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Recommended Procedures and Methodology of Coal Description

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By E. C. T. Chao, J. A. Minkin, and C. L. Thompson

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Steps and methods to be followed to characterize,
rapidly and quantitatively, the distinctive
properties and profiles of a given coal bed

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Abstract

This document is the result of a workshop on coal description held for the Branch of Coal Resources of the U.S. Geological Survey in March 1982. It has been prepared to aid and encourage the field-oriented coal scientist to participate directly in petrographic coal-description activities.

The objectives and past and current practices of coal description vary widely. These are briefly reviewed and illustrated with examples. Sampling approaches and techniques for collecting columnar samples of fresh coal are also discussed.

The recommended procedures and methodology emphasize the fact that obtaining a good megascopic description of a coal bed is much better done in the laboratory with a binocular microscope and under good lighting conditions after the samples have been cut and quickly prepared. For better observation and cross-checking using a petrographic microscope for identification purposes, an in-place polishing procedure (requiring less than 2 min) is routinely used. Methods for using both the petrographic microscope and an automated image analysis system are also included for geologists who have access to such instruments.

To describe the material characteristics of a coal bed in terms of microlithotypes or lithotypes, a new nomenclature of (V), (E), (I), (M), (S), (X_1), (X_2), and so on is used. The microscopic description of the modal composition of a megascopically observed lithologic type is expressed in terms of (VEIM); subscripts are used to denote the volume percentage of each constituent present.

To describe a coal-bed profile, semiquantitative data (without microscopic study) and quantitative data (with microscopic study) are presented in ready-to-understand form. The average total composition of any thickness interval or of the entire coal bed can be plotted on a triangular diagram having V, E, and I+M+S as the apices. The modal composition of any mixed lithologies such as (X_1), (X_2), and so on can also be plotted on such a triangular ternary diagram. Such diagrams can be used either for tracing compositional variations throughout a single coal-bed profile or for comparing variations between different coal beds.

INTRODUCTION

This document is based on material presented at a workshop for the U.S. Geological Survey's Branch of Coal Resources on March 4, 5, and 8, 1982. It has been prepared to serve two major objectives: (1) to present, particularly for the benefit of field-oriented coal-research scientists, procedures and methodology that have been developed for rapid, semiquantitative to quantitative characterization of bituminous coals, especially megascopic coal-bed profiles, and (2) to encourage the field-oriented coal scientist or his assistant to participate directly in coal-description activities without having to rely on results from coal petrographers.

For both megascopic and microscopic quantitative characterization of coal, we normally recommend using an automated image analysis system (AIAS) and presenting the descriptive data in columnar sections and triangular diagrams using the VEIM nomenclature described below and discussed in detail by Chao and others (1982a, b). Not all field-oriented coal scientists, however, will have access to an AIAS or to a research petrographic microscope, nor will they have the time or the inclination to describe the coal or coal bed as a coal petrographer would. Therefore, the emphasis of this document is on the procedures and methodology for preparing coal drill-core or block samples to obtain the maximum amount of descriptive petrographic data quickly by using a binocular microscope under laboratory lighting and space conditions. Methods involving the petrographic microscope and the AIAS are also included here for geologists who do have access to such instruments.

Those engaged in coal investigations need to describe coal beds in their study area to make their maps and their reports more meaningful and complete. The description of a particular coal bed should bring out its characteristics, such as certain properties that are similar to or different from those of other coal beds, and should evaluate whether these features vary locally or are consistent regionally.

Objectives of coal description will differ according to whether the work is to be done in the field or carried out in the laboratory. These objectives must fit either the purposes of the study and the problems to be solved (coal preparation, utilization, sale, mining operations) or the geologic studies for developing models of depositional and geochemical environments to predict coal-bed variations.

The motives for developing a rapid quantitative descriptive methodology are rooted in the question, "Why hasn't coal petrography played a major role in coal geology, coal mining, or coal chemistry investigations?" The two main reasons probably are:

1. Obtaining coal petrographic descriptions in the past was time consuming. Once the samples had been collected and prepared and the investigations had been completed, it took months or even years before the results were available for use by coal geologists, coal-mining engineers, or coal chemists. For petrographic study results to be of value, the study must be completed in a timely fashion. Therefore, the speed of obtaining petrographic data must be increased.
2. After a detailed petrographic study had been completed, the data presented included many technical terms, some of which were ambiguous, and quantitative data painstakingly obtained were presented in difficult-to-follow graphic form. To make the results of petrographic study more convenient and immediately useful to other coal scientists, the use of ambiguous technical terms in petrographic descriptions should be reduced, and graphic display of the detailed quantitative data on coal composition and characteristics should be simplified.

These objections and needs should be satisfied by the procedures recommended below.

NOMENCLATURE, IDENTIFICATION, AND CLASSIFICATION

To minimize possible confusion and to provide the field-oriented coal scientist with a quick reference to the terms used in describing coal components, some of the terms and examples of organic and inorganic single and aggregate components are given and are illustrated as follows:

Megascopic (macroscopic) observation or description. The term "megascopic" is defined in the *Glossary of Geology* (Bates and Jackson, 1980) as, "Said of an object or phenomenon, or of its characteristics, that can be observed with the unaided eye or with a hand lens." In our usage, megascopic observation is made with the naked eye, with a hand lens, or with a low-magnification binocular microscope (generally about 10× and in no case in excess of 32×).

Microscopic observation or description. The term "microscopic" is defined in the *Glossary of Geology* (Bates and Jackson, 1980) as, "Said of an object or phenomenon or of its characteristics that cannot be observed without the aid of a microscope." In our usage, the microscope is a research petrographic microscope with a minimum magnification of 56×.

Macerals. A coal description must deal with both organic and inorganic components. The organic components of coal, equivalent to mineral species of the mineral kingdom, are called macerals. They generally have a range of organic composition that depends on the plant materials from which they are derived and on the degree of coalification or rank of the coal. Optically, in either reflected or transmitted light, they generally can be identified by their shape, color, fluorescence characteristics, and reflectance or index of refraction. X-ray diffraction patterns for macerals show diffuse and broad peaks characteristic of amorphous or poorly crystallized substances. The major chemical components of macerals are the light elements H, C, N, O, and S. Modern equipment can now quantitatively analyze most of these light elements in place except hydrogen. Because macerals also have a range of hydrogen-to-carbon ratios, a definitive maceral identification by microprobe analytical methods is still in the future. Coal macerals currently are identified petrographically on the basis of their optical and textural properties, which are sometimes not entirely free of ambiguity. All maceral names end in "nite." The maceral groups are vitrinite, exinite or liptinite, and inertinite. Table 1 lists the macerals found in bituminous coals (International Committee for Coal Petrology (ICCP), 1971, 1975). Low-rank coals (subbituminous and lignite) contain precursors of some of the macerals of bituminous coals.

TABLE 1.—*Macerals in bituminous coals*

[Stopes-Heerlen system, after *International Handbook of Coal Petrography* (1963, 1971, 1975). Macerals are described by Stach and others (1975)]

Maceral group	Maceral
Vitrinite	Collinite Telinite Vitrodetrinite
Exinite-liptinite	Sporinite Cutinite Resinite Alginite Liptodetrinite
Inertinite	Micrinite Macrinite Semifusinite Fusinite Sclerotinite Inertodetrinite

TABLE 2.—*Macerals in brown coals and lignites*

[After *International Handbook of Coal Petrography* (1963, 1971, 1975). Macerals are described by Stach and others (1975)]

Maceral group	Maceral
Huminite	Textinite Ulminite Attrinite Densinite Gelinite Corpohuminite
Liptinite	Sporinite Cutinite Resinite Alginite Liptodetrinite Chlorophyllinite Suberinite Bituminite
Inertinite	Sclerotinite Inertodetrinite Fusinite Semifusinite Macrinite

Some maceral names for these coals are different (table 2) but will not be discussed here.

Microlithotype. The term "microlithotype" is defined in the *International Handbook of Coal Petrography* (International Committee for Coal Petrology, 1971) as "a typical association of macerals in coals, occurring in bands at least 50 microns wide. Microlithotype names bear the suffix 'ite.' "

Basically, microlithotypes can be subdivided into monomacerite (consisting of macerals of a single maceral group), bimacerite (macerals of two maceral groups), and trimacerite (macerals of all three maceral groups). Figure 1 is a ternary diagram that illustrates the various microlithotype terms approved by the International Committee for Coal Petrology (1971, 1975). Additional microlithotype names, such as carbominerite and carbosilicite, indicate combinations of macerals and minerals. As figure 1 shows, the names for trimacerites are long, and their compositions cover a wide range; hence, their usefulness in coal description becomes limited. As will be discussed below and as figure 1 shows, microlithotype compositions can be more specifically represented in terms of volume percentages of vitrinite, exinite, and inertinite.

Assemblages of microlithotypes. The maximum width of a microlithotype is not defined clearly. In different countries, however, the minimum band thickness of a lithotype varies from 3 mm to 1 cm (Cameron, 1978). We use assemblages of microlithotypes to mean an association of two or more microlithotypes in alternating lamellae or overlapping lenses in thicknesses up to 2 mm or more; then other terms become more appropriate.

Lithotype. The International Committee for Coal Petrology (1963) defines "lithotype" as "a macroscopically visible band in humic coals, analyzed by physical characteristics rather than by botanical origin. The four lithotypes of banded bituminous coal are vitrain, clarain, durain and fusain. These were originally described by Stopes in 1919." The American Society for Testing and Materials (1980) includes in this definition attrital coal and any specific mixture of two or more of the five principal lithotypes, such as clarodurain. Most petrographers are aware that lithotypes contain microlithotypes and (or) assemblages of microlithotypes. Examples of lithotypes and microlithotypes are shown in figures 2, 3, and 4.

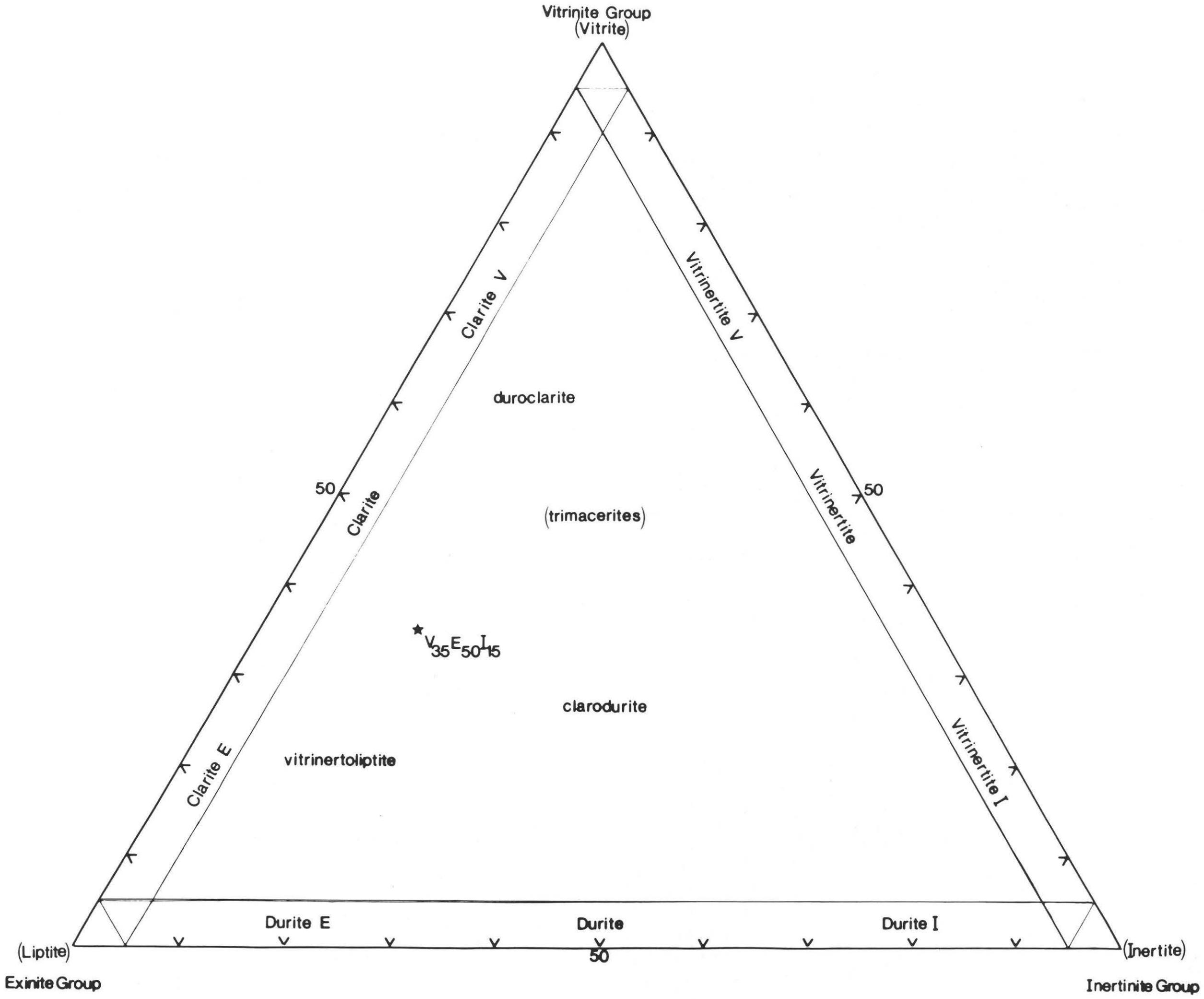


FIGURE 1.—Microlithotype ternary diagram. The VEI point is much more specific than the generalized areas represented by ICCP-recommended microlithotype names.

Mixed lithologies (X_1), (X_2), (X_3), and so on. For megascopic description, the lithotype terms clarain, clarodurain, and durain are not much more informative than the terms bright, medium-bright, and dull attrital coals. Instead, for quantitative description of megascopically discernible units other than the pure lithotypes vitrain and fusain, we have adopted the term "mixed lithologies." Mixed lithologies are mixtures or assemblages of microlithotypes.

In analogy to brightness differences, the mixed lithologies (X_1), (X_2), (X_3), and so forth are characterized by differences in light scattering and reflecting characteristics (figs. 3, 4) when they are viewed with the naked eye, the hand lens, and (or) the binocular microscope. When the sample surface is prepared consistently and uniformly (ground flat and partially polished with 800-grit abrasives), the light scattering and reflecting properties of (X_3) are distinctly greater or stronger than

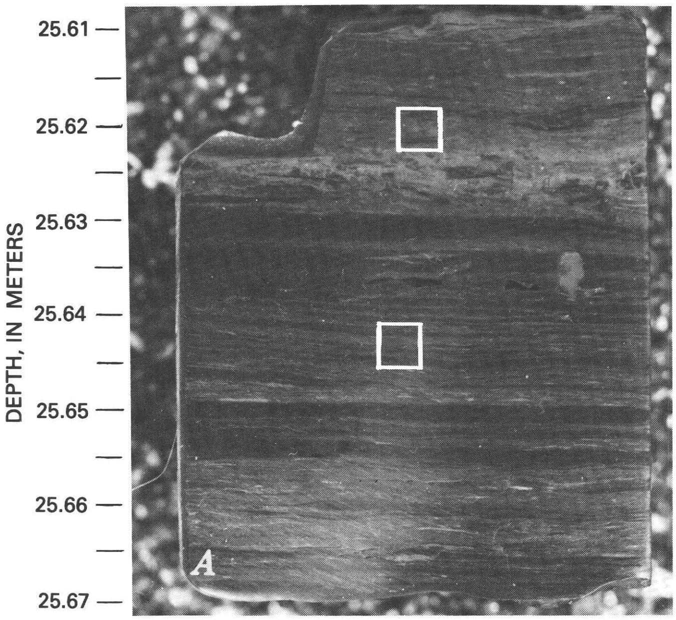


FIGURE 2*A*.—Split drill core of bituminous coal, ground flat and polished with 800-grit abrasives, showing a well-developed banded or layered structure. The dark bands are made up of the microlithotype vitrite or the lithotype vitrain (depending on the width of a particular band). The light-gray bands are assemblages of microlithotypes or mixed lithologies. The well-banded texture is typical of coal of autochthonous origin. A quantitative megascopic description of this portion of the coal bed is shown in figure 5. The lower outlined area is enlarged and illustrated in figures 3*A* to 3*E* and the upper outlined area in figures 3*F* to 3*H*. Hazard coal, Knott County, eastern Kentucky.

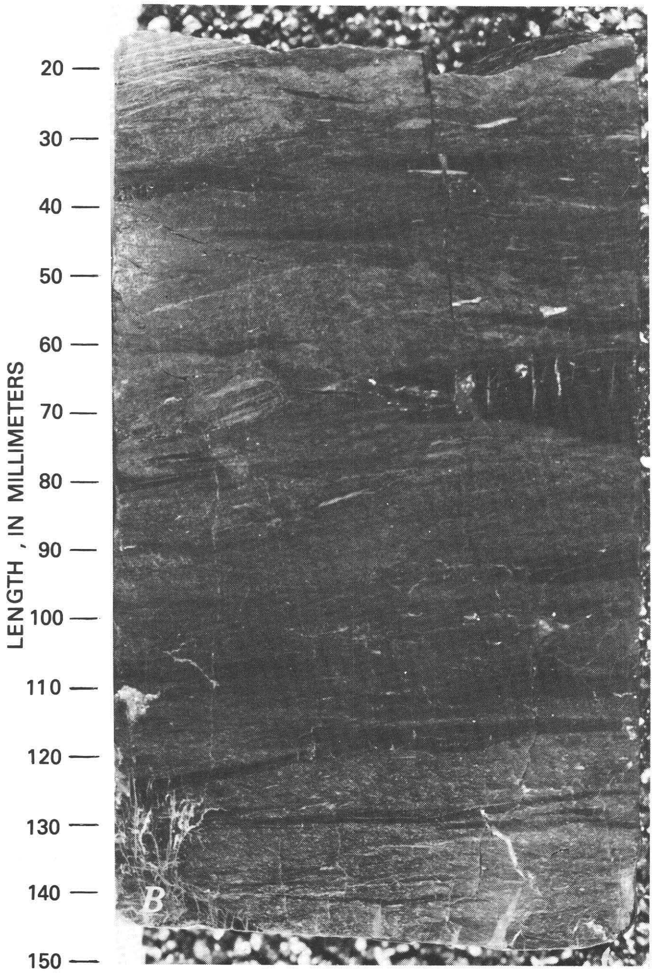
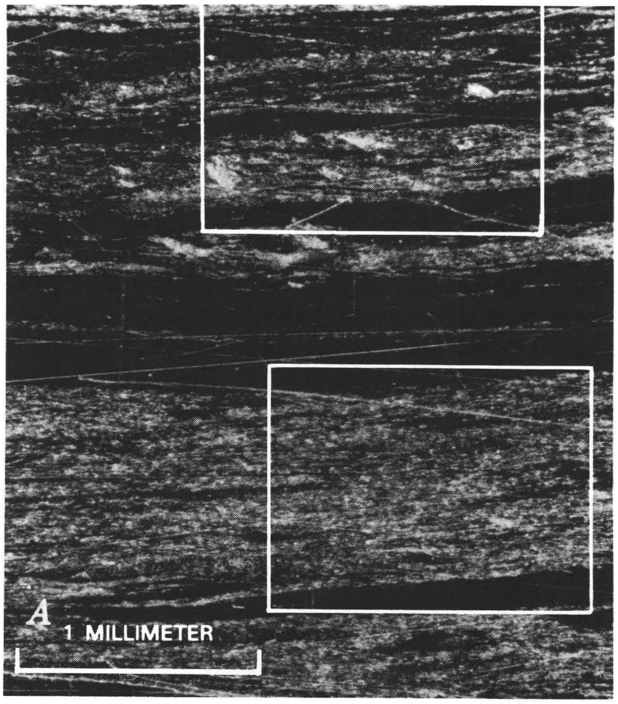


FIGURE 2*B*.—Split drill core, ground flat and polished with 800-grit abrasives, showing irregular lenses of vitrite and vitrain in juxtaposition with less vitrinite rich layers. We interpret this texture as typical of a coal of allochthonous origin, where the plant material was transported from the growth site to the site of deposition before coalification. I coal, Cretaceous Ferron Sandstone Member of the Mancos Shale, Emery Coalfield, central Utah.

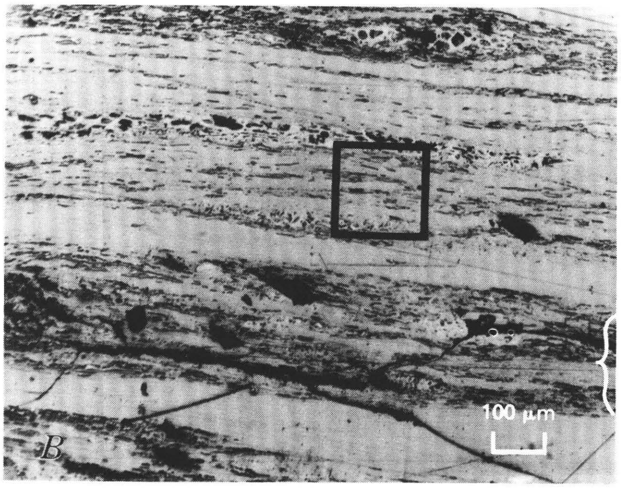


3A

FIGURE 3*A*.—Enlarged view of lower outlined area shown in figure 2*A*. This area of the sample has been polished in place with 1- and 1/4-μm diamond abrasives. Shown are an assemblage of microlithotypes consisting of alternating bands and lenses of vitrite (dark) and mixed lithologies (light gray). The areas outlined are shown at higher magnifications in succeeding photomicrographs. Hazard coal, Knott County, eastern Kentucky. Photograph (shown actual size) was taken through a binocular microscope at 32× in diffuse illumination.

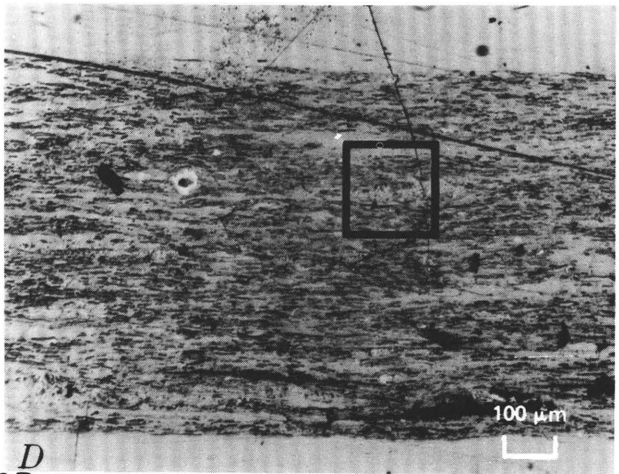
FIGURE 3*B*.—Enlarged view of upper outlined area shown in figure 3*A*. A microlithotype band of a trimacerite (bracket) containing dark mineral grains and lenses of white inertite lies between smooth and featureless microlithotype bands of vitrite. Three lenses of fusinite-semifusinite having cell structures are seen in the upper part of the photomicrograph. The outlined area of mixed lithology (X_1) is shown at higher magnification in figure 3*C*. Photomicrograph taken with reflected light, oil immersion.

FIGURE 3*C*.—Enlarged view of area outlined in figure 3*B*. The mixed lithology (X_1) is shown to consist of lenses of fusinite above and below a band consisting of vitrinite (gray) containing dark elongate sporinites and white inertinites. Photomicrograph taken with reflected light, oil immersion.

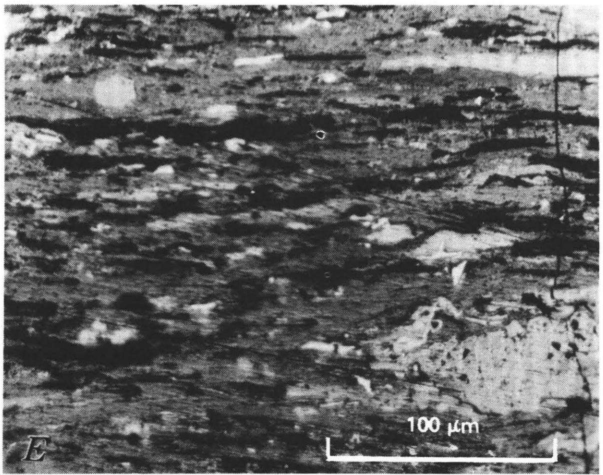


3B

3C



3D



3E

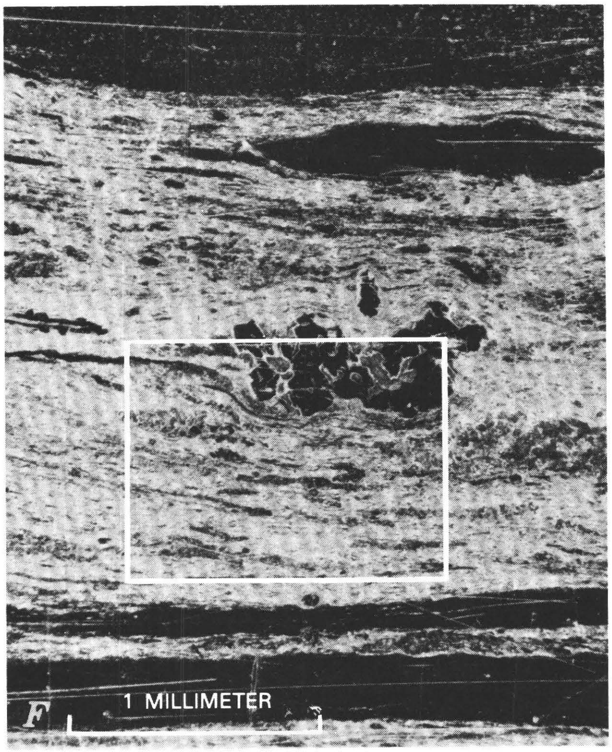
FIGURE 3*D*.—Enlarged view of lower outlined area shown in figure 3*A*. The mixed lithology (X_2) is bounded by microlithotype vitrite lenses (smooth gray area). The outlined area is shown at higher magnification in figure 3*E*. Photomicrograph taken with reflected light.

FIGURE 3*E*.—Enlarged view of area outlined in figure 3*D* showing details of mixed lithology (X_2) containing dark exinite (mostly sporinite) and white inertinite in a matrix of gray vitrite. Photomicrograph taken with reflected light, oil immersion.

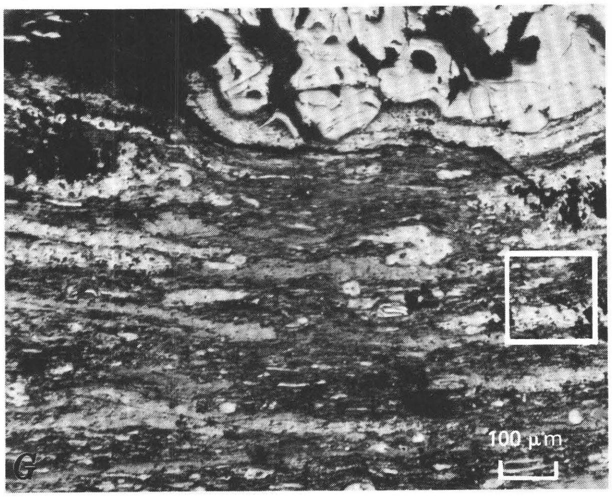
FIGURE 3*F*.—Enlarged view of upper outlined area shown in figure 2*A*. The light-colored band is dominantly mixed lithology (X_3) containing abundant inertinite. The bronzy gray inertite is obvious in this unit when it is viewed with the naked eye or with the binocular microscope. The outlined area is shown at higher magnification in figures 3*G* and 3*H*. Sample has been polished in place with diamond abrasive. Photograph (shown actual size) taken at 32× through a binocular microscope in diffuse illumination.

FIGURE 3*G*.—Enlarged view of the area outlined in figure 3*F*, mixed lithology (X_3), showing details of the overlapping thin lenses of inertite and inertinite (light gray to white) in a matrix of vitrinite (medium gray). Black areas are mineral grains and holes. The area outlined at the right side of the photomicrograph is magnified further in figure 3*H*. Reflected light, oil immersion contrast.

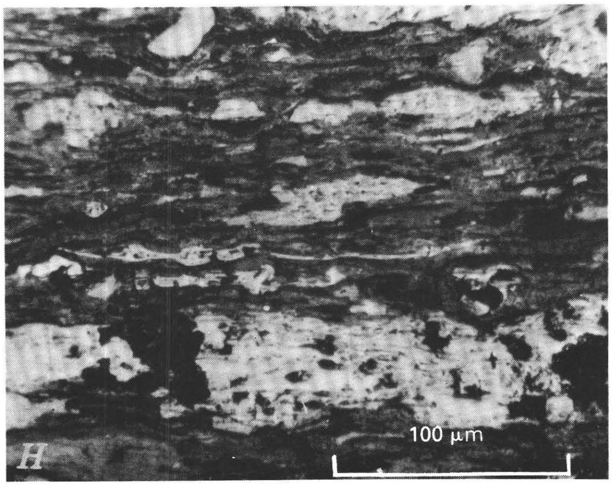
FIGURE 3*H*.—Enlarged view of the area outlined in figure 3*G* showing greater details of the mixed lithology (X_3) containing inertinite grains and inertite lenses (light gray and white) in a vitrinite matrix (medium gray). Exinite is dark gray. Black areas are mostly minerals and some holes. Photomicrograph taken with reflected light, oil immersion.



3*F*

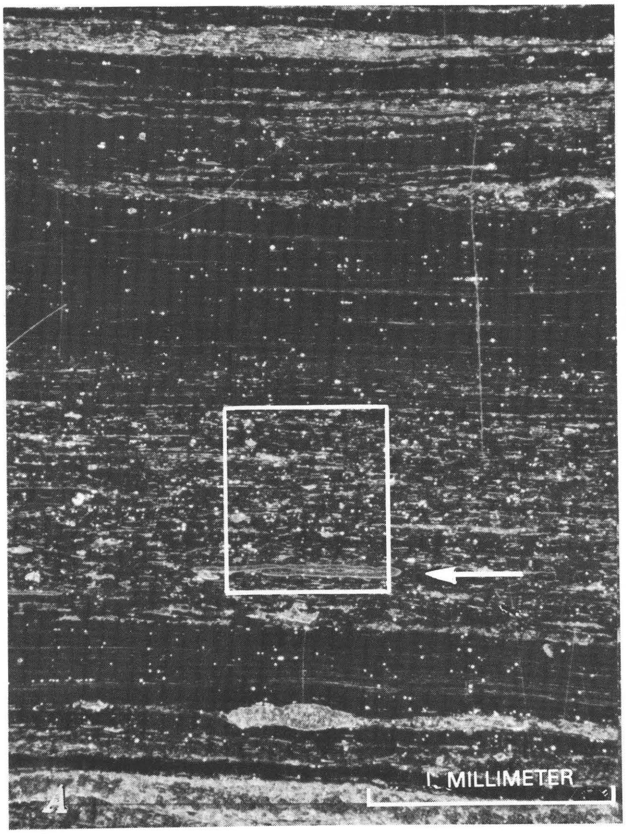


3*G*



3*H*

FIGURE 4*A*.—Block sample of bituminous coal showing a portion of an in-place polished area consisting of alternating dark vitrinite-rich and lighter colored exinite-rich microlithotype bands. The arrow in the lower central part of the photograph indicates a megaspore. In the outlined area, most white elongate particles are microspores. The tiny white dots are iron sulfide (pyrite) particles, readily recognizable under the binocular microscope because of their brightness. No. 6 coal, Webster County, western Kentucky. Photograph (shown actual size) taken at 32× through a binocular microscope in diffuse illumination. ▶



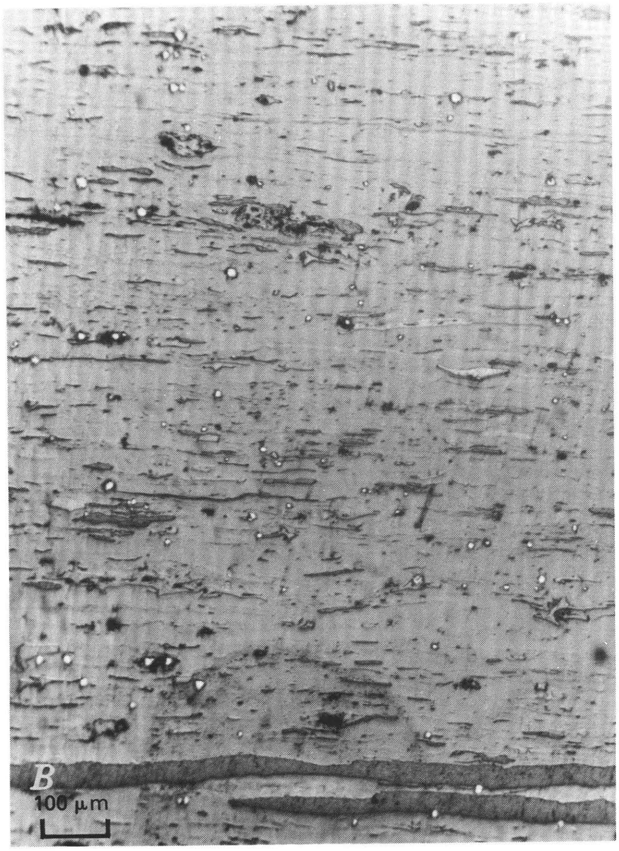
those of (X_2), and those of (X_2) are greater than those of (X_1). Under the AIAS, they can be quantitatively separated and classified by different gray-value intervals (Chao and others, 1982a, b); on this basis, a quantitative megascopic profile of the coal sample can be prepared (fig. 5). The uniform sample provides a more consistent basis for observation and classification, even if one wishes to continue using brightness for megascopic differentiation of lithotypes of clarain, clarodurain, and durain. The modal composition of mixed lithologies generally cannot be determined or described without using a petrographic microscope.

Larger coal units. Coal units larger than lithotypes, such as assemblages or packets of lithotypes, have not been defined or specified by the ICCP. Australian petrographers use subsections and plies to describe such units in coal profiles (fig. 6). We prefer to use the following sequence, in order of increasing size of lithologic unit:

1. Microlithotype.
2. Lithotype or microlithotype assemblage.
3. Petrographic type—Lithotype assemblage.
4. Petrographic unit—Packet of petrographic types.
5. Subsection—Packets of petrographic units.
6. Section—One or more units of subsections.

In addition to the above nomenclature, the literature contains terms such as splint, attrital, bone, impure coal and partings, tonsteins, and so forth (American Society for Testing and Materials, 1980; International Committee for Coal Petrology, 1963, 1971, 1975).

FIGURE 4*B*.—Enlargement of area outlined in figure 4*A* showing details of the microlithotype containing dark microspores in parallel orientation in vitrinite (gray) and scattered round framboidal pyrite (white). Photomicrograph taken with reflected light, oil immersion. ▶



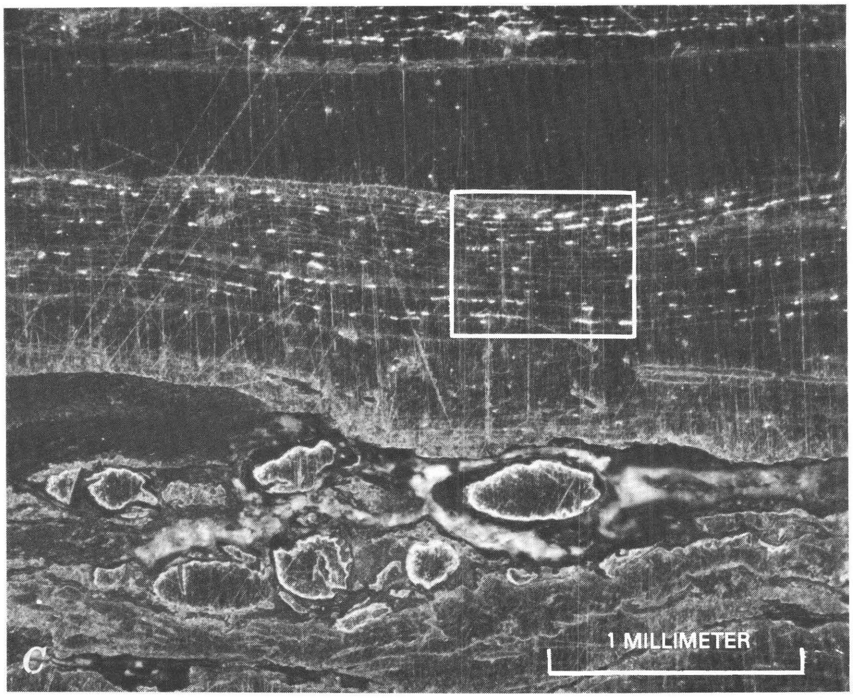


FIGURE 4*C*.—Area on another block sample from the same coal polished in place with 1-μm diamond (vertical scratches). Thin "lines" of cutinite and white areas of iron sulfide (pyrite) are visible in the middle part of the photograph. Note the oval-shaped cross section of fusinitized rodlets in the lower part (gray areas rimmed with white). Photographed through the binocular microscope at 32× in diffuse illumination.

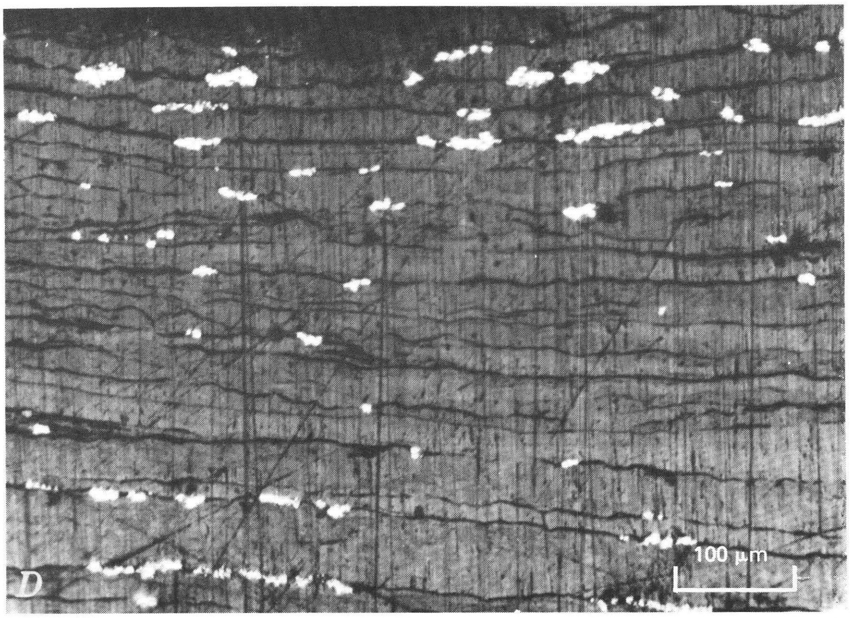
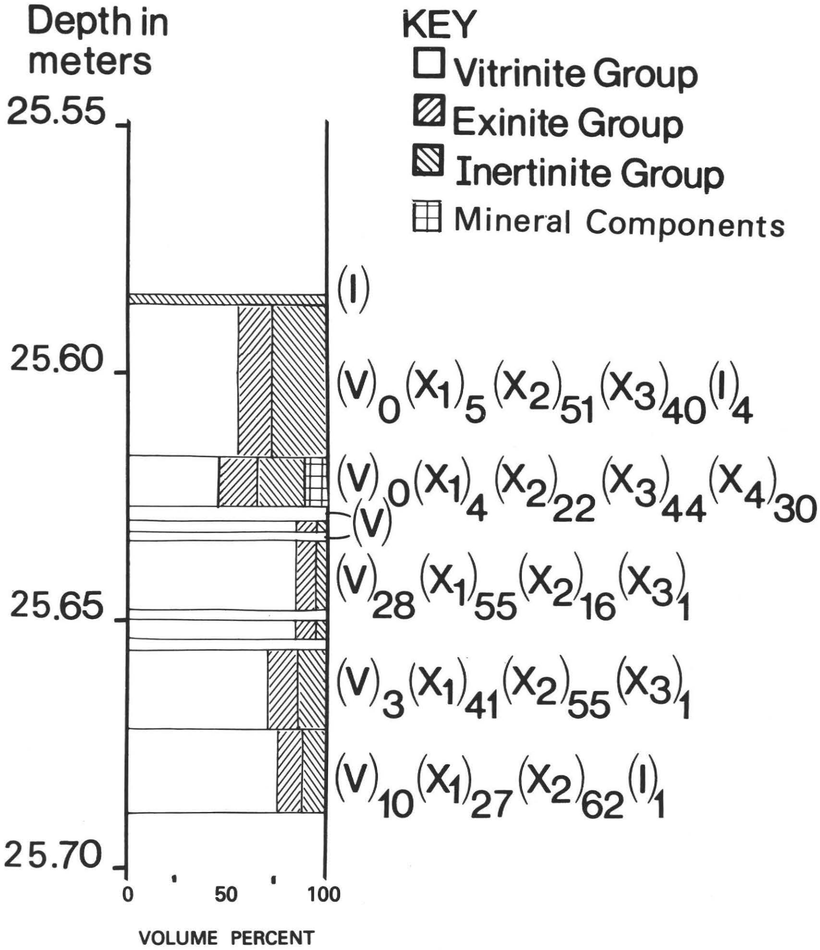


FIGURE 4*D*.—Enlargement of microlithotype area outlined in figure 4*C* showing details of thin linear cutinite (dark stringers) along which blocky aggregates of iron sulfide (pyrite, white) have nucleated and developed. Photomicrograph taken with reflected light, oil immersion.



Depth,[1] in m	Mixed lithology	V, in vol. percent	E, in vol. percent	I, in vol. percent
25.583–25.617- - - - - - -	(X_1)	88	10	2
	(X_2)	67	12	20
	(X_3)	53	21	23
25.617–25.630- - - - - - -	(X_1)	88	10	2
	(X_2)	58	14 (E + M)	28
	(X_3)	49	28	16
	(X_4)	22	18	40
25.630–25.654- - - - - - -	(X_1)	83	13	4
	(X_2)	64	18	13
	(X_3)	49	28	16
25.656–25.672- - - - - - -	(X_1)	89	7	4
	(X_2)	61	20	13
	(X_3)	49	28	16
25.672–25.689- - - - - - -	(X_1)	88	8	4
	(X_2)	68	18 (E + M)	14

[1] Distance along the drill core from the ground surface.

FIGURE 5.—Columnar profile for the portion of drill-core sample shown in figure 2*A*. Compositions of the petrographic units in terms of volume percentages of microlithotypes and mixed lithologies are shown to the right of the column. After the average microscopic modal compositions of the mixed lithologies have been determined for the various thickness intervals (see table), the VEIM bulk compositions are calculated and plotted across the column.

QUANTITATIVE NOMENCLATURE

In our methodology, we propose to replace most microlithotype and lithotype terms with quantitative symbols such as (V), (E), (I), (M), (S), (X_1), (X_2), and so forth to eliminate the ambiguity of the composition of the component and the long descriptive words. In this quantitative megascopic notation, (V) represents vitrite or vitrain, (E) liptite, (I) inertite or fusain, (M) mineral layers or lenses other than iron sulfide, (S) iron sulfide, and (X_1), (X_2), and so forth mixed lithologies. Compositions of the mixed lithologies (X_1), (X_2), and so forth are in turn described microscopically in terms of V, vitrinite; E, exinite; I, inertinite; and M, optically resolvable mineral fragments. The volume percentage of each component is expressed as a subscript. This system, discussed further below and described in detail by Chao and others, (1982a, b), is used to generate columnar profiles such as that in figure 5.

We also need to describe coal by its physical and chemical properties. Rank, color, luster, texture, bulk density, structural terms, ash, and chemical characteristics all should be included in a good coal description.

CATEGORIES AND DEGREE OF DETAILS OF MEGASCOPIC AND MICROSCOPIC COAL DESCRIPTION

As mentioned above, the objectives of coal description vary depending on the purpose of the investigation and on the information required by the user. Therefore, details of description and emphasis will vary accordingly.

The range and categories of details of coal description are as follows: (1) field description; (2) first-round lab megascopic description; (3) second-round lab description supplemented by microscopic description; and (4) detailed and refined description, with additional data from chips.

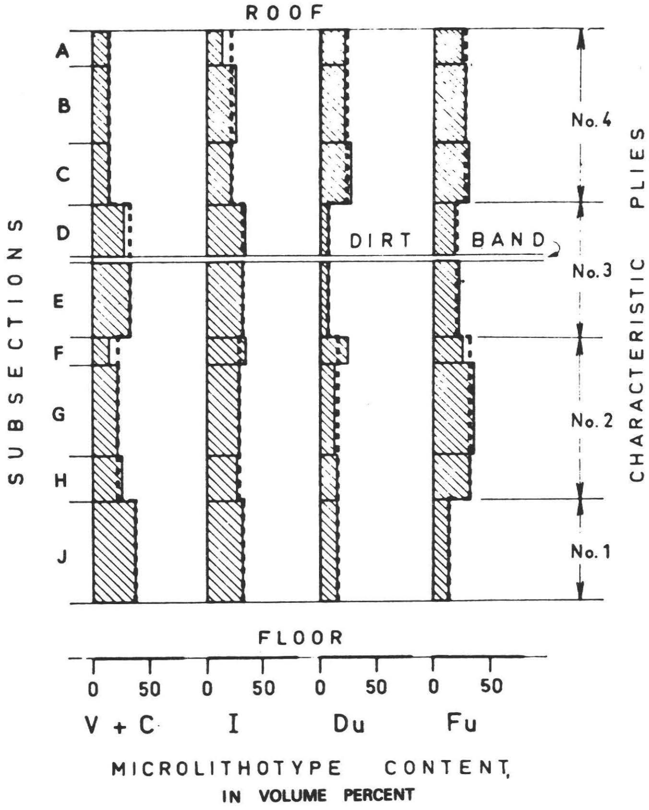
Category 1 entails a brief field description made by using the naked eye or a hand lens and terms such as vitrain, fusain, and partings. It serves a limited purpose: locating the number of partings that are boundaries of megascopic units and that may be traceable in the field. This information is minimal.

Category 2 involves study with the binocular microscope of block or drill-core samples in the laboratory after the samples have been ground and polished with 800-grit abrasives (figs. 2*A*, 2*B*). If a strip 1 to 2 cm wide along one side of the sample is polished further by an in-place polishing procedure using diamond abrasives (appendices 1 and 2), what one can see under the binocular microscope will be greatly improved. This first-round laboratory megascopic description is carried out without any supplementary study by petrographic microscope. Resolution, depending on the quality of the binocular microscope and illumination, can be as good as 10 microns. Under this condition, one can describe the entire coal bed in great detail (see appendix 3 for the kind of details to be recorded and described).

Category 3 differs from category 2 in that it includes supplementary microscopic description, particularly of fine-grained mixed lithologies that are not easily resolved under the binocular microscope. After in-place polishing, anything that is not resolved clearly by megascopic study can be observed under the petrographic microscope by dry or oil-immersion objective lenses. Although microscopic study involves a great workload, selective sampling based on the first-round observations is the key to reducing the number of areas to be studied at higher magnification (appendix 1).

Category 4, still more detailed, requires that chips of particular lithotypes or microlithotype assemblages be taken for bulk specific gravity determination. (This step could be included in category 3 if desired.) Such chips are later made into polished thin sections for study in both reflected and transmitted light as well as for electron microprobe analysis if desired. The details observed in this manner plus the quantitative megascopic and (or) microscopic analysis using an AIAS (or point counting) provide a complete characterization. Such details of information are aimed at solving a specific problem or are needed for facies analysis, which requires a highly interpretive approach.

FIGURE 6.—Petrographic profile of the Permian Garrick seam of Australia, modified from Smyth (1970), showing the distribution of V+C (vitrite plus clarite), I (intermediate), Du (durite), and Fu (fusite) divided into plies and subsections.



TYPES OF DESCRIPTIVE INFORMATION REQUIRED FOR DIFFERENT PURPOSES

COAL CHEMISTRY AND TECHNOLOGICALLY RELATED INFORMATION

Using coal for coking or for steam coal requires knowledge of the rank, the modal composition, and the sulfur and ash content of the coal. Describing the coal profile in terms of VEIM and pyrite is pertinent because the amount of vitrinite- and exinite-group macerals present affects caking and expanding properties, and the amount of inertinite affects the strength of the coke. Such information is useful also for blending different coals for coke making.

Besides knowledge of pyrite and mineral abundance and distribution in the coal based on petrographic data, chemical, plasticity, and fusion characteristics are supplemental data required for such applications.

COAL WASHABILITY AND PREPARATION INFORMATION

Washability and preparation of coal depend on the size, abundance, and distribution of pyrite and other minerals in the coal. Information on bulk specific gravities of specific lithologies is particularly useful for guiding processing based on different specific gravity cutoffs in the preparation plants. The success of coal preparation is critical not only to the particular use of the coal for blending, for coal conversion, or for sale but also for predicting the extent of pollution after burning.

COAL-BED PROFILES

Information regarding the coal "seam" profile also is pertinent to mining problems. For example, knowing the position of shale partings or the frequency of mineral-rich bands can aid in selecting the type of mining machine or mining methods to be used.

INFORMATION RELATED TO GEOLOGIC PROCESSES

Information related to geologic processes not only shows the percentage of good-, medium-, or poor-quality coal in a coal "seam" or coal bed but also helps to reconstruct or interpret depositional and (or) geochemical environments. This description, broadly referred to as coal-facies characteristics, is perhaps the most important element in constructing predictive models that show possible correlation of coal-bed thickness and quality variations. It requires the most detailed information on lithologic characteristics as well as phyteral characteristics.

INFORMATION FOR COAL-BED CORRELATION

For possible coal-bed correlation, we need both detailed lithologic and phyteral information. Smith (1962) and Kutzner (1967) have already demonstrated the usefulness of such detailed petrographic information, as figures 7 and 8 show.

SAMPLING AND SAMPLE COLLECTING TECHNIQUES

The scheme for sampling a single coal bed or a series of coal beds in a coal field or basin should be problem oriented. Samples should be collected when exposures are fresh and available. Sample collection should be iterative to fill the gaps of information needed.

The types of samples to be collected can be grouped into two major categories:

1. Channel samples of a whole coal bed or of benches.
2. Complete drill-core or block samples representing the columnar stratigraphic section of the whole coal bed.

A single channel sample of a whole coal bed gives its average composition. The advantage of such a sample is that the method of collecting it is quick and simple (Schopf, 1960). If the coal bed consists of distinct benches, then bench channel samples need to be collected. The major disadvantage of collecting channel samples of a whole coal bed is the loss of stratigraphic information representing both petrographic type and facies changes of the coal bed. Even if bench channel samples are collected, the benches may not have been selected correctly, and variations within a bench are lost. One further serious disadvantage is the fact that, if thin partings such as millimeter-thick clay-rich bands occur anywhere in the coal bed, they are included in the channel sample for all chemical

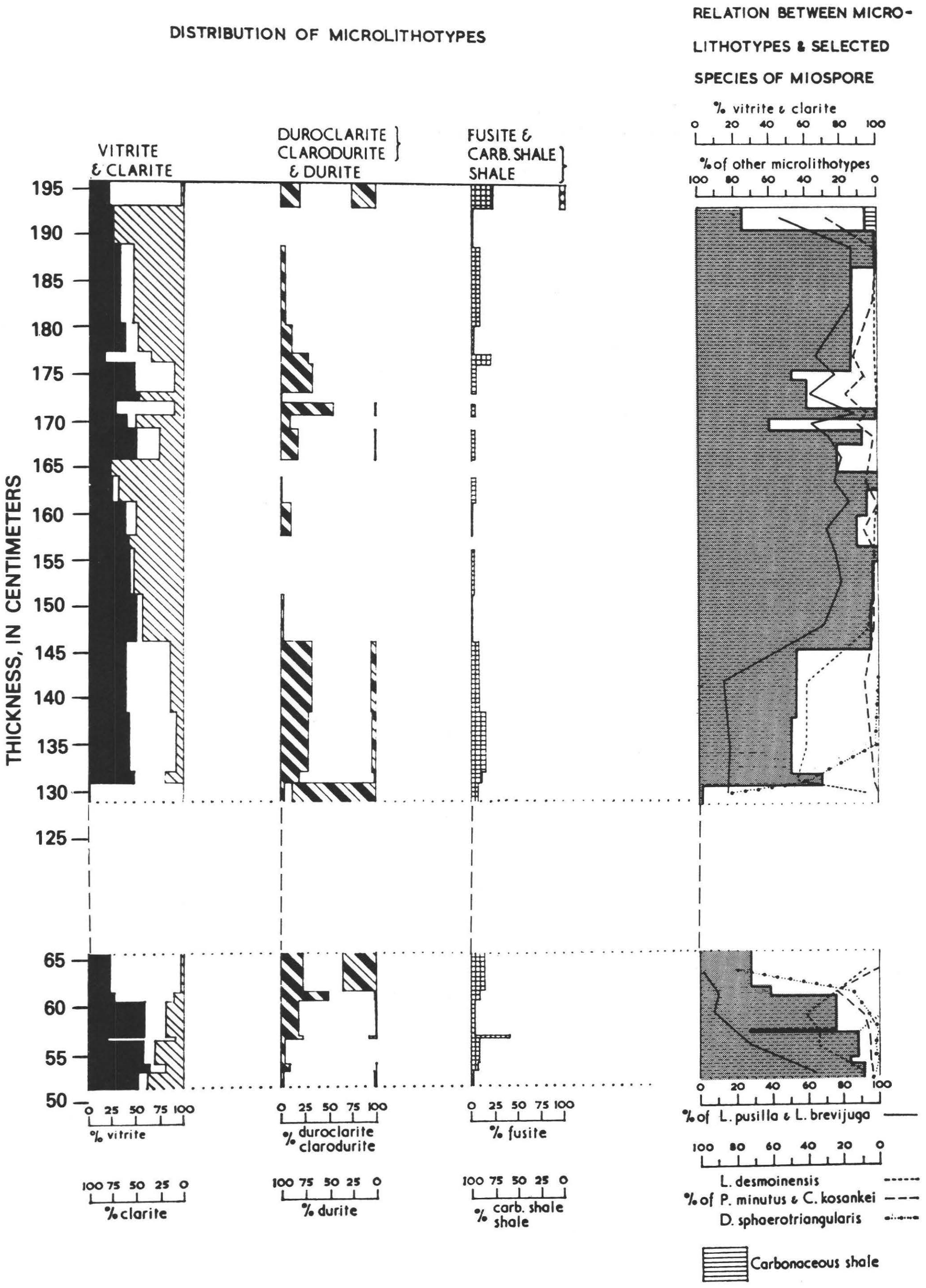


FIGURE 7.—Coal-bed profile showing correlation of microlithotype and miospore distribution of a Carboniferous coal from Great Britain, modified from Smith (1962).

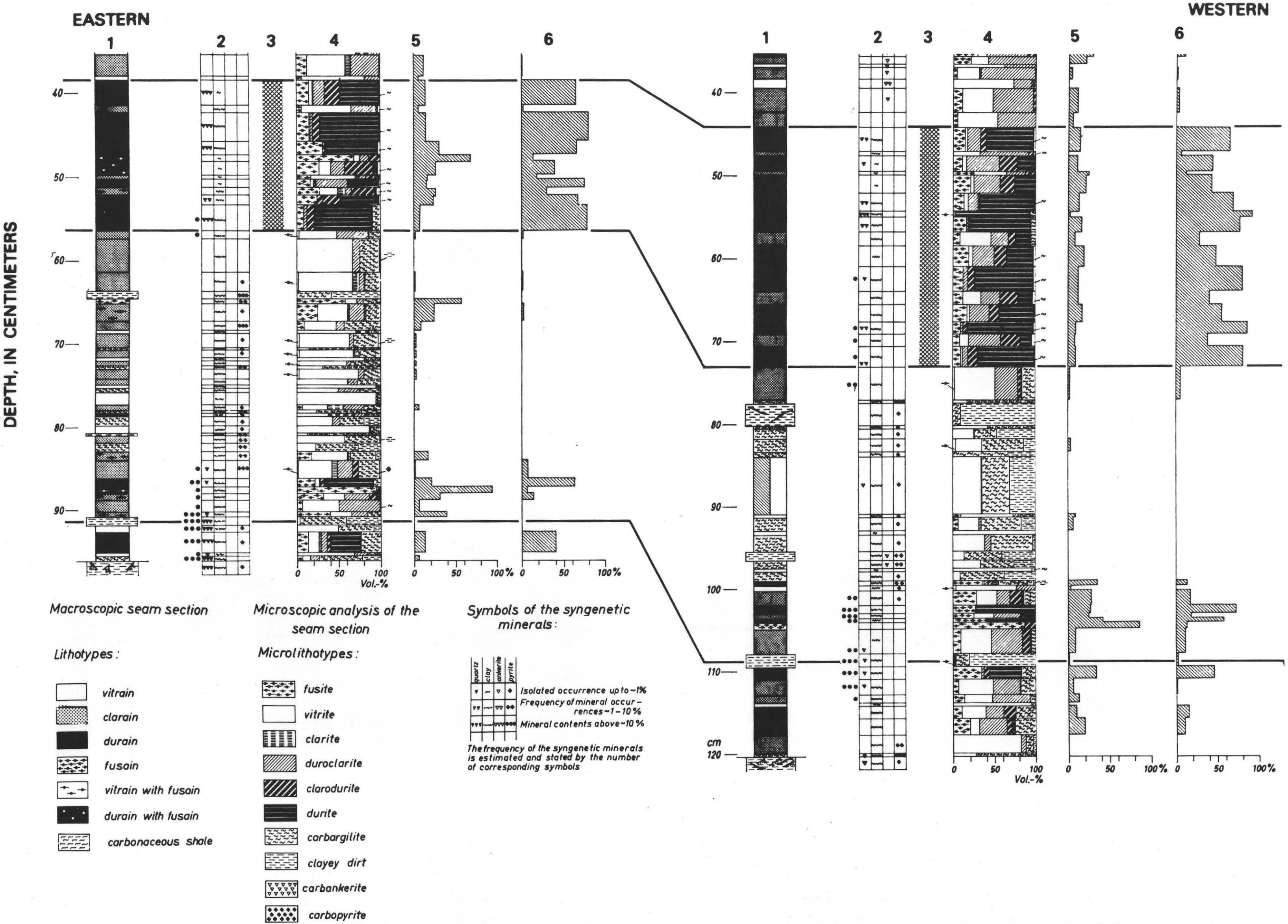


FIGURE 8.—Coal-bed profile showing the use of microlithotype distribution for correlating the eastern and western parts of the Wilhelm coal bed, Germany (modified from Kutzner, 1967). For each section of the coal bed, the columns show (1) lithotypes, (2) syngenetic minerals, (3) crassispores, (4) percentage variations of fusite, vitrite, clarite, duroclarite, clarodurite, and durite, (5) vertical variations of the percentage of fusite, and (6) vertical variations of clarodurite plus durite.

analyses. Because clays provide sites for many trace-element associations, the total picture of the trace elements in the coal itself may be drastically distorted or very misleading. If the partings can be removed by washing, the chemical data obtained from channel samples could affect seriously the prediction of pollution problems depending on whether washed or unwashed coals are to be used.

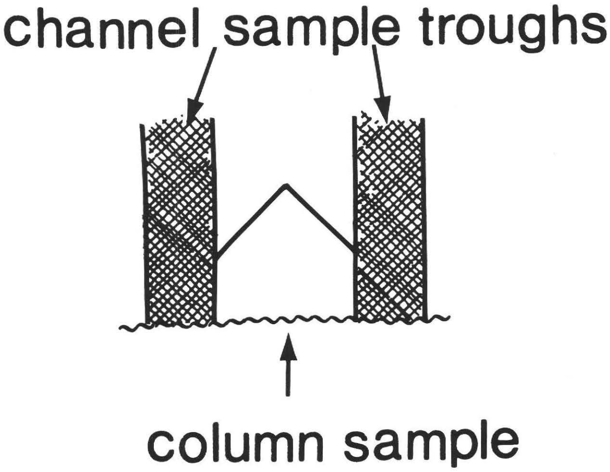
Drill-core or block samples that represent the entire coal bed are necessary to provide the history of stratigraphic, facies, and quality changes and variations during the entire accumulation of the coal bed. Indications of the depositional and geochemical environments will be recorded in these columnar samples. Columnar samples represent the total history of sedimentation of a coal bed; this history varies with the transgression and regression of water bodies and with the accumulation of plant materials themselves. It is, of course, important to understand the sedimentary surface of the basin on which the peat precursor of the coal accumulated. This sedimentary surface defines a depositional environment. As a general rule, for autochthonous deposition, approximately 1 mm of coal accumulates in 30 years (carbon dating indicates that approximately 1 ft of peat is deposited in a thousand years). Therefore, for autochthonously deposited coal, a 10-ft-thick coal bed represents about 100,000 years of depositional history. The stratigraphic history of 100,000 years can be revealed only by the coal bed and the coal facies that it represents. The roof or sediments overlying the coal bed generally represent a drastic change in the energy level of the water body that caused the accumulation of organic matter to cease. Therefore, variations of coal thickness and quality are influenced by the bottom of the basin and by the actual products of organic accumulation. Neglecting the description of the stratigraphy and facies variation of a coal bed can never be justified.

Traditionally, columnar (block or core) coal samples have been used for coal-bed correlation and related studies. If drill-core samples are not available, many geologists shy away from collecting block samples instead of channel samples because they fear that it will be too time consuming. The most common hand, pick, and chisel method of collecting such samples is a tedious and time-consuming process, but it will continue to be used until a better and more mechanized way has been devised and tested successfully. We are interested in any improved technique for collecting block samples under a high wall of a strip mine or from underground mines where no drill-core samples are available. Figure 9 shows a yet untried and unproven plan for collecting a columnar block coal sample suggested by James Currens (personal commun., 1982) of the Kentucky Geological Survey. It is a plan view looking down from the top of the coal bed. Two troughs, each 10 to 15 cm wide and on either side of a columnar sample 10 to 20 cm wide, could be cut by a gasoline-driven masonry circular saw. The material from the troughs would constitute the channel sample or bench channel samples if so desired. While the vertical coal face is held in place, either by heavy aluminum foil or by a coat of plastic material, two angled cuts would be made to intersect behind the coal column to remove it.

The next key question is how to generate a well-planned, realistic sampling scheme. As mentioned before, the sampling design should be problem oriented. The coal geologist plays a key role not only because he is familiar with the coal geology and knows where to collect good, fresh coal samples but also because he can outline the problems that the sampling scheme will be aimed at solving.

We realize that the coal geologist is more than fully occupied while he is mapping and measuring sections in the field. The coal samples, in any case, are best collected at a different time by anyone

FIGURE 9.—Proposed method of obtaining a columnar sample of a coal bed. Two troughs or channels 10 to 15 cm wide are cut and removed on each side of the column as a channel sample. Two 45° cuts are made with a masonry saw to remove the columnar sample, which is held intact either by heavy aluminum foil or by the application of plastic cementing materials.



trained to do so. We propose that the coal geologist accurately designate the location in the coal bed to be sampled. Both a channel sample and a columnar sample should be collected as described above. We propose that only a brief description of the sampling situation be prepared in the field and that the columnar sample have its thickness intervals clearly labeled and be brought back to the office or laboratory to be described. The sample should be split, ground flat, and polished with 800-grit abrasive before being described under a well-lighted binocular microscope. The time required to describe the coal samples should be a part of the office work schedule. The amount of time to be spent depends on the problem to be solved or on the priority set by the coal geologist as to the role of the coal description in his report on assessment of the coal resources.

A realistic sampling scheme should be problem oriented and take advantage of fresh exposures when they are available. We also recommend starting with widely scattered samples. Samples should be studied at the end of the first field season; on the basis of the megascopic descriptive information gained from this first study, the sampling pattern should be further filled in to cover lateral distribution variations. Depending on the region and the complexity of the coal-bearing formation and tectonic setting, sampling schemes and numbers of samples required will vary and should be adaptable.

EXAMPLES OF PAST AND CURRENT METHODS OF COAL DESCRIPTION

The first and most commonly used field description is one using terms proposed by Stopes (1919) such as vitrain, clarain, durain, and fusain. Thiessen (1920) used splint coal, semisplint, attritus, anthraxylon, and bright coal. Schopf (1960) recommended using vitrain, fusain, and attrital and impure coal and paying special attention to the thickness and spacing variation of vitrain bands. This approach serves certain field reference purposes. Although this kind of description makes all coal beds sound similar, the number of partings may be different. The information so conveyed tends to be minimal.

An example of a more informative description is the Australian coal "seam" or coal-bed profile, which gives details on the abundance of various lithologic types on the basis of combined megascopic and microscopic analysis. Figure 6 is such a profile of the Garrick seam or coal bed taken from Smyth (1970). The profile was shown in nine subsections and four columns representing their microlithotype contents. Total thickness of the coal bed was about 90 cm. Smyth (1970) grouped the subsections into four characteristic "plies" and interpreted the plies as typically representative of a depositional environment. In this present example, the first subsection J (no. 1 ply) and E and D (no. 3 ply) are the best coal; subsections H, G, and F represent another ply. Subsections A, B, and C, very similar to one another compositionally, are grouped as the fourth ply. This method of representation in describing seam or coal-bed profiles was used for standard petrographic profiles of the Permian coal beds of New South Wales and Queensland, Australia (Smyth, 1970). One hundred and five coal beds so described were used for cyclicity analysis (Smyth and Cook, 1976). Certain coal beds of a certain age are represented by particular characteristic "seam" profiles. The method of presentation in figure 6 is a good demonstration of the usefulness of megascopic and microscopic lithologic information in correlating and determining coal-bed profile characteristics. The representation of the intermediate types is ambiguous, however, and could be interpreted wrongly.

A second example is given by Smith (1962), who described and correlated the statistical data on species of microspores and the lithologies of Carboniferous coal beds of Great Britain. In figure 7, Smith shows in three columns the lithologic variation of a certain coal bed. The percentage of vitrite is on the left and clarite on the right of the first column. The second column shows the percentage variation of the sum of duroclarite and clarodurite on the left and that of durite on the right. The third column shows the percentage variation of fusite on the left and that of carbonaceous shale and shale on the right. Subdivisions of this coal-bed profile are located at thicknesses of 61, 131, 146, and 194 cm, on the basis of both the lithologic characteristics and the spore content statistics. The column on the far right shows the relation between microlithotypes and selected species of miospores. As an example, the distribution of abundance of *Lycospora pusilla* and *L. brevijuga* follow closely the variation in abundance of vitrite plus clarite. Smith has demonstrated the good correlation of microlithotypes and biological phyteral spore abundance statistics, which are both useful for coal-bed correlation purposes. One problem with the detailed quantitative information on the microlithotypes presented in Smith's approach is that it requires three columns. Another possible problem with this type of description is that the terms clarodurite and duroclarite are not only ambiguous but also, like the intermediate category used by Smyth for Australian coals, possibly erroneous because high-exinite duroclarites and clarodurites are not common microlithotypes in most bituminous coals.

A third example is a much more detailed presentation of the macroscopic (megascopic) and microlithotype composition of the Wilhelm coal bed of Germany by Kutzner (1967). As shown in figure 8, the left-hand column is a megascopic profile description using terms such as vitrain, clarain, durain, fusain, impure coal, and so forth. Kutzner then uses a set of microlithotype terms to characterize the microscopic lithologic characteristics of the Wilhelm coal bed. The second column shows the abundance and distribution of syngenetic minerals; the third column shows the percentage variation of fusite, vitrite, clarite, duroclarite, clarodurite, and durite. The fourth column shows the vertical variation of the percentage of fusite and the fifth column the variation of clarodurite plus durite. Kutzner certainly demonstrates that microlithotypes can be used successfully for correlating parts of the coal bed several kilometers apart. The information so presented, however, is rather difficult to follow, and one needs to correlate the microscopic description with the megascopic description.

One of the most recent examples of megascopic description of coal was given by Daniel and Cole (1982) on the Mammoth coal seam in the Bull Mountain Basin of Montana. They follow the method of Cameron (1978) and use the following lithotype terms: vitrain, bright clarain (with or without pyrite), dull clarain (with or without pyrite), durain, durain with fusain, fusain, pyrite, impure coal, and shale. Our recommended methodology retains the lithotype terms of vitrain and fusain and substitutes for various clarains and durain the mixed lithologies having more specific modal compositions in terms of major maceral groups and minerals.

The preceding examples demonstrate the usefulness of detailed microlithotype information for coal-bed correlation and characterization. Our goal is to improve the speed of getting such detailed petrographic information and to present the detailed information in readily understandable and useful terms.

PROPOSED METHODOLOGY AND RECOMMENDED PROCEDURES FOR COAL AND COAL-BED PROFILE DESCRIPTION BASED ON QUANTITATIVE PETROGRAPHY

The objectives of the proposed methodology and recommended procedures for coal description based on quantitative petrographic information are reviewed below:

1. To improve the speed of obtaining quantitative petrographic information.
2. To eliminate the ambiguity introduced by many of the quantitatively less precise microlithotype terms.
3. To use visual estimates for obtaining quantitative petrographic data, calibrations being provided as necessary by the use of the AIAS.
4. To reduce the amount of duplicative microscopic observations in order to drastically increase the speed of detailed petrographic study.
5. To render possible comparison of quantitative coal descriptions (both megascopic and microscopic) by graphic columnar sections and plots on ternary diagrams.

CONDITIONS AND EXPECTATIONS OF MEGASCOPIC OBSERVATION, EXAMINATION, AND DESCRIPTION

Two aspects that may greatly improve the completeness and speed of petrographic description of coal quite possibly may have been overlooked or may not have received their due emphasis in the past. One aspect is the necessity and advantage of sample preparation before megascopic observation in the laboratory; the second is the resolution and amount of specific information on coal components observable or identifiable under megascopic conditions by using a 32× binocular microscope.

Before preparing a portion of the block sample for megascopic examination, we recommend dividing the sample in half by using a band saw equipped with a continuous-edged tungsten carbide blade without liquid lubricant. One-half of the sample is reserved for chemical and palynological analysis, and the other half is for petrographic study.

The procedure for preparing the coal sample for megascopic examination is given in appendix 1. Contrary to the usual practice, where megascopic examination is conducted on naturally fractured, irregular surfaces of coal, we strongly recommend preparing the coal sample to produce a uniformly flat surface that not only would reveal clearly the constituents in the coal but also would insure that the differences in the light scattering and reflecting properties of the coal components would not be distorted by the shadows and angles of irregular surfaces. To attain this uniformity, we recommend that the entire flat surface of the coal sample be ground and partially polished with 800-grit abrasives. The 800 grit is chosen because (1) the polishing can be accomplished quickly, (2) details of the coal are well revealed, and (3) the surface produced will not reflect the illuminating light source under the macroscopic setup of the AIAS. In addition, we recommend that a strip 1 to 2 cm wide, covering the entire length normal to the banding structure of the coal sample, be highly polished by using the in-place polishing technique described in appendix 2.

Photographic documentation of each series of coal-bed samples is desirable as a record for annotation and classification of lithologic variations.

For observation, we also recommend using a ring light with the binocular microscope for uniform illumination. The sample can be viewed flat lying or tilted (using a hemisphere rotating substage). Normally, there is no need to tilt the sample unless one wishes to change the angle of illumination for comparing the light properties or for improving the contrast of certain features. The resolution at 32× magnification is slightly better than 10 microns; that is, any component or particle 10 microns or larger can be distinguished under this binocular microscope setup on the basis of its shape, texture, or light properties.

MEGASCOPIC RECOGNITION OF MACERALS AND MICROLITHOTYPES

By observing the combined size, shape, texture, and light-dispersing and reflecting properties, we can generally distinguish or identify the following components: (1) pyrite or mineral grains (quartz or clay) down to approximately 10 microns (figs. *4A*, *4C*); (2) vitrite (figs. *2A*, *2B*, *3A*, *3F*, *4A*, *4C*), which appears dark, and inertite, which appears bronzy gray (fig. *3F*), particles, lenses, or lamellae; (3) megaspores (fig. *4A*), microspores (only by shape) (fig. *4A*), and cutinite of the exinite group (fig. *4C*); (4) fusinitized rodlets (fig. *4C*); and (5) microlithotypes of mixed lithologies (figs. *3A*, *3F*, *4A*, *4D*). What are usually not readily distinguishable or identifiable megascopically are semifusinites and fine-grained inertinite such as micrinite. The semifusinites can be confused easily with aggregates of exinites. Both contribute to the lighter color of microlithotypes of mixed lithologies under the illumination conditions for megascopic observation.

The next stage of investigation is to check microscopically what is megascopically discernible but unidentified, since the sample is prepared for microscopic observation as well. This step will improve the petrographer's ability to make better megascopic observations and identifications.

BRIDGING THE GAP BETWEEN MEGASCOPIC AND MICROSCOPIC OBSERVATIONS

The ability to classify microlithotypes or assemblages of microlithotypes under the binocular microscope can be improved by examination under the AIAS macroscopic setup. The binocular examination and AIAS gray-value intervals are used jointly for classifying categories of mixed lithologies. Consistency in classification is a basic requirement; correlation between macroscopic AIAS analysis and megascopic classification and microscopic description (AIAS analysis) of the classified mixed lithologies must be completely free of ambiguity. A few weeks of training will greatly help the operator-observer in making the transition from megascopic observations to microscopic observations.

Our experience, although as yet somewhat limited, has shown the potential usefulness of a detailed megascopic description of a coal bed accompanied by a fair amount of photographic documentation and has demonstrated that the amount of supplementary microscopic description required can be reduced.

PROCEDURES FOR FIRST- AND SECOND-ROUND LABORATORY MEGASCOPIC DESCRIPTION

After the sample is polished with 800-grit abrasives, a first-round binocular observation can be accomplished quickly by using an ocular micrometer for visual quantitative estimates of various microlithotype assemblages and lithotypes.

The lower limit of 2 mm suggested in step 3a of appendix 1 for delineating microlithotypes is intended for coal beds less than 3 m thick. A cutoff limit greater than 2 mm may be chosen for describing coal beds of much greater thickness. A suggested checklist of what to observe and describe for various types of information is given in appendix 3. This list may be adjusted accordingly for different coals.

The purpose of step 4a in appendix 1 is to demarcate thickness intervals of petrographic types that appear to be different from adjacent units in relative abundance of microlithotypes and lithotypes.

The number of meaningful subdivisions of mixed lithologies in a coal is determined by the observer-operator on the basis of the amount of detail desired. The fewer the number of details, the quicker the description can be accomplished. We recommend that, on the basis of the ease or the sharpness of natural distinctions, the fewer mixed lithologies to be described microscopically, the better.

If several mixed lithologies are subdivided megascopically, their relative thickness intervals should be obtained by micrometer traverse under the binocular microscope. If the macroscopic AIAS is available, the resolution or the minimum width of the mixed lithologies to be classified is 0.5 mm. If the AIAS is not available, then the classification of mixed lithologies is based solely on binocular examination. The observer-operator can then have the flexibility of deciding what the minimum width of units of mixed lithology should be. Depending on the nature of the coal, for some autochthonous Pennsylvanian age eastern U.S. coals, where the coal-bed thickness is generally less than 3 m and where the coal is generally finely laminated and well banded, one may choose 1 or 2 mm as the minimum width for traverse measurement. For some Mesozoic western U.S. coals, particularly those of allochthonous origin having coal-bed thicknesses greatly in excess of 3 m, the bands of different lithotypes or mixed lithology are generally thicker. In such cases, one may set a minimum width of 5 mm or even 1 cm for entities of mixed lithologies to be measured by the traverse method under the binocular microscope.

At the end of the first-round laboratory description, the entire coal-bed profile is demarcated and described. The distribution of lithologic types greater than 2 mm thick is shown on the columnar section in terms of vitrite or vitrain, fusite or fusain, mineral- or pyrite-rich bands, and mixed lithologies (X_1), (X_2), and (X_3), and so forth (consisting of assemblages of microlithotypes in alternating or overlapping lamellae or lenses between 0.5 and 2 mm in thickness). The columnar coal-bed profile, completed after the first-round laboratory description, is comparable in informational content to the combined microscopic and megascopic description shown in the example of an Australian Permian coal discussed above and shown in figure 6 (Smyth, 1970).

The major function of the second-round laboratory description is to provide the quantitative microscopic average modal composition of each mixed lithology by using either point count techniques or, if available, the AIAS method. This method is described in steps 5 through 7 in appendix 1.

If the observer-operator decides to have only one single mixed lithology that ranges in composition between the end members of vitrite or vitrain and fusite or fusain, then an average modal composition for this one mixed lithology is obtained. We should keep in mind that any vitrite or fusite greater than 0.5 mm in extent (resolved by AIAS macroanalysis) is not a part of a mixed lithology, whereas those smaller than 0.5 mm are included in the microscopic modal analysis of the mixed lithology. The discrete vitrite or vitrain, fusite or fusain, and mineral lenses or bands greater than 0.5 mm in dimension are treated as individual components scattered within or interlayered between lenses or layers of the mixed lithology that acts as the surrounding "matrix." This method entails a minimum amount of microscopic analysis, so we recommend it. The "average" modal composition of the mixed lithology, however, may vary stratigraphically within the coal bed. Differences in composition should be recorded as desired. This type of description is comprehensive. No further microscopic analysis is required.

If more than one type of mixed lithology is discerned—for example, an exinite-rich mixed lithology (X_1) (analogous to clarite or duroclarite), an inertinite-rich mixed lithology (X_2) (representing clarodurite or some undefined intermediate type), and an inertinite- and mineral-rich mixed lithology (X_3) (corresponding to durite)—then great care must be exercised to avoid uncertainty or ambiguity during microscopic analysis of these megascopically classified mixed lithologies. If the operator is inexperienced, we recommend the use of photographs and medium-scale photomicrographs to make certain that the area analyzed microscopically is actually the one classified megascopically under binocular examination and quantitatively analyzed under the AIAS macroscopic setup.

When more than one mixed lithology is discerned, another constantly encountered problem is that the criteria for classification or boundary between two or more mixed lithologies greater than 0.5 mm must remain consistent and unchanged. Furthermore, this procedure should be followed for each stratigraphic or thickness interval for the entire coal bed where the average modal composition of a particular mixed lithology changes. These precautions are necessary for beginners. Such possible mistakes can be avoided easily through experience or the exercise of a certain amount of care when areas for microscopic analysis are selected. There is rarely any need, in our experience, to have more than three categories of mixed lithologies in most coals as a data base for detailed coal-facies analysis.

Once the average modal compositions of all the mixed lithologies have been obtained either by point count or by the use of AIAS, step 9 of appendix 1 can be accomplished easily by using a computer program, so that the total amount of the major maceral groups and observed minerals in any stratigraphic or thickness interval of the coal-bed profile is described and outlined clearly. This procedure completes the second-round description.

METHODS OF AIAS QUANTITATIVE ANALYSIS

As we have already indicated, the AIAS is an invaluable tool for rapidly obtaining quantitative information on microlithotype and lithotype abundances. Figure 10 is a flow diagram of our AIAS, figure 11*A* shows the overall configuration of the equipment, and figure 11*B* shows the macroscopic setup and a block sample of coal placed under a circular fluorescent lamp below the TV camera. Under the macroscopic AIAS setup, a thickness interval of about 5 cm can be analyzed at one time. The different types of microlithotype or lithotype or mixed lithologic units can be classified and distinguished according to their light properties by

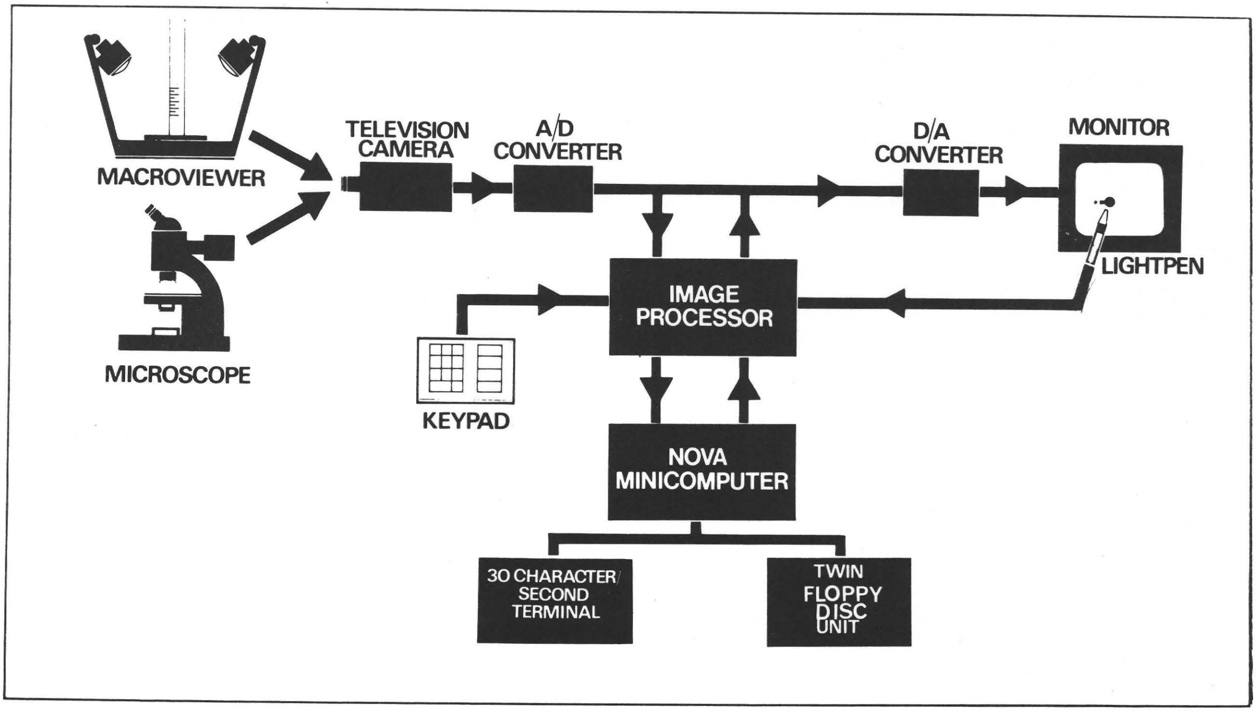
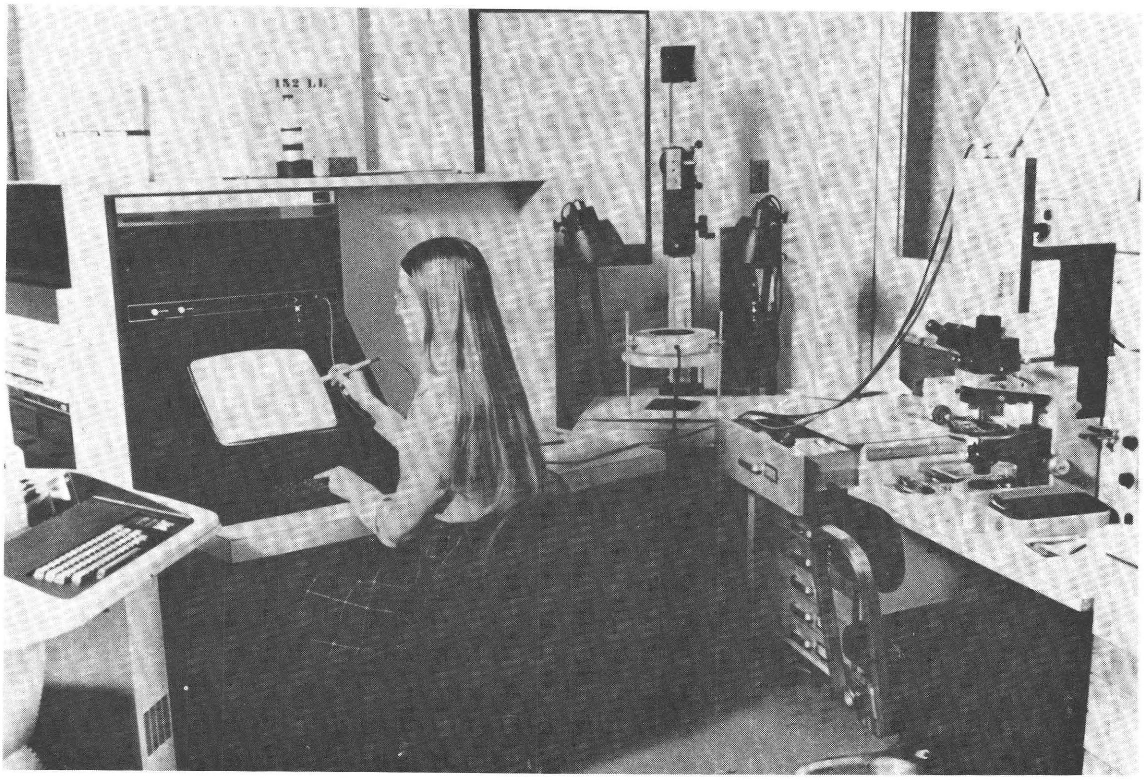
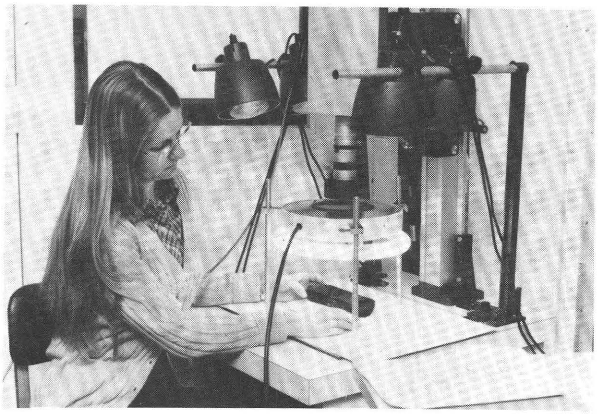


FIGURE 10.—Flow diagram of the Joyce-Loebl MAGISCAN automated image analysis system. Modified from the equipment description brochure of the manufacturer.





▲ FIGURE 11*A*.—Overall configuration of the MAGISCAN automated image analysis system showing, clockwise from the left, (1) the computer terminal, (2) the console containing the minicomputer (left), the TV monitor screen, the keypad, the light pen, and (inside the cabinet) the microprocessor and analog-to-digital and digital-to-analog converters, (3) macroscopic setup for analysis of hand samples and photographs, and (4) the TV camera, positioned on the petrographic microscope.

◀ FIGURE 11*B*.—Setup for macroscopic analysis of hand samples with the MAGISCAN automated image analysis system. From the top: TV camera with zoom lens, fluorescent ring light, and partially polished split-core coal sample. Floodlights are used when photographs are to be analyzed.

scattering and diffuse reflection. These properties are measured in terms of a range of 64 gray values for our AIAS instrument. The light-contributing properties of macerals, singly or in aggregates under the AIAS macroscopic illumination setup, are generally as follows. Vitrinite, vitrite, and vitrain are dark. They have a gray-value interval ranging from 0 to less than 11. Individual exinites or small particles of semifusinite and fusinite of the inertinite group, although they are not resolved megascopically, contribute to the light properties and make a gray-value interval higher than that for vitrite. Thus, a lithotype consisting of mixtures of substantial vitrite and various amounts of exinite and inertinite could have gray values ranging from 10 to 20 or from 20 to 25 as the amounts of exinite and inertinite increase. Nearly pure fusite or fusain lenses or bands range in gray values from about 25 to 30. As mineral content increases, the gray values increase to greater than 30 or 40. Iron sulfide minerals have gray values above 50. Therefore, according to the gray-value intervals, the various types of microlithotypes, lithotypes, and mixed lithologies in bituminous coal can be distinguished generally and described quantitatively.

The image on the 14-in. TV monitor screen consists of 512×512 picture points (pixels). The total number of pixels registering a particular gray-value interval can be calculated quickly by the minicomputer as a percentage of the total area analyzed and therefore as volume percent (Chayes, 1956). In the macroscopic analysis mode, after classification of the various lithologic categories observed repeatedly for the entire coal bed, analysis can proceed rapidly. For each 5-cm thickness interval (figs. 12*A*, 12*B*), the normal time required for an analysis is about 3 min. However, classifying the segmentation of each category (assigning of gray-value intervals by the operating petrographer) usually requires 10 min or more.

AIAS microscopic analysis of the in-place polished strips, polished mounts, or polished thin sections follows the same general principle, but the analysis is based on gray levels corresponding to reflectance from the macerals (figs. 13*A*, 13*B*). For microscopic analysis, the TV camera is mounted on top of a research petrographic microscope using xenon lamp illumination. (We also hope to have, in the future, an additional TV camera sensitive to low-level images in fluorescence, important for studying lower rank coals.)

SELECTION OF CHIPS FOR FURTHER INVESTIGATIONS

To return to step 6, appendix 1, the major objective for removing from a block sample a chip

FIGURE 12*A*.—TV screen view of a split core polished with 800-grit abrasive illuminated by a fluorescent ring light. Vitrite-rich areas appear dark, fusite and mineral-rich areas appear bright, and mixed lithologies appear intermediate gray. Sample of I coal from the Emery Coalfield, central Utah. Area inside white frame is 5.5×5.5 cm².

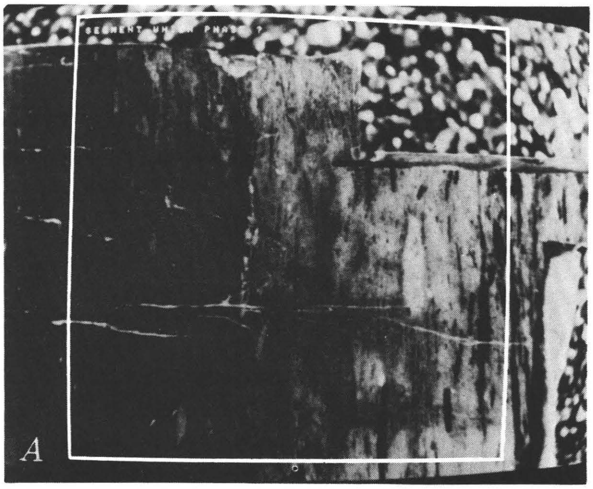
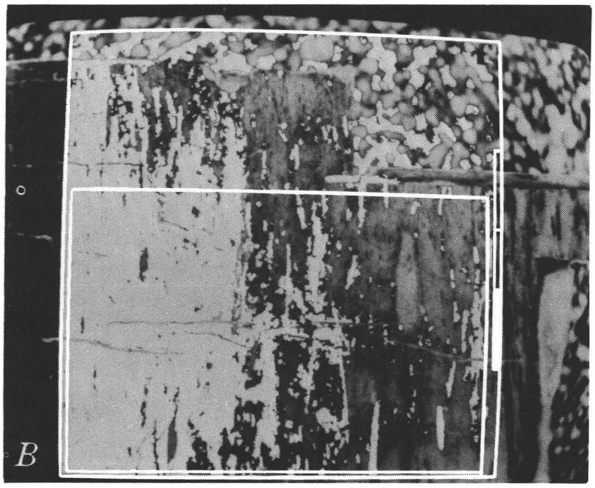


FIGURE 12*B*.—Segmentation of vitrite-rich areas (covered by a white overlay) in the same field shown in figure 12*A*. At the right edge of the screen, a gray-level "thermometer" display shows the gray-value interval assigned to vitrite.



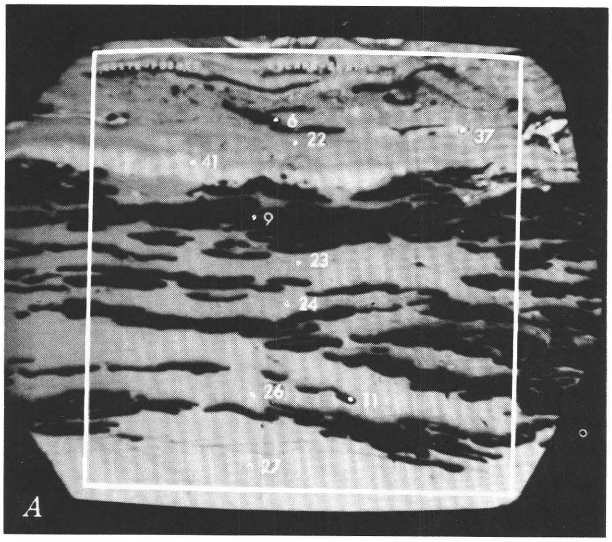


FIGURE 13*A*.—TV screen view of an area in a polished block of No. 6 coal from Webster County, western Kentucky, in incident light. Gray values are displayed for exinite (6–11), vitrinite (22–27), and inertinite (37–41). Area outlined by white frame is approximately 200×200 μm^2.

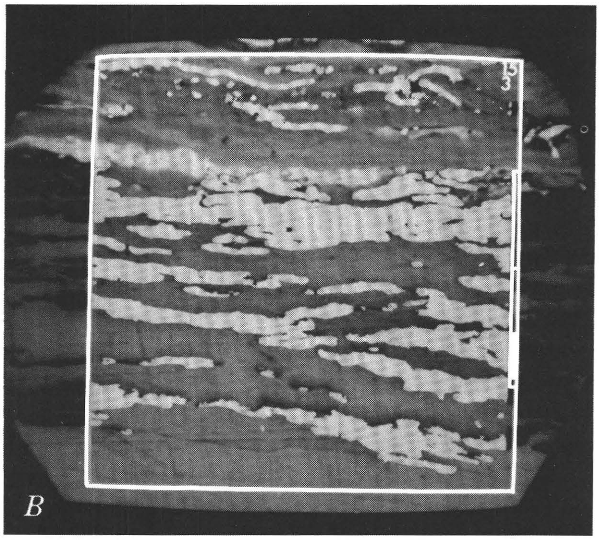


FIGURE 13*B*.—Segmentation of exinite (covered by a white overlay) in the same field shown in figure 13*A*. At the right edge of the screen, the filled region of the gray-level "thermometer" display and the digital values in the upper right-hand corner show the gray-value interval assigned to exinite. Area outlined by white frame is approximately 200× 200 μm^2.

greater than $(0.5\ cm)^3$ that is representative of a particular lithologic type is to obtain further information on its bulk density, modal maceral composition, and chemistry. The first problem is where to remove the chip. Careful monitoring by in-place polishing can indicate clearly where the chips should be removed, so that no ambiguity can occur as to what the chip represents. The chip can be removed by using a pen knife or a razor blade, but, for better control, a thin saw blade should be used.

The "Certigrav" liquids[1] that we use for bulk specific gravity determinations on the removed chips are organic liquids that are nontoxic and that maintain their specific gravity even upon evaporation. The specific gravities of the set of liquids used are calibrated by pycnometer or hygrometer methods, and their refractive indices are determined by using a refractometer. Then a working curve is constructed relating the specific gravities of the series of liquids to their refractive indices with a ±0.0002 precision and a temperature correction. This working curve makes it easy to determine the specific gravity of a mixture of the reference liquids by its refractive index. This method is much more rapid than direct specific gravity determination for a small amount of liquid. Any coal chip to be tested is dropped in a liquid to see if it sinks or floats. If it floats, then a much lighter liquid is added until it just begins to sink, and the refractive index of this liquid (RI_1) is determined; then a heavier liquid is added until the chip begins to float, and the refractive index of the heavier liquid (RI_2) is determined. The midpoint between RI_1 and RI_2 determines the corresponding specific gravity from the working curve and thus establishes the bulk density of the chip. The bulk density of a chip generally reflects its modal composition, because vitrinite and exinite of a certain rank of coal represent the lighter end members of the density spectrum, whereas fusinite (which has a specific gravity of ~1.5) and minerals (which have a specific gravity greater than 2.65) represent the heavier end of the spectrum. A coal chip having a bulk specific gravity greater than 1.40 generally signifies an impure coal. High-vitrinite coals have a bulk specific gravity ranging from about 1.22 to generally less than 1.30, and coal chips containing various amounts of fusinite and minerals range in bulk specific gravity generally from 1.30

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[1] Available from American Minechem Corp., Coraopolis, PA 15108. The use of trade or brand names does not constitute endorsement of products by the U.S. Geological Survey.

to 1.40. The specific gravity liquid sink-and-float method is easy to use and can be used in the field for quick tests of coal chips to aid evaluations of impure coal versus better quality coal.

The removed coal chip can also be polished for study under the microscope. Its modal composition can be determined quickly by using the AIAS. For observing in combined transmitted and reflected light, a polished thin section can be made. Making a polished thin section of such a small chip (those removed are usually about 0.5 cm across) requires far less skill and time than making one that is 2 to 3 cm across. Those who know the benefits of using both transmitted light and reflected light will appreciate this substantial advantage. These polished thin sections provide the opportunity for more detailed study of the phyterals (figs. 14*A*, 14*B*) and textures of the chip's components and for trace-element analysis of various macerals by either the electron or the PIXE microprobe methods.

For correlation between quantitative petrographic data in terms of VEIM and coal chemistry, such chips will and should be chemically analyzed. Research in this area is in progress.

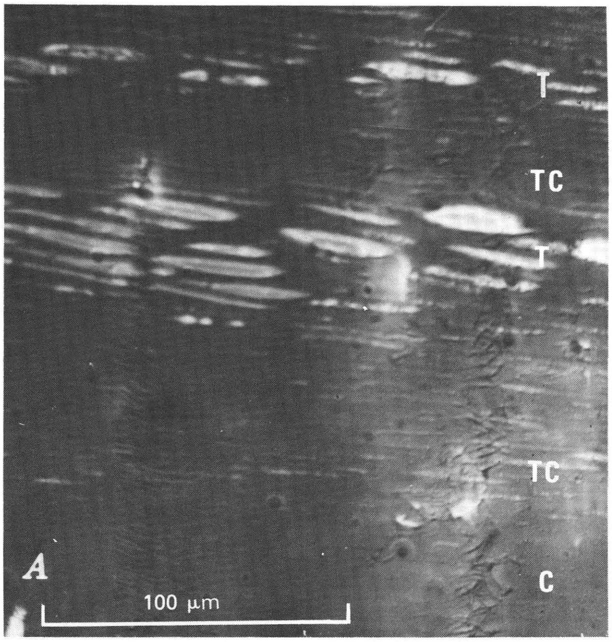
The third round of laboratory description includes all the petrographic information from the chips supplemented by photomicrographic documentation of all the mixed lithologies and their phyteral characteristics.

The fourth round of laboratory description deals with the interrelationship and association of lithologic types, particularly the presence or absence of cyclicity of the various lithotypes, and provides the basis for interpretation with respect to depositional environment. Because of the great detail directed toward the interpretation of the petrographic description, fourth-round studies are more specialized and are to be carried out by coal petrographers and petrologists. They fall in the realm of the methodology of petrographic analysis of coal facies, a subject for another paper.

DATA PRESENTATION AND USE

We have shown examples of coal "seam" or coal-bed profiles used for Australian Permian coals by Smyth (1970) (fig. 6), for British Carboniferous coals by Smith (1962) (fig. 7), and for German coals by Kutzner (1967) (fig. 8). For greater ease of comprehension, we recommend the presentation of the

FIGURE 14*A*.—Area of vitrite in a polished thin section of bituminous coal. Vitrinite-group macerals telinite (with well-preserved cell structure, upper half of photograph) are labeled T; transitional zone traces of cell structure (adjacent to telinite areas) are labeled TC; and collinite (showing no cell structure, bottom of photograph) are labeled C. Upper Freeport coal, Indiana County, Pa. Photomicrograph taken in transmitted light, oil immersion.



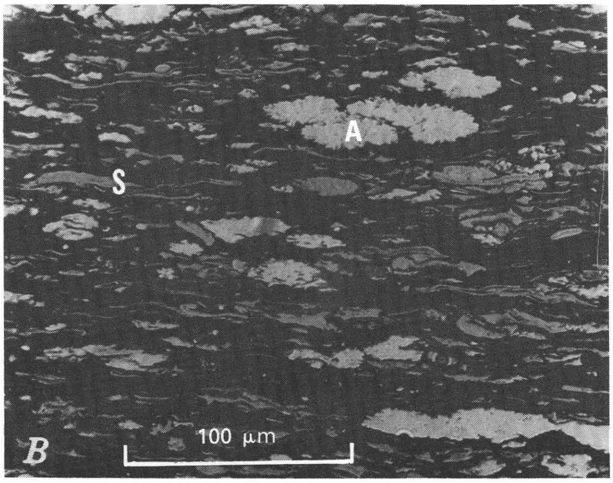


FIGURE 14*B*.—Polished thin section of commercial cannel coal from eastern Kentucky showing alginite (A) (light gray, scalloped edges) and sporinite (S) (medium gray, smooth margins). Photomicrograph taken in transmitted light.

coal-bed profile shown in figure 5. For each megascopically demarcated thickness interval, we indicate the relative abundance of the various component lithologic types. Such results are similar to the "seam" or coal-bed profiles used for describing Australian coals. If the composition of the mixed lithologies is determined microscopically, the conversion to the total composition of a thickness interval in terms of VEIM can be carried out (fig. 5; step 9, appendix 1). The entire coal-bed profile is represented in terms of the detailed lithologic and quality variation from bottom to top.

We can also compare several columnar sections side by side. If a large number of such profiles are to be compared, however, it is easier to plot the total composition of any segment of a coal bed or of the entire coal bed on a ternary diagram. Figure 15, an attempt at such a plot by Strauss and others (1976), does not, however, consider the mineral component, which is a very important parameter concerning the impurity of the coal. Figures 16*A* and 16*B* are ternary plots, the apices of which are represented by vitrinite group V, exinite group E, and the combined total of I (inertinite) plus M (minerals other than iron sulfide) plus S for iron sulfide. The position of a point on such a diagram represents the V, E, (I+M+S) composition, whereas the solid line or tail of the dot normal to side VE of the triangle represents the percent M, the dashed line between the crossbar and the dot would represent the percent S, and the distance from the end of this line to side VE is the measure of percent I. We believe that the use of this ternary diagram is straightforward and simple.

The V, E, (I+M+S) diagram can be used to plot the composition of all types of mixed microlithotype lithologies (fig. 16*A*) and to compare them stratigraphically throughout a coal bed. It can also

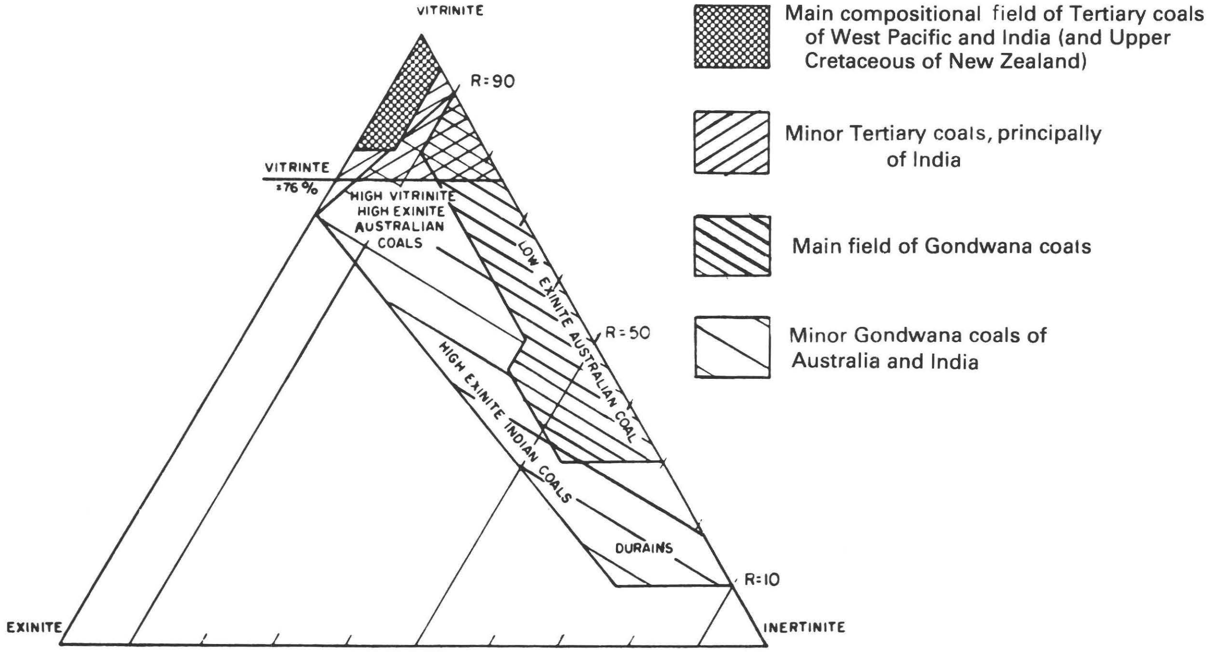


FIGURE 15.—VEI (mineral-free) ternary diagram comparing petrographic characteristics of Tertiary, Cretaceous, and Gondwana coals of the West Pacific and India (Strauss and others, 1976). Reactive component R=vitrinite+exinite.

be used to plot the average composition (VEIM) of various stratigraphic or thickness intervals of a single coal bed (fig. 16*B*) to show the stratigraphic variation of composition. If the extent of the thickness interval is important, then different symbols can be used to illustrate different categories of thickness intervals. For comparison of different coal beds, different symbols can be used to represent different coal beds on the same diagram, or separate diagrams can be prepared on transparent overlays.

QUANTITATIVE COAL-BED DESCRIPTION: A NEW DATA BASE

We suggest that, for most investigations, the information gained after the second-round descrip-

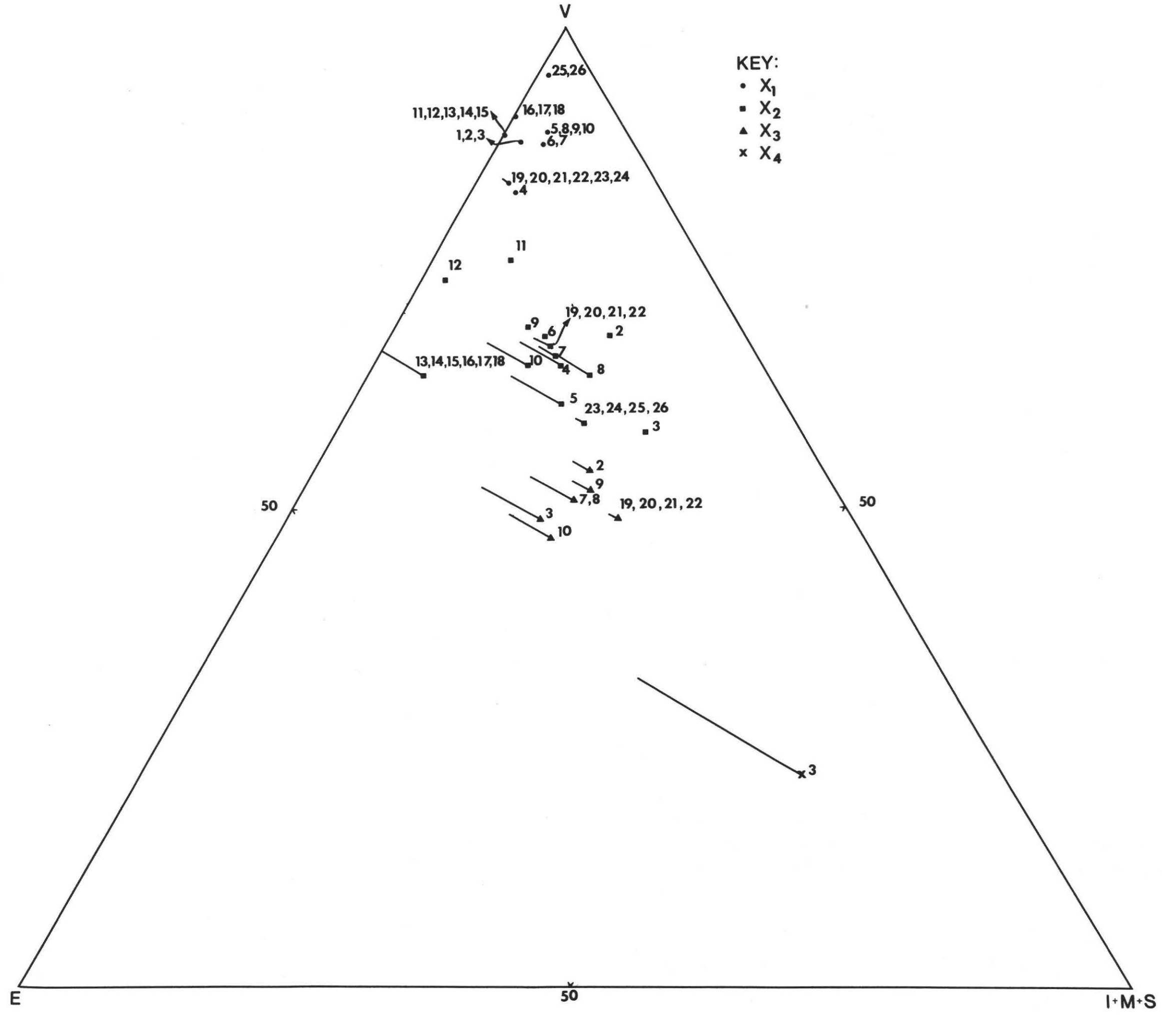


FIGURE 16*A*.—Recommended ternary diagram for plotting microscopic modal compositions of mixed microlithotype lithologies to show stratigraphic variations for a single drill-core sample of a coal bed (Hazard coal, Knott County, eastern Kentucky). Apex V represents the vitrinite group; E, the exinite group; and (I+M+S), the combined total of inertinite plus optically observable minerals (other than iron sulfide) plus iron sulfide. The length of each solid line extending from a data point represents volume percent M, and the distance from the end of this line to side VE of the triangle represents percent I. Any S present would be plotted as a dashed-line segment complementary to M (sulfide was present in this sample only in amounts less than 1 vol. percent). Numbers adjoining the data points identify the thickness intervals numbered sequentially from top to bottom of the coal bed. (Intervals 2 to 6 correspond to the thickness intervals included in the columnar profile of figure 5.) Only mixed lithology (X_1) is present in all intervals; some numbers will be observed to be missing for the other mixed types, which may be present but in amounts less than 1 percent.

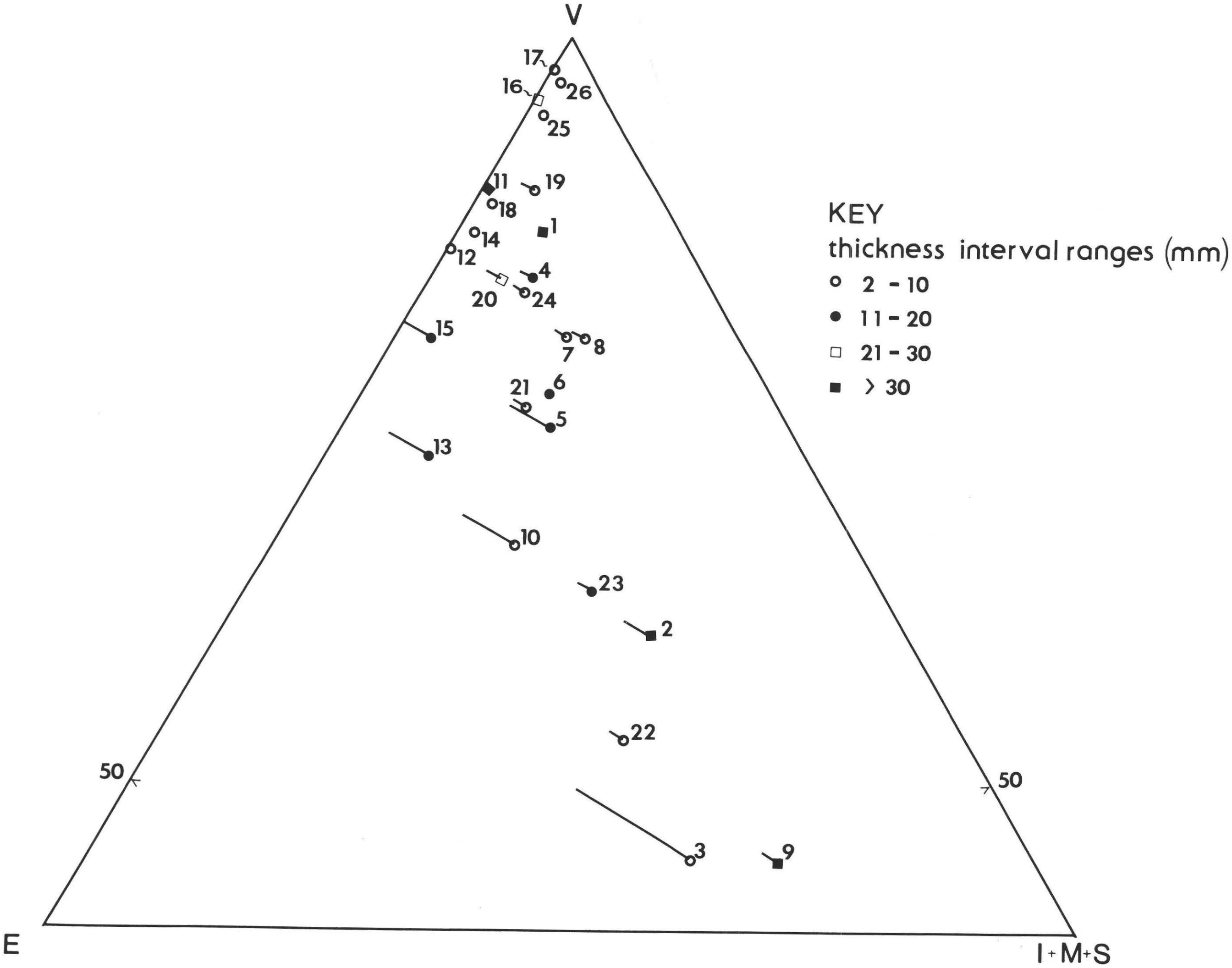


FIGURE 16*B*.—V, E, (I+M+S) ternary diagram showing average total VEIM compositions for the thickness intervals of the coal sample shown in figure 16*A*. Pure vitrain or fusain bands 2 mm or more in thickness normally should be included in the total thickness interval composition calculation. Such bands are omitted on this diagram.

tion is adequate. The end products are the completed coal-bed profile shown by a columnar section, documentation photographs or photomicrographs of the principal coal lithotypes and petrographic types, and ternary diagrams of coal composition in terms of VEIMS. Such information can stand alone for comparison with other sections of the same coal bed or other coal beds. If more columnar sections or triangular plots of the same coal bed are made, a regional variation picture can be constructed. If comparison with different coal beds is to be made, clues to possible correlation may be established. The methodology and procedures recommended here use quantitative petrography to provide a new data base on coal beds that should facilitate ready comprehension of the coal quality and provide a reliable means for coal-bed comparison and correlation.

SUMMARY: THE WHY, WHAT, WHO, AND HOW OF COAL DESCRIPTION

Why describe coal? Any report on coal investigation should convey to the reader the nature and characteristics of the coal bed or beds under investigation. The details and emphasis of such a description will vary, depending on the objectives of the investigation and on the user of the report. It is not a subject that can be avoided. The quality and the usefulness of the report depend very much on how informative and useful the descriptions are.

What should be included in a coal description? Appendix 3 gives a check list of what to describe for any coal-bed profile.

Who should be describing the coal? Naturally, the investigator, the author of the coal report, or anyone trained to assist him. It is somewhat mysterious why most coal geologists do not describe the coal beds that they are mapping and evaluating.

How to describe coal or a coal bed? Our emphasis is on quantitative coal petrography and megascopic description. Our goals in improving coal description are to drastically improve the speed of getting the descriptive data, to expand the usefulness of the informational content, and to present the data in a form that can be comprehended easily.

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APPENDIX 1: PROCEDURE FOR LABORATORY MEGASCOPIC DESCRIPTION OF COAL—BLOCK OR DRILL-CORE SAMPLES

1. Sample preparation:
    a. Labeling of samples to preserve record of stratigraphic interval and orientation represented.
    b. Cutting of sample into two halves, one of which is reserved for chemical and palynological analysis.
    c. Grinding and partial polishing (to 800 grit) of other half of sample for megascopic study.
2. Photographic documentation of prepared samples, recommended for standard coal-bed description; optional for others.
3. Visual and binocular examination:
    a. Demarcation of (V), (I), (M), (S), and partings (2 mm thick or more). Entry of data on columnar section.
    b. Documentation of significant structural features observed, such as thickness and repeat pattern of layers, fragmental nature of components, and so forth. (See appendix 3.)
4. Megascopic quantitative visual estimate of modal composition of microlithotypes and microlithotype assemblages:
    a. Make visual estimate of the amount of (V), (I), (M), (S), (X_1), (X_2), and so on present in any clearly marked megascopic petrographic unit by measuring the total thickness intercept of each lithology by using a calibrated ocular micrometer. The fraction of a microlithotype, microlithotype assemblage, or lithotype present is that thickness intercept divided by the total thickness interval of the megascopic unit. Enter data on columnar section (fig. 5).
    b. Where 2-mm (or larger) bands of the same microlithotype or lithotype are closely spaced, the petrographer may combine these bands and the intervening microlithotypes and (or) microlithotype assemblages into one megascopic petrographic unit to simplify the description.
5. Using in-place polishing procedure, polish a strip 1 to 2 cm wide from each block or core sample from top to bottom with 1- and 1/4-μm diamond abrasives (appendix 2). A very rapid and simple procedure that allows observation of petrographic units in greater detail.
6. Removal of representative sample chips from (X_1), (X_2), and others:
    a. Determination of bulk specific gravity of removed chips by sink and float "Certigrav" liquids.
    b. Optional: Preparation of polished mounts and (or) polished thin sections from the specific gravity chips for microscopic examination.
7. Optional: Visual estimates of microscopic modal analysis of mixed lithologies (X_1), (X_2), and others.
8. Addition of the VEIM data for (X_1), (X_2), and others to the columnar section if available.
9. Recalculation of total VEIM composition for each demarcated lithologic unit:
    a. Plotting of the VEIM data as percentages across the columnar section (fig. 5).
    b. If desired for greater clarity, additional plotting of the data on a V, E, I+M+S ternary diagram (figs. 16*A*, 16*B*).
10. After completion of the entire columnar section, compare the petrographic description and classification with the photographic documentation (step 2) to check for inconsistencies.

APPENDIX 2: THE IN-PLACE POLISH PROCEDURE

The objective of this procedure is to obtain quickly a maximum degree of polish for each lithotype area on the coal-sample surface. Polishing an entire block sample of coal to a high degree is laborious and time consuming because of the large surface area involved. By means of in-place polishing, one can considerably reduce the time required to prepare a small area along the surface of the sample, which is amply suitable for detailed megascopic observation and microscopic analysis. The procedure involves polishing only a strip, 1 to 2 cm wide, on the surface of a block of coal already ground flat and partially polished with 800-grit abrasives. The strip can cover any part of the block or its entire length, as preferred. The degree of polish should be as good as that of a polished mount or a polished thin section and as scratch free as possible.

The technique involves the following steps:

1. Use a stick or rod with a flat end about 1 cm in diameter. For convenience, we use a 5-cm-long metal bolt having a 1-cm hexagonal or circular flat top surface. Cut a piece of TEXMET[2] polishing substrate 1 cm in diameter backed by pressure-sensitive adhesive and attach it to the flat end surface of the rod or bolt.
2. Charge the TEXMET on the bolt with 1-μm diamond paste; a small amount of oil is used as the required lubricant and diluent.
3. Hold the TEXMET-covered surface of the rod or bolt flat against the coal sample from above and polish the desired length of the surface, exerting moderate pressure for 20 to 30 s and making sure that the flat polishing surface is not tilted with respect to the flat coal surface at any time. Keep the TEXMET surface clean; replace, when necessary, to prevent scratches.
4. Wash the polished surface with soap solution and distilled water, thoroughly removing all the diamond abrasives. Dry with compressed air.
5. Check the 1-μm polished area under the binocular microscope to make sure that all the 800-grit scratches along this 1- to 2-cm-wide strip have been removed and only the fine scratches produced by the 1-μm diamond paste remain. These 1-μm scratches can be easily identified since they are parallel to the length of the sample.
6. Use another bolt or rod having a clean TEXMET substrate charged with 1/4-μm diamond paste. Again exerting moderate pressure and maintaining flat contact with the coal-sample surface, polish perpendicular to the 1-μm scratches. Polish for about 30 to 40 s. Wash with soap solution and distilled water, and dry the sample with compressed air. After it has been washed and dried, the surface should appear free of scratches or water or oil streaks. The sample is now ready for photographic documentation, observation, study, and microscopic image analysis.

We have encountered very few problems with scratches and polishing defects when we have used this procedure. Perhaps applying the polishing pressure downward and limiting the strip to be polished to a width of 2 cm or less are helpful. The entire in-place polishing process for a coal sample about 10 cm long should take less than 5 min on the average.

APPENDIX 3: CHECKLIST FOR BINOCULAR MEGASCOPIC DESCRIPTION

I. Structural and textural characteristics and description:

  A. Layering or banding characteristics:

    Information pertaining to the mode of formation of the coal: autochthonous (accumulated essentially in place); hypautochthonous (all subaquatically formed lithotypes, such as cannel and boghead coals); allochthonous (transported, redeposited).

    1. Well banded or layered (autochthonous)—Recommend that bands 2 mm and thicker be shown on the columnar section (fig. 2*A*).
    2. Nonbanded or not banded (hypautochthonous)—Example: Cannel and boghead coals; some mineral-rich, fine-grained, impure coals.
    3. Irregularly layered—Irregular, discontinuous, or lenticular texture suggesting accumulation after transport (allochthonous) (fig. 2*B*). Examples—For vitrite aggregates, describe thin (1–2 μm), several centimeters long as "vitrite lenses"; "vitrite laminae" (0.05–1 mm), several centimeters long; or "irregular vitrite," wedge-shaped, a few millimeters to several centimeters long; and so forth.

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[2] A product of Buehler, Ltd., Evanston, IL 60204. The use of trade or brand names does not constitute endorsement of products by the U.S. Geological Survey.

- B. Texture or grain size where appropriate:
    - 1. Coarse particulate texture, millimeter-sized particles, and so forth.
    - 2. Fine particulate texture, smooth and uniform, and so forth.
- C. Cleat and other fractures where appropriate; may be omitted if not significant or notable.

II. Microlithotype, lithotype, and petrographic unit identification and description:

- A. Describe and characterize (V) (vitrite or vitrain), (E) (liptite, usually rare), (I) (inertite or fusite or fusain), (M) (mineral band), (S) (pyritic band or lenses), and (X_1), (X_2), and other mixed lithologies.
- B. Demarcate lithologic bands or layers 2 mm thick or more on the columnar section at proper intervals.
- C. Note cyclicity of lithologic types if present.

III. Demarcation of petrographic units based on:

- A. Abrupt changes in lithologic composition.
- B. Abrupt changes in textural or structural features.

IV. By using a good binocular microscope and good, even illumination, it is possible, in some coals, to record observations such as:

- A. Association of exinites in different lithologic types:
    - 1. Microspores versus megaspores.
    - 2. Relative abundance of cutinite.
- B. Concentration and distribution of fusinitized rodlets.
- C. Abundance of minerals, clay, quartz, and sulfide.
- D. Abundance of inertinites.

V. Bulk property description in conjunction with lithologic types:

- A. Color and luster, such as dark gray and bright, light gray and dull, and so forth.
- B. Bulk density—During or after the binocular examination, to determine additional characteristics of certain lithologic units described, select chips for bulk density test using "Certigrav" density liquids. Be certain to select and remove chips that represent a single lithologic type and that do not include portions of overlapping units or adjacent partings.

VI. Miscellaneous notes:

Make note of anything that is unusual, such as the way that the coal breaks, liquid exuding, crosscutting veinlets filled with secondary minerals, reaction product with moisture or exposure to air, and so forth.