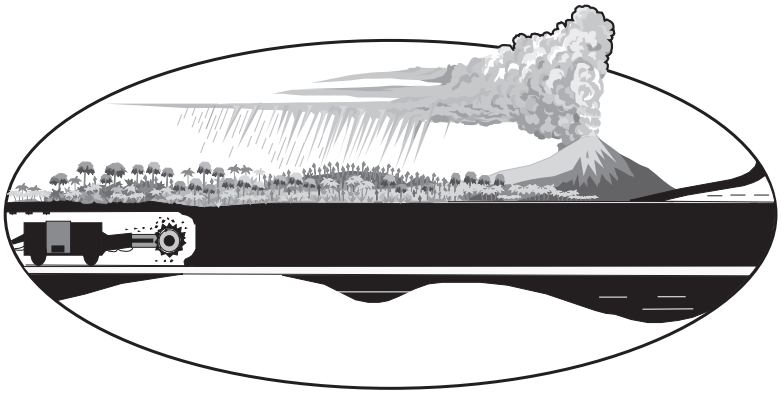
Kentucky Geological Survey
Donald C. Haney, State Geologist and Director
University of Kentucky, Lexington

Compositional Variations in the *Fire Clay Coal Bed* of Eastern Kentucky: Geochemistry, Petrography, Palynology, and Paleoecology



Cortland F. Eble,
James C. Hower, and
William M. Andrews Jr.

Report of Investigations 14

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Kentucky Geological Survey, University of Kentucky
For further information contact:
Manager, Office of Communications and Technology Transfer
Kentucky Geological Survey
228 Mining and Mineral Resources Building
University of Kentucky
Lexington, KY 40506-0107

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Compositional Variations in the Fire Clay Coal Bed of Eastern Kentucky: Geochemistry, Petrography, Palynology, and Paleoecology

Cortland F. Eble[1], James C. Hower[2], and William M. Andrews Jr.[1]

Abstract

Bench samples of the Fire Clay coal bed, collected from 28 localities in a study area of eight 7.5-minute quadrangles in the Eastern Kentucky Coal Field, were analyzed geochemically, petrographically, and palynologically to determine any spatial or temporal trends among the studied parameters.

At most sample sites the Fire Clay is split by a flint-clay parting of probable volcanic origin. The upper bench of the Fire Clay coal generally is thick, laterally continuous, low in ash yield and sulfur content, has a moderate to high calorific value, and is high in total vitrinite content. In contrast, the lower bench generally is thin, laterally discontinuous, moderate to high in ash yield and sulfur content, has a low to moderate calorific value, and has high liptinite and inertinite contents. Rider coals, present at two sample sites, are thin, laterally discontinuous, and high in both ash yield and sulfur content.

Fire Clay coal extracted from underground mines typically contains roof and floor rock, which is separated by conventional coal-cleaning methods. The analytical data were grouped into categories of increasing coal purity to approximate a cleaned coal product. Results indicate that some parameters (Btu and total vitrinite content) increase along a trend from higher ash to lower ash coal. Other parameters (ash yield, total sulfur content, and several minor elements) decrease. Still others (thickness and total moisture) show no trend at all. A comparison of these data with previously accumulated data from 64 cleaned coal samples (collected from preparation plants) confirms these trends. This is significant, especially with regard to Titles III and IV of the Clean Air Act Amendments of 1990, in that many deleterious components of coal appear to be removable by conventional coal-cleaning methods prior to combustion in an industrial furnace. Examples of these undesirable constituents include pyrite, chromium, cobalt, and nickel.

The Fire Clay coal was grouped into four compositional categories for paleoecological interpretation. The categories are (1) a *Lycospora*-dominant group with high vitrinite contents that is interpreted to have formed in areas of the Fire Clay paleomire that were kept very wet, to the point of having standing water, a majority of the time (this group probably developed in areas of the mire that were dominantly rheotrophic and planar); (2) a mixed-palynoflora group with high vitrinite contents that is defined by having a more diverse palynoflora than the first group (increased percentages of small lycopsid, fern, and calamite spores), and high percentages of vitrinite (this group is also interpreted to have formed in areas that were very wet most of the time, and were predominantly rheotrophic and planar); (3) a mixed-palynoflora group with moderate to low vitrinite contents that contains increased percentages of inertinite compared to the first two groups and a diverse palynoflora, possibly because the mire became more ombrotrophic and domed; and (4) a mixed-palynoflora group with high ash yield whose palynoflora is marked by various mixtures of lycopsids (trees and small forms), ferns (tree-like and small forms), calamites, and cordaite spores; samples defined by this group contain elevated percentages of liptinite and inertinite macerals, as well as higher ash yields. The conditions under which group 4 formed probably were rheotrophic and planar. Group 4 defines all the samples in the lower bench of the Fire Clay coal bed.

[1] Kentucky Geological Survey, University of Kentucky. William Andrews worked at the Center for Applied Energy Research while he was conducting research for this report.
[2] Center for Applied Energy Research, University of Kentucky.

We recommend collecting samples on a bench scale, which provides more detailed information than a set of full-channel samples. The additional information gained from bench samples might allow a surface-mine operator to selectively mine superior coal and isolate parts of a coal bed that are of inferior quality. This type of sampling is most beneficial when done using drill cores taken in advance of mining, because the thickness and quality of individual benches can be determined, mapped, and planned prior to mining.

We recommend that when the Fire Clay coal bed is being mined in the eight-quadrangle study area, the bottom bench be left and mining should be confined to the upper bench. The results of this study clearly indicate that the lower bench is, with few exceptions, thin and of poor quality. The same is true for any rider coals that may be present.

INTRODUCTION

The Appalachian coal region extends through 10 states along the eastern margin of the United States, from northeast Pennsylvania to central Alabama and eastern Mississippi, a distance of some 1,380 km (Fig. 1). The Fire Clay coal bed occurs in a part of this area known as the Eastern Kentucky Coal Field. Correlatives of the Fire Clay coal have been identified in adjacent states, including West Virginia and Tennessee (Chesnut, 1985; Lyons and others, 1992). Stratigraphically, it occurs in the middle part of the Breathitt Group, is mid-Middle Pennsylvanian in age, and correlates with the Upper Morrowan Series of the Eastern Interior (Illinois) Basin and the upper Westphalian B of western Europe (Fig. 2). The Fire Clay is an areally extensive, mineable coal resource in the Eastern Kentucky Coal Field. In 1992, approximately 23.6 million short tons of Fire Clay coal was produced, making it the second most heavily mined coal bed in Kentucky, according to the Kentucky Department of Mines and Minerals. Reserve estimates suggest that it should continue to be a major producer for years to come.

This detailed geologic investigation of the Fire Clay coal bed covers an area of eight 7.5-minute quadrangles in the Eastern Kentucky Coal Field (Fig. 3). Vertically continuous, small-scale (less than 0.2 m thick) bench samples were collected from 28 locations in the study area, and were analyzed geochemically (for proximate and ultimate analysis and to determine sulfur, calorific value, major element oxides, and 12 minor elements), petrographically, and palynologically to detect any spatial and temporal (vertical, within-bed) trends among these parameters. Although a majority of the samples were collected from active underground mines, samples were also collected from abandoned surface-mine highwalls and highway outcrops. An effort was made to collect from areas of thick (greater than 1 m) and thin (less than 1 m) outcrops to document any compositional changes related to bed thickness. Figure 4 is an isopach map of the Fire Clay coal bed in the Eastern Kentucky Coal Field showing generally thicker, more laterally continuous coal in the southeastern parts of the coal field, and thinner, more laterally discontinuous coal in the northwest.

A study of this detail and magnitude is both time-consuming and costly, especially in terms of analytical expenses. Perhaps the most important reason for this study was to form a foundation for future work on the Fire Clay and other Kentucky coal beds. Data acquired from this work will be used to determine the level of detail needed for future sampling programs. This will expedite the completion of future programs, and keep analytical costs to a minimum.

Fire Clay Coal Project

This is the first in a series of three publications concerning the Fire Clay coal. The second publication is a summary of the geology of the Fire Clay coal, and especially deals with coal thickness and roof geology trends in a 15-quadangle study area that includes the eight-quadrangle study area of this report (Greb and others, in press b). The third is a study of the available Fire Clay coal resources in the same 15-quadrangle study area as the second report (Greb and others, in press a). These three studies were coordinated in order to determine factors important to future coal development.

PREVIOUS INVESTIGATIONS

The Fire Clay coal bed has received a great deal of study, primarily because of its flint-clay parting. Flint clay is a hard claystone that typically breaks with a conchoidal fracture. It is composed of a microcrystalline to cryptocrystalline kaolinite matrix and lesser amounts of quartz, sanidine, rutile, zircon, and other accessory minerals (Hoehne, 1957; Patterson and Hosterman, 1962; Huddle and Englund, 1966; Chesnut, 1985; Keiser and others, 1987; Belkin and Rice, 1989; Lyons and others, 1992; Hower and others, 1994). Although most investigations have suggested the parting, which has been dated at approximately 311 million years, is of volcanic origin (Ashley, 1928; Nelson, 1959; Seiders, 1965; Robl and Bland, 1977; Stevens, 1979), at least one study (Tankard and Horne, 1979) points toward a detrital origin for the parting. A comprehensive review by Chesnut (1985) concludes that the majority of the evidence favors a volcanic origin.

Figure 1. The position of coal-bearing strata in the Appalachian region, an area that extends through 10 states in the east-central United States (white area).

Palynologic studies of the Fire Clay coal are not uncommon either. Studies from Kentucky include those of Kosanke (unpublished U.S. Geological Survey paleontology and stratigraphy reports), Grosse (1979), Helfrich (1981), and Unuigboje (1987). Cross (1947) and Kosanke (1988) have reported on the Fire Clay coal in neighboring West Virginia. Eble (1988) and Eble and Grady (1990, 1993) studied the Fire Clay coal bed in detail using samples that were collected in West Virginia and Kentucky. A report by Eble and others (1994) discusses the paleoecology of the Fire Clay coal bed in the present study area. One other paper (Currens, 1981) discusses some aspects of Fire Clay coal quality characteristics in the Eastern Kentucky Coal Field.

Materials and Methods

Vertically continuous bench samples were collected from 28 localities in an area covering eight 7.5-minute quadrangles (approximately 2,000 km^2) of the Eastern Kentucky Coal Field for combined geochemical, palynologic, and petrographic analysis (Fig. 5). Benches were selected primarily on macroscopic appearance of the coal lithotypes. Thick intervals that could not be distinguished lithologically were sampled in benches not exceeding 0.2 m; most of the samples were less than 0.15 m in thickness. All samples of inorganic layers (partings) were collected separately. Full-bed-thickness channel samples were also collected at 18 of the 28 locations using the Holmes (1918) method, which excludes inorganic partings greater than 1 cm thick. Three hundred thirty samples were used for this study.

The samples were first reduced in size to –850 micrometers (µm) (–20 mesh) in accordance with American Society for Testing and Materials (ASTM) standards (ASTM, 1992b). Two splits, each weighing approximately 50 g, were removed for palynologic and petrographic analysis. Two additional splits were further reduced in size to –200 µm (–60 mesh) for geochemical analysis in accordance with ASTM standards (ASTM, 1992b).

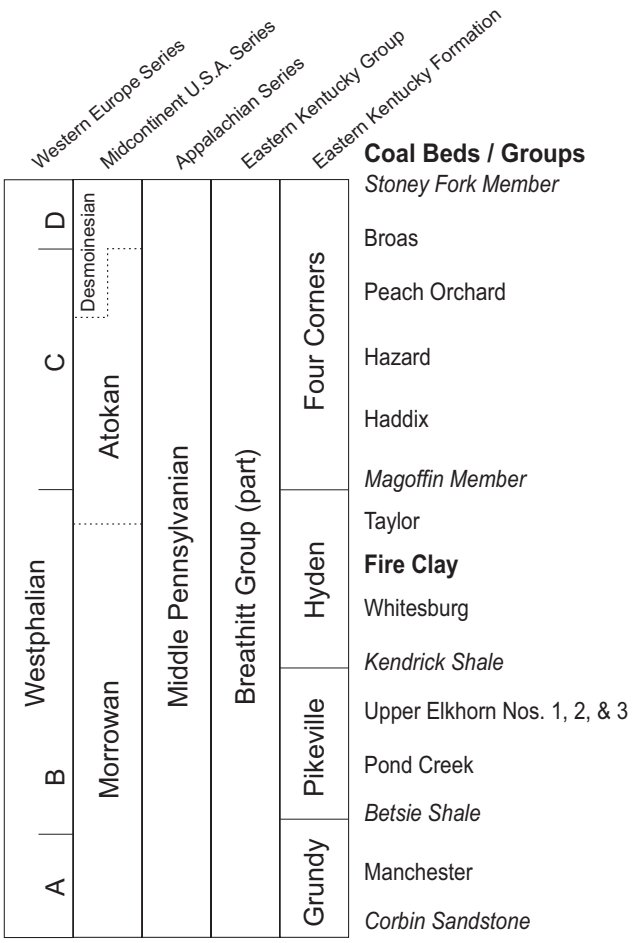

Figure 2. Generalized stratigraphy for the Eastern Kentucky Coal Field showing the position of major mineable coal beds, including the Fire Clay coal bed.

All samples were submitted for proximate (as-determined moisture, volatile matter, fixed carbon contents, and ash yield), total sulfur, sulfur forms (sulfatic, pyritic, organic), and X-ray fluorescence (major oxide and minor element determination) analyses, as well as for the determination of 12 minor element concentrations (Mo, Mn, Zn, Rb, Cu, Sr, Ni, Zr, Co, Cr, Ba, and V). Coal samples (increment and full-channel) were subjected to ultimate (elemental carbon, hydrogen, nitrogen, and oxygen contents) and calorific value (Btu) analyses. Tests to determine chlorine, free-swelling index, vitrinite reflectance, and ash fusion temperatures (reducing environment) were performed only on full-channel samples.

All analyses provided technical and scientific information about the physical and chemical composition and combustion properties of coal. For example, coal-burning electric utilities routinely require analytical data on the moisture, ash yield, total sulfur content, calorific value, chlorine content, and ash-fusion temperature of the coal they burn. This allows them to determine (1) how much coal will have to be burned to achieve a desired furnace temperature (moisture content, calorific value), (2) how much ash will be generated and disposed of (ash yield), (3) how much corrosion of the boiler should be expected (chlorine content), and (4) if ash must be removed from the boiler in a solid or liquid state (ash-fusion temperature). Likewise, Hardgrove grindability index is used by electric utilities to determine whether or not a particular coal can be used in their pulverized air-injection furnaces. In the steel industry, free swelling index is an important parameter when coal is heated in pressurized ovens and converted to coke. Determination of element concentrations by ultimate analysis and X-ray fluorescence is especially important with the implementation of the Clean Air Act Amendments of 1990, which may require the monitoring of several elements normally found in bituminous coal.

Palynologic analyses were performed on 16 bench samples in order to determine the ancient flora whose remains (plant litter) gave rise to the Fire Clay coal bed.

Isolation of the fraction from coal followed procedures outlined by Barss and Williams (1973) and Doher (1980), with minor modifications to achieve the most satisfactory results. Five grams of –20-mesh coal were oxidized in Schulze's solution (nitric acid saturated with potassium chlorate), digested in 5 percent potassium hydroxide, concentrated in a zinc chloride solution (specific gravity, 1.8), and stored in ethylene glycol monoethylene (2-ethoxyethanol). Two hun-

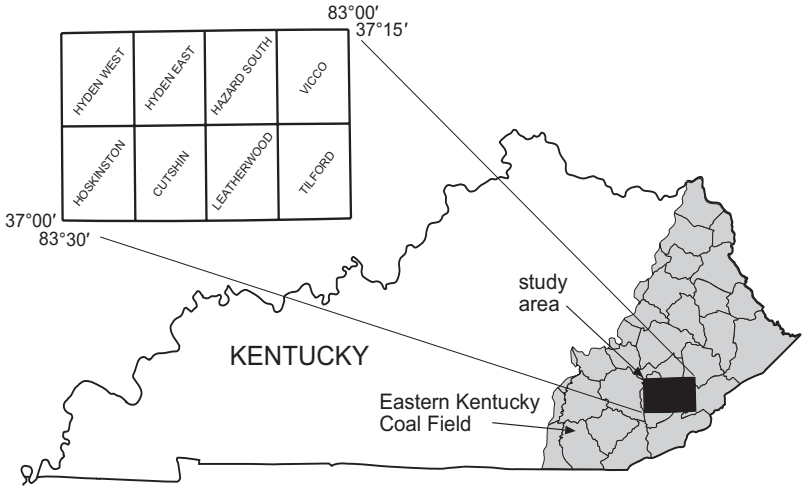

Figure 3. The position of the study area in the Eastern Kentucky Coal Field.

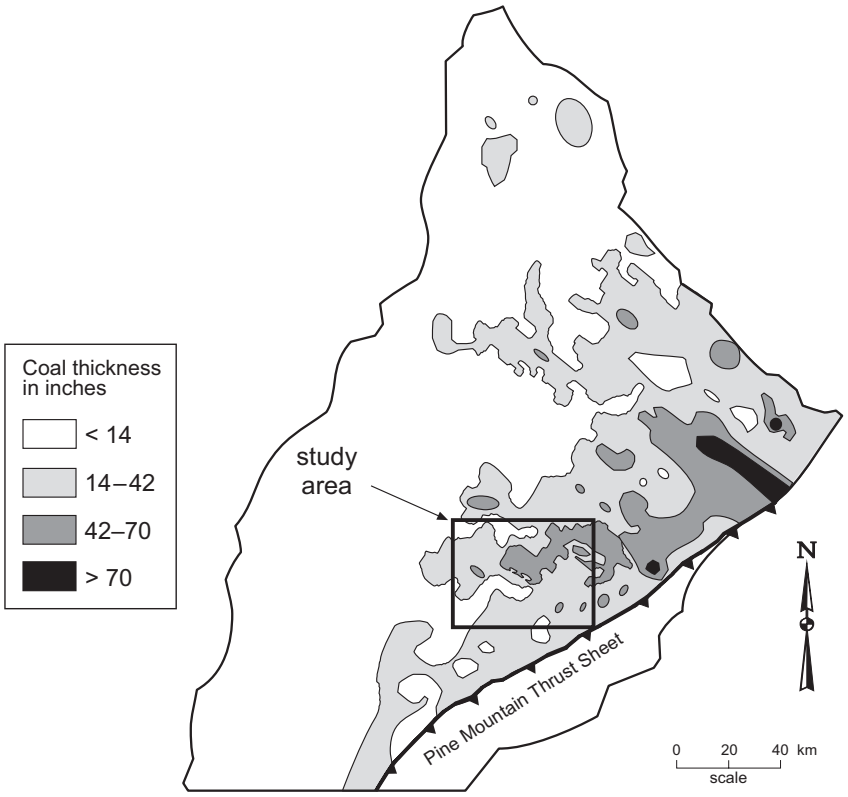

Figure 4. Thickness of the Fire Clay coal bed in eastern Kentucky. Modified from Brant and others (1983).

dred fifty spores were counted from Canada balsam mounts to record the relative proportions of the various taxa in each sample.

All the increment and full-channel coal samples were petrographically analyzed. Coal is made up of components called macerals (Table 1). Macerals are to coal what minerals are to rocks. There are three major maceral groups in bituminous coal: vitrinite, liptinite, and inertinite. They are differentiated based on degree of reflectance in incident light. Vitrinite macerals, which are medium gray in reflected light, represent coalified stem and root tissues (mainly wood and bark), and typically are the dominant macerals (more than 60 percent) in Kentucky coal. The vitrinite macerals telinite and telocollinite are large (generally greater than 50 µm in diameter); in addition, telinite possesses discernable cellular structure. These two macerals are sometimes referred to as "structured vitrinites." In contrast, the maceral vitrodetrinite consists of small (generally less than 20 µm in diameter), disaggregated pieces of vitrinite. Gelocollinite is an amorphous form of vitrinite whose origin is primarily owed to partial degradation of the original plant litter. Quite often, vitrodetrinite and gelocollinite occur together as a mixture, and are called desmocollinite. Vitrodetrinite, gelocollinite, and desmocollinite, sometimes referred to as "unstructured vitrinites," are indicative of accelerated levels of biodegradation. Corpocollinite is the term used to describe ovoid pieces of vitrinite of varying size. These bodies are the fill of cellular cavities.

Liptinite macerals are dark brown to black in reflected light, and are mainly derived from hydrogen-rich plant parts such as spores and pollen, cuticles, and resins. With a few exceptions, the individual maceral names are self-descriptive. For example, sporinite is coalified spores and pollen, cutinite is coalified cuticles, resinite is coalified resins, and so on. Liptodetrinite consists of small fragments of liptinite that are too disaggregated to assign to another liptinite maceral.

Inertinite macerals are white to white-yellow in reflected light, and are derived from previtrinite plant components that have be-

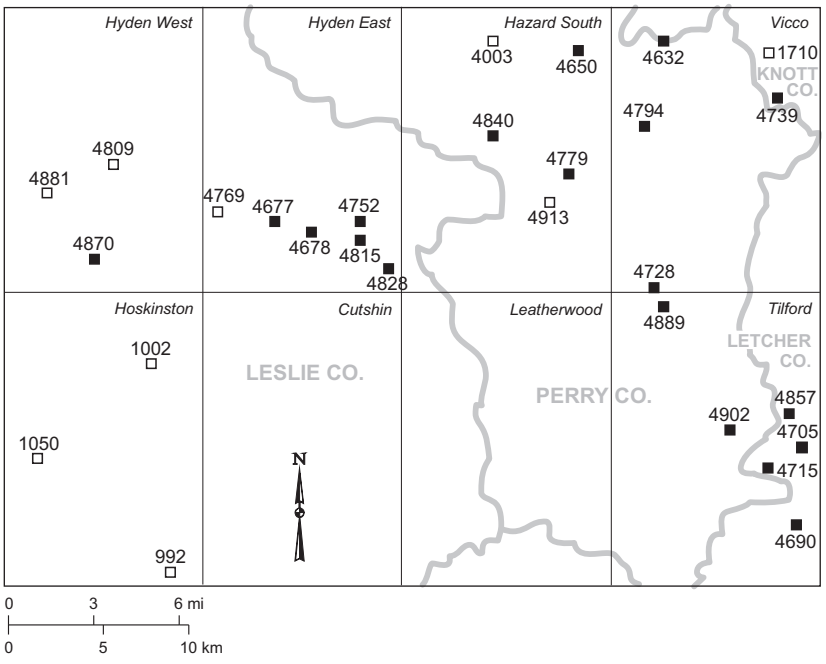

Figure 5. Locations of 28 sampling sites in the study area. Sample locations marked by black squares have both full-channel and bench samples. Sample locations marked by white squares have bench samples only.

Table 1. Breakdown of macerals in bituminous coal (after Pierce and others, 1991).

Maceral Group	*Maceral*	*Description*
Vitrinite	Telenite (well preserved)	Structured vitrinite with visible cellular detail; positive relief after etching
	Telenite (poorly preserved)	Structured vitrinite lacking cellular detail; positive relief after etching
	Corpocollinite	Ovoid bodies representing cell fillings; positive relief after etching
	Gelocollinite	Unstructured groundmass vitrinite; negative relief after etching with brown-black color
	Vitrodetrinite	Small fragments of unstructured vitrinite; positive relief after etching
Liptinite	Sporinite	Spores and pollen
	Cutinite	Cuticles
	Alginite	Algae
	Resinite	Resins
	Liptodetrinite	Unidentifiable liptinite fragments
Inertinite	Fusinite	Strongly oxidized previtrinite tissues
	Semifusinite	Moderately oxidized previtrinite tissues
	Macrinite	Oxidized cell fillings
	Micrinite	Coalification by-product of liptinites (mainly)
	Sclerotinite	Oxidized cell walls of fungi (in part)
	Inertodetrinite	Unidentifiable inertinite fragments

come oxidized, either by fire or the activity of fungus and bacteria. Fusinite and semifusinite are large pieces of inertinite, fusinite being the higher reflecting of the two. Macrinite has a concentric shape and is composed of highly oxidized humic gels. Micrinite particles are extremely small (less than 10 µm in diameter), and look like fine grains of sand or salt dispersed among other macerals. They are believed to be primarily the result of liptinite diagenesis during coalification. Sclerotinite owes its origins to fungal activity in the ancient peat. Inertodetrinite is small, fragmented pieces of inertinite.

Maceral percentages for each sample are based on a count of 1,000 points from two pellets in incident light (ASTM, 1992a). Maceral terminology follows that prescribed by ASTM (1992a). Bench samples from selected sample sites were etched in an acidified potassium permanganate solution to make vitrinite macerals more discernable (Mackowsky, 1974; Moore and Stanton, 1985). This was done to determine any vertical or lateral trends among the vitrinite macerals. Terminology for vitrinite macerals determined on etched surfaces follows that of Pierce and others (1991). These vitrinite macerals carry the prefix "crypto."

RESULTS

In the study area the widespread flint-clay parting naturally divides the Fire Clay coal into an upper bench and a lower bench that are disparate in distribution, appearance, and composition. The upper bench generally is thick (avg 2.64 ft, n=27), laterally continuous, mainly composed of bright clarain, and typically is low in ash yield (avg 7.95 percent, dry basis) and sulfur content (avg 0.93 percent, dry basis). Its calorific value (avg 13,732 Btu/lb) generally is higher than for the lower bench. Petrographically, the upper bench contains high percentages of vitrinite macerals (avg 75.6 percent, mineral matter free [mmf]), and relatively low to moderate amounts of liptinite (avg 8.0 percent, mmf) and inertinite macerals (avg 16.4 percent, mmf) (Table 2).

In contrast, the lower bench generally is thin (avg 0.77 ft, n=23), laterally discontinuous, contains more dull clarain and durain, and typically is higher in ash yield (avg 18.69 percent, dry basis) and sulfur content (avg 1.84 percent, dry basis). Its calorific value (avg 12,036 Btu/lb) is lower than for the upper bench. Petrographically, the lower bench contains lower percentages of vitrinite macerals (avg 65.6 percent, mmf) and higher percentages of liptinite (avg 12.5 percent, mmf) and inertinite macerals (avg 21.9 percent, mmf) than the upper bench (Tables 2–3). Analysis of polished, etched surfaces also indicates that cryptogelocollinite and cryptovit-

Table 2. Average, maximum, and minimum values for selected parameters in the upper bench of the Fire Clay coal bed in the study area (n=27).

	Thickness (ft)	*Ash Yield (%, dry)*	*Total Sulfur (%, dry)*	*Btu (dry)*	*Vitrinite (mmf)*	*Liptinite (mmf)*	*Inertinite (mmf)*
Average	2.64	7.95	0.93	13,732	75.6	8.0	16.4
Maximum	4.49	24.06	1.79	14,313	90.7	20.6	26.6
Minimum	1.0	4.13	0.43	12,731	57.8	4.1	5.2

Table 3. Average, maximum, and minimum values for selected parameters in the lower bench of the Fire Clay coal bed in the study area (n=23).

	Thickness (ft)	*Ash Yield (%, dry)*	*Total Sulfur (%, dry)*	*Btu (dry)*	*Vitrinite (mmf)*	*Liptinite (mmf)*	*Inertinite (mmf)*
Average	0.77	18.69	1.84	12,036	65.6	12.5	21.9
Maximum	1.75	35.44	13.15	13,441	90.0	26.0	41.9
Minimum	0.15	9.78	0.58	8,983	32.1	2.7	7.3

rodetrinite, which are indicative of more degradation, occur more frequently in the lower bench than the upper bench (Fig. 6). Figure 6 also emphasizes an important petrographic characteristic of the Fire Clay coal bed: rather large vertical (within-bed) variability. For instance, a wide range of petrographic signatures can be observed in column 4728; total vitrinite contents range from 17.2 to 88.9 percent, total liptinite contents from 2.9 to 31.4 percent, and total inertinite contents from 8.2 to 51.4 percent.

Thin, discontinuous rider coals were present in samples 4650 and 4632 (Fig. 5). These thin coals were high in ash yield (avg 26.5 percent) and total sulfur content (avg 4.4 percent), which contrasts greatly with the generally low ash yields and sulfur contents of the upper bench.

Full-Channel Samples

Nineteen full-channel samples were analyzed for selected geochemical and petrographic parameters; average, maximum, and minimum values are shown in Tables 4 through 6. Complete analytical data for the full-channel and bench samples are found in Eble and others (1996). An analysis of the accumulated data shows that although many parameters have a rather uniform distribution across the study area, others do not. For instance, ash yield, total sulfur content, and calorific value (Fig. 7, Table 4) are relatively uniformly distributed across the study area. In contrast, chlorine and total vitrinite contents are higher in the western part of the study area, whereas total inertinite and liptinite contents generally are higher in the eastern part of the study area (Figs. 8–9, Table 5). Chlorine content is important because it corrodes the internal parts of combustion furnaces and, as such, is regarded as a detrimental element in coal; concentrations over 0.2 percent (2,000 parts per million [ppm]), and in some cases over 0.1 percent (1,000 ppm), may be regarded as excessive in some cases. Coal samples from the western part of the study area have higher chlorine contents, averaging 0.21 percent, whereas samples from the eastern part have lower chlorine contents, averaging 0.14 percent (Fig. 8). This may, in part, be a function of chlorine being mainly associated with vitrinite, and the western sample sites, on average, contain higher percentages of vitrinite than the eastern sample sites do.

High percentages of liptinite and inertinite in coal have been shown to contribute to low Hardgrove grindability index (HGI) values (Hower and Wild, 1988). Coal with HGI values less than 50 may be rejected by some power plants, especially those with pulverized air-injection furnaces, because the coal is too difficult to grind. Regardless, the consistent thickness, high calorific value, low to moderate ash yields, and total sulfur contents of the Fire Clay coal make it a prime fuel source for many utilities in Kentucky, and also for states along the east coast of the United States (e.g., South Carolina, Georgia, and Florida). The consistently high ash fusion temperatures (avg 2,861°F) make it a good choice for dry-bottom boilers, because the ash remains in a solid form after combustion.

Parameter Variability According to Ash Yield

Of the 330 bench samples that were collected and analyzed, 234 were coal (less than 50 percent ash yield by weight) and the rest were inorganic partings.

Tables 7 through 9 show the average values of selected analytical parameters in groups of coal with increasing levels of purity to demonstrate how the parameters vary with ash yield. In part, these groupings were developed because they

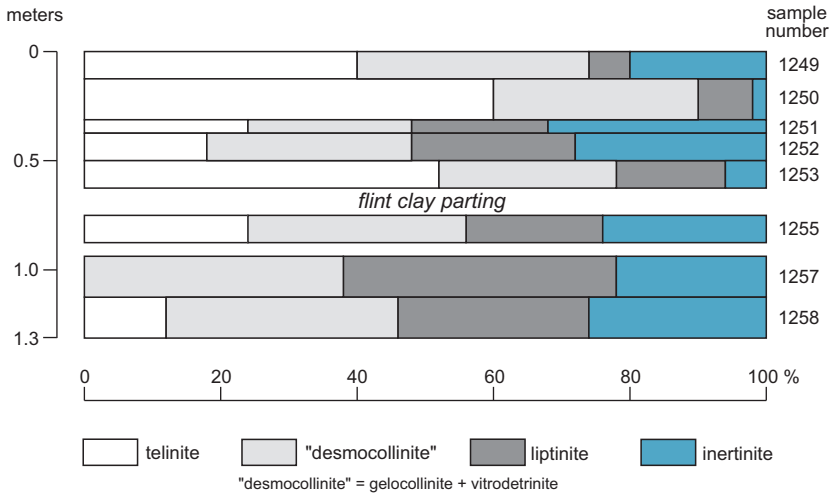

Figure 6. Petrographic profile for sample 4728 showing temporal variability among coal macerals.

Table 4. Average, maximum, and minimum values for selected parameters in full-channel samples from the Fire Clay coal bed.

	Average	*Maximum*	*Minimum*
Bed thickness	3.71	5.45	2.36
Moisture (as-determined)	2.06	2.79	1.57
Volatile matter (as-determined)	34.96	36.52	32.39
Fixed carbon (as-determined)	54.49	58.28	47.1
Ash yield (as-determined)	11.56	20.38	6.91
Pyritic sulfur (dry)	0.26	0.99	0.02
Organic sulfur	0.72	1.11	0.58
Sulfatic sulfur (dry)	0.01	0.03	0
Total sulfur (dry)	0.98	2.11	0.67
Carbon	74.57	79.02	66.67
Hydrogen	4.79	5.14	4.36
Nitrogen	1.61	1.86	1.39
Oxygen	6.54	7.56	5.81
Btu	13,210	13,987	11,942

approximate a cleaned coal product (i.e., coal that has undergone beneficiation). Most eastern Kentucky coal that is mined, including the Fire Clay coal in the study area, is cleaned in preparation plants prior to use. The purity groups are: (1) total coal + rock samples, (2) total coal samples that are ≤ 50 percent ash, (3) coal samples that are ≤ 20 percent ash, (4) coal samples that are ≤ 15 percent ash, and (5) coal samples that are ≤ 10 percent ash. Data from five cleaned Fire Clay + Fire Clay rider coals ("Clean FC" in Tables 7 through 9) and 64 other eastern Kentucky coals that were cleaned in preparation plants ("Clean EK" in Tables 7 through 9) are also presented for comparison.

Some parameters vary little for all the groupings. These parameters are bench thickness and moisture, as-determined volatile matter, and organic and sulfatic sulfur contents. Some parameters increase in concentration as ash yield decreases. These are fixed carbon content, calorific value (Btu), total vitrinite content, and elemental carbon, hydrogen, nitrogen, and oxygen contents. Other parameters decreased as ash yield decreased. These include ash yield, total liptinite and inertinite contents, and contents of every major and minor element that was tested for. Total sulfur and pyritic sulfur contents increased from the total coal + rock group to the total coal ≤ 50 percent ash group, and then progressively decreased through the ≤ 20, ≤ 15, and ≤ 10 percent ash groups. Average parameter values for the cleaned coal samples are very similar to the values for the ash-delimited categories: a comparison shows nearly identical values for contents of moisture, volatile matter, fixed carbon, total sulfur, and sulfur forms; calorific value; petrographic composition; and elemental carbon, hydrogen, nitrogen, and oxygen contents (Tables 7–8).

Many of these trends are significant if the Fire Clay coal is to remain a viable economic resource in light of recently imposed restrictions on the emission of sulfur dioxide (SO_2) by coal-fired power plants. Title IV of the Clean Air Act Amendments of 1990, entitled "Acid Deposition Control," has forced coal-burning electric utilities, which are the primary consumers of coal, to burn lower sulfur coal or retrofit some of their existing boilers with expensive methods of sulfur reduction (e.g., flue-gas desulfurization, fluidized-bed combustion). Because the Fire Clay is an economically important low-sulfur coal bed in the Eastern Kentucky Coal Field, knowledge of its approximate sulfur reduction characteristics is valuable. The average total sulfur content and calorific value for the ≤ 20 and ≤ 15 percent ash categories compare very closely with the values for cleaned Fire Clay + Fire Clay rider coal, and for other cleaned eastern Kentucky coals (Table 7). The SO_2 emission values for the ≤ 20 and ≤ 15 percent ash categories are 1.45 and 1.43 lb SO_2/million Btu, respectively, whereas the average SO_2 emission value for the five cleaned Fire Clay + Fire Clay rider coal samples is 1.44 lb SO_2/million Btu.

Table 5. Average, maximum, and minimum values for selected parameters in full-channel samples from the Fire Clay coal bed.

	Average	*Maximum*	*Minimum*
Total vitrinite	73.8	87.5	44.3
Total liptinite	7.5	19.5	3.1
Total inertinite	18.7	36.2	9.4
Maximum vitrinite reflectance (oil immersion)	0.87	0.97	0.63
Final ash fusion temperature (reducing environment)	2,860	3,000	2,525
Magnesium	0.04	0.22	0.01
Sodium	0.04	0.07	0.02
Iron	0.44	1.01	0.17
Titanium	0.11	0.19	0.06
Silica	2.99	4.71	2.06
Calcium	0.10	0.32	0.05
Potassium	0.160	0.440	0.008
Phosphorus	0.006	0.01	0
Aluminum	1.59	3.03	0.85

Table 6. Average, maximum, and minimum values for selected trace elements in full-channel samples from the Fire Clay coal bed. Values are in parts per million on a whole-coal basis.

	Average	*Maximum*	*Minimum*
Chlorine	0.17	0.28	0.11
Molybdenum	0.78	2.50	0.00
Manganese	56.80	323.90	7.93
Zinc	12.90	41.80	1.04
Rubidium	10.80	35.00	0.17
Copper	17.60	31.60	3.82
Strontium	84.40	172.70	2.89
Nickel	13.10	26.70	2.42
Zirconium	60.00	123.60	2.11
Cobalt	3.57	5.46	0.55
Chromium	45.70	80.90	25.20
Barium	313.60	720.10	164.80
Vanadium	58.40	112.50	16.50

Trace Elements in Coal

Title III of the Clean Air Act Amendments of 1990, entitled "Hazardous Air Pollutants," concerns 189 trace elements (mainly organic chemical compounds) whose emission levels may require monitoring. Thirteen of these elements routinely occur in trace concentrations (parts per million) in coal, and may require monitoring. They are Sb, As, Be, Cd, Cl, Cr, Co, Pb, Mn, Hg, Ni, P, and Se. Two additional elements, thorium and uranium, are also included in Title III because they fall under the category of radionuclides. Currently, no limitations have been established for trace elements, nor has the U.S. Environmental Protection Agency (EPA) decided that all of the above-listed elements will require monitoring. Of these elements, Cr, Co, Mn, Ni, P, and Cl were determined for most samples.

Recognizing abundance trends for these elements is difficult because of extreme spatial and vertical variability. It is possible, though, to establish that all of the tested elements are partially, if not dominantly, inorganic. When considered on a whole-coal basis, all of the trace-element concentrations decrease as ash yield decreases (see Tables 9–10). This indicates that coal beneficiation techniques, in addition to lowering ash and sulfur, may be an effective method for lowering potentially detrimental trace-element concentrations in coal prior to combustion.

Several of the element concentrations for the cleaned coal samples fall between the range of concentrations for the ash categories. These elements are Mg, Na, Fe, Ti, Si, Ca, K, Al, Zn, Rb, Cu, Ni, Zr, and Co. There is poor correspondence between cleaned coal samples and ash category samples for some elements, however. For example, the average molybdenum concentration for the cleaned Fire Clay + Fire Clay rider coals (0.15 ppm) is much lower than the range for the ash-delimited categories (0.66 to 0.78 ppm), and the average concentration for the 64 cleaned eastern Kentucky coals (0.97 ppm) is above the ash-delimited range. Average manganese, chromium, barium, and vanadium concentrations for both the cleaned Fire Clay + Fire Clay rider coals and the 64 cleaned eastern Kentucky coals are below the ranges for the ash-delimited categories, and strontium values are above the range (Table 9). We do not know why half of the tested elements fell within the ranges of the ash-delimited categories and half did not, but this lack of correspondence may be related to different coal beds, as well as coal from different geographic locations, being directly compared. This is especially true for the 64 cleaned coal samples from the

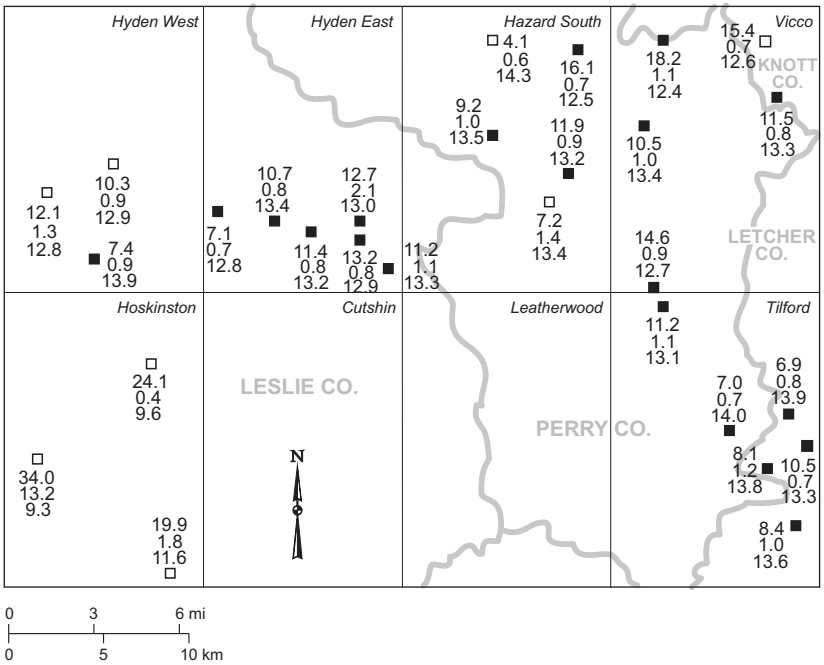

Figure 7. Distribution of ash yield (top number), total sulfur content (middle number), and Btu (bottom number, X 1,000) for full-channel (black squares) and calculated full-channel (white squares) samples in the study area. The calculated full-channel values were derived using weighted averages of values from the bench samples. Sample location numbers are shown on Figure 5.

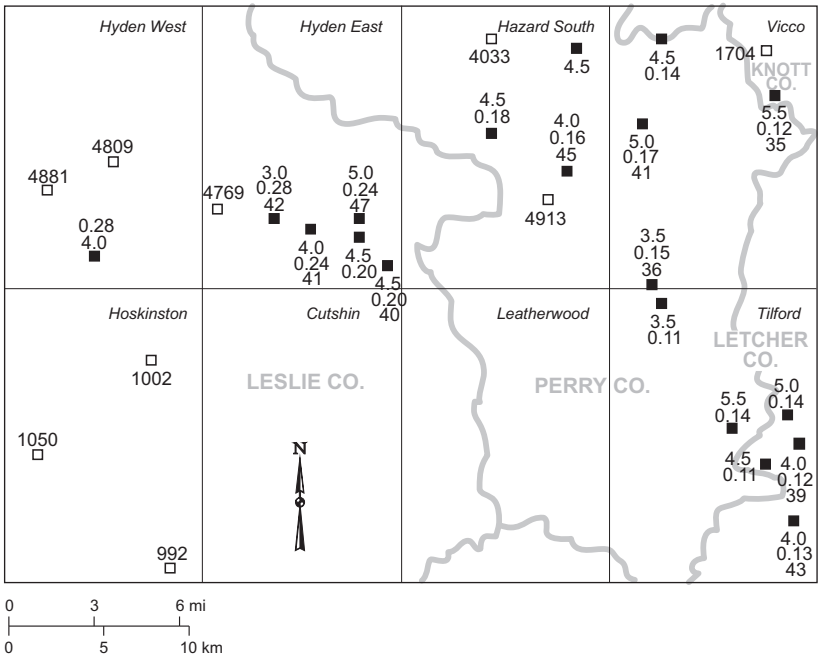

Figure 8. Distribution of chlorine content (top number), free-swelling index (middle number), and Hardgrove grindability index (bottom number) at 18 of the 28 sample locations. Chlorine analyses were not performed on bench samples. Sample location numbers are shown on Figure 5.

Eastern Kentucky Coal Field, which came from several different coal beds. A fairer, and perhaps more accurate, comparison probably would be to examine coal from a mine that has a preparation facility specifically dedicated to it. With the topic of trace elements in coal continuing to be an important issue, a study of this type certainly appears worth pursuing.

Paleoecology of the Fire Clay Coal Bed

Samples from 16 locations were analyzed palynologically to document the palynofloras in the study area and, by inference, the types and abundances of plants that grew in the Fire Clay paleomire. This part of the study is an extension of prior palynologic work on the Fire Clay coal bed (Eble, 1988; Eble and Grady, 1990, 1993; Eble and others, 1994). As was noted previously, the upper and lower benches of the Fire Clay coal bed are geochemically and petrographically distinct. They are also palynologically distinct. In the upper bench the most abundant spore is usually *Lycospora*, and *Lycospora pellucida*, *L. granulata* (both produced by *Lepidophloios*), and *L. pusilla* (produced by *Lepidodendron*) are generally the most abundant species. *Lycospora micropapillata* and *L. orbicula* (both produced by *Paralycopodites*) are locally abundant. In contrast, the lower bench tends to be more diverse in composition, with spores of small lycopsids (mostly *Densosporites*), ferns (tree-like forms such as *Punctatisporites minutus* and *Apiculatasporites saetiger*, and small varieties such as *Granulatisporites*), calamites (*Calamospora* and large species of *Laevigatosporites*), and cordaite pollen (*Florinites*) occurring more frequently.

Compositional Groupings for the Fire Clay Coal Bed

In an effort to make the collective data set on the Fire Clay coal less cumbersome and more understandable from a paleoecological standpoint, the data were summarized qualitatively into four compositional groups on the basis of spore and maceral content, ash yield, and sulfur content. This approach has been successfully used in previous studies of the Fire Clay coal bed (Eble, 1988; Eble and Grady, 1990,

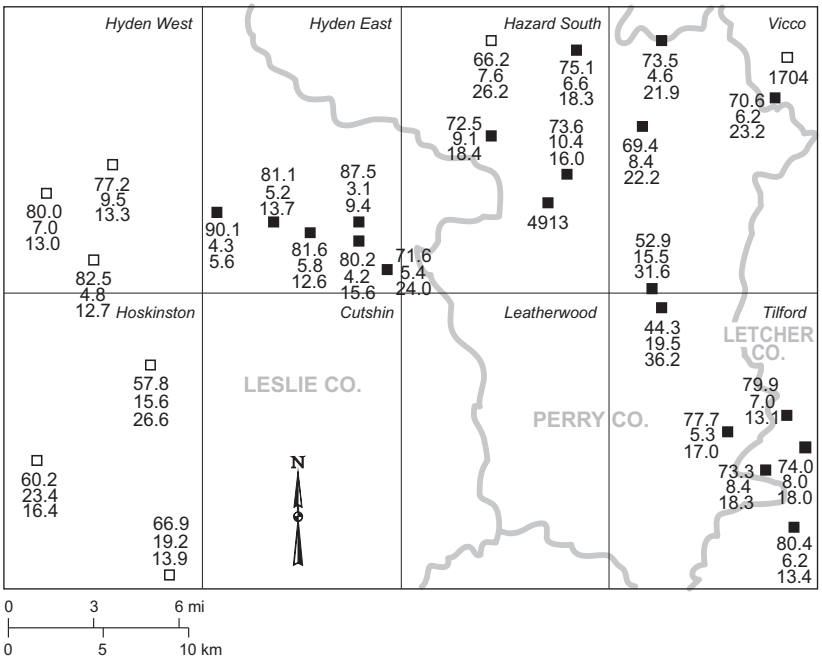

Figure 9. Distribution of maceral groups (top to bottom: vitrinite, liptinite, and inertinite, mmf basis) for full-channel (black squares) and calculated full-channel (white squares) samples. The calculated full-channel values were derived using weighted averages of values from the bench samples.

Table 7. Average values for selected parameters in samples in the Fire Clay coal bed.

	Average Total Coal + Rock Increments (n=312)	*Average Total Coal Increments ≤ 50% Ash (n=235)*	*Average Coal Increments ≤ 20% Ash (n=199)*	*Average Coal Increments ≤ 15% Ash (n=181)*	*Average Coal Increments ≤ 10% Ash (n=138)*	*Clean FC**	*Clean EK†*
Bed thickness	0.39	0.40	0.40	0.41	0.42		
Moisture (as-determined)	2.33	2.47	2.53	2.55	2.46	2.07	
Volatile matter (as-determined, dry)	32.29	34.28	35.23	35.51	36.15	36.46	36.86
Fixed carbon (as-determined, dry)	50.46	54.67	56.96	57.64	58.61	54.51	56.08
Ash yield (as-determined, dry)	29.40	11.00	7.78	6.82	5.20	8.56	7.03
Pyritic sulfur (dry)	0.28	0.32	0.23	0.22	0.14	0.24	0.22
Organic sulfur	0.57	0.73	0.73	0.72	0.73	0.75	0.75
Sulfatic sulfur (dry)	0.02	0.02	0.01	0.01	0.01	0.00	0.01
Total sulfur (dry)	0.90	1.11	0.99	0.99	0.89	0.99	0.97
Carbon	63.42	75.55	78.12	78.99	80.36	76.96	78.46
Hydrogen	4.24	4.90	5.04	5.09	5.19	5.09	5.11
Nitrogen	1.36	1.60	1.67	1.70	1.74	1.68	1.63
Oxygen	6.29	6.31	6.38	6.44	6.51	6.67	6.79
Btu	13,152	13,198	13,671	13,823	14,104	13,790	

*Average parameter values for five samples of cleaned Fire Clay + Fire Clay rider coal (from Hower and others, 1994)

†Average parameter values for 64 samples of cleaned eastern Kentucky coals (from Hower and others, 1994)

Table 8. Average values for selected parameters in samples from the Fire Clay coal bed.

	Average Total Coal + Rock Increments (n=312)	*Average Total Coal Increments ≤ 50% Ash (n=235)*	*Average Coal Increments ≤ 20% Ash (n=199)*	*Average Coal Increments ≤15% Ash (n=181)*	*Average Coal Increments ≤10% Ash (n=138)*	*Clean FC**	*Clean EK†*
Total vitrinite	72.20	72.40	74.30	76.20	79.90	74.80	76.50
Total liptinite	9.3	9.0	8.0	7.5	6.4	6.6	7.9
Total inertinite	18.9	18.6	17.7	16.3	13.7	18.6	15.6
Magnesium	0.15	0.04	0.03	0.02	0.02	0.04	0.04
Sodium	0.11	0.04	0.03	0.03	0.03	0.04	0.03
Iron	0.95	0.62	0.50	0.47	0.35	0.43	0.41
Titanium	0.33	0.10	0.08	0.06	0.05	0.09	0.06
Silica	8.15	2.81	2.04	1.72	1.23	2.14	1.72
Calcium	0.14	0.11	0.10	0.10	0.09	0.10	0.09
Potassium	0.64	0.16	0.09	0.07	0.05	0.15	0.14
Phosphorus	0.020	0.006	0.005	0.004	0.004	0.008	0.008
Aluminum	4.45	1.54	1.14	1.01	0.83	1.38	1.11

*Average parameter values for five samples of cleaned Fire Clay + Fire Clay rider coal (from Hower and others, 1994)
†Average parameter values for 64 samples of cleaned eastern Kentucky coals (from Hower and others, 1994)

1993; Eble and others, 1994). Table 11 and Figure 10 summarize the four compositional groups. See Eble and others (1996) for a list of the identified spores and pollens, grouped according to parent-plant affinity, and their distribution in the studied samples.

Group 1: *Lycospora*–Vitrinite Dominant. This group is marked by high percentages of arboreous lycopsid spores (avg 80.6 percent), namely *Lycospora* and, to a lesser extent, *Granasporites medius*. It is typically associated with bright coal lithotypes (vitrain, clarain) that contain high percentages of vitrinite macerals (avg 83.7 percent, mmf). The ash yields (avg 7.6 percent, dry basis) and sulfur contents (avg 1.4 percent, dry basis) of coal samples in this group are commonly low, but tend to be variable (Table 11). The *Lycospora*–vitrinite-dominant group formed in areas of the Fire Clay mire that were covered with water a majority of the time. This environment would be conducive for arboreous lycopsid growth, reproduction, and expansion (Phillips, 1979; DiMichele and Phillips, 1985), and also would have prevented oxidation of the peat surface, thereby promoting the formation of a coal

Table 9. Average values for selected trace elements in samples from the Fire Clay coal bed. Values are in parts per million on a whole-coal basis.

	Average Total Coal + Rock Increments (n=312)	*Average Total Coal Increments ≤ 50% Ash (n=235)*	*Average Coal Increments ≤ 20% Ash (n=199)*	*Average Coal Increments ≤ 15% Ash (n=181)*	*Average Coal Increments ≤ 10% Ash (n=138)*	*Clean FC**	*Clean EK†*
Molybdenum	1.23	0.78	0.69	0.66	0.69	0.15	0.97
Manganese	128.60	52.40	43.22	37.66	27.71	11.93	16.15
Zinc	30.93	17.72	12.17	9.73	6.57	14.71	11.13
Rubidium	45.85	11.39	6.28	4.32	3.25	11.25	11.58
Copper	31.91	21.08	17.11	16.14	13.68	14.47	15.34
Strontium	137.40	100.40	101.40	99.78	105.90	144.80	143.20
Nickel	22.70	16.24	13.84	12.83	11.68	10.53	12.09
Zirconium	124.10	64.41	52.24	46.75	36.51	64.40	34.97
Cobalt	6.59	4.08	3.10	2.81	2.48	2.63	2.59
Chromium	86.50	43.00	31.53	27.35	20.85	14.27	13.18
Barium	548.86	243.45	203.22	189.72	179.65	126.40	103.58
Vanadium	110.00	59.69	44.42	38.38	30.91	28.35	24.91

*Average parameter values for five samples of cleaned Fire Clay + Fire Clay rider coal (from Hower and others, 1994)

†Average parameter values for 64 samples of cleaned eastern Kentucky coals (from Hower and others, 1994)

with high vitrinite content. The commonly low, but variable ash yields and sulfur contents of samples in this group (Table 11) may be the result of localized, periodic detrital influx.

Group 2: Mixed Palynoflora–Vitrinite Dominant. This group is petrographically and geochemically similar to group 1, with high vitrinite contents (avg 87.3 percent, mmf) and low ash yields (avg 5.3 percent) and sulfur contents (avg 0.9 percent), but it is not as variable as group 1. Group 2 is palynologically more diverse than group 1, with higher percentages of tree fern (avg 18.3 percent), small fern (avg 18.2 percent), and calamite (avg 11.8 percent) spores. This group, as indicated by its high vitrinite content, also formed in areas of the Fire Clay mire that were covered with water (or at least in areas that maintained supersaturated peat substrates; see above), or it was spared the effects of frequent fire. The palynoflora that characterizes this group may be a response to changes in acidity, nutrient availability, or some other related edaphic factors. The low ash yields and sulfur contents of samples in this group (avg 5.3 and 0.9 percent, respectively) indicate that detrital input and emplacement of authigenic mineral matter and pyrite were minimal.

Table 10. Average, maximum, and minimum values for 14 elements in full-channel samples of Fire Clay coal (n=19). Values are in parts per million on a whole-coal basis.

	Average	*Maximum*	*Minimum*
Molybdenum	0.8	2.5	0.0
Manganese	56.8	323.9	1.4
Zinc	12.9	41.8	1.0
Rubidium	10.8	35.0	0.2
Copper	17.6	31.6	3.8
Strontium	84.4	172.7	2.9
Nickel	13.1	26.7	2.4
Zirconium	56.0	123.6	2.1
Cobalt	3.6	5.5	0.6
Chromium	45.7	80.9	25.2
Barium	313.6	720.1	164.8
Vanadium	58.4	112.5	16.5
Arsenic	24.6	146.8	0.0
Lead	12.7	24.5	3.2

Group 3: Mixed Palynoflora–Moderate to Low Vitrinite. This group palynologically consists of various mixtures of lycopsid (trees and small varieties), fern (tree-like and small forms), and, usually to a lesser extent, calamite spores (Table 11). Petrographically, it contains more liptinite and inertinite macerals (avg 10.2 and 24.5 percent, mmf, respectively) than the previous two groups. Samples in this group are generally low in ash yield and sulfur content (avg 4.5 and 0.9 percent, respectively). The increased percentages of liptinite and inertinite (mainly fusinite and semifusinite) macerals suggest that peat in the areas of the Fire Clay mire that supported this group may have been intermittently exposed to air and oxygenated rain waters.

The relative paucity of arboreous lycopsid spores (avg 49.8 percent) in this group may have been the result of an inconsistent water cover, which would have inhibited the lycopsids' specialized reproductive mechanism. This suggests that the parts of the Fire Clay mire in which this group developed were relatively well drained (had a depressed water table)

Table 11. Summary of geochemical, palynologic, and petrographic parameters for the four compositional groups.

	Ash Yield	*Sulfur Content*	*Arboreous Lycopsids*	*Small Lycopsids*	*Tree Ferns*	*Small Ferns*	*Calamites*	*Cordaites*	*Unknown*	*Vitrinite*	*Liptinite*	*Inertinite*
Group 1	avg 7.6	1.4	80.6	2.8	3.8	5.5	5.8	0.7	0.7	83.7	7.3	9.0
	max 21.7	10.4	97.6	11.2	12.0	11.6	13.1	6.0	2.4	93.9	18.6	18.1
	min 2.3	0.5	70.8	0.0	0.0	0.0	0.0	0.0	0.0	74.8	2.5	2.8
Group 2	avg 5.3	0.9	45.9	2.5	18.3	18.2	11.8	1.0	2.3	87.3	4.6	8.1
	max 9.8	2.6	66.4	11.6	48.4	28.4	18.0	2.4	6.0	91.4	8.4	14.4
	min 2.9	0.7	14.8	0.0	1.6	11.6	5.2	0.0	0.0	81.2	2.2	3.0
Group 3	avg 4.5	0.9	49.8	12.5	16.5	10.8	7.2	1.7	1.6	65.3	10.2	24.5
	max 9.1	2.6	76.4	62.0	69.6	20.8	16.8	7.2	4.8	79.9	23.2	44.3
	min 1.4	0.5	11.6	0.0	0.0	4.0	1.6	0.0	0.0	41.7	3.8	14.7
Group 4	avg 22.0	1.6	34.2	9.5	24.9	14.3	11.5	3.6	2.1	59.4	14.7	25.9
	max 53.2	13.2	78.0	89.2	65.6	36.0	29.6	14.4	14.8	89.1	39.2	56.6
	min 10.7	0.1	3.2	0.0	2.4	1.6	0.8	0.0	0.0	19.0	3.7	7.2

at least some of the time. The low ash yields and sulfur contents that characterize this group further suggest that this part of the Fire Clay mire was protected, to a large degree, from detrital contamination. Well-drained conditions might also promote the leaching of mineral matter or mineral precursors from the peat.

Group 4: Mixed Palynoflora–High Ash Yield. This group is usually dominated by fern spores (tree-like and small forms), with lycopsid (trees and small varieties), calamite, and cordaite spores also occurring frequently (Table 11). The petrographic composition of this group tends to be variable; generally, however, it contains high percentages of liptinite and inertinite (avg 14.7 and 25.9 percent, respectively). Ash yields typically are high for this group (avg 22.0 percent), but also tend to be variable. Sulfur contents generally are low to moderate (avg 1.6 percent). This group probably formed in areas of the Fire Clay mire that were subject to periodic detrital influx that may have included both sediment and inertinite (e.g., buoyant charcoal). This would effectively raise both the mineral matter and inertinite content of the peat. The diverse nature of the palynoflora and maceral composition suggests that the prevailing environmental conditions under which this group developed probably were variable and, to some degree, related to the introduction of sediment-laden (and inertinite-laden?) extra-mire waters.

In certain cases, high levels of aerobic degradation may have been caused by a depressed water table. A moderate-ash durain (avg vitrinite 44.2 percent, liptinite 17.7 percent, inertinite 38.0 percent, and ash yield 14.5 percent) that occurs in the upper bench at most sample localities may be the result of such a mechanism. A period of reduced moisture input to the mire may have allowed for a general lowering of the local water table, which resulted in increased aerobic conditions in surficial peat layers, and the production of inertinite macerals and inertinite maceral precursors. Alternatively, this distinctive lithotype may be the result of a raised water table and a widespread flood. If this latter scenario is correct, then at least some of the spore and maceral assemblage may be foreign, brought into the paleomire along with sediment.

INTERPRETATION

Modern domed mires (bog forests) similar to the ones presently developing in equatorial Indonesia and Malaysia have been cited as attractive analogs for Carboniferous peat systems (White, 1913; Smith, 1962; Cecil and others, 1985). Our results show that a majority of the studied samples are in the *Lycospora*–vitrinite-dominant group and the mixed-palynoflora–high-ash-yield group. This suggests that much of the Fire Clay mire in the study area developed in areas with near-constant water cover (or at least peat supersaturation), and also in areas that were subject to frequent, and often repeated, inundation by extra-mire waters. Morphologically, these areas were probably planar to slightly domed, and hydrologically they were rheotrophic. Rheotrophic mires receive part of their moisture from surficial waters and part from atmospheric waters. The mixed-palynoflora–high-vitrinite group, which is the least represented group, also is characterized by very high percentages of vitrinite (avg 87.3 percent), suggesting that peat developed under conditions very similar to those described for group 1 (i.e., abundant moisture). This group also formed in a planar to slightly domed mire setting.

In contrast, the low ash yields and sulfur contents, paucity of arboreous lycopsids, and increased inertinite and liptinite contents of samples from the mixed-palynoflora–moderate-to-low-vitrinite group could have resulted from peat formation in a domed mire setting that was mainly ombrotrophic (receiving all of its moisture from rain waters) and periodically exposed. A domed mire morphology would effectively curtail widespread detrital input, simply because of its positive relief. This hypothesis is supported by the general lack of inorganic partings in the upper bench. If present, inorganic partings almost invariably occur close to the flint-clay part-

***Lycospora*–Vitrinite Dominant**
- Abundance of arboreous lycopsid spores (avg 80.6%) and vitrinite (avg 83.7%)
- Low ash yields (avg 7.6%), moderate total sulfur contents (avg 1.4%)
- Rheotrophic mire with a consistent water table; flooded conditions common

Mixed Palynoflora–Vitrinite Dominant
- Increased percentages of tree fern (avg 18.3%), small fern (avg 18.2%), and calamite (avg 11.8%) spores
- High vitrinite contents (avg 87.3%)
- Low ash yields (avg 5.3%) and total sulfur contents (avg 0.9%)
- Rheotrophic mire with a consistent water table; flooded conditions less common(?)

Mixed Palynoflora–Moderate to Low Vitrinite
- Lycopsid (tree + small), fern (tree + small), and calamite spores in varying proportions
- Increased percentages of liptinite (avg 10.2%) and inertinite (avg 24.5%)
- Very low ash yields (avg 4.5%) and total sulfur contents (avg 0.9%)
- Ombrotrophic mire with an inconsistent water table; surficial peat exposure and oxidation

Mixed Palynoflora–High Ash Yield
- Palynologically diverse; admixtures of lycopod, fern, calamite, and cordaite spores and pollen
- Variable petrography; elevated liptinite (avg 14.7%) and inertinite (avg 25.9%) percentages
- High ash yields (avg 22.0%), moderate total sulfur contents (avg 1.6%)
- Rheotrophic mire with an inconsistent water table; clastic influx common

Figure 10. Summary of four compositional groups in the Fire Clay coal bed.

ing. Additional field data (S. Greb, oral commun.) indicate that this trend of lack of inorganic partings continues to the southeast (Fig. 4).

The Fire Clay coal bed in the study area is probably the result of both planar and domed mire components contributing to the formation of the bed. The *Lycospora*-dominant–high-vitrinite group, mixed-palynoflora–high-vitrinite group, and mixed-palynoflora–high-ash-yield group all suggest peat formation in planar or slightly domed mire settings. In contrast, the mixed-palynoflora–moderate-to-low-vitrinite group may have formed in a domed mire that was acidic, protected from detrital contamination, and subject to periods of surficial oxidation. Planar and domed morphologies are closely related and not mutually exclusive, however. Modern domed peat systems consist of both planar and domed peat phases (Anderson, 1964; Gore, 1983; Moore, 1987). In these systems, peat bodies start out as planar mires and, as long as high moisture conditions are maintained, evolve into domed mires.

Bench composition in the Fire Clay coal can be directly related to mire morphology and hydrologic regime. The lower bench paleomire is interpreted as having been rheotrophic, planar, and subject to frequent clastic contamination. This resulted in a coal that varies greatly in extent and thickness, and is high in ash yield, inertinite, and liptinite. The deposition of the flint-clay parting, probably the result of volcanic activity, arrested peat accumulation and provided a stable platform on which the upper-bench paleomire developed. Unlike in the lower bench, peat development in the upper-bench paleomire was widespread, and proceeded relatively unhindered by detrital input (much less so than in the lower bench). Part of this upper-bench paleomire may have been ombrogenous and domed, which may have been a contributing factor in protecting the mire from detrital contamination. As a result, the coal that was derived from this peat is thick, and low in ash yield and sulfur content. Figure 11 illustrates the interpreted development of the Fire Clay coal bed.

Recommendations for the Coal Mining Industry

The detailed geochemical, petrographic, and palynologic information gathered from a study of this type is invaluable, but also costly in terms of time and money. Unless very detailed information is needed, collection of bench-scale samples, rather than small-scale increment samples, is recommended. Bench sampling will provide more detailed information than a set of full-channel samples, and decrease analysis time and overall analytical costs. Also, the additional information gained from bench-scale samples may allow a surface-mine operator to selectively mine coal of superior quality and isolate parts of a coal bed of inferior quality. This type of sampling is most beneficial using exploratory drill cores taken in advance of mining, which allows the thickness and quality of individual benches to be determined and mapped prior to mining. We also recommend that, wherever possible, samples of cleaned coal and coal refuse from coal preparation facilities be collected along with in-mine samples. This is especially necessary in cases where individual mines, or a group of closely spaced mines producing coal from the same bed, have dedicated preparation facilities. Many more data are needed on coal that has been cleaned, because much of the coal mined in Kentucky is washed prior to utilization.

For the Fire Clay coal bed in the eight-quadrangle study area, the bottom bench should be left alone, and mining should be confined to the upper bench. The results of this study clearly indicate that the lower bench is, with few exceptions, thin and of poor quality. The same is true for any rider coals in the

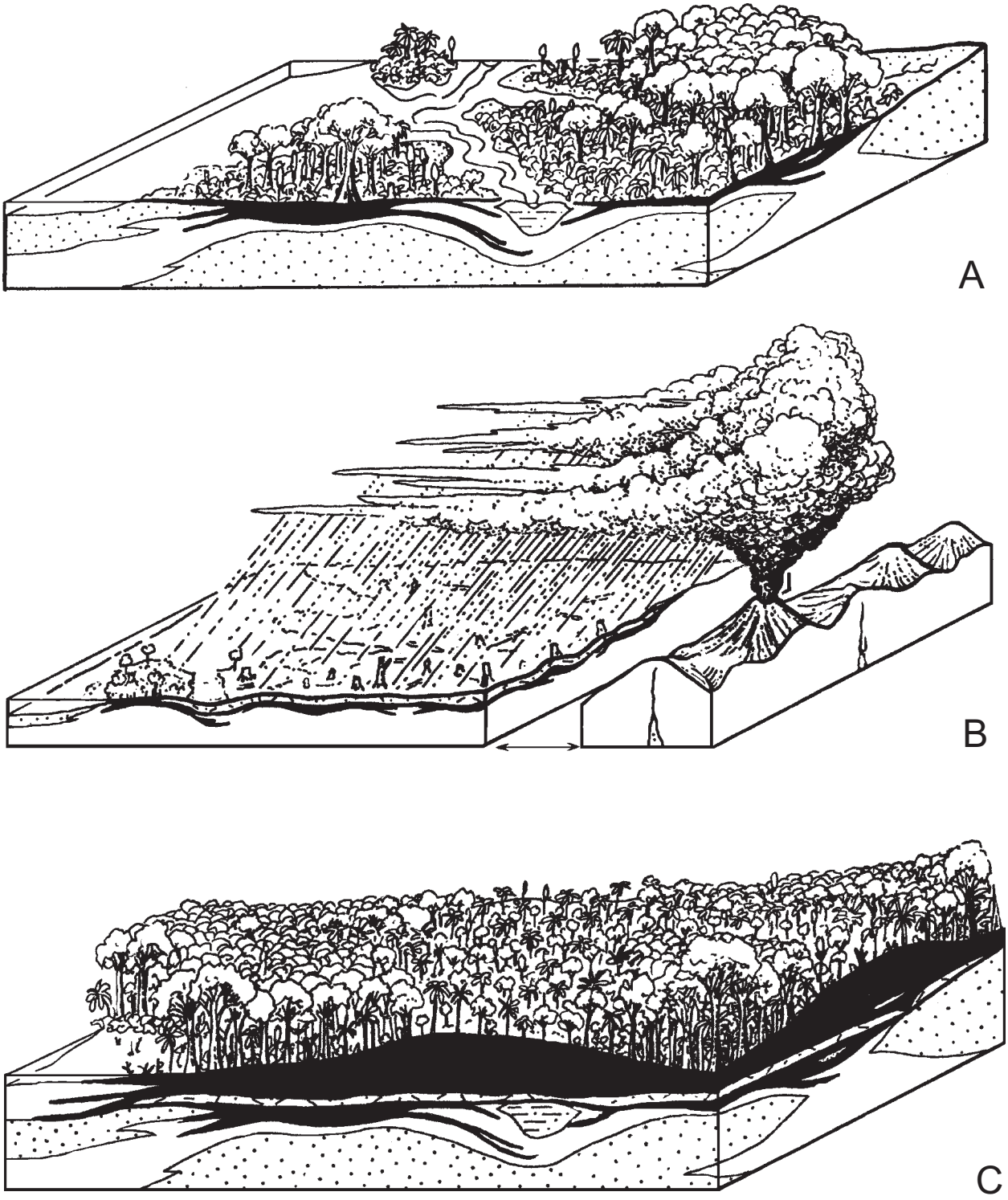

Figure 11. The evolution of the Fire Clay paleomire. (a) Peat started accumulating in a planar, rheotrophic mire that was discontinuous and subject to clastic influx. This peat is preserved as the lower bench of the Fire Clay coal bed. (b) Volcanic ash, which is ultimately preserved as a flint-clay parting, is deposited. (c) Peat accumulates after the ash fall and is preserved as the upper bench of the Fire Clay coal bed. Some parts of this bench are interpreted as having been derived from domed, ombrogenous peat.

study area, which are also thin, discontinuous, and of poor quality. At one location, the rider coal was 10 percent total sulfur.

Finally, the data gathered from this study probably are best applied to unmined coal in the study area. If conclusions are to be extrapolated to Fire Clay coal (or some other coal) in another part of the Eastern Kentucky Coal Field, additional bench samples should be analyzed to confirm or modify any trends reported on here. The results of this study provide an invaluable set of guidelines for future sampling programs in the Fire Clay and other Kentucky coals, however.

SUMMARY

Closely spaced bench samples from the Fire Clay coal bed, collected at 28 localities in a study area of eight 7.5-minute quadrangles in the Eastern Kentucky Coal Field, were analyzed geochemically, petrographically, and palynologically to determine any spatial or temporal trends among the studied parameters. Results indicate that the upper bench of the Fire Clay coal is generally thick, laterally continuous, low in ash yield and sulfur content, moderate to high in Btu content, and high in total vitrinite content. In contrast, the lower bench is generally thin, laterally discontinuous, moderate to high in ash yield and sulfur content, low to moderate in Btu content, and enriched in liptinite and inertinite macerals, compared with the upper bench. Where present, rider coals tend to be thin, laterally discontinuous, and high in both ash yield and sulfur content. In other areas of the Eastern Kentucky Coal Field, especially southeast of the study area, these rider coals are quite thick and can be of good quality; in some cases, the rider coals are mined along with, and in certain instances in place of, the upper and lower benches.

At most locations, both benches of the Fire Clay coal bed, including the flint-clay parting and some roof strata in some instances, were mined together as a single unit; the inorganic material was separated from the coal later at a coal preparation plant. Grouping the analytical data into categories of increasing coal purity to approximate a cleaned coal product (i.e., total coal + rock, total coal ≤ 50 percent ash, coal ≤ 20 percent ash, coal ≤ 15 percent ash, and coal ≤ 10 percent ash) revealed that some parameters increased as ash content decreased (e.g., Btu and total vitrinite content), some decreased (e.g., ash yield, total sulfur content, and several minor element contents), and others showed no trend at all (e.g., thickness and total moisture content). A comparison of these data with data from 64 cleaned coal samples (coal that had been treated in a preparation plant) largely confirmed these trends. This is significant, especially with regard to Titles III and IV of the Clean Air Act Amendments of 1990, because it indicates that many deleterious components of coal appear to be removable using conventional coal cleaning methods prior to combustion. Examples of these undesirable constituents include pyrite, chromium, cobalt, and nickel.

Collectively, the geochemical, petrographic, and palynologic data assembled for this report were used to define four compositional groups, which allowed for paleoecological interpretation of the Fire Clay coal bed in the study area. Group 1, *Lycospora*-dominant with high vitrinite content, is interpreted as having formed in areas of the Fire Clay paleomire that stayed very wet, to the point of having standing water, a majority of the time. This group probably developed in areas of the mire that were dominantly rheotrophic and planar. Group 2, a mixed palynoflora with high vitrinite content, is defined by having a more diverse palynoflora than group 1 (increased percentages of small lycopsid, fern, and calamite spores) and high percentages of vitrinite. This group is also interpreted as having formed in areas that were very wet most of the time, and that were predominantly rheotrophic and planar. Group 3, a mixed palynoflora with moderate to low vitrinite content, contains higher percentages of inertinite than the first two groups and a diverse palynoflora, possibly because the mire was becoming more ombrotrophic and domed. Group 4 is a mixed palynoflora with high ash yield, whose palynoflora are marked by various mixtures of lycopsid (trees and small varieties), fern (tree-like and small forms), calamite, and cordaite spores. Samples in this group contain high percentages of liptinite and inertinite macerals, as well as higher ash yields than in the other groups. The conditions under which this group formed probably were rheotrophic and planar. This group includes all samples from the lower bench of the Fire Clay coal bed.

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