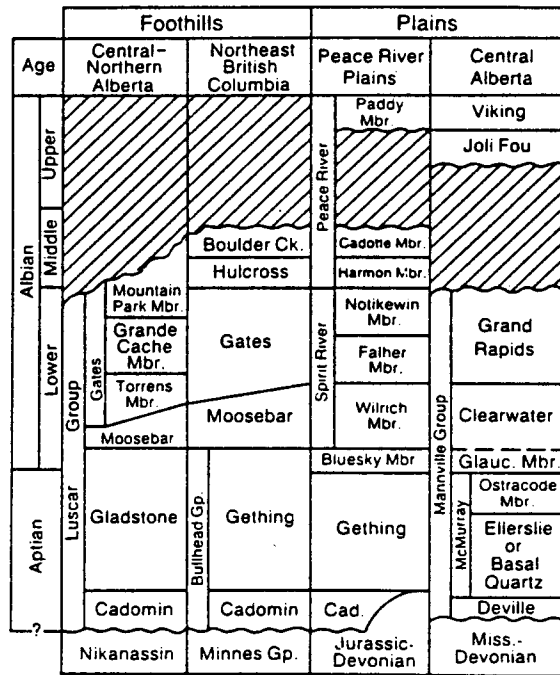Figure 1. Location map of Luscar Group.

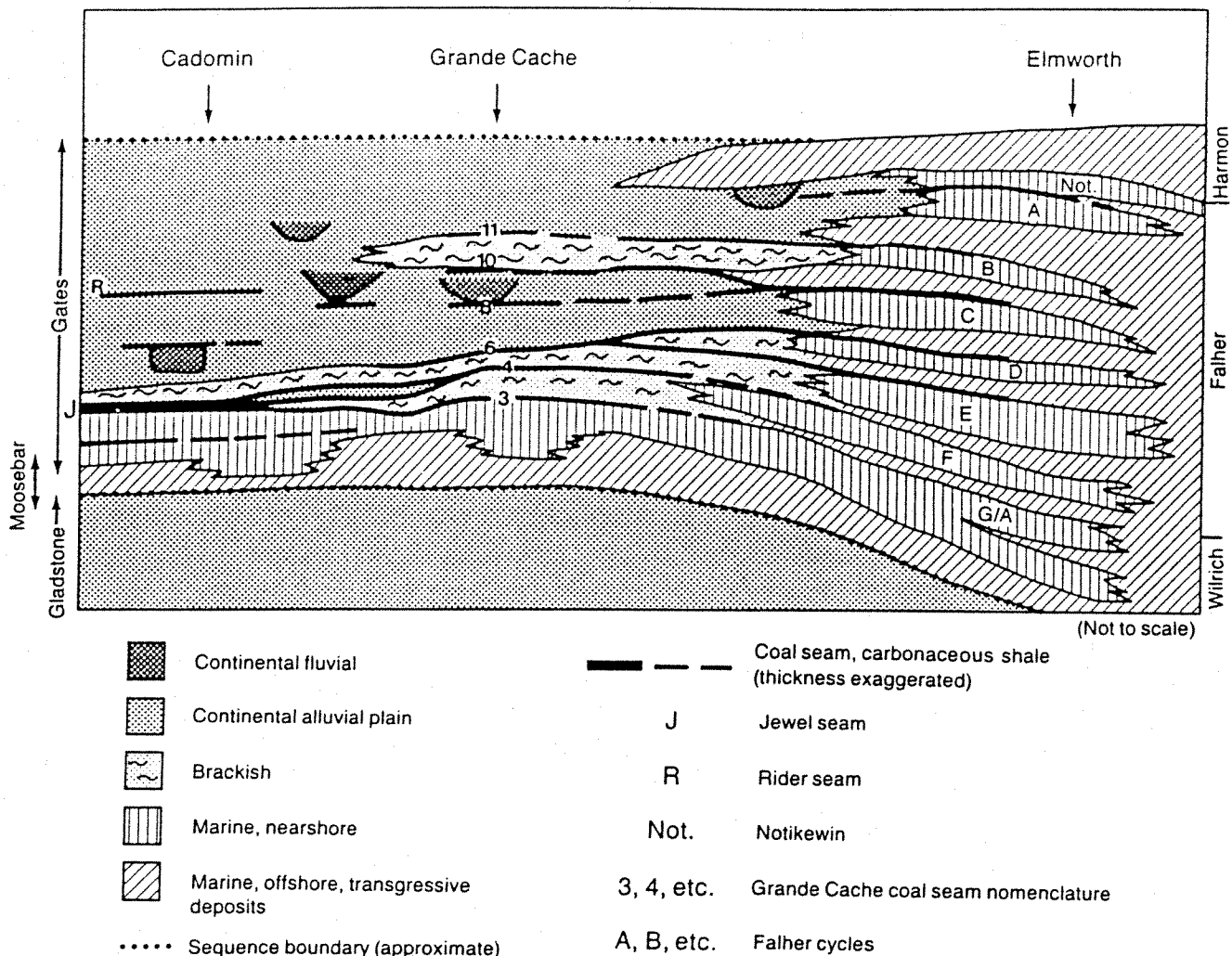Figure 2. Stratigraphic nomenclature of Luscar Group.

Figure 3. Architecture of the Luscar/Spirit River
clastic wedge (from Macdonald et al., 1988).

CADOMIN FORMATION

The Cadomin Formation was deposited in alluvial fans and on braided river pediment plains with chert pebble conglomerates, and is unconformably overlying the Nikanassin Formation. Much of the Cadomin that developed in the west as alluvial fans was transported and reworked into the northwest trending Spirit River channel that developed parallel to the mountain front during the early Aptian. The Cadomin likely represents a major drop in sea level and a major sequence boundary.

Large reserves of gas are present in the Cadomin Formation in the northern Deep Basin region. The Cadomin Formation is an excellent marker horizon, both at the surface and in the subsurface.

GLADSTONE FORMATION

The Lower Cretaceous (Aptian-Albian) Gladstone Formation is equivalent to the coal-bearing Gething Formation in northeastern British Columbia and the oilsands-bearing

McMurray Formation in northeastern Alberta. The formation lies conformably on the Cadomin with no apparent major stratigraphic break. The section at Cadomin shows a transition from well drained alluvial plain deposits with thin coals near the base, to coastal plain deposits with thicker coals near the top.

The Bluesky Member occurs at the top of the Gladstone as a near-shore marine transgressive, upward-coarsening sequence. Gas is produced from the northeast end of a barrier island or bar sand in the Bluesky in the Edson gas field.
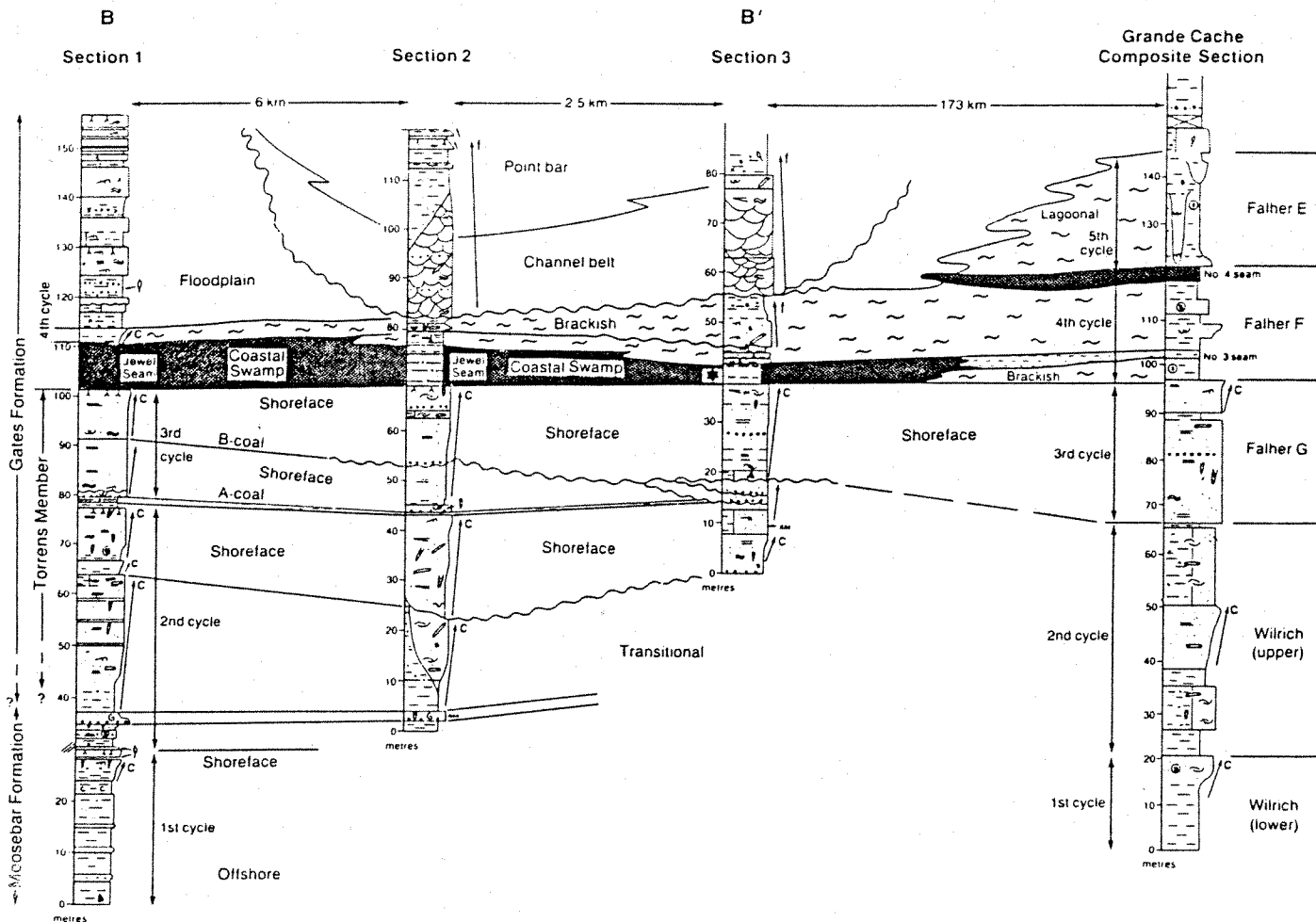
MOOSEBAR FORMATION

Several marine cycles can be recognized in the Moosebar/lower Gates succession (Macdonald et al., 1988). At Cadomin, these strata are divided into the 1st, 2nd and 3rd regional cycles (figure 4), forming a series of prograding shorelines and coastal plain deposits. The fully marine succession includes offshore to lower shoreface (with storm deposits) and shoreface to foreshore (and possibly beach, figure 4).

The lower Moosebar Formation (lower Wilrich or 1st cycle) in the Cadomin area consists of a series of fine-grained mudstones interbedded with sharp based siltstones and thin sandstones (figure 4). A thin argillaceous coal is present, as well as *Planolites* and *Skolithos* burrows. The cycle terminates in a 3 m coarsening-up sequence that is capped by a thin rooted coal. Well preserved conifer cones and leaf impressions are present in a thin shale bed near the coal.

This first cycle in the Moosebar Formation is interpreted to have formed in an offshore environment in which storm events periodically deposited thin sand units. In this area, the cycle terminated in an offshore bar. A fairly major relative lowering of sea level, and consequent exposing of the shelf, is indicated by the preservation of well preserved plant fossils and the development of thin rooted coals.

The lower part of the 2nd marine cycle corresponds to the upper part of the Moosebar Formation. A glauconitic, sharp based pebble conglomerate bed, commonly graded, is found near the base of the cycle in Section 1 and 2 (figure 4) and is interpreted as an offshore transgressive deposit. It may in part represent very slow deposition of a condensed section as described by Haq et al. (1987). The boundary between Moosebar and Torrens is gradational and is somewhere in the 2nd cycle. Alternatively, it could be placed either at the top or the base of the 2nd cycle.

Figure 4. Stratigraphic cross section through the Cadomin and
Grande Cache area (BB' part of section in Cadomin area).
From Macdonald et al. (1988).

GATES FORMATION

The Gates Formation consists of the Torrens, Grande Cache and Mountain Park members. Both shallow marine and non-marine sedimentary environments are deduced for this formation.

TORRENS MEMBER

The 2nd marine cycle, at Cadomin, consists of two or more coarsening-up sequences stacked on top of each other. The coarsening up cycles are commonly heterolithic, with fine sand dominating. Hummocky cross stratification, soft sediment deformation, wave ripples, and parallel laminations are all found in this cycle. Trace fossils include *Planolites, Diplocraterion* and *Skolithos*. The second cycle is capped by a rooted coal or carbonaceous mudstone, herein called the "Torrens A-coal". This coal can be traced in the subsurface as far north as township 57 (south of Grande Cache), where it disappears in another coarsening up sequence (Macdonald et al., 1988). The Torrens A-coal is seen to vary from a 90 cm coal in the south (Section 1) to a carbonaceous shale at Section 2, and is locally eroded at Section 3 (figure 4).

The second cycle is interpreted to have formed, primarily, in the offshore to shoreface environments. The offshore/transgressive deposits of the Moosebar give way upsection to lower shoreface and finally foreshore sediments of the Torrens Member. The trace fossil assemblage is consistent with this interpretation. The hummocky cross stratification supports the storm deposited origin and has been found in other locations of the Moosebar to Gates transition (Leckie and Walker, 1982).

The 3rd marine cycle consists of massive (though occasionally thinly bedded), fine to very fine grained sandstone, which has been called the Torrens Member. Faint parallel laminations are the predominant structures, with some trough cross bedding and hummocky cross stratification also present. Scour surfaces, with pebble lag deposits, are also common in the cycle. Mudstone is a very minor lithology in this cycle and is usually associated with the hummocky cross stratification. Trace fossils are particularly abundant near the top of the 3rd cycle and include *Skolithos, Ophiomorpha, Planolites,* and *Diplocraterion*. The sequence is capped by the 10m thick Jewel seam. The sandstones below the coal seam are commonly well rooted and show a discoloration in the top 50 cm. Tree trunk impressions and root casts can be found on the uppermost bedding plane surface of these sandstones. A more medium-grained, intraclast rich, trough cross stratified facies occurs at one locality within this area.

The 3rd cycle is interpreted to be a succession of two prograding shorelines sequences, with upper shoreface to foreshore environment transitions being present. The thin Torrens "B-coal" that is present at Section 1, very likely represents a shifting away from this area of the prevailing sediment source and the development of a small lagoonal environment. This coal is not traceable throughout the Cadomin area (figure 4). The trace fossil assemblage is typical of the Skolithos ichnofacies, which is most commonly found in high energy beach or beach-like facies (Ekdale et al., 1984). The presence of hummocky cross stratification high up in the sequence precludes a true beach environment for parts of the Torrens, because these structures generally form below fair wave base. The more medium-grained, trough cross stratified facies is interpreted to be a later tidal channel deposit.

GRANDE CACHE MEMBER

The 10m thick Jewel Seam forms the base of the Grande Cache Member and has a well rooted base and represents a major drop in relative sea level (see chapter on sedimentary environments). Part of the Jewel seam is stratigraphically equivalent, though not necessarily time equivalent, to the No. 3 seam at Grande Cache. To the east, in the subsurface, the Jewel seam appears to be correlative with the Mannville "Medicine River coal marker" described by Strobl (1988). Farther towards the north, into the Deep Basin, the Jewel equivalent is seen to disappear into marine strata (figure 3).

McCabe (1987) describes coals from the Upper Cretaceous Horseshoe Canyon Formation and Judith River Group, forming in north-south belts parallel to the paleo coastlines and having the thickest accumulation of peats (coals) some 40-80 km landward of the shoreline. The low-lying Okefenokee Swamp, which is some distance from active shoreline processes, is cited as a modern day analog for the Upper Cretaceous coals. This would also be the model for the Jewel seam and other thick seams of the Luscar Group. Langenberg and Kalkreuth (in press) concluded from maceral data that these peats were dominantly planar, low-lying and were formed under seasonable wet (relatively dry) conditions. Because of the close connection with regionally extensive foreshore deposits below the coal, Kalkreuth and Leckie (1989) introduced the term strandplain coals for these coastal plain coals.

A 4th marine cycle (directly above the Jewel Seam) extends upsection until the first major fluvial sandstones are encountered. A brackish water interpretation is based on the presence of trace fossils (*Diplocraterion* and *Planolites*) at Section 2, and the presence of lenticular bedding throughout this interval. Specimens of the siliceous forams *Hippocrepina (?) sp.*, *Miliammina (?) sp.* and *Saccammina sp.*

have been recovered from three locations above the Jewel seam in this area and are indicitive of ..."a shallow brackish (not normal marine) marine environment" (John Wall, pers. comm.). The fourth cycle is thought to be related to the transgressive portion of the Falher F cycle in the Deep Basin further north. In the Grande Cache area a 5th and 6th marine cycle is found above the No.4 and No.10 seams respectively.

The succession above the 4th marine cycle is essentially non-marine (except the 5th and 6th cycle in the Grande Cache area) and contains some fining-upward sequences. Major coal seams (No. 10 and 11 seams) are present in the Grande Cache area. The R seam of the Cadomin area is at about the same stratigraphic position as the No. 10 seam and is a typical alluvial plain coal and has high ash contents.

MOUNTAIN PARK MEMBER

The base of the Mountain Park Member is generally defined at the base the first major greenish colored sandstone encountered going upsection from the marine cycles. These sandstones are interpreted to be large scale fluvial deposits and may occur at various stratigraphic levels, making this field mapping criteria somewhat arbitrary. The first major sandstone above the highest major coal seam (over 0.6m thick) in the Grande Cache Member is alternately used, when no major greenish sandstone is present (e.g. Langenberg et al., 1987).

The contact between the Mountain Park Member and the overlying dark grey mudstones of the Blackstone Formation (Shaftesbury) is generally sharp and usually contains a thin transgressive pebble lag deposit. Thin upward-coarsening cycles are occasionally seen in the lower part of the Blackstone Formation. The Blackstone transgression is related to the accretion of terranes during the Columbian Orogeny and the onset represents a sequence boundary. The Blackstone Formation may also be an important source rock for gas generation in this area.

RANK VARIATION

Regional coalification patterns of the Luscar group are revealed by changes in volatile matter yields and vitrinite-reflectances. For the present discussion we concern ourselves only to seams in the basal part of the Gates Formation, i.e. the Jewel Seam of the Cadomin area, the Kennedy Seam of the Mountain Park area, the No. 3 and 4 seams of the Grande Cache area, and equivalent seams of adjacent areas. The maximum vitrinite-reflectances for the base of the Grande Cache Member range from R_{max} = 0.86 % (west of Rock Lake) to 1.97 % (from 2779 m depth in a well in the Outer Foothills). These reflectances indicate a rank range

from high volatile A to low volatile bituminous. To produce
the regional rank map shown in figure 5, all vitrinite-
reflectances were converted to dry ash free volatile matter
contents (Langenberg and Kalkreuth, 1989). The contour map
of figure 5 shows a very consistent rank pattern, where the
highest rank coals(low volatile bituminous) are present along
the northeastern side and the lowest rank (high volatile A
bituminous) are present along the southwestern side of the
area. It should be noted that no sudden changes in rank
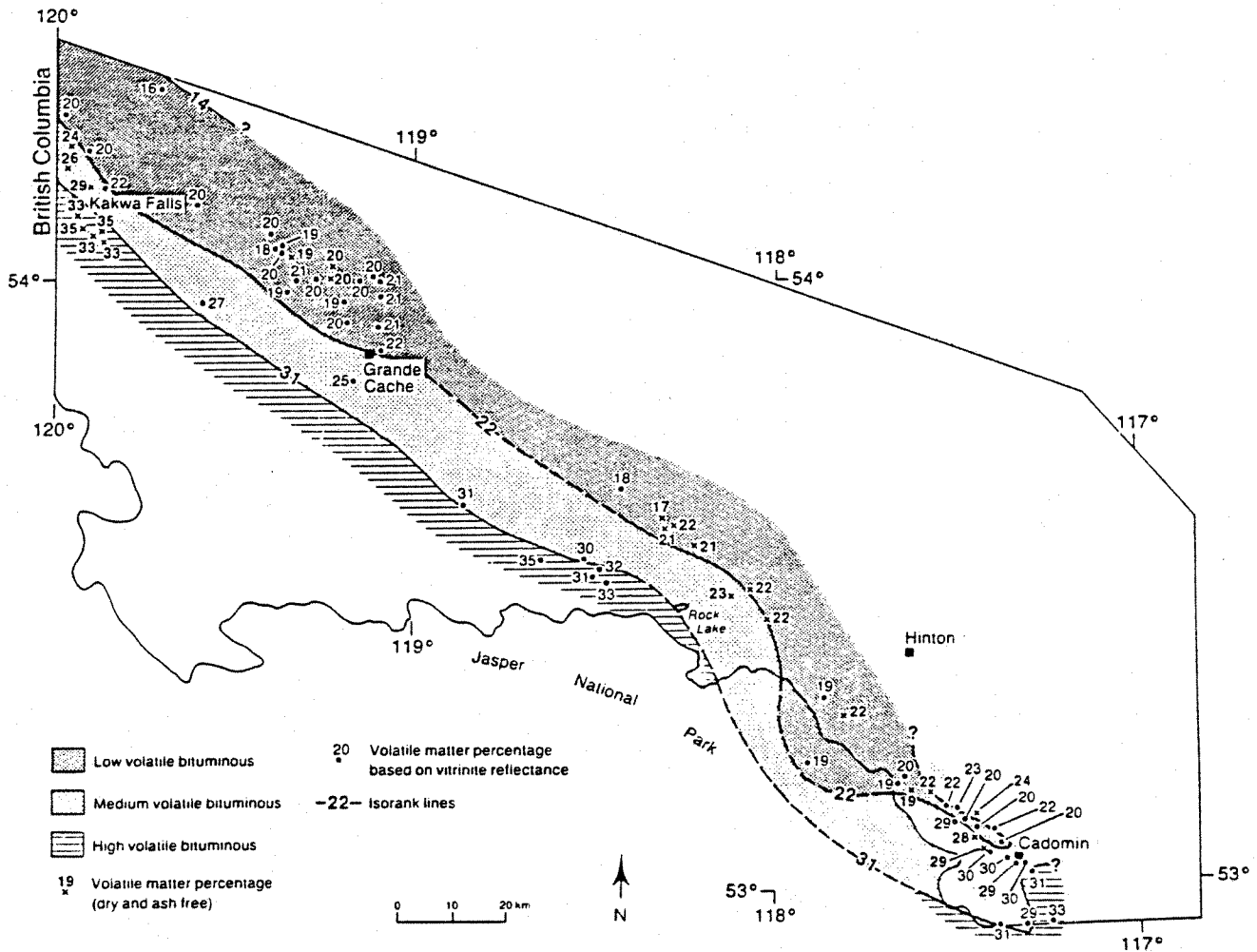across major thrust faults are observed.

Figure 5. Coal rank variation at the base of the Grande
Cache Member (from Langenberg and Kalkreuth, 1989).

The rank variation at the base of the Grande Cache
Member (figure 5) can be explained in three ways: 1) lateral
variability in paleo-geothermal gradients, 2) variation in
depth and duration of sedimentary burial, 3) variation in
tectonic burial history, or by a combination of these factors
(see also Kalkreuth and McMechan, 1988). No definite model
for variation in paleo-geothermal gradients is available for
the study area. Kalkreuth and McMechan (1988) found that
paleo-geothermal gradients similar to the present day

geothermal gradients give reasonable results in their time-depth (burial) curves for the area northwest of Grande Cache. This may also apply for the present study area, implying a range of paleo-geothermal gradients of 20-30°C/km. However, the variation in geothermal gradients is quite different from the rank variation shown in figure 5. Therefore, variation in sedimentary burial has to be considered.

Little information is available on the variation in depth of sedimentary burial because of extensive erosion. Based on stratigraphic arguments, one can assume about 5500 m of burial for the base of the Gates Formation (see Kalkreuth and McMechan, 1984). The isorank lines run largely parallel to the trend of the Foothills (figure 5), suggesting that the degree of coalification is entirely related to sedimentary burial in a foreland basin. The broad areas of equal rank in the Kakwa Falls, Grande Cache and Rock Lake areas support this interpretation. This would imply that stratigraphic thicknesses of Late Cretaceous and Paleocene sequences are decreasing in southwesterly direction in the Foothills, indicating that this area was near the deformation front at that time.

REFERENCES

Cant, D.J. (1983): Spirit River Formation-A stratigraphic diagenetic gas trap in the deep basin of Alberta; Bulletin American Association of Petroleum Geologists, v. 67, pp. 577-587.

Ekdale, A.A., Bromley, R.G. and Pemberton, S.G. (1984): Ichnology - The use of trace fossils in sedimentology and stratigraphy; Society of Economic Paleontologist and Mineralogists, Short course notes no. 5, 317p.

Haq, B.U., Hardenbol, J. and Vail, P.R. (1987): Chronology of fluctuating sea levels since the Triassic; Science, v. 235, no. 6, pp. 1156 - 1167.

Kalkreuth, W. and Leckie, D.A. (1989): Sedimentological and petrographical characteristics of Cretaceous strandplain coals: a model for coal accumulation from the North American Western Interior Seaway; International Journal of Coal Geology, v.12, pp.381-424.

Kalkreuth, W and McMechan, M. (1984): Regional pattern of thermal maturation as determined from coal-rank studies, Rocky Mountain Foothills and Front Ranges north of Grande Cache, Alberta - Implications for petroleum exploration; Bulletin of Canadian Petroleum Geology, v.32, pp. 249-271.

Kalkreuth, W and McMechan, M. (1988): Burial history and thermal maturity, Rocky Mountain Front Ranges, Foothills

and Foreland, east-central British Columbia and adjacent Alberta, Canada; AAPG Bulletin, v.72, pp. 1395-1410.

Langenberg, W. and Kalkreuth, W. (1989): Influences of structural deformation on coal quality in the northern Alberta Foothills; *in*: Advances in western Canadian coal geoscience - Forum proceedings, Alberta Research Council Information Series No. 103, pp.241-253.

Langenberg, W. and Kalkreuth, W. (in press): Sedimentological and tectonic controls on coal quality of a thick coastal plain coal in the foothills of Alberta; Special Paper of the Geological Society of America.

Langenberg, C.W. and McMechan, M.E. (1985): Lower Cretaceous Luscar Group (revised) of the northern and north central Foothills of Alberta; Bulletin of Canadian Petroleum Geology, v. 33, pp. 1-11.

Leckie, D.A. and R.G. Walker. (1982): Storm- and tide-dominated shorelines in the Cretaceous Moosebar - Lower Gates interval - outcrop equivalents of Deep Basin gas trap in Western Canada;American Association of Petroleum Geologist Bulletin, v. 66, pp. 138-157.

Macdonald, D.E., Langenberg, C.W. and Strobl, R.S. (1988): Cyclic marine sedimentation in the Lower Cretaceous Luscar Group and Spirit River Formation of the Alberta Foothills and Deep Basin. *In*: Sequences, Stratigraphy, Sedimentology: Surface and subsurface,D. P. James and D. A. Leckie (eds), Canadian Society of Petroleum Geologists, Memoir 15, pp. 143-154.

McCabe, P.J. (1987): Facies studies of coal-bearing strata. from Scott, A.C. (ed), Coal and coal-bearing strata: recent advances; Geological Society of Special Publication No. 32, pp. 51-66.

Smith, D.G., Zorn, C.E. and Sneider, R.M. (1984): The paleogeography of the Lower Cretaceous of western Alberta and northeastern British Columbia in and adjacent to the Deep Basin of the Elmworth area; *in* Elmworth - Case study of a deep basin gas field. Edited by Masters, J.A., Journal American Association of Petroleum Geologists, Memoir 38, pp.79-114.

Strobl, R.S. (1988): The effects of sea-level fluctuations on prograding shorelines and estuarine valley-fill sequences in the Glauconitic Member, Medicine River Field and adjacent areas; *In*: Sequences, Stratigraphy, Sedimentology: Surface and Subsurface,D. P.James and D. A. Leckie (eds), Canadian Society of Petroleum Geologists, Memoir 15, pp. 221-236.