LUGUS

THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

PETROGRAPHIC ANALYSIS OF THE CROWEBURG COAL AND ITS ASSOCIATED SEDIMENTS

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

MASTER OF SCIENCE

BY

JAMES S. McKINNEY

Norman, Oklahoma

1959

PETROGRAPHIC ANALYSIS OF THE CROWEBURG COAL AND ITS ASSOCIATED SEDIMENTS

A THESIS

APPROVED FOR THE SCHOOL OF GEOLOGY

BY

[redacted]

[redacted]

[redacted]

ACKNOWLEDGMENTS

The writer wishes to express his appreciation to Dr. E. L. Lucas, Professor of Geology, who as director of this thesis provided the encouragement and help necessary to the compilation of this research.

The writer is also deeply indebted to Dr. C. C. Branson, Director of the School of Geology and the Oklahoma Geological Survey, for his patient guidance and helpful criticism.

The writer wishes to thank Dr. A. J. Myers for his constructive criticism of this paper.

Special gratitude is held for Mr. Alfred Meyer of Norman for his time and assistance in the construction of the equipment necessary to complete this study.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Panel

Figure Page

LIST OF TABLES

PETROGRAPHIC ANALYSIS OF THE CROWEBURG COAL AND ITS ASSOCIATED SEDIMENTS

CHAPTER I

INTRODUCTION

General Information

Coal petrography is that branch of geology dealing with the microscopic study of the several constituents that form coal. Coal petrography has shown the relationship of the several constituents of coal to its physical and chemical properties. It has in some areas replaced chemical analyses. Lack of homogeneity in coal makes petrographic analysis invaluable in the determination of the physical and chemical processing methods and the ultimate use of a particular seam. This has enabled the coal industry to eliminate harmful components through selective mining, and to mix the constituents of several coals in order to gain the best possible grade of coal for a particular task. Coal petrography has also shown the relationship of the various constituents to the origin of particular types of coal.

Oklahoma ranks fifteenth among the states in the production of coal. Commercial grade coal is located in the east-central and northeastern portions of Oklahoma, an area of 20,000 square miles (after Ham as in the Semi-Centennial Report, Okla. Geol. Survey, 1958) in Atoka, Coal, Craig, Haskell, Latimer, LeFlore, McIntosh, Muskogee, Okmulgee, Pittsburg, Rogers, Tulsa, and Wagoner Counties. This area is continuous into the Southeastern Kansas coal field and the eastern portion of the Arkansas-Oklahoma coal basin. These areas form the western portion of the Interior province. The Oklahoma coal field is bounded on the east by the Ozark uplift and the Arkansas state line, on the south by the Ouachita Mountains, westward by younger coal barren rocks, and on the north by the Kansas border. Minor bituminous and lower grade coal deposits occur in Carter, Bryan, and Cimarron Counties.

Production figures used in this paper for years prior to 1952 are from Trumbull (1957). Those after 1952 are from Mineral Reports, no. 25, 31, 32, and 34, of the Oklahoma Geological Survey. In some cases the sources were combined to form more complete data. The average yearly production from the Oklahoma coal field is 2,104,520 short tons. In the period 1873-1957, 176,635,168 short tons were mined in Oklahoma. In 1957, 1,950,000 short tons were mined. This is a 6 percent decline over 1956 production; however, it is in keeping with the declining production trend of recent years.

The Oklahoma coal field may be loosely divided into two areas:

1. The Arkansas-Oklahoma coal basin of Atoka, Coal, Haskell, Latimer, LeFlore, and Pittsburg Counties contains coals of late Pennsylvanian (Desmoinesian and Atokan) age, specifically, in ascending order, the Atoka formation, Hartshorne sandstone, McAlester formation, Savanna formation, and the Boggy formation. Structurally the Arkansas-Oklahoma coal basin is a series of eastward and northeastward trending folds. The structural characteristics of this area do not lend themselves to extensive strip mining; therefore, the majority of the coal has been mined by underground methods. The use of the more expensive underground mining methods dictates that only the best grade and thicker seams be mined; thus many thin seams are ignored. In the period 1908-1952, the above mentioned counties have produced 59 percent of the state's total production, or 74,816,300 short tons.

2. The Northern Oklahoma coal field of Craig, McIntosh, Muskogee, Okmulgee, Rogers, Tulsa, and Wagoner Counties contains coals of Pennsylvanian (Desmoinesian and Missourian) age, specifically, in ascending order, the Krebs, Cabaniss, and Marmaton groups, and the Seminole formation. Structurally, the coals of this area are found in rocks which dip gently westward, broken only by a few faults and gentle folds. Due to this type of deposit, the greater part of the coal produced in the area is by strip mining methods. The hilly topography and gently folded nature of the sediments in the Henryetta district of Okmulgee County in the southern portion of this region lends itself to underground mining, and there are a few scattered slope mines of minor production throughout the region. In plotting the production of the above counties and those of the Arkansas-Oklahoma coal basin against the strip mine-underground mining production, it may be seen that the production of this region has surpassed that of the Arkansas-Oklahoma coal basin as the more economical strip mining methods were developed. After 1935, as strip mining became more widely used in Oklahoma, the Northern Oklahoma coal field assumed the lead in state coal production. For the period 1940-1952, this region produced 51 percent of the coal in Oklahoma. In the period 1908-1952,

this region produced 37 percent of the State's total production, or about 47,558,895 short tons.

Scope and Purpose

To discuss the various petrographic classifications and techniques, and show the results of a limited petrographic analysis, which can be used as a technique guide for further studies of this nature, is the immediate purpose of this study. To provide a scientific basis for mixing, selective mining, and treating the several Oklahoma coal seams, thereby producing higher grade coals and finding new uses and markets for Oklahoma coal is the ultimate purpose of this research.

The Croweburg coal of the Northern Oklahoma coal field was chosen because of its wide extent and economic importance. Original reserve estimates of this seam were 433.92 x 10^6 short tons. The coal is classified as a high volatile B bituminous. The area of investigation extends from T. 16 N., R. 14 E., in Okmulgee County, to T. 28 N., R. 20 E. in Craig County, Oklahoma, a distance of approximately 90 miles through Okmulgee, Wagoner, Tulsa, Rogers, Nowata, and Craig Counties. The study was supplemented by chemical and petrographic analyses from: Analyses of Oklahoma Coals, U.S. Bureau of Mines Technical Paper 411, Oakes (1944), Hambleton (1953), and Davis and others (1944). A detailed study of the plant microfossils of this seam (Wilson and Hoffmeister, 1956), coupled with these studies, forms a more complete picture of the geology of the Croweburg coal.

The underclay and roof stone samples were analysed to determine if there was a relationship between the frequency of occurrence of the several minerals in each sample and the maceral, microlithotype, or bright-dull percentages of the 5 cm of coal in direct contact with that sediment sample. Further analysis was not within the scope of this investigation.

Stratigraphy

The Croweburg coal occurs in the Senora formation of the Cabaniss group. This group is Middle Pennsylvanian (Desmoinesian) in age. The Marmaton and Krebs groups are respectively above and below the Cabaniss group.

The major portion of the Croweburg coal lies in the marginal shelf facies of northern Oklahoma, where the sediments are cyclic. In the southern portion of the area the coal bed lies in rocks of the basinal facies.

The Croweburg coal may be recognized as lying under the Verdigris limestone, separated from this limestone by 10-50 feet of medium-gray to black fissile shale containing numerous phosphate nodules. Throughout the area average thickness of the coal is approximately 1 foot 7 inches.

The coal bed, being very widespread in Oklahoma and Kansas, has been known as the Broken Arrow coal, Henryetta coal, Fireclay bed, Huntsinger bed, and the Mud seam. At a conference held in Nevada, Missouri, the name Croweburg was adopted by geologists from Oklahoma, Kansas, Nebraska, and Missouri to replace the above mentioned names (Searight and others, 1953). It is possible that the Senora coal of the basinal facies is Croweburg (Branson in Wilson and Hoffmeister, 1956, p. 7).

The following is a stratigraphic column showing the relationship of the Croweburg coal to the other coal cycles of the Cabaniss group (after Branson, 1954, and Wilson and Hoffmeister, 1956):

Desmoinesian series	Cabaniss group	Senora formation	Mulky coal cycle	Excello shale Mulky coal (absent in Oklahoma) Breezy Hill limestone Kinnison shale, limestone at base in Craig County
			Lagonda coal cycle	Iron Post coal Upper Lagonda sandstone Lagonda shale Lagonda sandstone

Desmoinesian series	Cabaniss group	Senora formation	Bevier coal cycle	Bevier coal underclay shale and sandstone
			Bevier coal cycle?	Limestone (thin and local)
			Verdigris coal cycle	Wheeler coal Verdigris limestone Verdigris black shale shale, sandstone
			Croweburg coal cycle	Croweburg coal underclay McNabb limestone shale
			unnamed coal cycle	Sequoyah coal shale, sandstone limestone or clay-ironstone
			Fleming coal cycle	Fleming coal underclay shale limestone or clay-ironstone
			Robinson Branch coal cycle	Robinson Branch coal (absent in Oklahoma) shale, sandstone Russell Creek limestone
			Mineral coal cycle	Mineral coal underclay, shale
			Scammon coal cycle	Scammon coal (absent in Oklahoma) Chelsea sandstone shale Tiawah limestone Tiawah black shale
			Tebo coal cycle	Tebo coal shale Upper Taft sandstone black shale
			unnamed coal cycle	unnamed coal shale sandstone shale

Previous Work

Plant microfossils of the Croweburg coal have been studied by Wilson and Hoffmeister (1956). Davis and others (1944), at Henryetta, Oklahoma, and Hambleton (1953) at Frontenac, Kansas, Have made petrographic analyses of the Croweburg coal using the American thin section technique. The geology, chemistry, and coal resources of the Oklahoma coal field are discussed by Shannon (1926), Moose and Searle (1929), and in publications of the Oklahoma Geological Survey. Unpublished master's theses at the University of Oklahoma discuss the surface geology of the greater portion of the area concerned in this study. They are: Branson (1952), Cade (1952), Campbell (1957), Chrisman (1951), Claxton (1952), Gruman (1954), Leitner (1957), Lohman (1952), Lontos (1952), Luff (1957), Manhoff (1957), Meek (1957), Simpson (1951), Sparks (1955), and Tillman (1952).

CHAPTER II

COLLECTION OF SAMPLES

The original plan was to collect six samples at equal lateral intervals throughout the area; however, the actual sampling was governed by availability and accessibility of mines because fresh samples are imperative in petrographic analysis. Outcrop facies in undeveloped areas could have been used, but the labor involved in removing overburden and cutting deep enough into the seam to obtain a fresh sample was not practical for a single collector using ordinary tools.

Coal Collection

Samples to be used in the petrographic analysis were taken as a column, being careful to obtain the entire thickness of the seam. The U.S. Bureau of Mines, Thiessen, Sprunk, and O'Donnel (1938) recommends that a 9 to 13 inch "square" column be taken of the seam's entire thickness. The writer found that a sample this size was too large and heavy for collection by a single worker. The advantage of the Bureau's sample size is that a column of that magnitude usually will not break along weak bedding planes; therefore, there will be no loss in thickness during collecting or handling.

Columns collected for this investigation ranged from 6 to 10 inches, a size controlled by the nature of fracturing in the Croweburg coal. The butt and face cleats form natural columns which made it virtually impossible to obtain columns of any other size without special equipment. Samples of this size are unsatisfactory because they break along fusain lenses, resulting in the loss of a portion of the column.

The samples were placed in boxes, clearly labeled as to location, top of seam, and thickness. The boxes were then packed with sawdust. The samples were kept moist by wetting the sawdust periodically. This prevents drying of the sample, oxidation, and resultant crumbling. The sample should not be left in this state for more than three months if satisfactory results are to be obtained in the preparation of sections.

Sediment Collection

In theory, two samples should be collected at each location in direct contact with the sampled coal column, one taken directly under the seam in the underclay, and the other immediately above the seam in the roof stone; however, in practice, only the underclay could be sampled in this manner. The roof stone was stripped away at many collecting sites, making it necessary to obtain a sample some distance from the coal column, usually in the high-wall of the strip pit. Each underclay or roof stone sample taken was a column, approximately 4 inches square and 2 inches deep.

Sample Locations and Descriptions

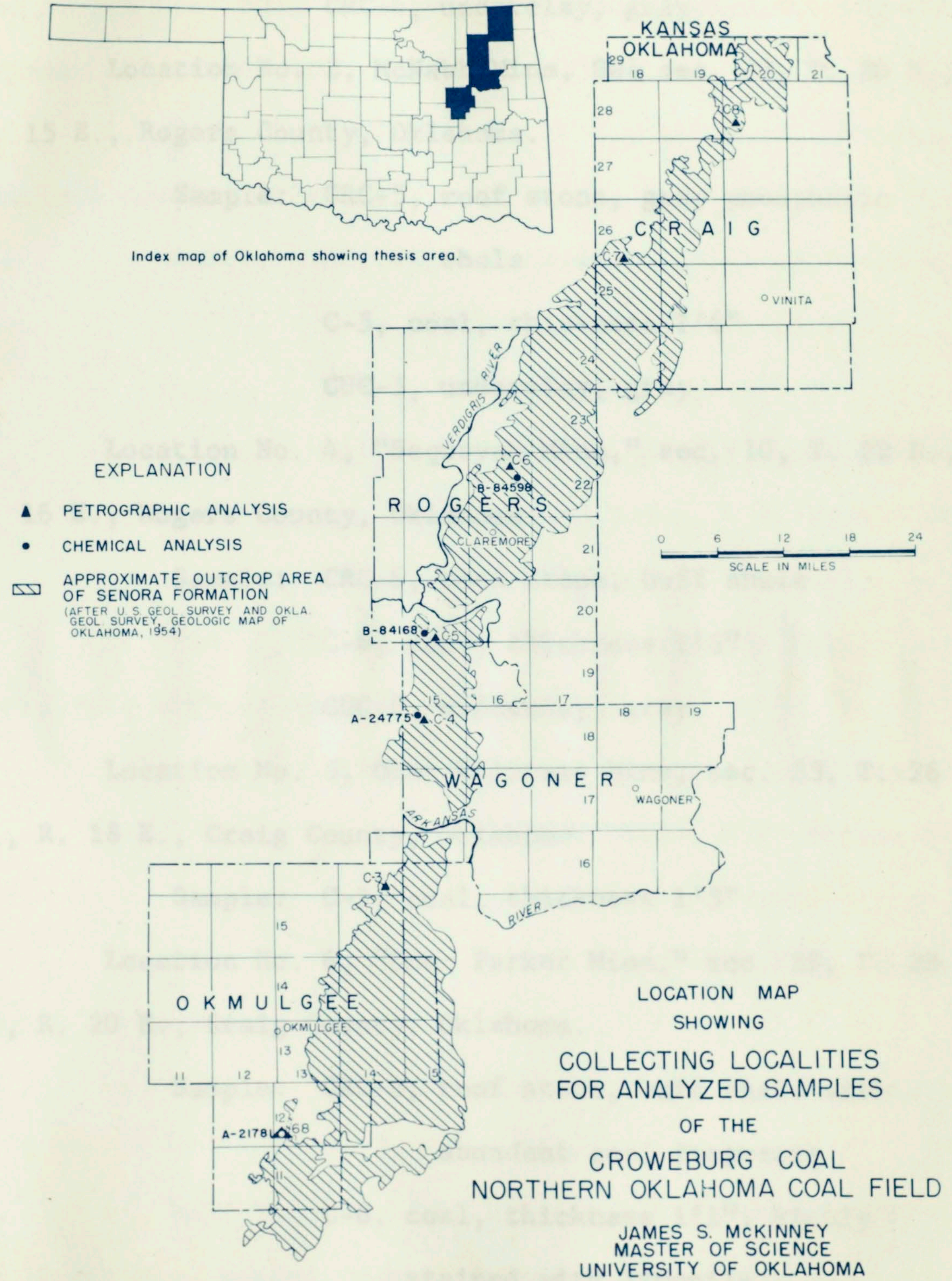
Location No. 1, Sam Crabtree Mine, NC sec. 26, T. 16 N., R. 14 E., Okmulgee County, Oklahoma.

Sample: CRC-3, roof stone, dark gray shale
C-3, coal, high pyrite content, thickness 1'7"
CUC-3, underclay, gray

Location No. 2, Fisher Mine, sec. 8, T. 18 N., R. 15 N., Wagoner County, Oklahoma.

Sample: CRC-4, roof stone, gray shale, coal fragments disseminated throughout

FIGURE 1



LOCATION MAP
SHOWING
COLLECTING LOCALITIES
FOR ANALYZED SAMPLES
OF THE
CROWEBURG COAL
NORTHERN OKLAHOMA COAL FIELD

JAMES S. McKINNEY
MASTER OF SCIENCE
UNIVERSITY OF OKLAHOMA
1959

C-4, coal, thickness 1'9", top 11 inches not available for analysis

CRC-4, underclay, gray

Location No. 3, McNabb Mine, SW¼ sec. 33, T. 20 N., R. 15 E., Rogers County, Oklahoma.

Sample: CRC-5, roof stone, gray phosphatic shale

C-5, coal, thickness 1'6"

CUC-5, underclay, gray

Location No. 4, "Sequoyah Mine," sec. 10, T. 22 N., R. 16 E., Rogers County, Oklahoma.

Sample: CRC-6, roof stone, buff shale

C-6, coal, thickness 1'6"

CUC-6, underclay, gray

Location No. 5, Omer Williams Mine, sec. 33, T. 26 N., R. 18 E., Craig County, Oklahoma.

Sample: C-7, coal, thickness 1'5"

Location No. 6, "Omer Parker Mine," sec. 29, T. 28 N., R. 20 E., Craig County, Oklahoma.

Sample: CRC-8, roof stone, buff shale with abundant coal fragments

C-8, coal, thickness 1'1", highly stained with limonite

CUC-8, underclay, gray

Sample locations of chemical and petrographic analyses of the Croweburg coal from prior publications used to augment this study are:

1. Sec. 30, T. 12 N., R. 13 E., Atlas No. 2 Mine, Okmulgee County, Oklahoma.

Sample: No. 68, petrographic analysis, American classification, Davis and others (1944, p. 17)

A21781, chemical analysis, Analyses of Oklahoma Coals, U.S. Bureau of Mines Technical Paper 411, p. 21

2. Sec. 5, T. 18 N., R. 15 E., Arkansas Valley Strip Pit, Wagoner County, Oklahoma.

Sample: A24775, chemical analysis, Analysis of Oklahoma Coals, U.S. Bureau of Mines Technical Paper 411, p. 30

3. Sec. 28, T. 20 N., R. 15 E., McNabb Mine, Rogers County, Oklahoma.

Sample: B-84168, chemical analysis, Oakes (1944, p. 31)

4. Sec. 14, T. 22 N., R. 16 E., Rogers County Coal Co. Strip Pit, Rogers County, Oklahoma.

Sample: B-84598, chemical analysis, Oakes (1944, p. 32)

5. Sec. 28, T. 29 S., R. 25 E., Mackie Clemens Fuel Co. Strip Pit, Crawford County, Kansas.

Sample: Cr-1-C, petrographic analysis, American classification, Hambleton (1953, p. 44)

Cr-1-C, chemical analysis, Hambleton (1953, p. 31)

CHAPTER III

EQUIPMENT

A major problem in the preparation of coal for petrographic analysis is the sawing. A standard diamond immersion saw will cause the coal to crumble and to cut unevenly; therefore a dry saw must be used. The writer constructed a table saw employing two silicon carbide cut-off wheels, a 12 x 3/32 inch wheel for rough cutting and a 8 x 3/32 inch fine cut-off wheel for more delicate work. The wheels, having a common arbor, were turned by a ½ HP variable speed motor, with speeds from 360 to 5,520 rpm. A dust-catcher to trap the dust caused by dry sawing was constructed and connected to casements enclosing the saw blades. The dust was drawn through a squirrel cage blower and collected in a chamber consisting of a series of baffles and filters. Though this apparatus was about 90 percent effective the writer advises use of a respirator at all times when cutting. The saw blades are flexible, but may possibly break and fly about with considerable force if broken when operated at high speeds. It is advisable not to stand in front of or behind the blades, and to provide a means of eye protection when operating the machine.

It was necessary for the preparation of coal sections to construct special grinding apparatus. A fine-grained yellow Belgian hone was placed on a slanting table constructed so that a constant stream of water could be run over it at all times, leaving both hands free for grinding. A miniature light table with a frosted glass front was built so that grinding progress might be readily viewed and as a means of applying the final polish.

A board with 60 depressions was constructed to insure proper orientation of the coal cubelets, during sectioning and for storing between grinding operations.

A series of wooden boxes, each having a piece of Sylvet cloth or fine billiard table felt attached, was made for use in the polished section process.

CHAPTER IV

PREPARATION OF SAMPLES FOR MICROSCOPIC ANALYSIS

There are three petrographic techniques used in coal analysis, the American (thin section), the European (polished section), and the polished thin section method which combines the first two into one section. The writer was unable to obtain satisfactory polished thin sections using the equipment available, nor did the time involved in making usable thin sections seem justified. Analytical results of the same value, if not better than those obtained by thin section analysis, are achieved by using polished sections.

The rough column samples collected in the field were sawed into columns 3 inches "square" the length of which was controlled by the thickness of the seam, then placed in plaster of paris molds for preservation and ease of handling in future operations, and labeled as to sample location and top of the seam. This should be done as soon as possible after collection or the samples will be ruined through drying and oxidation; however, once encased in the molds they may be left indefinitely without any undesirable effects.

A slab was made by cutting through the sample parallel to one 3 inch side so that it contained approximately 3/4 of an inch of the encased coal. The remaining portion of the column was either re-covered with plaster of paris for preservation, or polished for display by grinding on a large piece of plate glass using successively finer grits (120, 200, 400, and 600). Final polish was achieved by stroking the column with an extremely fine-grained yellow Belgian hone, and buffing, using a Sylvet cloth saturated with a paste consisting of a mixture of Goddard's Non-Mercurical Plate Powder and water (hereafter referred to as Goddard's paste). After drying the display column was sprayed with a clear vinyl plastic to prevent surface oxidation. If desired, squares may be drawn on the surface, using white india ink, and the squares labeled showing the exact number and location of each thin or polished section.

The slab containing the 3/4 x 3 inch column of coal was in turn cut into sub-columns measuring 3/4 x 1 inch, and labeled as to top and bottom of the seam. One sub-column was chosen and cut parallel to the bedding into cubelets measuring approximately 3/4 x 1 x 1 inch. The size of the cubelets is largely governed by the freshness and fracture of the coal. Very dry and badly weathered coal samples break apart more readily than fresh unweathered coals. The cubelets tend to separate along fusain bands so that when the operator encounters a megascopically thick fusain band, the cubelet should be cut so that the fusain is encased between two harder components, regardless of the resultant size of the section. This will aid in the ensuing operations as fusain is very friable and crumbles during the polishing process if on the edge of a cubelet. Each cubelet was marked as to top, bedding direction, and section number, and then dipped into a vinyl plastic solution. Very friable coals are not dipped into the plastic bath, but are impregnated with carnuba wax or paraffin, by immersion in the medium for 12-24 hours at 105°-110° C. Extremely difficult cases may be impregnated with bakelite varnish in the same manner.

The importance of a definite labeling system in these procedures cannot be overemphasized. The labeling code used in this project is as follows. A completed section may have the number 42310. The first digit, 4, refers to the geographical sample number, C-4, and thus its location (the samples are numbered from south to north in increasing order). The number 2 refers to the second 3/4 x 3 inch slab cut from the original plaster of paris column, the initial slab being no. 1. The numeral 3 is the third 3/4 x 1 x 1 inch subcolumn as numbered from left to right. The 10 is the tenth section or cubelet from the top of the seam.

After thorough drying, following the plastic or wax bath, the cubelets were polished on one side, perpendicular to the bedding. This was done by grinding on successive glass plates, using 120, 200, 400, and 600 carborundum powders, until all scratches made by each preceding grit were eliminated and final smoothing was achieved by grinding on a smooth glass plate using Goddard's paste. The glass plates used in this step must have a uniformly smooth surface, because any depressions on the surface of the glass, caused by improper grinding (grinding only on the center portion of the plate or using coarser grits on a plate reserved for fine grits), will in turn cause the polished surface of the cubelet to be uneven. An uneven surface will doom all ensuing operations to failure. The smoothed face was then given a light shine by rubbing it on a mounted Sylvet cloth thoroughly impregnated with Goddard's paste.

The cubelet was dried and then mounted on a frosted glass slide (frosting insures a better bond in very thin friable materials). Some coal investigators use a mixture of three parts Canada balsam dissolved in xylene and two parts marine glue at 105°-110° C, but the writer used Lakeside 70 thermoplastic cement because of its east of handling and constant optical properties (RI=1.563). The slide was heated to a temperature between 135°-140° C and the cement applied. While the bubbles were cooking out of the cement, the cubelet was gently heated over a flame to drive off any trapped coal gasses in the polished surface. This is important, as gas coming off, when a cold block is mounted, adds greatly to the difficult task of eliminating all bubbles and maintaining the desired even mount. The warmed block was then placed on the slide so that the direction of the seam's top was away from the body when the numbered end of the slide was to the left of the observer. Bubbles were eliminated by lateral movement of the cubelet and even pressure on the block thus forcing the bubbles to the edge and out of the slide. The elimination of bubbles, uniform mount (uniform thickness of cement between the glass and cubelet), and flat polished surface of the cubelet will determine the success or failure of the completed section; therefore any imperfect slide should be discarded at this point. When a satisfactory mount was achieved the slide and cubelet were again dipped into the vinyl plastic solution in order to strengthen the bond and coal.

Excess coal was removed from the mounted cubelet by sawing (using the 8 inch cut-off wheel) or grinding (on the 120 grit lap), parallel to the slide, until the coal remaining on the slide was approximately 2 mm thick. All excess Lakeside cement surrounding the mounted block was then removed using a sharp knife.

Each of the ensuing steps must be followed by thorough washing of the section and all materials that will come into contact with it. Further operations differ in thin, polished thin, and polished section techniques; therefore each will be considered separately under its own heading.

Thin Section Technique

The mounted block was ground to a thickness of 10 microns using 200 and 400 grits in succession. The section was then transferred to a 400 grit rim type rotating lap and ground until a very bright light passes through the cuticle material (see p. 38 and fig. 7 for description). High spots may largely be eliminated by bending the slide slightly, thus putting pressure on the desired spot. Care must be taken not to apply too much pressure or the section will shatter. The lap should run slowly, with a loose drive belt which the operator can adjust so that the wheel will stop when pressure great enough to break the section is applied.

The section was then transferred to a fine-grained yellow Belgian hone with a constant stream of water running over the surface. The slide was honed by stroking in one direction only, either away from or toward the body depending on the individual's deftness of hand. At first, individuals may find it easier to stroke lightly toward the body. After some practice, however, it will be found that longer and more even strokes are achieved by stroking away from the body. Honing was continued until the section presented a uniformly illuminated field.

The section was then placed on the small light table for the elimination of any remaining high spots. This was done by rubbing the desired area with a water-soaked cork or pencil eraser dipped in Goddard's paste.

Final polish was obtained by rubbing the section with a finger dipped in Goddard's paste. The section was then sprayed with vinyl plastic and considered complete.

Polished Thin Section Technique

In this technique the section is handled exactly as it is in the thin section method with the exception of the final polish and plastic spray steps. The section is transferred from the light table to a mounted Sylvet cloth saturated with Goddard's paste and rubbed several times parallel to the bedding. The section should be thoroughly washed and inspected, after each rub, for signs of "pulling away."

When the desired relief is achieved, final polish is obtained by rubbing the section on a mounted billiard table felt saturated with jeweler's rouge. The section is then considered complete.

Polished Section Technique

There are two methods of producing polished sections; namely relief and plain polishing. For the majority of coals, relief polishing is satisfactory, but for coals rich in ash or fusain, plain polishing is superior. The polished sections used in this project were of the relief type; however, in some instances plain polishing could have been used advantageously. It may be of interest to discuss the plain polishing technique even though the equipment necessary was not available.

In both methods the sections were smoothed by grinding on a series of glass plates and ground using 200, 400, 600 grits and finally levigated alumina. Further steps in the preparation of plain or relief polished sections require different procedures. They are:

1. Relief polishing. This technique requires first a uniformly smooth surface, which should have been achieved in the above step, after which the section was then rubbed, parallel to the bedding, on a series of mounted Sylvet cloths saturated with pastes of 800 grit and levigated alumina. The above step may be followed by etching with a mixture of 30 parts saturated solution of chromic oxide, 5 parts water, and 10 parts of strong sulphuric acid. The solution is kept at boiling during immersion of the section. The time required for etching varies from 10 to 60 seconds depending upon the nature of the coal and the depth of action desired. Etching is particularly useful in bringing out the components of durain (def. p. 66) and claro-durain (def. p. 65); however, it is not a necessary step in all the sections. The sections were washed and again rubbed on the Sylvet cloth series, discussed above, to restore the polish. Final polish was achieved using a mounted billiard table felt saturated with jeweler's rouge. Goddard's paste should be used instead of jeweler's rouge on fusain rich sections. The section was then transferred to clean mounted billiard table felt and rubbed, using no abrasive, with a heavy

stream of hot water flooding the mount. The section was then considered complete.

2. Plain polishing. This technique requires that after the levigated alumina on glass step, discussed above, is reached, the section is transferred to a slowly revolving iron lap covered with a 3-5 mm lay of pitch (a residue of tar) until a high polish is achieved. The section is then considered complete.

Preparation of Sediment Samples

The samples were crushed to pass through a 40 mesh screen (0.42 mm) and then split into 50 gm fractions. These were boiled for 12 hours in a 10 percent HCl solution. They were then decanted (after a 1 minute settling period), washed, and agitated for 1 hour in a blender partially filled with small glass beads to insure complete separation of the grains. The samples were washed and decanted, as above, and boiled again for 12 hours in HCl. They were then washed, decanted, and dried for 24 hours in an oven at low temperature. The samples after drying were then prepared for petrographic analysis through the use of the standard heavy mineral separation by settling technique. The heavy liquid used was bromoform. The light and heavy fractions were mounted on slides using Lakeside 70 cement. Cover glasses were applied, after which the slide was cleaned with xylene and considered complete.

CHAPTER V

PETROGRAPHIC TERMINOLOGY AND CLASSIFICATIONS

General History

Witham (1883), and Hutton (1883) made the first microscopic analysis of coal. They used thin sections and discovered that the bright megascopic bands observed in coal were composed of a translucent homogeneous substance with vegetable structure occasionally visible. They also described the materials (spores, pollen, cuticle, etc.) found in the dull bands as "plant cells." Their discoveries showed that these layers were interbedded, and in many instances separated with mineral charcoal (fusinite). From these observations, they concluded that all coals are derived from vegetable matter, and that different types of coal were due to different vegetable sources and materials. They described many plant structures, and their methods and findings became the dominant means of coal investigation until the early 1900's.

Hickling (1917), a follower of the Witham and Hutton school, stated that all bright bands in coal show plant structure.

In 1920, R. Thiessen introduced the terminology for the microscopic analysis of coal by the thin section method based on botanical origin, i.e., the recognition of plant parts and pieces as well as plant decomposition products. This terminology evolved, through improvement of microscopic techniques, preparation methods, and compilation of data, into the American (Pittsburgh) Classification.

Stopes began studying polished sections after the introduction of her megascopic terminology (1919) and attempted to apply those terms to her microscopic examinations.

Duparque (1926), after studying polished sections, proposed the term "xylovitrain" for structureless bright bands, and "xylain" for bright bands with structure. This contradicted Hickling's findings and the argument over structureless bands is still going on among coal petrographers. Potonié (1924, 1926) proposed the terms "euvitrit" for structureless bright bands and "provitrit" for bright bands exhibiting structure. Potonié also proposed that some structureless bright bands are colloidal.

Evans, Slater, and Wheeler (1929) studied polished and etched surfaces of coal and stated that all surfaces of coal show structure.

Stopes (1935) proposed a revised terminology for the examination of polished sections based on the recognition of petrographic entities with similar physical and chemical properties. This terminology was adopted the same year with some modifications by European coal petrographers at a conference at Heerlen, The Netherlands. This terminology has since evolved into the present European (Heerlen) Classification.

American (Pittsburgh) Classification

Cady (1942) introduced and defined the basic petrographic entity of the American classification, the phyteral. He defined phyteral as those petrographic entities based on the recognition of plant parts, pieces, and plant decomposition matter. Thus the American terminology is a genetic classification with the phyteral content being fixed at the beginning of coalification. A phyteral retains its identity throughout the metamorphic cycle of coalification, although its chemical and physical composition varies pronouncedly with the degree of coalification. Recognition becomes more difficult with advancing metamorphism.

TABLE I. NOMENCLATURE OF COAL CONSTITUENTS

EUROPEAN-HEERLEN CONGRESS CLASSIFICATION, 1951				AMERICAN-PITTSBURGH CLASSIFICATION	
MACERAL	SUB-MACERAL	CONSTITUENTS	REFLECTANCE	CONSTITUENTS	PHYTERAL
VITRINITE	TELINITE	WOODY TISSUE WITH CELL STRUCTURE	MODERATE	TRANSPARENT CELL MATERIAL	ANTHRAXYLON
	COLLINITE	COLLOIDAL MATERIAL DEVOID OF STRUCTURE (NOT SEEN IN THIN SECTION)		HUMIC DEGRADATION MATTER	TRANSLUCENT ATTRITUS
	PERIBLINITE	CORTICAL TISSUE		BROWN CELL WALL MATTER	
	SUBERINITE	CORKY TISSUE			
EXINITE	SPORINITE	SPORE EXINES	LOW	SPORES, POLLEN, AND SEEDS	
	CUTINITE	CUTICAL MATERIAL		CUTICLES	
RESINITE		RESINOUS BODIES		RESINOUS BODIES	
ALGINITE		ALGAL BODIES			
MICRINITE	GRANULAR MICRINITE	OPAQUE SUBSTANCES (NOT YET IDENTIFIED WITH VEGETABLE TISSUE)	HIGH	GRANULAR OPAQUE MATTER	OPAQUE ATTRITUS
	MASSIVE MICRINITE			AMORPHOUS OPAQUE MATTER	
SCLEROTINITE		FUNGAL BODIES		PARTICLES OF FUSINIZED TISSUE	
SEMI-FUSINITE		OPAQUE MATERIAL WITH DISTINCT CELL STRUCTURE TRANSITIONAL IN REFLECTANCE BETWEEN VITRINITE AND FUSINITE	HIGH MODERATE	NOT RECOGNIZED IN THIN SECTION	
FUSINITE		OPAQUE MATERIAL WITH DISTINCT CELL STRUCTURE	VERY HIGH	OPAQUE MATERIAL WITH DISTINCT CELL STRUCTURE	FUSAIN

J.S. McKinney, 1959

The phyterals of the American classification are defined as follows:

Fusain. A minor constituent of most coals, fusain in thin section always appears opaque, being recognized by its cell structure.

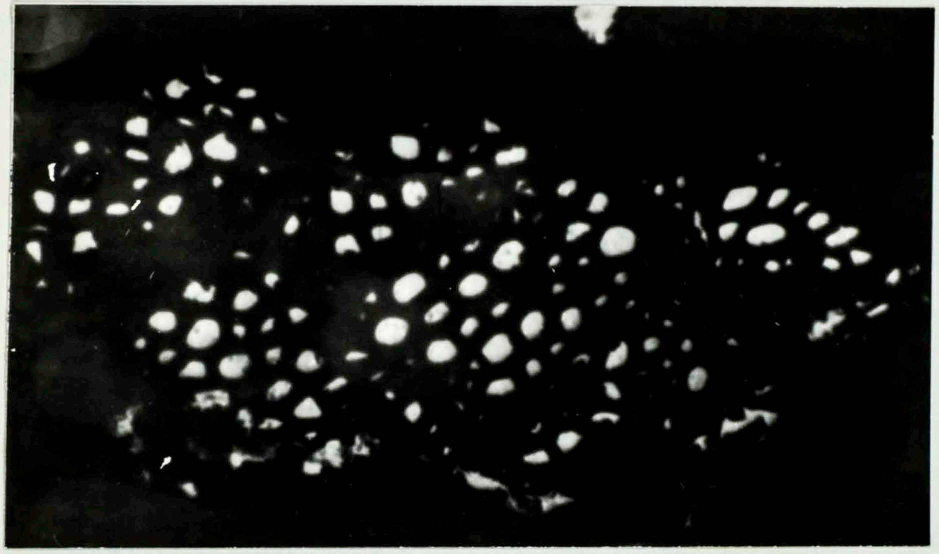


Figure 2. Fusain; dark portions are the cell walls, light portions cell lumens. x290.

Schopf (1948) defined the microscopic subsize threshold of fusain at 37 microns when viewed at 60x. All fusain-like material of smaller size was grouped with opaque attritus, discussed later in this section.

Anthraxylon. Microscopically, anthraxylon appears bright red-orange, red, or brownish in color, often exhibiting some degree of cellular structure. It is botanically composed of the cellular tissues of stems, branches, twigs, roots, sporangia, and leaves.

Figure 3. Anthraxylon, showing very faint distorted cell structure. The Croweburg coal characteristically shows poor, if any, cell structure. x110.

Schopf (1948), while in search of a practical size limit for the several phyterals recognized in coal petrography, set the subsize threshold of anthraxylon at 14 microns when viewed at 150x. All smaller anthraxylon bands were grouped with translucent attritus. This is the standard now used by the U S. Bureau of Mines. Other investigators have set the subsize threshold at their convenience ranging from 14 microns to 2 mm. A practical approach was suggested by Cady (1942), in a comparison study of the American and European classifications. Cady proposed that anthraxylon (vitrain of the European terminology) bands thicker than 2 mm, with a tolerance of 1 mm, be termed as at present, and all smaller anthraxylon bands be termed "micro-vitrain." Cady's limit was based on the crushing and screening properties of coal. Anthraxylon, in the crushing process, naturally breaks away from the coal blocks, if in bands greater than 1 mm. A microscopic critical limit, set at such a point, based on the physical properties of coal, is well taken.

<u>Attritus</u>. Viewed microscopically in thin section, attirtus consists of a mixture of translucent red, brown, yellow, and opaque substances. These constituents are a mixture of finely macerated plant debris, resulting from plant decay and subsequent coalification. In the petrographic analysis attritus is further divided according to the amount of opaque material present. Those bands consisting mainly of translucent material are termed <u>translucent attritus</u> and

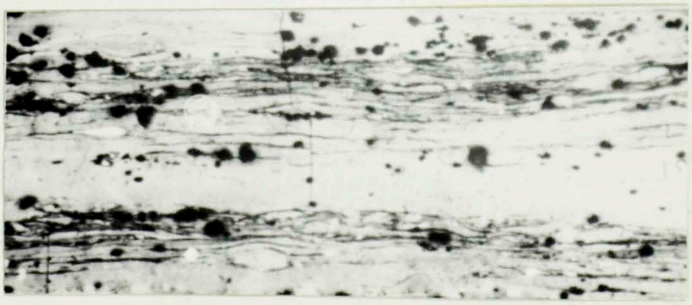


Figure 4. Attrital bands (middle and base of picture) separating two structureless anthraxylon bands. Black dots are pyrite. x250?

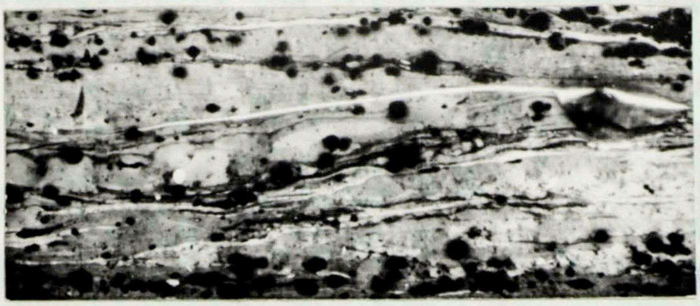


Figure 5. Translucent attritus. x250?

are made up of the following:

1. Translucent cell wall or Humic degradation matter: Celulosic or ligno-cellulosic fragments of wood, phloem, cortex and leaves. This is essentially anthraxylon; however, it is that material thinner than the designated critical limit of anthraxylon. Humic degradation matter often forms the groundmass of attritus (Fig. 5,a).

2. Brown cell wall matter: Bark tissue (Fig. 5,b).

3. Spores, pollen and seeds: Brilliant orange to yellow rings, flattened during coalification, representing the exines of spores, pollen, and seeds.

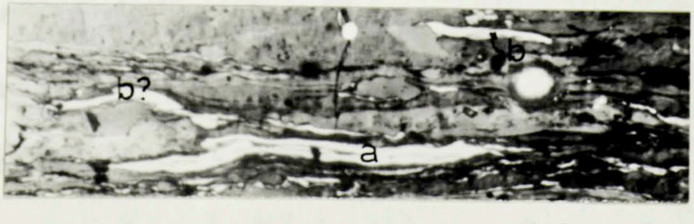


Figure 6. Mega- or isospore (a) and microspores (b) in translucent attritus. x190.

4. Cuticles: Bright orange to gold bands, with serrated edges, representing the former edges of leaves and stems.

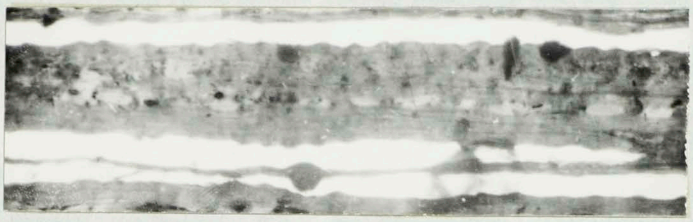


Figure 7. Three cuticles in translucent attritus. x210.

5. Resinous bodies: Dark yellow to light-brown ovules, of resin and wax, which have been extruded from xylem and leaves during coalification (Fig. 5,e).

6. Some opaque matter.

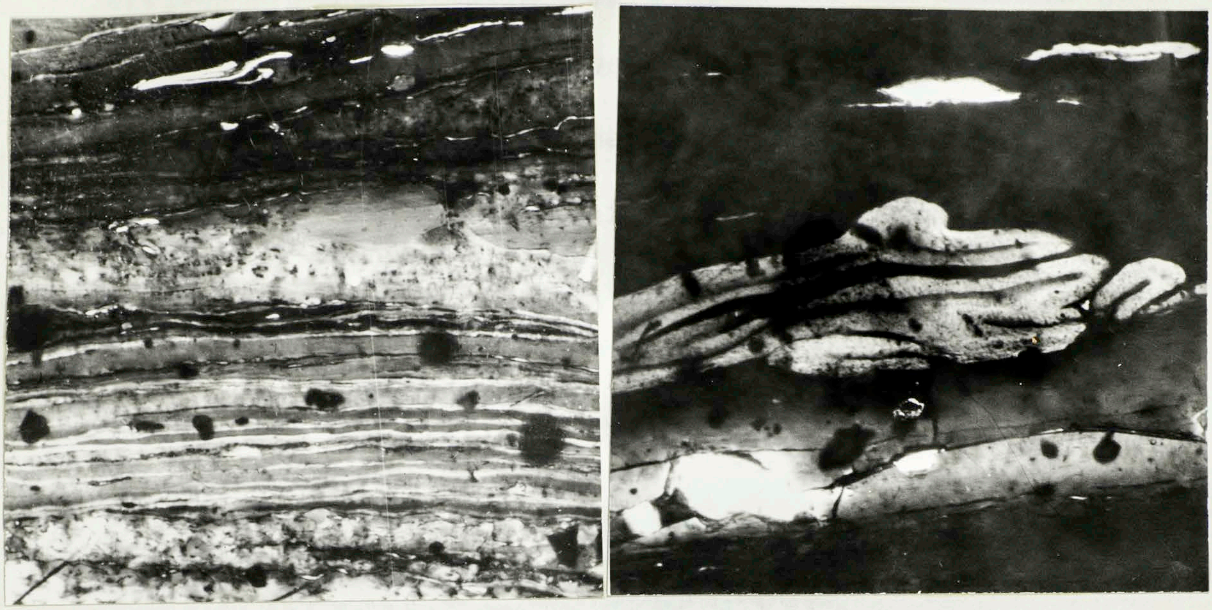
Those attrital bands consisting mainly of opaque substances are termed opaque attritus. Opaque attritus is a mixture of the following:

1. Granular opaque matter: Opaque materials derived from highly decomposed wood fibers, mainly coniferous wood (Thiessen and Sprunk, 1935), and fungal tissue.

2. Amorphous opaque matter: The botanical relationship of this material is unknown.

3. Particles of fusinized tissue.

4. Some translucent attrital matter.



A B

Figure 8. Opaque attritus. (A) Gradation of translucent attritus, at the base of the figure, to opaque at the top portion. x210. (B) highly distorted mega- or isospore in opaque attritus. x200.

European (Heerlen) Classification

In 1935, Stopes defined the basic petrographic entity of the European classification the maceral. Macerals are identified on the basis of physical and chemical similarities of composition, as are minerals. This classification, through division of the attrital components, is more specific than the American classification, thereby allowing physical and chemical property studies of the several macerals resulting in better and more valuable analytical data for use by the coal industry.

The maceral terminology adopted by the Heerlen conference was used in this analysis, with some slight modifications deemed optional by the members of that conference. The terminology and petrographic description of the several macerals is as follows:

Fusinite. Fusinite is identical to the fusain of the American classification. In polished section this maceral is recognized by its extremely high reflectance, high-white to yellow-white under magnifications of 200x or greater, using blue filtered light, and by its cell structure, thin or thick, carbonified, hard, cell walls with either mineral filled or empty lumens.

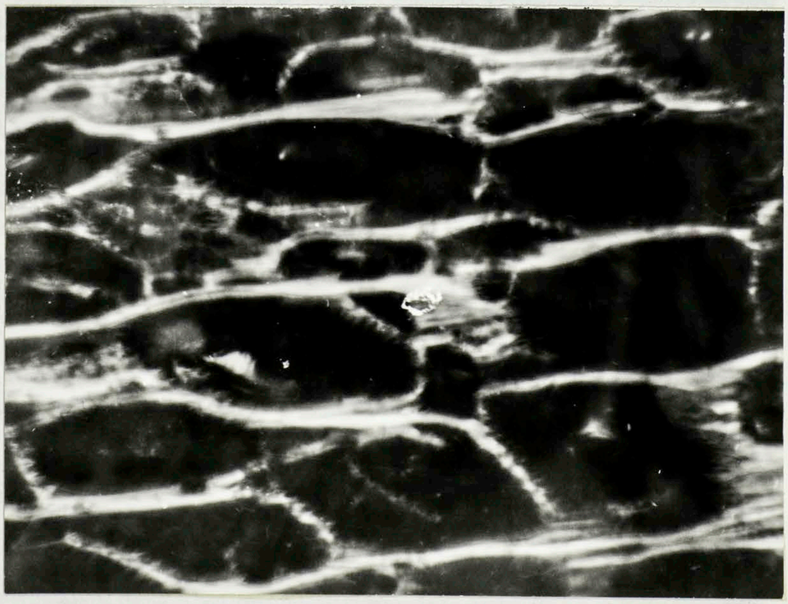


Figure 9. Fusinite, thin walled, typical of the type found in the Croweburg coal. x325.

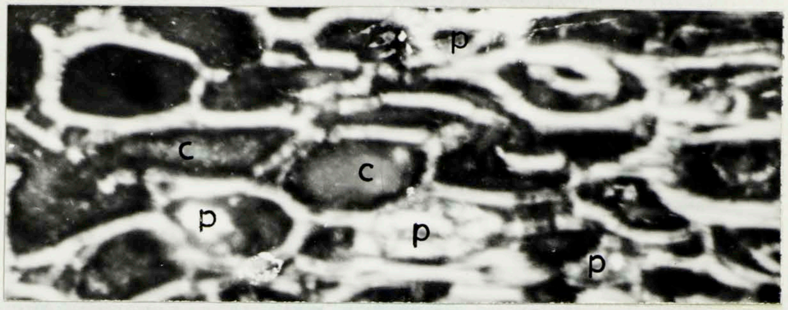


Figure 10. Fusinite, with lumens filled with (p) pyrite, (c) calcite. x230.

If the cell walls are crushed, as is often the case, the resulting structure is termed "bogenstruktur."

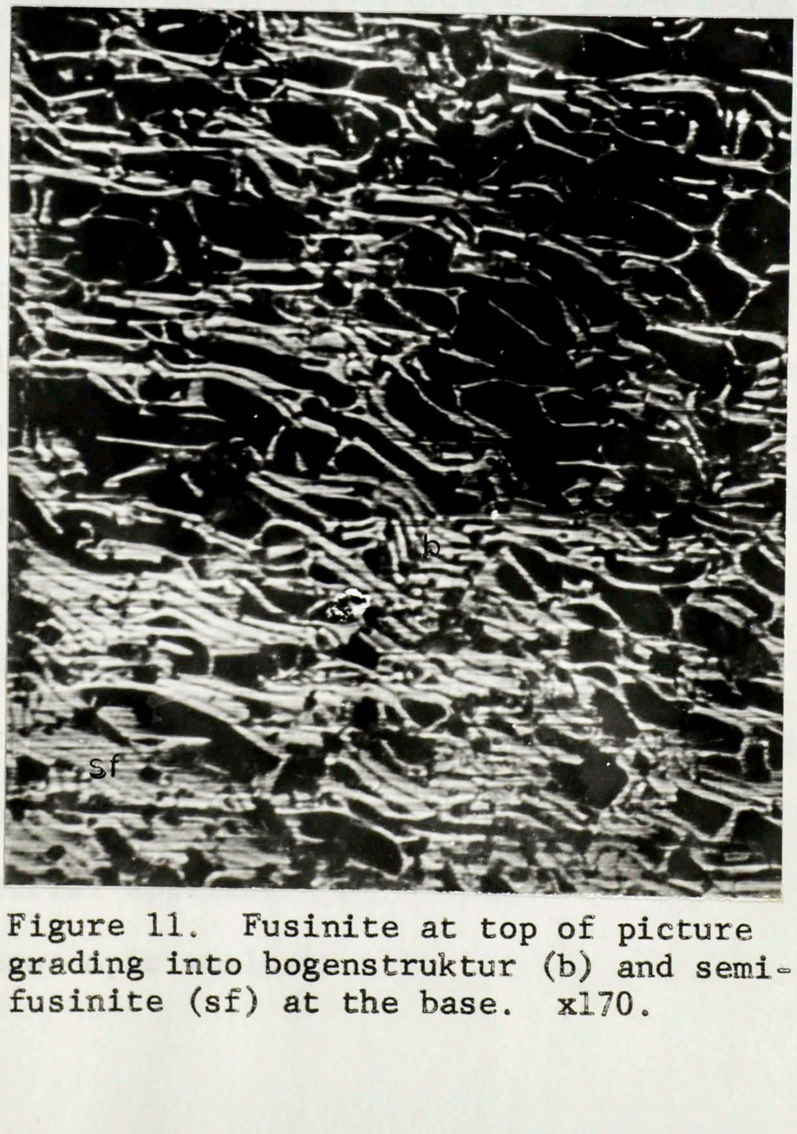


Figure 11. Fusinite at top of picture grading into bogenstruktur (b) and semi-fusinite (sf) at the base. x170.

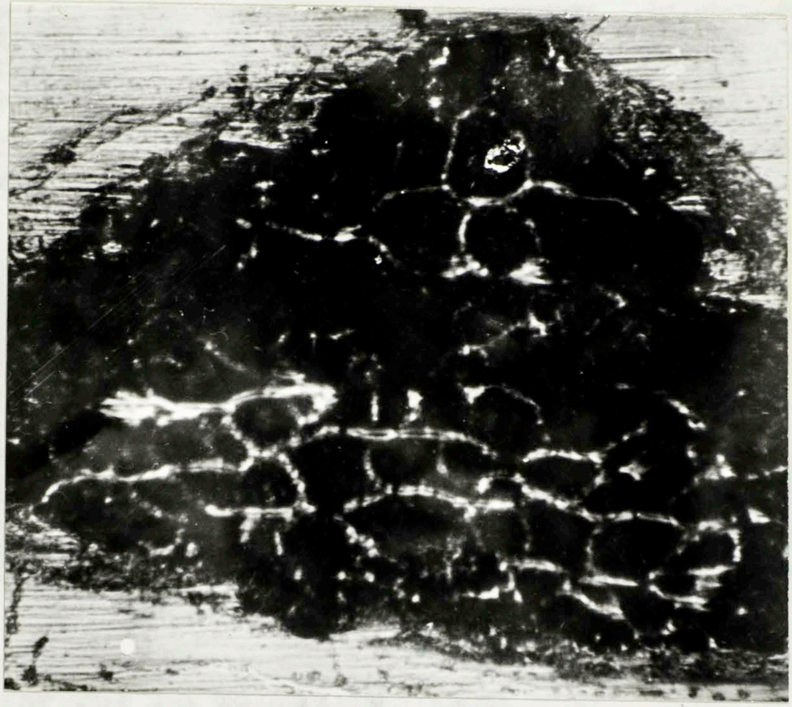


Figure 12. Transverse section of a fusinized twig. x160.

Vitrinite. Vitrinite, the principal maceral in coal, is botanically analogous to anthraxylen of the American classification. This maceral is readily recognized by its light gray color, extremely smooth silky luster, or by its cell structure, if present.

Hacquebard (1950) set the critical limit of vitrinite at 1 mm. Stach placed the critical limit at 25 microns. The writer prefers the use of the 1 mm critical limit because of its industrial applications; however, the use of this limit in microscopic analysis will, in the writer's opinion,

Figure 13. Vitrinite, structureless, diagonal striae due to polishing. x75.

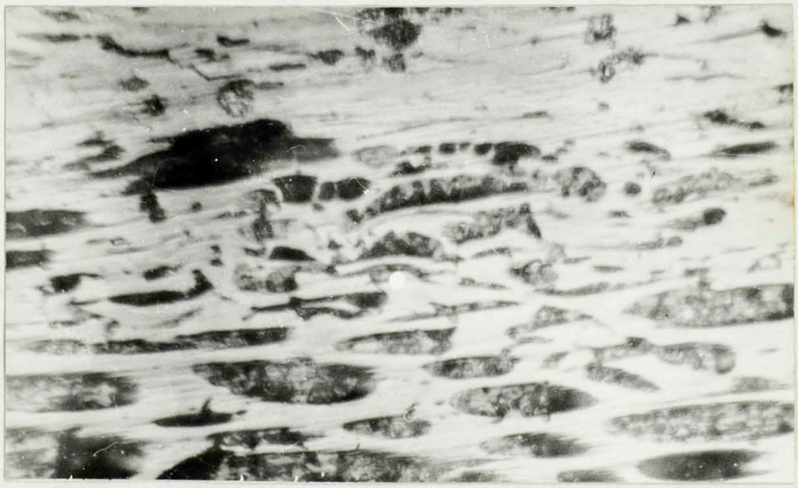


Figure 14. Vitrinite?, showing cell structure. x395.

allow errors in the quantitative analysis. This problem was solved by using a 17 micron critical limit for vitrinite, thus using a datum that may be translated by the American petrographers, and counting only those bands of 1 mm containing 95 percent or more vitrinite in the quantative analysis (Chapter VI), thereby giving a usable industrial figure based on the physical properties of vitrain (Chapter VII).

Vitrinite may be divided into "sub-macerals" as follows:

1. Telinite: Woody tissue having cell structure (Fig. 13).

2. Collinite: Colloidal material devoid of structure which permeates all coals.

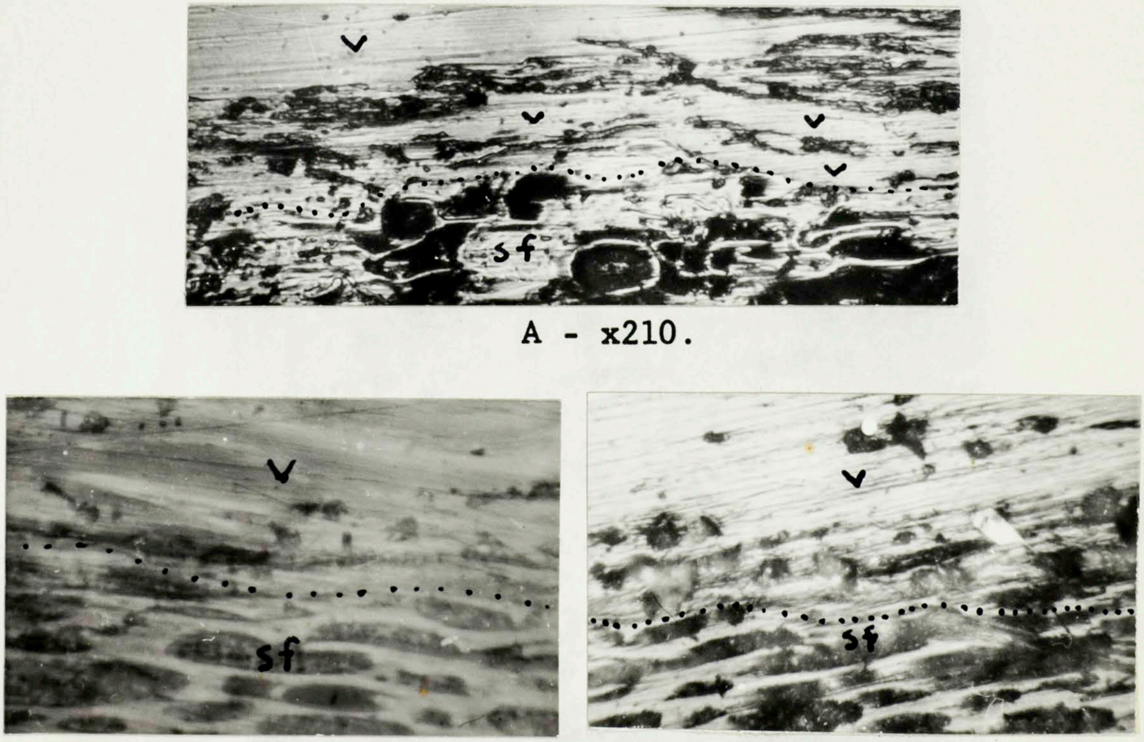
Telenite for the convenience of the paleobotanist may be further divided on a botanical basis into:

1. Periblinite: Cortical tissue.

2. Suberinite: Corky tissue.

Semi-fusinite. It has become more apparent to coal petrographers, using the polished section method, that fusinite and telinite are the same botanical entity, being end members of a transition dictated by the depositional environment and the degree of coalification. Semi-fusinite is therefore used to describe all transitional entities between the two end members. Semi-fusinite is difficult to identify because of its usual lack of or poorly defined cell structure, and its reflectance, being intermediate between

Figure 15. Semi-fusinite (sf) easily separated from vitrinite (v). x300.



A - x210.

B - x300.

C - x320.

Figure 16. Three stages (A-C) of semi-fusinite (sf), becoming increasingly difficult to differentiate from the end member vitrinite (v) until in picture C recognition is extremely doubtful.

fusinite and vitrinite. This maceral in a given coal sample is usually represented by a series of isolated intermediate reflectance and structure stages between the two end members, rather than a continuous gradation. Once these intermediate stages are identified as semi-fusinite by comparison with the two end members, recognition becomes relatively simple, as long as a particular stage is not too similar to one of the end members.

Figure 17. Complete transition from vitrinite (v) to semi-fusinite (sf) to fusinite (f). x160.

A continuous complete transition from vitrinite to fusinite is the exception rather than the rule; often, however, one may find half series of fusinite to semi-fusinite or semi-fusinite to vitrinite.

Exinite. Remains of spore and pollen exines, seed coverings, cuticle, and bituminous fragments comprise the maceral, exinite. Exinite is recognized by its low reflectivity and by the characteristic shapes of its botanical entities. Exinite may be further divided into "sub-macerals," for botanical purposes, as follows:

Figure 18. Exinite in vitrinite (v) groundmass. Note mega- or isospore (x), microspores (y) unidentifiable bituminous fragments (z). x140.

1. Sporinite: Spore and pollen exines with characteristic flattened "doughnut" shape are termed sporinite.

2. Cutinite: Cuticle material recognized by its elongate, slender strands, and serrated edges.

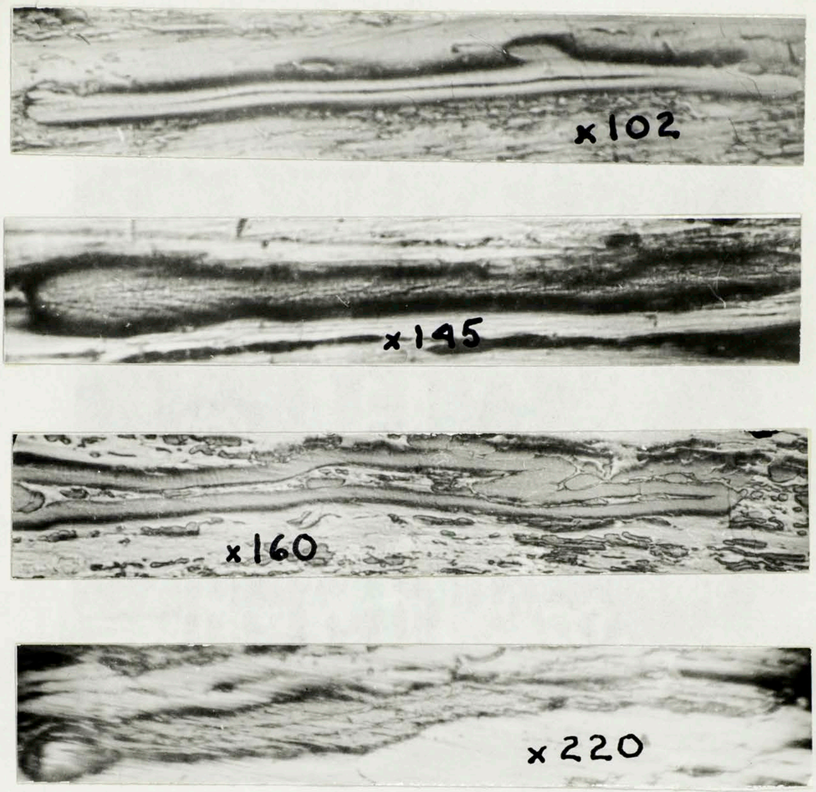


Figure 19. Mega- or isospores.

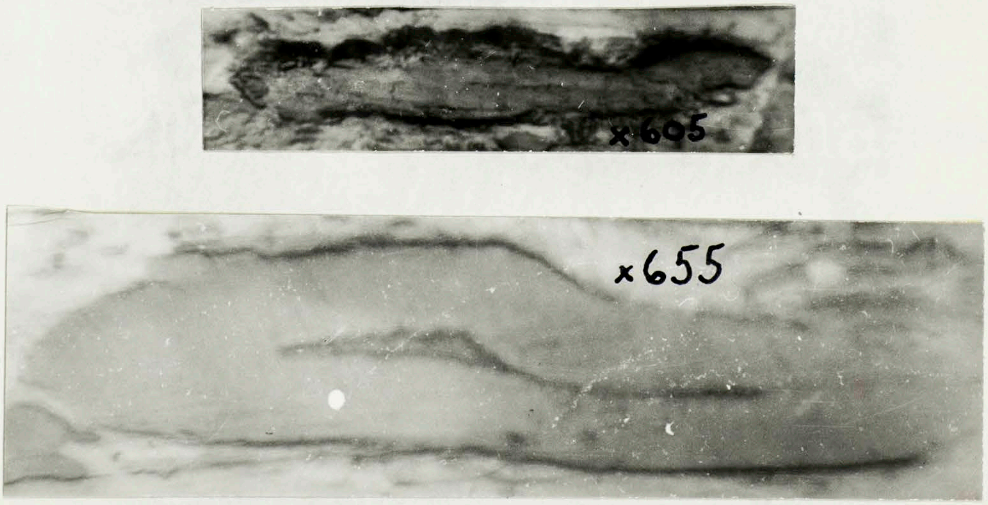


Figure 20. Microspores.

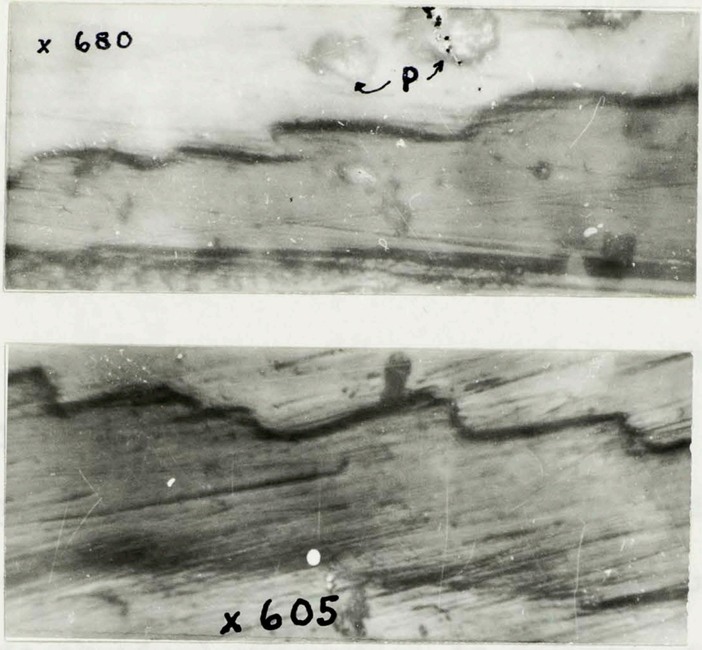


Figure 21. Cuticles showing typical serrated edges. Note pyrite (p) in vitrinite.

<u>Resinite</u>. Oval to rod-like shaped bodies of resin or wax having a low reflectance are termed resinite.

Figure 22. Resinite (r). Note similarity in reflectance between resinite and vitrinite (v). x300.

In this study these bodies were usually recognized by their shape rather than reflectance, because the reflectance of resinite in the Croweburg coal was not consistent, usually being the same as vitrinite. Depending on the desired results and purpose of the analysis, resinite may be combined with exinite as a "sub-maceral" due to their similar physiochemical properties.

Alginite. Algal remains with a serrated oval shape and low reflectance are termed alignite. Inasmuch as it has similar physio-chemical properties to exinite, this maceral may be classed as a "sub-maceral" under exinite.

Micrinite. Substances which have a high reflectance are structureless and are probably derived from humic mud or other unrecognizable fragments of fusinite-like material are termed micrinite. Micrinite may be subdivided into:

1. Granular micrinite: Botanically unrecognizable material having granular appearance.

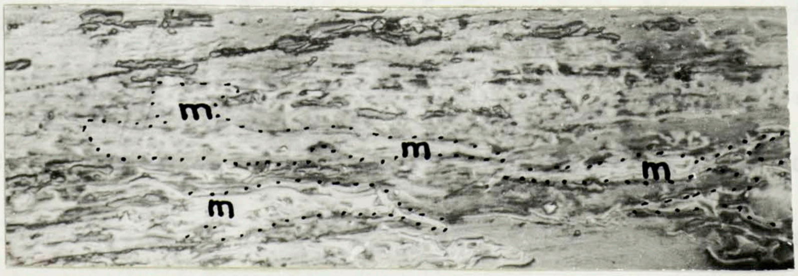


Figure 23. Granular micrinite (m). x180.

2. Massive micrinite: Botanically unrecognizable material having no structure, high reflectance, and smooth texture.

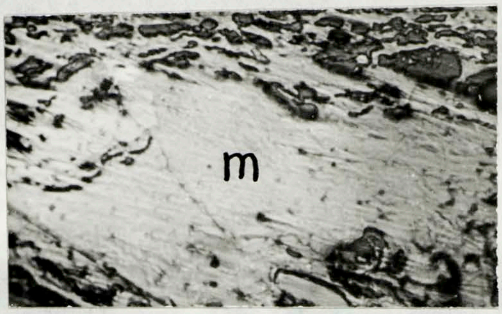
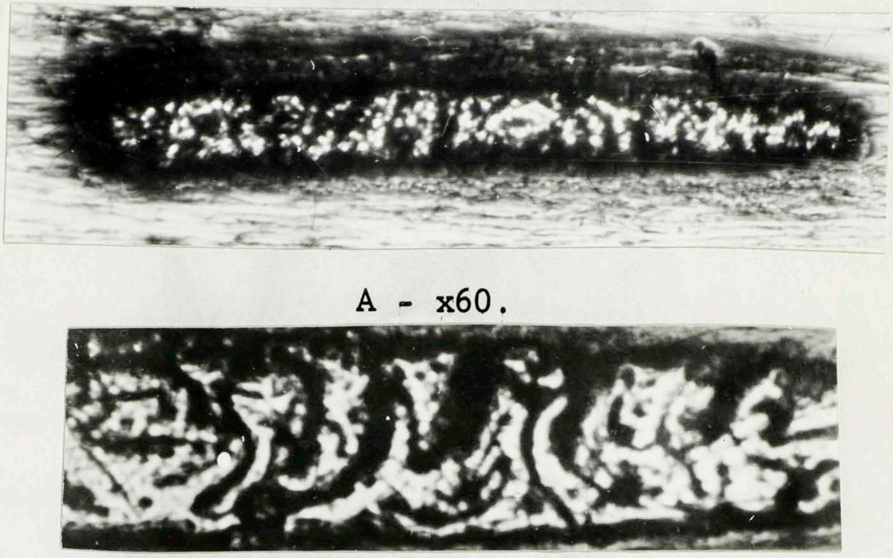


Figure 24. Massive micrinite (m). x165.

Hacquebard (1950) has shown that as seen in thin section much of the opaque material in opaque attritus bands is micrinite. This is particularly apparent through the use of polished thin sections. In the thin section methods used by the American coal petrographers this opaque material is not identifiable, but grades into the surrounding constituents leaving indefinite outlines. Under reflected light these opaque constituents become readily discernible as micrinite, or semi-fusinite and selerotinite (fungal bodies).

Sclerotinite. Remains of fungal bodies having a characteristic oval shape, irregular cell structure, and high reflectance, are termed sclerotinite. This maceral appears to have the same physical and chemical properties as fusinite, semi-fusinite, and micrinite. Some coal petrographers classify sclerotinite as a "sub-maceral" under semi-



A - x60.

B - x150.

Figure 25. Elongate sclerotinite. (A) Entire body. (B) Enlargement of same showing cell structure.

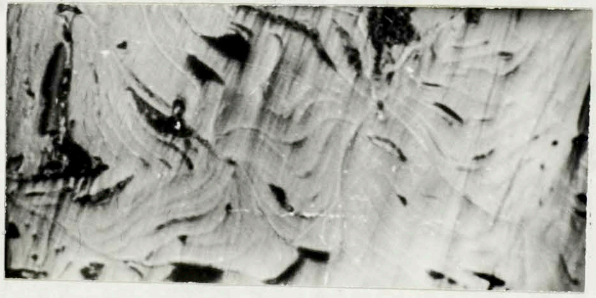


Figure 26. Irregular sclerotinite showing irregular cell arrangement. x180.

fusinite, but the writer chooses to group sclerotinite as a "sub-maceral" under micrinite for the following reason. Semi-fusinite is a transitional phase between two similar botanical entities, therefore sclerotinite, which is a botanical entity (fungal matter) in itself, has no place in

Figure 27. Oval sclerotinite, typical of the type found in the Croweburg coal. x605.

the vitrinite - semi-fusinite - fusinite series. As sclerotinite is not a major constituent of the coal in question, but is important in the determination of coal types (because it is an opaque constituent) it is grouped under micrinite in this analysis.

Grouping macerals in the European classification.

As has been pointed out in the preceding discussion, certain macerals, designated on a botanical basis for the convenience of the paleobotanist, may be grouped according to physical and chemical similarities under the appropriate maceral which has those physio-chemical similarities. This is one of the advantages of the European system, as it allows dual study, that which is advantageous to the paleobotanist and that which, on the basis of physio-chemical characteristics, is advantageous to the coal industry with both using the same terminology.

Mineral Matter

Though an important constituent of coal, minerals are considered accessory entities in coal petrography because of their random occurrence geographically in a given seam and their random maceral association. Minerals are considered separately in all complete analyses because of their physio-chemical influence on the industrial properties of coal and their sedimentological significance.

The two types of mineral matter found in coal are:

1. Inherent: That mineral matter which is organically combined with the coal by the plants for nutrition and preserved in the coalification process with them.

2. Extraneous: The more important of the two types is extraneous mineral matter which is foreign to the plant material comprising coal. Extraneous mineral matter may be further divided into allogenic and authogenic mineral matter for paleogeological purposes.

CHAPTER VI

MICROLITHOTYPES

Industrial reports based on the microscopic entities found in coal would be cumbersome, over-detailed, and of little or no value; therefore, larger groups using the microscopic entities as a foundation were developed. Coal type and microlithotype classifications were proposed in the several countries based on differing criteria, just as the microscopic entities differed from country to country. These classifications cause confusion in coal petrography, because some use terms in common but with different connotations, and others introduce a multitude of new terms. This confusion of terminology is the result of a lack of communications between coal petrographers of different countries. Dissemination of new concepts and information is hindered by the confusion. There is need of a compromise classification to insure the dissemination of information on a common basis among the several countries. The Sydney and Modified Sydney

TABLE II. GERMAN, SYDNEY, MODIFIED SYDNEY AND PITTSBURGH CLASSIFICATIONS OF BANDED COALS

<table>
<tr><th>PERCENT VITRINITE</th><th>GERMAN (E. STACH, 1935)</th><th colspan="2">SYDNEY (P. A. HACQUEBARD, 1950)</th><th colspan="5">MODIFIED SYDNEY (J. S. McKINNEY, 1958)</th><th colspan="2">PITTSBURGH (R. THIESSEN & B. C. PARKS, '48)</th><th>PERCENT OPAQUE MATTER</th></tr>
<tr><td>96-100%</td><td>VITRIT</td><td rowspan="3">BRIGHT COAL</td><td>VITRAIN</td><td rowspan="3">BRIGHT COAL</td><td>VITRAIN</td><td colspan="3">±95-100% VITRINITE</td><td rowspan="4">BRIGHT COAL</td><td rowspan="4">BRIGHT COAL</td><td rowspan="4">< 20%</td></tr>
<tr><td rowspan="2">51-95%</td><td rowspan="2">HUMODURIT</td><td rowspan="2">CLARAIN</td><td rowspan="2">CLARIAN</td><td>PRE-DOMINANTLY</td><td colspan="2">±51-95% VITRINITE
EXINITE</td></tr>
<tr><td>VERY LITTLE</td><td>0-6%</td><td>FUSINITE
SEMI-FUSINITE
MICRINITE
SCLEROTINITE</td></tr>
<tr><td rowspan="4">11-50%</td><td rowspan="4">EUDURIT</td><td rowspan="8">DULL COAL</td><td rowspan="3">CLARO-DURAIN</td><td rowspan="7">DULL COAL</td><td rowspan="2">CLARO-DURAIN</td><td rowspan="2">±15-50% VITRINITE HIGH EXINITE</td><td rowspan="2">DULL CLARAIN
6-20%
20-30%
SEMI-SPLINT</td><td rowspan="2">FUSINITE
SEMI-FUSINITE
SCLEROTINITE
MICRINITE</td></tr>
<tr><td rowspan="7">DULL COAL</td><td>SEMI-SPLINT</td><td>20-30%</td></tr>
<tr><td rowspan="5">DURAIN</td><td rowspan="3">PRE-DOMINANTLY</td><td rowspan="3">>30%</td><td rowspan="3">FUSINITE
SEMI-FUSINITE
MICRINITE
SCLEROTINITE</td><td rowspan="5">SPLINT</td><td rowspan="6">> 30%</td></tr>
<tr><td>— ? — ? — ? —</td></tr>
<tr><td rowspan="4">0-10%</td><td rowspan="3">OPAKDURIT</td><td rowspan="3">DURAIN</td></tr>
<tr><td>SOME</td><td colspan="2">EXINITE</td></tr>
<tr><td>VERY LITTLE</td><td colspan="2">< ±15% VITRINITE</td></tr>
<tr><td>FUSIT</td><td>FUSAIN</td><td>FUSAIN</td><td>PRE-DOMINANTLY</td><td colspan="2">FUSINITE & SEMI-FUSINITE</td><td>FUSAIN</td></tr>
</table>

J.S. McKinney, 1958

classifications, used in this analysis, are attempts at such a compromise.

Megascopic descriptions of coal using microscopic terminology are impractical, just as it is impossible to describe the microscopic constituents using terminology based on megascopic entities. When coal petrography was in its infancy, this was attempted, and some of the terms are still used, i.e., fusain. This adds to the confusion. It has become imperative to have a dual terminology, a microscopic physio-chemical and botanical classification for the petrographer or paleobotanist, and a more general megascopic terminology, having a physio-chemical basis for industrial use. Stopes initiated a classification of this type, using the botanical entities (macerals) found in coal as a petrographic foundation. These macerals were then considered as a normal petrographer would consider minerals. Larger units, microlithotypes, were assigned, based on the relative abundance of the several macerals. The microlithotypes would then be comparable to the several rock types of the normal petrographer. This type of classification places coal petrography on a sound petrographic basis. Unfortunately, it has not been studied and accepted by petrographers of all countries. Until a compromise classification is adopted, the coal petrographer will have to be familiar with the several classifications now in use; therefore, the most common of these will be considered separately in this chapter.

European (Heerlen) Classification

After defining the four megascopic components of coal in 1919, Stopes realized that they were not applicable to microscopic analysis. Upon development of the microscopic terminology, the original megascopic definitions were not adequate, and required modification. These terms being redefined were adapted with slight modification by the Heerlen Conference. The resulting classification was based on the relative amounts of the several macerals. There are no percentage limits based on the macerals present. This creates confusion when comparing the studies of various investigators using this system, because their interpretation can be very broad in a classification without definite boundaries.

The microlithotypes of the European classification are as follows:

Vitrain.

Megascopic bands of very shiny vitreous material composed of vitrinite.

Clarain.

Shiny bands with striated smooth surface, composed predominantly of vitrinite and exinite (including resinite and alginite), having some fusinite, semi-fusinite and micrinite (including sclerotinite).

Durain.

Dull bands appearing rather granular with matted surface, composed of very little vitrinite and much micrinite, exinite, fusinite and semi-fusinite.

Fusain.

Dull bands or lenses having the appearance of charcoal composed mainly of fusinite.

German Classification

Stach (1935) proposed a type classification using the percentage of vitrinite as the controlling factor. The megascopic terms suggested by Stopes were applied to microscopic botanical (as in Thiessen's classification) entities. This results in new definitions of the terms suggested by Stopes, therefore adding to the confusion in coal science. Stach defines coal as being composed of two petrographic entities:

Vitrit.

Bands thicker than 25 microns, conforming to anthraxylon of the American classification. Thinner bands were termed micro-vitrit and are comparable to translucent humic matter.

Durit.

Bands comparable to opaque attritus minus all translucent humic matter.

The five coal types are defined based on the percentage of vitrit:

Vitrit: 96 to 100 percent vitrit.

Humodurit: 51 to 95 percent vitrit.

Eudurit: 11 to 50 percent vitrit.

Opakdurit: 0 to 11 percent vitrit.

Fusit: 0 to 11 percent vitrit, predominantly fusinit.

It should be said that some German petrographers use the European classification rather than that proposed by Stach. They have modified the European terminology to be divided on the basis of vitrinite percentages, as in Stach's classification.

American (Pittsburgh) Classification

Thiessen proposed a coal type classification based on the relationship of anthraxylon and opaque attritus. As in the European classification, there were no critical percentages assigned for the phyteral content of each coal type. As the need for definite for boundaries became apparent, Parks and O'Donnell (1948) introduced the critical amounts for this classification. The American classification is divided into two major groups, based on the percent of anthraxylon present, and the nature of banding.

Banded coal.

Coals with distinct banding having more than 5 percent anthraxylon are termed banded coal. This group contains the most desirable (industrial) coal types. Banded coals are divided on the basis of opaque detritus into:

Bright coal. Coal containing less than 20 percent opaque attritus is termed bright coal. Bright coals are the most desirable industrially.

Dull coal. Coals having more than 20 percent opaque attritus are termed dull coal. Dull coal is subdivided into:

1. Semi-splint coal, containing 20 to 30 percent opaque attritus.

2. Splint coal, containing more than 30 percent opaque attritus.
3. Fusain, coal type composed predominantly of the phyteral fusain (fusinite).

The division of banded coal into bright and dull coal types is misleading in the American classification. Some coal types termed bright may contain little anthraxylon, a great amount of translucent attritus, and up to 20 percent opaque attritus. A coal of this composition physically will appear dull, but is classed as a bright coal according to the American terminology. This contradiction makes the present definitions of the American classification undesirable. Care should be used in the interpretation of bright coal types and their comparison with the bright microlithotypes of the European, Sydney, and Modified Sydney classifications.

Non-banded coal.

Coals exhibiting no banding and containing less than 5 percent anthraxylon are termed non-banded coals. They are divided botanically into:

Cannel coal. Predominantly translucent attritus, having little or no oil algae (alginite). The predominant botanical entities are spores.

Boghead coal. Coal composed predominantly of translucent attritus, with oil algae being the dominant botanical entity.

Sydney and Modified Sydney Classifications

The Sydney classification proposed by P. A. Hacquebard (1950) is a compromise between the European, German, and American terminology, and endeavors to include the most desirable features of each. The Modified Sydney, used in this analysis, contains minor changes in order to form a clearer, more concise terminology. Both classifications use macerals as the petrographic foundation because of their excellent adaptation to botanical and industrial studies. The microlithotypes used in the Sydney and Modified Sydney classifications are those of the European System; however, definite limits are defined for each microlithotype, based on the relative amounts of vitrinite and opaque constituents (micrinite, semi-fusinite, fusinite, and sclerotinite) present. Percentage limits assigned opaque matter in the Modified Sydney classification are identical with those of the Sydney and American classifications. Vitrinite percentages were made flexible because of the critical limit assigned vitrinite and its uncertain measurement. This is due to the occurrence of vitrinite, i.e., as separate bands, and more often as a groundmass containing the other macerals. Vitrinite, when forming a groundmass, often cannot be measured with certainty, because of its varied thickness, and when approaching the assigned critical limit it may or may not be counted, depending on the analyst's interpretation. Measurements made by four persons viewing the same field showed that the judgment of vitrinite varied as much as 7 percent. The opaque macerals usually occur as distinct entities being easily recognized and having clear outlines. This makes their measurement relatively simple. Interpretations by the same four observers on opaque material varied only 0.67 percent. For these reasons, border line cases were assigned microlithotypes, primarily on a rigid basis of opaque percentages, and secondarily on the amount of vitrinite. This is also the reason for the flexibility of the vitrinite percentages in the Modified Sydney classification.

The microlithotypes of the Modified Sydney classification were assigned on the basis of the relative percentages of macerals present per 1 mm, i.e., a given millimeter containing 37 percent vitrinite, 22 percent micrinite (including sclerotinite), 40 percent exinite (including resinite and alginite) is termed claro-durain (for detailed petrographic method see Chapter X).

There are five microlithotypes recognized in the Sydney and Modified Sydney classification:

Vitrain.

Shiny bands greater than 1 mm in thickness composed of approximately 95 to 100 percent vitrinite.

Clarain.

Slightly striated shiny bands composed of approximately 51 to 95 percent vitrinite. Exinite is the predominant maceral other than vitrinite. Opaque macerals may be present from 0 to 6 percent. Clarain is comparable to humodurit.

Claro-durain.

Transitional microlithotype between clarain and durain, with approximately 15 to 51 percent vitrinite and a high exinite content. Claro-durain is not comparable to eudurit because the lower limit of vitrinite has been raised to approximately 15 percent. This microlithotype is subdivided on the basis of opaque macerals in order to correspond to the American classification. The subdivisions of claro-durain are:

Dull clarain. Containing 6 to 20 percent opaque macerals.

Semi-splint. Containing 20 to 30 percent opaque macerals.

Durain.

Microlithotype composed of 30 percent or more opaque macerals with some exinite and less than approximately 15 percent vitrinite. This microlithotype is comparable to splint coal of the American classification but not to opakdurit, because of its higher vitrinite content limit.

Fusain.

Microlithotype composed predominantly of fusinite and semi-fusinite per 1 mm. This microlithotype may be subdivided into two microlithotypes as follows:

Fusain. Composed predominantly of fusinite.

Semi-fusain. Composed predominantly of semi-fusinite.

Vitrain and clarain may be grouped as bright coal. Claro-durain and durain are dull coals. Fusain and semi-fusain, though dull in appearance, remain separate, due to their more direct relationship to vitrain (see p. 44, 46, and 72).

In conjunction with the microlithotypes just discussed, it is desirable to express the banding type of a particular column or seam. This is important in the crushing, screening, mixing and washing of coal in order to eliminate certain undesirable microlithotypes and retain the desirable ones. The banding types are:

Thin-banded: bands 1 to 2 mm thick.
Medium-banded: bands 2 to 5 mm thick.
Coarse-banded: bands greater than 5 mm thick.
Mixed-banded: bands of varying thickness.
Non-banded: no apparent banding.

CHAPTER VII

ORIGIN OF THE COAL COMPONENTS

The discussions of the several classifications in Chapters V and VI should provide a basis of comparison between them; therefore, all ensuing discussions will use those terms as defined in the Modified Sydney classification.

The scope of this study does not permit the discussion of the several concepts of coal formation; however, for the reader's convenience, the following is a partial list of authors whose publications are concerned with the origin of coal: Barghoorn (1952), Lahiri (1950), Moore (1940), Schopf (1948), Seyer (1952), Stutzer (1940), Thiessen (1947), Van Krevelen and Schuyler (1957), White (1925 and 1933), and White and Thiessen (1913). These studies provide a fundamental understanding of the origin of coal and its components, the problems involved, and numerous questions worthy of investigation. The discussion in this chapter will be limited to general concepts concerning the origins of the several macerals. The problem of microlithotype origin may be inferred from this discussion by considering the various origins of the macerals comprising them.

The problem of origin is relatively simple for several of the macerals, because of their botanical implications and modes of preservation.

Exinite.

This material is composed of a host of chemically and physically allied botanical entities and may be best described by subdividing it into its several botanical components. They are:

1. Sporinite. Originating in the reproductive bodies of plants, spores, pollen, and seeds which have similar chemical compositions and behaviors, sporinite is composed of cutical material and waxes, which are very resistant to decay and are plastic enough to withstand distortion during diagenesis. The presence of these bodies in coal is not indicative of depositional environment, except when studied in detail and found in specific generic concentrations within the coal body. Even then such findings should be corroborated by other data, due to the nature of their elimination, method of transportation, and deposition.

A coal type composed almost entirely of sporinite, termed cannel coal, is probably the result of floating spore masses carried to stagnant lakes and ponds by wind and water and ensuing deposition in vegetable mud.

2. Cutinite. Representing the epiderms of plants, cutinite is found principally on leaves, leaf-like organs, and stems. This sub-maceral is composed of cutical impregnated with wax. Cutinite is highly resistant to decomposition, as is sporinite, and is therefore well preserved in coal.

3. Bituminous matter. Materials optically similar to sporinite and cutinite, but too broken and distorted for positive botanical identification. These materials seem to be allied, physically and chemically, to sporinite and cutinite.

4. Resinite. A group of materials composed of resin, wax, and oily bodies, of which resin is the most important. Resins represent secretion products of vegetable metabolism formed in and by the cells. They are also found in the canals and cavities of plants, being stored as a protective agent against decay. Resins leave the plant body in liquid form to close injuries. Resin bodies preserved in coal are rarely of this type, but are the result of inter-

cellular decay during coalification, accompanied by compression which forces the resin out of the decayed cell and into concentrated pockets.

Other rarer types of resinite bodies are formed of fats, oils, and waxes. Fats originate through the break-up of starch and sugar molecules by the plant. Oils form in ripening seeds. Waxes are secreted on the surface and in the epidermal layers of leaves, etc. They are preserved through the decay of the holding parent body with concentration resulting from compaction.

5. Alginite. Algal bodies of a hardened colloidal material which are very rich in fat and protein. The living algae seem to have varying chemical properties which result in various modes and stages of preservation. Modern observations indicate that these algal masses originate in clear, deep, fresh water lakes. This would account for the rarity of such bodies in the normal carboniferous environment and their rarity in the coal products of these swamps.

A coal type consisting almost entirely of alginite, termed boghead coal, is considered to be a transitional stage between coal and mineral oil. Some oil shales may represent concentration of algal masses of this type with a high airborne ash content.

The processes by which vitrinite, fusinite, micrinite, sclerotinite, and semi-fusinite originate are at present largely unknown. The various hypotheses pertaining to their genesis are here discussed:

Vitrinite.

That vitrinite is derived from woody material is undisputible; however, the metasomatic processes involved in vitrinization are unknown, A solution to this problem must explain the banding in high rank coals, absence of cell structure in some forms of vitrinite, and the nature of vitrinite when forming the groundmass in claro-durain and durain.

A logical solution was proposed by Lahiri (1950). Coalification of vegetable material is due to two overlapping processes. The first of these, the lignitic phase, takes place during peat accumulation and is marked by chemical and biological degradation of vegatable material into a swollen polydisperse polymeric gel. This gel in peats and lignites does not exhibit banding or the vitreous luster of vitrinite in high ranked coals. Microscopically, it exhibits all the characteristics of vitrinite in the higher rank coals. Banding, therefore, must be a post-depositional metamorphic effect and not due to differences in plant constituents or plant sorting during deposition. The second or metamorphic stage is marked by compaction of the peat or lignite resulting in dehydration. The larger polymeric units coagulate upon dehydration forming segregated bands and force the smaller molecules out of the system and into the interspacial pores and cavities between the masses of spore exines and other bituminous matter, thus forming the groundmass in which these entities are found in higher rank coal. Therefore, this hypothesis accounts for both collinite and tellinite in coal and the origin of banding.

Another hypothesis explains the genesis of vitrinite by botanical segregation. This solution proposes that woody material is deposited in a swamp under fairly dry conditions. The material sinks rapidly into weak humic soil where all the water is stagnant. In this toxic environment the material is protected from the influence of microorganisms and mummified thus preserving the cell structure. Segregation into bands is due to occasional currents that redistribute the material. Variations of this hypothesis account for gel vitrinite, which forms the groundmass of dull coal, as being formed in deeper water. This environment results in a higher degree of degradation.

Fusinite.

Fusinite is derived primarily from woody materials, but leaves may also be preserved as fusinite. The genesis of fusinite is yet to be solved. It is known that fusinization is the result of rapid carbonization of woody materials under dry conditions. The method in nature of rapid carbonization is unknown . There are three means of rapid carbonization known, none of which fully explain the formation of fusinite. They are:

1. Incomplete combustion. Fusinite formed as the result of forest fire. This is the obvious answer when one initially views fusinite and was considered correct for years. Truly, some fusinite is formed in this manner as evidenced by the presence of ash associated with it. Material resulting from forest fires is not of sufficient quantity to account for all fusain bodies, some of which are 20 feet thick and would require simultaneous growth and burning for a considerable time. The forest fire hypothesis is also refuted in many cases by the presence of resins associated with the fusinite that should have been destroyed by the heat of combustion.

2. Fermentation. Vegetable matter when tightly packed may ferment as the result of exothermic micro-

biological processes accompanied by gradual carbonization. Heat generated by this action occasionally leads to spontaneous combustion. It is significant that in a process of this type, the cell structure would be preserved. It seems probable that combustion of this type would result in the weakening of the cell walls, thus causing them to crumble if pressure were applied.

3. Rapid carbonization in the presence of catalysts. The association of organic matter with fusinite suggests that inorganic matter may act as a catalyst in fusinization.

None of these proposals completely answers the problem of fusinization. Still to be explained are how:

1. Plants of the same type may be either fusinized or vitrinized.

2. The same plant fragment may contain a fusinized portion and a vitrinized portion, plus a gradational zone.

3. Vitrinite and fusinite have different physiochemical properties yet originate from the same material.

4. Semi-fusinite is related to fusinite and vitrinite.

The vitrinite-fusinite problem merits further investigation. Vitrinite is the predominant maceral in coal. Its presence or absence controls the physical and chemical properties of coal. If the physio-chemical processes involved in its formation were known, coal scientists could find better methods of treatment of it in order to produce more coal of industrial value.

Micrinite.

The origin of micrinite is unknown because this material has yet to be identified. It is probably derived from humic mud in a wet open water environment. Some material identified as micrinite is probably finely divided fusinite or sclerotinite. Though not a valid criteria for determining the genesis of micrinite, its similar appearance to fusinite is a possible indication of rapid carbonization.

Sclerotinite.

Fungal bodies which are responsible for the destruction and conversion of organic material in a damp aerobic environment. These bodies are preserved and chemically similar to micrinite or fusinite; therefore, their genesis may be similar.

CHAPTER VIII

RANK VARIATION

Coalification in theory begins with the formation of peat, followed by the lignite, bituminous, and anthracite stages. Compression by overlying sediments seems to be the principal coalification factor until reaching the anthracite stage, at which point heat and pressure must be involved. Gross chemical and physical studies independent of petrographic analysis have shown definite physio-chemical variations with increasing coalification. The various ranking classifications of the several countries have evolved from these relationships. The criteria used to rank coal in the several countries varies with the type of coal available and the ultimate use of that coal. The predominant ranking system in the United States is the American Society for Testing Materials classification, based on the proximate chemical analysis and calorific determination to a mineral-matter-free basis (Table III). An international system, not yet used in

TABLE III

MODIFIED A.S.T.M. CLASSIFICATION BY RANK

(After Hambleton, 1953, as in A.S.T.M., 1938, p. 2)

Class	Group	Limits of fixed carbon or B.t.u. on mineral-matter-free basis	Requisite physical properties
I Anthracite	1. Metanthracite	Dry F. C. 98 percent or more	
	2. Anthracite	Dry F. C. 92 percent or more and less than 98 percent	Nonagglomerating
	3. Semianthracite	Dry F. C. 86 percent or more and less than 92 percent	
II Bituminous	1. Low-volatile bituminous	Dry F. C. 78 percent or more and less than 86 percent	
	2. medium-volatile	Dry F. C. 69 percent or more and less than 78 percent	
	3. High-volatile A bituminous	Dry F. C. less than 69 percent* and moist B.t.u.** 14,000 or more	
	4. High-volatile B bituminous	Moist B.t.u. 13,000 or more but less than 14,000	
	5. High-volume C bituminous	Moist B.t.u. 11,000 or more but less than 13,000	Either agglomerating or nonweathering

TABLE III--Continued

Class	Group	Limits of fixed carbon or B.t.u. on mineral-matter-free basis	Requisite physical properties
III Subbituminous	1. Subbituminous A coal	Moist B.t.u. 11,000 or more but less than 13,000	Both weathering and nonagglomerating
	2. Subbituminous B coal	Moist B.t.u. 9,500 or more but less than 11,000	
	3. Subbituminous C coal	Moist B.t.u. 8,300 or more but less than 9,500	
IV Lignitic	1. Lignite	Moist B.t.u. less than 8,300	Consolidated
	2. Brown coal	Moist B.t.u. less than 8,300	Unconsolidated

* Coals having 69 percent or more fixed carbon (F.C.) on the dry, mineral-matter-free basis are classified according to fixed carbon regardless of B.t.u.

** Moist B.t.u. refers to coal having its natural bed moisture but not including visible water on the surface of the coal.

this country to any extent, is the International Classification system, proposed in 1949 by the United Nations Committee of the Economic Commission for Europe, Van Krevelen and Schuyer (1957). It is a three parameter system based on the volatile matter content, coking properties, and caking index of coals.

Physio-chemical Rank Variations of the Coal Components

Macerals and microlithotypes vary optically when coals of various rank are analysed. The gross physio-chemical features of coal vary with rank; therefore, the physio-chemical properties of the petrographic components must vary similarly. To determine the rank variations of the petrographic components, they must first be separated. Pure separations of all the components have not yet been achieved. Therefore, the various attempts to determine the physio-chemical properties exhibited by the petrographic components contain numerous contradictions and are generally open to question. Some reliable data are available for bituminous coal. Separation of the microlithotypes has been achieved; however, inconsistencies among the several investigators in defining the maceral percentages of clarain, clao-durain, and durain, have resulted in some confusing and contradictory data. The following statements pertaining to the physiochemical properties of the microlithotypes within a given rank may be considered reliable:

1. Vitrain has a lower volatile matter, hydrogen, nitrogen, carbon, and ash content than clarain.

2. Clarain generally has a lower ash and carbon content, higher volatile matter and sulfur content than dull coals. Dull coals, being a random mixture of macerals, may exceed clarain in volatile matter content when they are high in exinite.

3. Fusain has a higher ash and carbon content, and lower volatile matter content than dull coals. Fuasin is chemically inert.

Data pertaining to the macerals are largely hypothetical, due to the extreme difficulty in achieving a pure separation. Vitrinite probably has the same properties as vitrain, but if occurring in two forms as suggested previously, these forms would be expected to have two separate physical and chemical properties. Vitrinite is known to be the coking component in coal; however, pure bands of vitrinite of the vitrinite-fusinite series do not readily coke. Gelled vitrinite may therefore be the more active coking agent, or it may act as a catalyst, causing the vitrinite of the vitrinite-fusinite series to coke more readily. At present separation of pure vitrinite, in its two forms, is impossible, so that there are little reliable data available to support this theory.

Exinite, resinite, and alginite have been isolated, and are the components which contribute volatile matter. These macerals could be termed hydrogenites.

Fusinite, micrinite, and semi-fusinite are chemically inert and could be termed inertites. Sclerotinite, though not separated in pure form for chemical analysis, may be included in the inertite grouping on the basis of its optical similarity to the other macerals comprising this group.

Using the above relationships, which pertain to bituminous coal, as a basis of comparison, the physical and chemical properties of the coal components that vary with rank are:

1. With increasing rank the elemental differences of the components decrease. There is a general decrease in moisture and volatile matter content, and an increase in carbon, thereby approaching the chemical composition of fusain.

2. The maximum degree of polymerization and uniformity of particle size is reached in anthracite.

3. Vitrinite is the coking component only in coals having 19-33 percent volatile matter content. It is non-coking in higher ranked coals.

4. The refractive and reflective indices of vitrinite increases with increasing rank.

5. The bitumen content of durain decreases with increasing rank.

CHAPTER IX

INDUSTRIAL APPLICATIONS OF COAL PETROGRAPHY

The ultimate purpose of coal petrography is the improvement of mined coal for industrial use, and the provision of a basis for mining low grade coals in order to expand the coal mining industry. This can be accomplished only through the knowledge of the relationship existing between the physio-chemical properties of coal and its components. This knowledge may be achieved through the cooperation of the several sciences concerned with coal. Comprehension of the physio-chemical properties of the coal components will enable the coal petrographer to produce coals suited for the specific tasks required by modern industry. The method in which mining and chemistry may be allied with coal petrography, in order to obtain the best fuels and chemicals from the available raw materials, may be demonstrated by the following hypothetical example of the mining, preparation, and processing of a bituminous coal.

Analysis of the seam prior to mining can provide data on where to mine the best grade coal, component concentrate zones which may be used for a specific type fuel or chemical, areas and zones within the seam not suitable for mining, and areas designated for mixing in order to raise the quality of a lower grade coal.

During mining, the extraction of coal is effected by two fracture zones perpendicular to the bedding, called cleats, cleavage, or slynes and by parting parallel to the bedding. The most pronounced cleat, usually found normal to the strike of the seam, is termed the face cleat. Coal is worked away from the face cleat. The less prominent fracture zone, usually perpendicular to the face cleat, is termed the butt cleat, and is used to control the width of blocks removed from the face. Parting parallel to the bedding is controlled by concentrate zones of the petrographic constituents, usually fusain or vitrain. A seam with thick vitrain and fusain bands will respond more readily to cutting and shooting. Mine dust encountered during mining is largely governed by the amount and thickness of fusain in the seam. Vitrain contributes dust to a minor degree because of its brittleness, causing it to break into small pieces. Coal dust produced in mining is rich in fusain and vitrain, whereas lump coal is durain and claro-durain rich.

The mined coal is cleaned and screened for size at the preparation plant, to be sold directly or used in further processing to produce a coal for a specific task. Coals for specific industrial uses are crushed, concentrated, and mixed on the basis of their petrographic constituents. Superficial separation of the petrographic constituents governed by the breaking properties is achieved during mining and initial commercial screening. The initial separates are crushed by elastic pounding in order to achieve the best separation of the components. The success of this crushing is controlled by the nature of banding and the mutual relationship of the macerals. If the microlithotypes contain bands high in vitrinite, a good separation is obtained. The crushed coal is again screened. Vitrain, vitrinite rich clarain, and fusain are concentrated in the finer screenings. Durain and claro-durain concentrate in the larger screens in the form of large irregular flat splinters, because the random mixture of the macerals comprising these microlithotypes are usually cemented by fine bands of gel vitrinite thus providing a strong mutual adherence. The fractions are further purified by gravity separation, flotation, or electrostatic separation. In gravity separation vitrain and clarain are concentrated in the lighter portion, and the dull coals are concentrated in the heavy portions. Fusain may be removed from vitrain and clarain by electrostatic separation, owing to its conductivity, or by flotation, due to its high specific gravity. Mineral matter is removed by commercial washing. The concentrates are now ready for processing.

At the processing plant, the concentrates are divided into coking or briquette fractions (vitrain and clarain), distilling fractions (claro-durain and durain), and additive fractions (fusain). The coking fractions are prepared for by-product coking. This process is more economical than the beehive coking method which was used to a great extent in the United States. In the United States, coals are mixed for coking on the basis of gross proximate analysis. In general coals are used and mixed to obtain a volatile matter content of 26 to 35 percent. Sulfur and ash must not exceed 1 and 5 percent respectively in first grade coke. Second grade coke may have a sulfur and ash content of 1.2 and 10 percent respectively. When coking coals are prepared with the aid of petrographic analysis, the mixture of vitrain and clarain is controlled depending on the type coke desired. Exinite found to some extent in vitrain and in larger amounts in clarain, upon heating, forms a dense plastic melt which is non-coking; however, its presence seems to activate the coking properties of vitrain. This may be due to the gelled vitrinite acting as the exinite groundmass. Exinite releases large amounts of gas during coking, causing the coke to be more porous. Vitrain and vitrinite rich clarain produce a low strength coke because of their very low ash content. Coke of this type may be strengthened by controlled addition of minor amounts of fusain or micrinite rich durain. Fusain is a non-coking chemically inert substance and if added to the coking mixture in excess of 8 to 10 percent is detrimental to coke. If the demand for coke is great, vitrinite rich bright coals may be added to durain or claro-durain to produce coke (the vitrinite groundmass in durain is the coking constituent). Dull coals used in coking must have a low bitumen content because the presence of bitumen reduces the volatile matter content. Due to the large amounts of inertite present in durain, the coke produced has a high ash content.

Eight to 20 tons of the mixture are placed in the oven, depending on its size, and heated to about 2000 F. Gas from the roasting coal is drawn off and used to heat the regenerators, which in turn heat the air and gas which is used to heat the oven. The charge is fired for 12 to 24 hours, depending on the type of coke desired. The coke is then removed, quenched, and upon cooling, is screened for size and distribution. The finer sizes, coke breezes, are sold for various industrial uses or briquetting. Gases produced during coking, in addition to supplying heat to the regenerators, are cooled and distilled into tars, oils, and gases. Uniform heat and low temperature produce the maximum amount of tar, which is collected by cooling the gases and by mechanical means. Tar is used for industrial purposes or further broken down into chemicals by fractional distillation. Oils and gases are distilled and sold as chemicals. Some of the gases produced during coking are used directly for illumination or domestic heating.

Briquettes are made by mixing coke breezes to the coal dust remaining after mining and preparation. Clarain produces the best grade briquet. Vitrinite rich briquettes are low strength, and fusain is added to the mixture in amounts up to 15 to 25 percent as a strengthening agent. It is claimed that the addition of fusain also reduces the smoking tendency of the briquettes. Pitch, a by-product of the fractional distillation of tar produced in coking, is used as a binding agent.

The heavy concentrates and the larger screenings remaining from the preparation step, which were not coked, are distilled into chemicals by destructive distillation. This fraction, being rich in durain and claro-durain, will usually produce large quantities of volatile matter if high in exinite, and will always produce great amounts of tar.

In this way all the available coal is utilized to its greatest advantage, thus producing better end products for industrial use.

CHAPTER X

PETROGRAPHY OF THE CROWEBURG COAL

Petrographic Technique

A reflecting microscope with a mechanical stage was used to make the analysis. The eyepiece was equipped with a micrometer grid 5 mm square, with sub-square divisions of 0.5 mm. A north-south column, two sub-squares wide in the center of the grid, was chosen to be used as the measurement path. The linear distance, covered by the measurement path and each of its sub-squares, was computed for magnifications of 100, 200, and 400. The illuminator and illuminating unit should have a field diaphragm to provide maximum contrast without unnecessary glare, and an aperture diaphragm placed in front of the plano-reflector to regulate the numeral aperture of each objective. The illuminating unit should be powered by a variable transformer. Blue light affords maximum observation with minimum eye fatigue.

A slide to be analysed was placed in the microscope with the section number to the left of the operator, thus assuring proper orientation of the section in respect to the seam (top of seam is away from observer). The section was then scanned, using 100x, to find two traverse paths perpendicular to the bedding, approximately 1/3 of the distance in from the left and right edges of the section. A double traverse reduces the margin of selective error on the part of the analyst and provides a statistical average for the composition of each section. Upon selection of the traverse paths, the magnification was changed to 200x, and all ensuing measurements were made using this magnification.

Due to the irregular shape of the sections, a line, "bedding line," parallel to the bedding near the top edge of the section (away from observer) was selected as a starting point. This assured parallelism between the two traverses, thus decreasing error in the statistical average.

The predominant maceral in each sub-square was counted, working away from the "bedding line" toward the outer edge of the section. When the total sub-square length of the grid was counted, the stage was moved, placing the bottom of the grid over the position formerly occupied by the top edge, thus moving the grid toward the top edge of the section by its exact length. The count was repeated for the area covered by the grid, and then the grid was moved again as above. The procedure was repeated until 1 mm had been traversed. The total count for each maceral was then recorded on a data sheet and the process begun anew for the next millimeter in the path. This procedure was repeated until the top edge of the section was reached.

Upon reaching the top edge of the section, the stage was moved, placing the grid back on the "bedding line," and the process repeated until reaching the bottom of the section. This traverse was then considered complete.

The grid path was then moved to the second traverse path at the "bedding line," and the above technique again applied.

This procedure was applied to each section in sequence from the top to base of the seam, thus producing a record of the macerals present for each millimeter throughout the sample.

A magnification of 400x was used to study particularly interesting portions of the sections in detail, or areas in the traverses which were difficult to distinguish.

Statistical Methods

The average percentage of maceral occurrence for each millimeter was computed and recorded using the following formula:

$$\text{Average percent of each maceral per mm} = \frac{\text{No. of sub-squares occupied by a particular maceral}}{\text{Total No. of sub-squares}} \times 100$$

Bar diagrams (panel I) were constructed showing the percent of maceral occurrence for each millimeter throughout the seam. These diagrams are not practical for seams of great thickness, in which case they are omitted except for zones of particular interest.

The percentage of occurrence for the microlithotypes per 50 mm interval from the base to top of the seam was determined and plotted as a composite bar (panel I). This was done by computing the microlithotype represented by each millimeter and finding the percentage of occurrence for each microlithotype for the 50 mm interval. This technique was used by Hacquebard in his earlier work; however, he now advocates the abandonment of the 50 mm interval and determines the microlithotype frequency of occurrence on the basis of natural lithologic zones within the seam. These zones vary in thickness, and are each characterized by a particular maceral relationship or occurrence. This method is liable to interpretive error when determined by an inexperienced analyst; however, if properly determined, the natural interval method is more descriptive of the seam and of more industrial value.

The percentage of bright and dull components (panel I) was determined for each 50 mm interval, and plotted as a composite bar diagram. The bright-dull profile provides a simplified illustration of the coal seam's gross features. These diagrams are easily read and are particularly useful comparing characteristics of numerous samples prior to industrial use.

Results of Analysis

The Croweburg coal is essentially a high volatile B bituminous, thin banded, bright coal, having an average thickness of 478 mm (1'7"). That portion analysed using the Modified Sydney classification is characterized by a predominance of clarain and dull clarain (Table IV).

Lateral variations. Lateral variations in thickness and petrographic composition are consistent to the north of sample C-4, near the town of Broken Arrow, Wagoner County, Oklahoma. The seam thins (Table V) consistently to the north of sample C-4 from 533 mm (1'9") to 292 mm (10") at Cr-1-C, sec. 28, T. 29 S., R. 25 E., Crawford County, Kansas. The dull components are the predominant microlithotypes at

TABLE IV

STATISTICAL AVERAGES FOR THE CROWEBURG COAL

Rank - High volatile B bituminous	
Thickness - 478 mm (1'7")	
Microlithotype content (percent)	
Fusain	3
Semi-fusinite	0
Vitrain	11
Clarain	49
Claro-durain	32
Dull clarain	27
Semi-splint	5
Durain	5
Sydney Bright-Dull Content (percent)	
Bright	60
Dull	37
Fusain & Semi-fusain	3
American Bright-Dull Content (percent)	
Bright	86
Dull	9
Fusain & Semi-fusain	5

TABLE V

AVERAGE PETROGRAPHIC COMPOSITION AND THICKNESS OF CROWEBURG COAL SAMPLES

Sample No.	No. 68*	C-3	C-4	C-5	C-6	C-7	C-8	Cr-1-C**
Microlithotype Content (Percent)								
Fusain	5	0.23	2	7	4	0.3	7	13.1
Semi-fusain	-	-	-	-	0.77	-	-	-
Vitrain	74	5	11	8	16	17	10	21.0
Clarain	-	50	36	50	49	51	59	-
Claro-durain	-	39	42	35	26	27	22	-
Dull clarain	-	34	34	29	22	20	20	-
Semi-splint	-	5	8	6	4	7	2	-
Durain	-	5	9	5	4	4	3	-
Sydney and Modified Sydney Bright-Dull Content (Percent)								
Bright	-	55	47	58	65	68	69	-
Dull	-	44	51	40	30	31	25	-
Fusain & Semi-fusain	-	0.23	2	7	5	0.3	7	-

TABLE V--Continued

Sample No.	No. 68*	C-3	C-4	C-5	C-6	C-7	C-8	Cr-1-C**
American Bright-Dull Content (Percent)								
Bright	91	89	81	82	87	89	88	79
Dull	4	10	17	11	8	11	5	8
Fusain & Semi-fusain	5	0.23	2	7	5	0.3	7	13.1
Thickness in mm	940	482	533	457	457	431	330	292

* No. 68 Analysis by O'Donnel using the American classification, Davis and others, 1944, Carbonizing properties of western region interior province coals and certain blends of these coals: U.S. Bureau of Mines Technical Paper 667, p. 17. Results of analysis: Anthraxylon, 74; Translucent Attritus, 17; Opaque Attritus, 4; Fusain, 5 percent respectively.

** Cr-1-C Analysis by Hambleton (1953, p. 44). Results of analysis: Anthraxylon, 21.0; Translucent Attritus, 58.2; Opaque Attritus, 7.7; Fusain, 13.1 percent respectively.

C-4. These microlithotypes decrease in percentage of occurrence to the north of C-4. The dull component decrease is accompanied by an increase of vitrain and fusain. Clarain occurrence is rather constant throughout the area, but exhibits a sharp rise at sample C-8.

Sample No. 68, sec. 30, T. 12 N., R. 13 E., Okmulgee County, Oklahoma, and sample C-3 are too widely spaced to draw accurate conclusions regarding the consistency of petrographic variations between them, and the use of the American classification in sample No. 68 prohibits an accurate comparison of these samples. Available data indicate a thinning to the south of sample C-4 to the vicinity of T. 14 N. South of T. 14 N. the seam thickens, reaching a maximum of approximately 3 feet at Henryetta, Oklahoma. The seam thins rapidly to the south of Henryetta. There appears to be a rise in fusain and vitrain to the south of C-4. Due to the incompatibility of the American method of recording petrographic data, it is not possible to compare the remaining microlithotypes with sample No. 68.

Mineral matter. Though not analysed in detail, mineral matter was noted as to type and mode of occurrence, but not percentage of occurrence. Pyrite is the predominant mineral, with lesser amounts of calcite, gypsum, phosphate, quartz, and clay minerals.

Pyrite occurs as sheets in cleats or euhedral crystals in other cleat filling minerals, and as cell fillings in fusain (Fig. 10) which are post-diagenetic. It is also found as fine particles (Fig. 4, 5, and 21) with diameters up to 50 microns, disseminated primarily in dull coal, less frequently in clarain, and rarely in vitrain. Where occurring in this manner, it is probably post-depositional-pre-lignitic stage of coalification. To further support this hypothesis, pyrite is seen replacing sclerotinite. This is probably the result of anaerobic bacterial action on sclerotinite after the fungal action (aeriated conditions) has ceased; therefore, this pyrite is post-sclerotal-pre-diagenetic (lignitic).

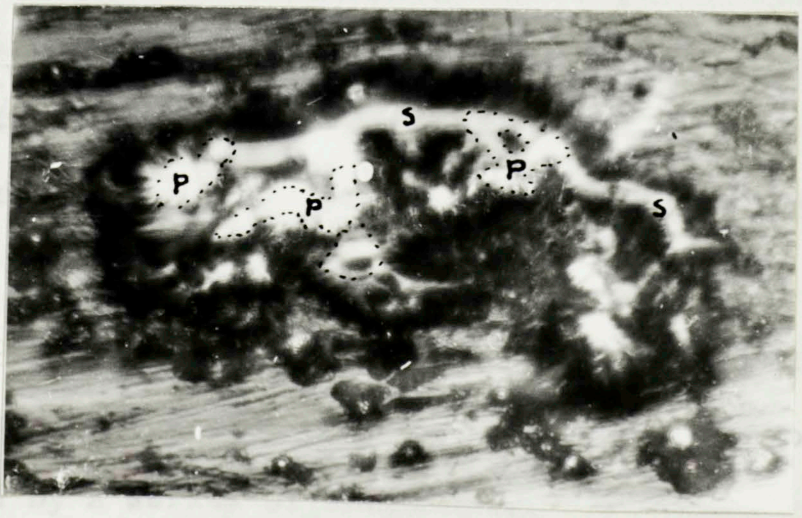


Figure 28. Sclerotinite (s) being replaced by pyrite (p). x390.

Calcite, gypsum, and phosphate occur as cleat fillings, and rarely as cell fillings in fusain. These are probably post-diagenetic minerals.

Quartz occurs as well-rounded colorless grains disseminated in dull coal and rarely in clarain. It is probably eolean. Clay is found in some cleats, rarely as clay balls, and finely disseminated in clarain. The clay is probably both authogenic and allogenic.

Depositional environments. The increase of vitrain and fusain to the north accompanied by a decrease in dull components, indicates that the main edge of the swamp was to the north and the deepest portion in the Broken Arrow region. The dull components, because of their high micrinite content and their environmental implications, indicate that the Broken Arrow vicinity was the scene of relatively deep, clear, aerated water, while to the north, drier, more shallow, oxidizing conditions are indicated by the rise of fusain and vitrain.

Economic implications. The industrial implications and applications of the petrographic analysis may best be illustrated by a series of statements:

1. The Croweburg coal is too thin for selective mining.

2. The various microlithotype bands are generally too thin and well intermixed to permit selective mining to eliminate any undesirable zone. The thin banding makes crushing, in order to separate the bright and dull components, unfeasible.
3. Fusain occurs as thin (rarely over 3 cm in thickness) lenticular bodies of limited lateral extent. With the exception of the lower 20 cm throughout the area, there is no fusain rich horizon in the seam. Occurrences seem to be of local extent.

   The fusain is normally devoid of mineral matter and is characterized by extremely thin cell walls, which make it very friable. Spot observations of mined coal indicate that the coal breaks along fusain planes, and a large percentage of it is eliminated as a result. Further commercial crushing and washing would eliminate the greater part of that which remained, and raise the commercial value of the coal.
4. Chemical analyses (Table VI) in close proximity to the petrographic samples, are available for samples No. 68, C-4, C-5, C-6, and Cr-1-C. The

TABLE VI

PROXIMATE ANALYSES OF THE CROWEBURG COAL

Chemical Sample No.	Related Petrographic Sample No.	As Received						Moist. & Min. Matter Free			
		Moist.	V.M.	F.C.	Ash	S	Btu's	V.M.	F.C.	S	Btu's
A21781*	No. 68	7.8	34.0	53.5	4.7	1.9	13,000	38.9	61.1	2.2	14,850
A24775*	C-4	7.0	34.9	50.1	8.0	3.0	12,460	41.1	58.9	3.6	14,670
B-84168**	C-5	6.9	31.8	55.8	5.5	0.4	12,940	36.3	67.3	0.5	14,770
B-84598**	C-6	8.7	21.4	55.2	4.7	0.8	12,910	36.6	63.7	1.0	14,910
Cr-1-C***	Cr-1-C	(Estimate)		69	---	---	13,000 to 14,000	41.8	58.0	8.7	13,570

* Analyses from Analyses of Oklahoma Coals, U.S. Bureau of Mines Technical Paper 411, p. 21 and 30.

** Analyses from Oakes (1944, p. 31 and 32).

*** Analysis from Hambleton (1953, p. 31).

sulfur (and ash) content of samples No. 68, C-4, and Cr-1-C is too high for metallurgical coke. C-3 was noted to have a high pyrite content which probably indicates a high sulfur content. C-8 contained a high percentage of limonite; therefore this sample is presumed to have too high an ash content for metallurgical coke.

It is doubtful whether the sulfur content of these samples could be lowered sufficiently by fine crushing, commercial washing, and separation, to produce a low sulfur coal. Ash content could be lowered considerably through the elimination of fusain.

Coal from the locality of sample No. 68 could be mixed, after commercial processing, with coal from sample C-5, to produce a metallurgical coke.

5. The sulfur and ash content of samples C-5 and C-6 are low enough to permit the coal to be used to make a first grade metallurgical coke.
6. Commercial mining does not seem practical north of T. 27 N., because of rising mineral matter, sulfur and ash content, plus the progressive thinning of the seam.

CHAPTER XI

SEDIMENTARY ANALYSIS

Method of Analysis

The percentage of occurrence for the several minerals present was determined by counting the various minerals comprising the light and heavy mineral fractions of 0.088-0.062 mm size range. The mineral grains were identified, with the aid of a standard petrographic microscope fitted with a mechanical stage, counted at 5 mm intervals throughout the slide, and recorded for future quantitative analysis. Quantitative analysis was limited to the occurrence of the several minerals at each sample site. Size, shape, and roundness were noted for the initial mineral identification, and considered the same for all subsequent grains of that specific mineral type.

Results of Analysis

The results of the underclay and roof stone analysis were sufficiently worthwhile to merit further investigations of this nature accompanying future petrographic analyses of Oklahoma coals. The analysis was both successful and unsuccessful. It was unsuccessful due to the inexperience of this writer in handling sediments of this type. Errors encountered in analysis and suggestions for rectifying them are as follows:

1. As was stated in Chapter III, samples of the roof stone were usually not available at the site of coal sampling, and in some coal samples (C-3 and C-4) the top portion of the seam was unavailable or doubtful, due to the commercial stripping methods employed. This led to sampling error because a sample was selected out of contact with the petrographic column. Because the nature of the roof stone was not known at the exact site of coal sampling, a sample was chosen that was representative of all the roof stone at the coal sampling site. Where the upper portion of the seam was missing or the contact doubtful, the roof stone could not be compared to the corresponding coal. For these reasons, comparisons of the roof stone to the coal were invalid in this study. It is suggested

that further analyses exclude the roof stone-coal relationship if collecting is not satisfactory, or that such analyses be conducted as a sedimentary analysis unrelated to the coal.

2. It is suggested that at the coal-sediment contact, sampling be altered to include 2.5 cm of coal and 2.5 cm of sediment respectively and comparisons be limited to this sample size.
3. The initial sample (50 gm) in many instances was not large enough to produce sufficient grains in the 0.088-0.062 mm size grade to be accurately analysed. The weight of the grains in the 0.088-0.062 mm size grade ranged from 0.003 to 6.43 gms with an average of 2.29 gms. These weights were too low to insure a representative sampling of the minerals present. This may be rectified by increasing the weight of the initial sample to 100 or 200 grams.
4. Grain count in this study (about 300 per slide) was not high enough to produce dependable data. It is probably valid for those slides made from the 0.088-0.062 mm size grade, which had an initial weight of 5 or more gms, but for those

fractions having less than 5 gms, the data should be considered dubious. This would be corrected by raising the initial sample weight and by spacing the counting fields at close intervals.

Underclay. No relationship was found between the various minerals present and the several macerals comprising the 5 cm portion of coal. When the mineral frequencies were compared to the coal samples on the basis of bright (including fusain and semi-fusain)-dull relationship, used as an indication of environment, a general association became apparent. These mineral associations may be grouped on the basis of environment as follows:

Group I. Minerals, whose frequency of occurrence increases as environment becomes drier or more shallow are:

1. Quartz
2. Garnet
3. Tourmaline

Group II. Minerals whose frequence of occurrence increases as environment becomes wetter or deeper are:

1. K Feldspar

2. Plagioclase
3. Muscovite

Group III. Minerals exhibiting no apparent relationship are:

1. Pyrite
2. Magnetite
3. Goethite and Limonite?
4. Leucoxene
5. Corundum
6. Opal
7. Zircon
8. Hornblende
9. Rutile
10. Sphene
11. Sillimanite

Variations in mineral occurrence that were found seem to be the result of environment and source variation or transportation. Group I minerals are durable, chemically stable minerals, that would resist the chemical and, to a minor degree, mechanical processes found in the drier, more shallow environments. The presence of feldspars in minor amounts in the more shallow regions is probably the result of their elimination by chemical alteration. This would explain

TABLE VII

UNDERCLAY GROUP I AND II MINERAL-BRIGHT COAL RELATIONSHIP

Sample No.	CUC-3	CUC-4	CUC-5	CUC-6	CUC-8
Group I Minerals (percent)					
Quartz	7.46	74.16	82.53	55.85	80.80
Tourmaline	0.81	8.69	22.31	6.91	11.53
Garnet	0.81	0.96	1.75	1.21	1.44
Percent Bright Coal Bottom 5 cm of seam	34	50	68	50	80
Group II Minerals (percent)					
K Feldspar	2.48	18.33	15.66	20.72	10.10
Plagioclase	3.98	4.16	0.60	1.80	1.01
Muscovite	9.75	34.24	7.60	15.04	10.09

TABLE VIII

UNDERCLAY HEAVY AND LIGHT MINERAL FREQUENCIES OF OCCURRENCE

Sample No.	CUC-3	CUC-4	CUC-5	CUC-6	CUC-8
Heavy Minerals (percent)					
Luecoxene	33.33	42.99	38.01	45.93	52.40
Goethite & Limonite?	46.34	0.96	13.45	18.29	10.57
Pyrite	2.43	4.83	8.18	6.91	0.48
Garnet	0.81	0.96	1.75	1.21	1.44
Muscovite	9.75	34.24	7.60	15.04	10.09
Tourmaline	0.81	8.69	22.31	6.91	11.53
Magnetite	4.06	1.93	2.92	2.43	---
Zircon	---	1.93	---	1.62	3.84
Sphene	---	---	0.58	0.40	5.76
Sillimanite	1.62	0.48	---	0.40	---
Corundum	---	0.48	---	0.40	0.96
Hornblende	---	1.44	0.58	---	---
Rutile	0.81	---	---	---	1.44
Others*	0.04	1.07	4.62	0.46	1.49
Total	100.00	100.00	100.00	100.00	100.00

* Includes: Spinel, Apatite, Topaz, Chiastolite, Glaucophane, Andalusite, and tremolite.

TABLE VIII--Continued

Sample No.	CUC-3	CUC-4	CUC-5	CUC-6	CUC-8
Light Minerals (percent)					
K Feldspar	2.48	18.33	15.66	20.72	10.10
Plagioclase	3.98	4.16	0.60	1.80	1.01
Quartz	7.46	74.16	82.53	55.85	80.80
Chalcedony	86.06?	3.33	1.20	18.01	7.07
Opal	---	---	---	3.60	1.01
Others	0.02	0.02	0.01	0.02	0.01
Total	100.00	100.00	100.00	100.00	100.00

the higher amounts of feldspar in the deeper areas, rather than concentration there by mechanical means. Muscovite, being chemically stable, may have been concentrated in the deeper areas by mechanical means. The minor fluctuations of water level which undoubtedly take place in the more shallow areas, would disturb the loose sediment and carry muscovite away to deeper areas, because of its shape which causes it to be lifted and carried more easily than other mineral grains of the same or larger size.

There is an almost universal drop in percentage of all the minerals south of C-4 irrespective of the associations found to the north. If sample C-3 is valid, the general source for Group I and II minerals appears to be to the north. To the south of C-4 this suite of minerals ceases to be important. A new rutile, sillimanite, magnetite, goethite (and limonite?) suite is indicated south of C-4.

Using the above associations as criteria, one could infer the environment or location of the greatest concentration of the several minerals in Group III with the exception of opal, leucoxene, goethite and limonite?, and pyrite, which are to some extent post-diagenetic alteration products.

Further studies of this type could substantiate or refute results obtained in this analysis. If substantial, they could be applied to larger thicknesses of the seam and possibly be used to determine an approximation of a seam's petrographic character at a given locality.

Roof stone. The errors involved in sampling the roof stone and the uncertainty of the actual tops of the coal seams restricted this analysis to a description of occurrence of the several minerals (see Table III).

TABLE IX

ROOF STONE HEAVY AND LIGHT MINERAL FREQUENCES OF OCCURRENCE

Sample No.	CRC-3	CRC-4	CRC-5	CRC-6	CRC-8
Heavy Minerals (percent)					
Leucoxene	6.25	8.01	33.33	49.66	43.72
Magnetite	1.04	---	8.33	---	0.71
Goethite & Limonite?	8.32	---	8.33	---	2.15
Pyrite	---	---	8.33	---	2.50
Zircon	5.20	0.47	4.16	0.65	3.58
Sphene	2.08	0.47	4.16	0.65	6.45
Apatite	1.04	1.41	---	0.65	0.71
Sillimanite	2.08	1.41	---	0.65	6.45
Chiastolite	2.08	0.47	---	---	1.43
Rutile	7.29	0.94	---	---	1.43
Muscovite	58.33	84.43	31.25	41.83	20.78
Garnet	---	0.94	---	0.65	0.71
Tourmaline	2.08	0.94	---	4.57	13.97
Others*	4.21	0.51	2.11	0.69	0.79
Total	100.00	100.00	100.00	100.00	100.00

* Includes: Corundum, Spinel, Diopside, Tremolite, and Topaz.

TABLE IX--Continued

Sample No.	CRC-3	CRC-4	CRC-5	CRC-6	CRC-8
Light Minerals (percent)					
K Feldspar	10.38	7.29	10.71	7.18	12.91
Plagioclase	2.59	1.28	1.19	3.59	0.95
Quartz	73.59	74.67	72.61	55.88	81.33
Chalcedony	10.82	15.87	7.14	32.67	3.82
Opal	2.59	0.85	8.33	0.65	0.95
Others	0.03	0.04	0.02	0.03	0.03
Total	100.00	100.00	100.00	100.00	100.00

CHAPTER XII

CONCLUSIONS

1. Rapidity and ease of preparation make polished sections more desirable than thin, or polished thin sections.

2. The Modified Sydney Classification, because of its flexibility, affords the most precise results of all the petrographic classifications.

3. Polished sections give better results, because they resolve a clearer, sharper picture of the various petrographic entities than thin sections.

4. Variations in proximate analyses are possibly reflected in variations of the microlithotypes, and are probably related to environmental changes.

5. The deepest portion of the Croweburg swamp was in the Broken Arrow, Oklahoma, area, with the main edge to the north.

6. The Croweburg coal is suitable for coking between samples C-5 and C-6 (possibly to C-7).

7. Coal from the area of sample No. 68 could be mixed with low sulfur and ash content coals, such as C-5, to produce a metallurgical coking coal.

8. It is doubtful that those coals with a high sulfur content could have the sulfur content lowered sufficiently by commercial washing to produce a coking grade coal.

9. Ash content could be lowered by the elimination of fusain.

10. Commercial mining is not practical north of sample T. 27 N.

11. A relationship does exist between the minerals in the underclay and the associated coal samples. Further study may provide the means of forming a rough approximation of the petrographic character of a seam through the mineral occurrence.

SELECTED REFERENCES

Abramski, C. and others, 1951, Atlas für angewandte Steinkohlenpetrographie: Essen, Verlag Glückauf G. M. B. H.

Barghoorn, E. S., 1952, Degradation of plant materials and its relations to the origin of coal: Nova Scotia Dept. Mines and Nova Scotia Research Foundation Second Conference on the Origin and Constitution of Coal, Crystal Cliffs, Nova Scotia, June 1952, p. 248-271.

Berry, W. F., and Dutcher, R. R., 1955, Coal petrography: remarks on terminology and methodology: The Compass, v. 32, no. 4, p. 305-319.

Branson, C. C., 1954, Field conference on Desmoinesian rocks of northeastern Oklahoma: Okla. Geol. Survey Guide Book II, p. 1-8.

Branson, C. C., and others, 1958, Fifty years progress, semi-centennial report: Okla. Geol. Survey Report 1908-1958, p. 63-75.

Breger, I A., and Whitehead, W. L., 1950, A thermographic story of the role of lignin in coal genesis: Nova Scotia Dept. Mines and Nova Scotia Research Foundation Conference on the Origin and Constitution of Coal, Crystal Cliffs, Nova Scotia, June 21-23, 1950, p. 120-142.

Cady, G. H., 1942, Modern concepts of the physical constitution of coal: Jour. Geology, v. 50, no. 4, p. 357-384.

Cross, A. T., 1952, The geology of the Pittsburgh coal: stratigraphy, petrology, origin and composition, and geological interpretation of mining problems: Nova Scotia Dept. Mines and Nova Scotia Research Foundation Second Conference on the Origin and Constitution of Coal, Crystal Cliffs, Nova Scotia, June 1952, p. 32-111.

Dapples, E. C., 1942, Physical constitution of coal as related to coal description and classification: Jour. Geology, v. 50, p. 437-450.

Davis, J. D., and others, 1944, Carbonizing properties of western region interior province coals and certain blends of these coals: U.S. Bur. Mines Tech. Paper 667, p. 17.

Dunham, R. J., and Trumbull, J. V. A., 1955, Geology and coal resources of the Henryetta mining district, Okmulgee County, Oklahoma: U.S. Geol. Survey Bull. 1015-F.

Fisher, C. H., and others, 1942, Hydrogenation and luquefaction of coal, part 2: U.S. Bur. Mines Tech. Paper 642.

Ganju, P. N., 1955, Petrology of Indian coals: Geological Survey of India, Memoirs, v. 83.

Gibbs, H. L., and Evans, L. G., 1950, Improvements in methods for preparing thin sections of rock: U.S. Bur. Mines Rept. of Invest. 4711.

Grandone, Peter, and Ham, W. E., 1957, The mineral industries of Oklahoma in 1955 and 1956: Okla. Geol. Survey Mineral Rept. no. 32, p. 1, 2, 9, and 10.

_______ 1958, The mineral industries of Oklahoma in 1956 and 1957: Okla. Geol. Survey Mineral Rept. no. 34, p. 4, 7, and 21.

Hacquebard, P. A., 1950, The nomenclature and classification of coal petrography: Nova Scotia Dept. Mines and Nova Scotia Research Foundation Conference on the Origin and Constitution of Coal, Crystal Cliffs, Nova Scotia, June 21-23, 1950, p. 8-49.

________1952, A petrographic investigation of the Tract seam of the Sydney coalfield, Nova Scotia: Nova Scotia Dept. Mines and Nova Scotia Research Foundation Conference on the Origin and Constitution of Coal, Crystal Cliffs, Nova Scotia, June 1952, p. 293-318.

________1952, Opaque matter in coal: Econ. Geology, v. 49, no. 5, p. 494-516.

Hacquebard, P. A., and Lahiri, K. C., 1954, Petrographic examination of washed, screened, and crushed samples of coal from the Sydney and St. Rose coalfields, Nova Scotia: Econ. Geology, v. 49, no. 8, p. 837-862.

Hambleton, W. W., 1953, Petrographic study of southeastern Kansas coals: Kansas State Geol. Survey Bull. 102, part 1.

Jongmans, W. J., and others, 1936, Nomenclature of coal petrography: Fuel in Science and Practice, no. 15, p. 14-15.

Kosanke, R. M., 1952, Petrographic and microchemical studies of coal: Nova Scotia Dept. Mines and Nova Scotia Research Foundation Second Conference on the Origin and Constitution of Coal, Crystal Cliffs, Nova Scotia, June 1952, p. 248-271.

Krumbein, W. C., and Pettijohn, F. J., 1938, Manual of sedimentary petrography: New York, Appleton-Century-Crofts, Inc., p. 309-521.

Lahiri, K. D., 1950, Metamorphism of coal: Nova Scotia Dept. Mines and Nova Scotia Research Foundation Conference on the Origin and Constitution of Coal, Crystal Cliffs, Nova Scotia, June 21-23, 1950, p. 85-99.

Lowery, H H., 1942, Reaction of the physical constitution of coal upon its chemical characteristics: Jour. Geology, v. 50, no. 4, p. 357-384.

Marshell, C. E., 1942, Modern concepts of the physical constitution of coal and related research in Great Britain: Jour. Geology, v. 50, no. 4, p. 385-405.

McCabe, L. C., 1942, Practical significance of the physical constitution of coal: Jour. Geology, v. 50, no. 4, p. 406-410.

McCabe, L. C., and others, 1934, Contributions to the study of coal-banded ingredients of No. 6 coal and their heating values as related to washability characteristics: Ill. State Geol. Survey Rept. of Invest., no. 34, p. 7-44.

Meyer, C., 1946, Notes on the cutting and polishing of thin sections: Jour. Geology, v. 54, no. 2, p. 166-172.

Milner, H. B., 1952, Sedimentary petrography: London, 3rd ed., Thomas Murby & Co., p. 215-357.

Moore, E. S., 1947, Coal: New York, 2nd ed., 2nd printing, John Wiley and Sons, Inc.

Moose, J. E., and Searle, V. C., 1929, A chemical study of Oklahoma coals: Okla. Geol. Survey Bull. 51, p. 15-37.

Netzeband, F. F., and others, 1954, Mineral industry of Oklahoma in 1952: Okla. Geol. Survey Mineral Rept. no. 25, p. 4, 7, and 8.

Oakes, M. C., 1944, Broken Arrow coal and associated strata: Okla. Geol. Survey Circ. no. 24, p. 31-32.

Parks, B. C., 1944, Petrographic analysis of coal by the particle count method: Econ. Geology, v. 44, no. 5, p. 376-424.

________1952, Mineral matter in coal: Nova Scotia Dept. Mines and Nova Scotia Research Foundation Second Conference on the Origin and Constitution of Coal, Crystal Cliffs, Nova Scotia, June 1952, p. 272-284.

Parks, B. C., and O'Donnell, H. J., 1948, Determination of the petrographic components of coal by the examination of thin sections: Am. Inst. Mining Metall. Engineers Tech. Pub. 2492.

Schopf, J. M., 1948, Variable coalification, the process involved in coal formation: Econ. Geology, v. 43, no. 3, p. 207-225.

Shannon, C. W., and others, 1926, Coal in Oklahoma: Okla. Geol. Survey Bull. 4, p. 1-65.

Snyder, C. A., 1925, The microstructure of coal: Amer. Inst. Mining Metall. Engineers, Trans., v. 71, p. 117-126.

Sprumk, G. C., 1942, Influence of the physical constitution of coal upon its chemical, hydrogenation, and carbonization properties: Jour. Geology, v. 50, no. 4, p. 411-436.

Sprunk, G. C., and O'Donnell, H. J., 1942, Mineral matter in coal: Fuel in Science and Practice, no. 14, p. 4-13.

Stopes, M. C., 1935, On the petrography of banded bituminous coal: Fuel in Science and Practice, no. 14, p. 4-13.

Stutzer, Otto, and Noé, A. C., 1940, Geology of coal: Chicago, The University of Chicago Press.

Thiessen, Reinhardt, 1920, Compilation and composition of bituminous coals: Jour. Geology, v. 28, p. 185-209.

________1935, Microscopic and petrographic studies of certain American coals: U.S. Bur. Mines Tech. Paper 564.

________1947, What is coal?: U.S. Bur. Mines Inf. Circ. 7397.

Thiessen, Reinhardt, and others, 1938, Preparation of thin sections of coal: U.S. Bur. Mines Inf. Circ. 7021.

Traverse, Alfred, 1954, Coal microscopy, an important research technique: Consulting Engineer, July 1954, p. 1-7.

Tribble, P. E., and others, 1957, The mineral industries of Oklahoma in 1954 and 1955: Okla. Geol. Survey Mineral Rept. no. 31, p. 1, 2, 9, and 10.

Trumbull, J. V. A., 1957, Coal resources of Oklahoma: U.S. Geol. Survey Bull. 1042-J, p. 308-382.

Van Krevelen, D. W., and Schuyer, J., 1957, Coal science: Amsterdam, London, New York, Princeton, Elsevier Publishing Co.

White, David, 1925, Environmental conditions of deposition of coal: Amer. Inst. Mining Metall. Engineers, Trans., v. 71, p. 21-31.

________1933, Role of water conditions in the formation and differentiation of common (banded) coals: Econ. Geology, v. 28, no. 6, p. 566-568.

White, David, and Thiessen, Reinhardt, 1913, The origin of coal: U.S. Bur. Mines Bull. 38.

Wilson, L. R., and Hoffmeister, W. S., 1956: Plant microfossils of the Croweburg coal: Okla. Geol. Survey Circ. 32, p. 6-12.