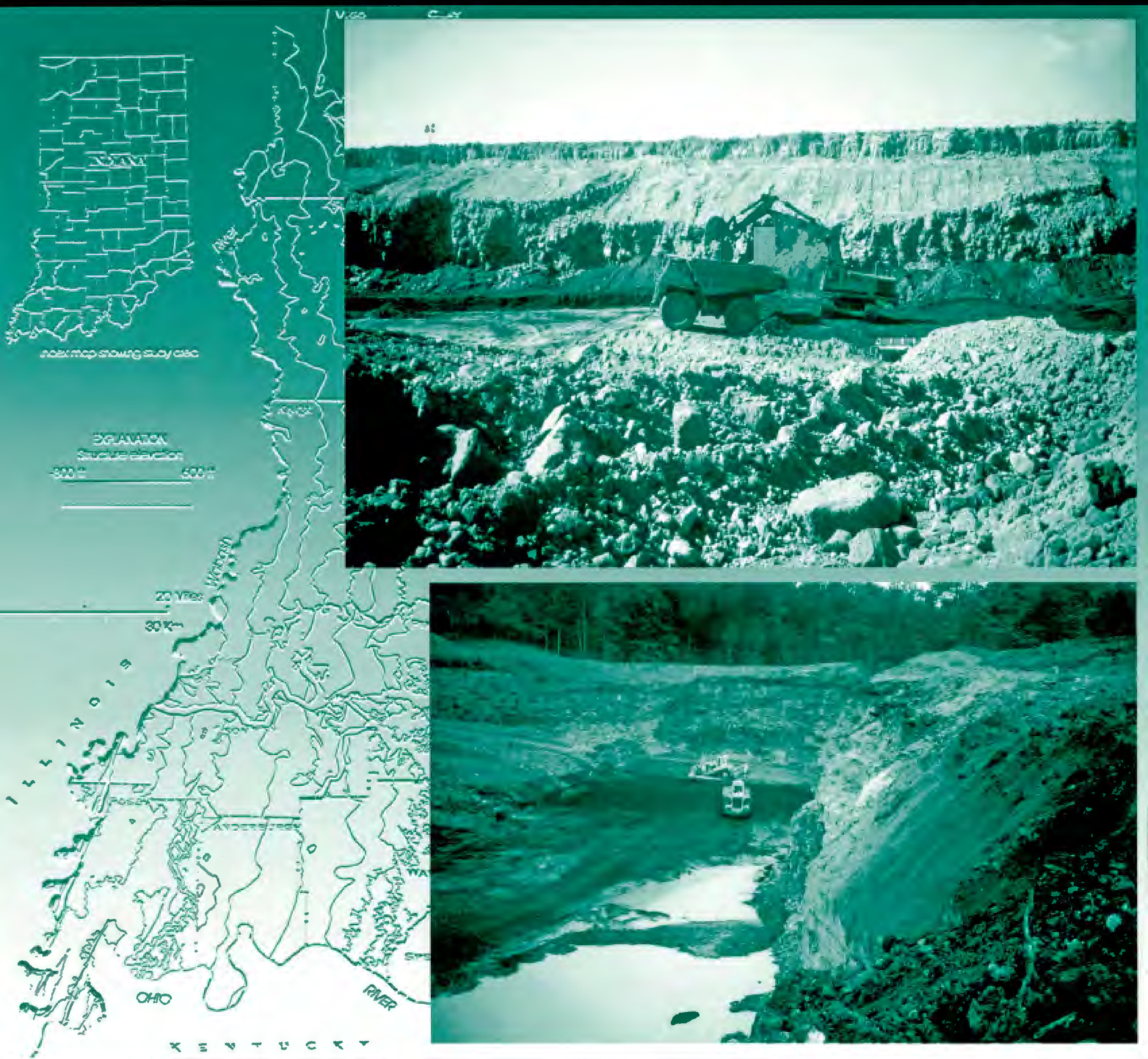
# COAL IN INDIANA: A Geologic Overview

## Special Report 60



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# Coal in Indiana: A Geologic Overview

*By* Maria Mastalerz *and* Denver Harper

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## CONTENTS

## ILLUSTRATIONS

Figure

## ILLUSTRATIONS (Cont.)

## TABLES

# COAL IN INDIANA: A GEOLOGIC OVERVIEW

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## INTRODUCTION

Coal is one of Indiana's most valuable natural resources. Since the 1830s, almost two billion tons of coal have been produced in the state (fig. 1). In 1994, total production was 31 million tons, of which 89 percent was produced by surface-mining methods, making Indiana the tenth largest coal-producing state in the United States (EIA Energy Information Administration, 1994).

There have been many investigations of the geology of Indiana's coalbeds. Much of this information is available in various publications, but much remains unpublished. The Indiana Geological Survey is engaged in an ongoing effort to convert these existing data into digital form that can be manipulated by computer. This will greatly enhance the ability of citizens, governmental agencies, electric power utilities, coal-mining companies, and others to gain access to the data, and more importantly, to visualize and quantitatively analyze the data in ways that were never before possible. But while a considerable amount of information has already been gathered, the markets for coal are constantly changing, and much additional information about the distribution and properties of coalbeds will be needed in the future if Indiana's coal-mining industry is to remain competitive in what has always been a highly competitive market.

This report provides a concise overview of what is currently known about the geology of Indiana's coalbeds and what sources of information are available (including digital and unpublished data, as well as traditional published sources), and to suggest directions for future research.

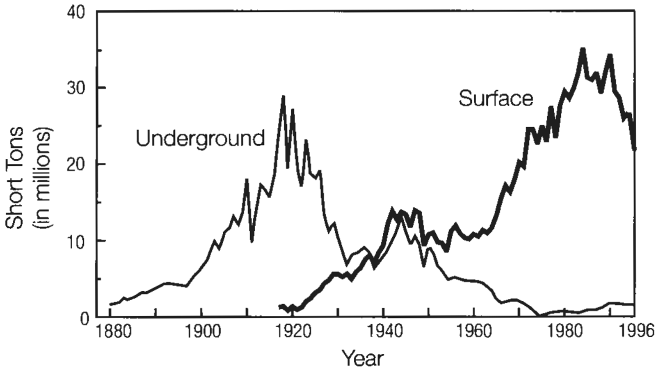

Figure 1. Annual coal production in Indiana from 1880 to 1996. Data are from the Indiana Inspector of Mines, Indiana Department of Mines and Mining, Indiana Division of Mines, Indiana Bureau of Mines and Mining, and the U.S. Bureau of Mines.

### *Coal Formation and Properties*

Coal is derived from plant material that accumulates in layers, is preserved by subsequent burial beneath sediments, and is gradually compressed and chemically transformed by heat and pressure. Thus, the character of a coalbed is determined by the conditions that existed at the time of its deposition (depositional environment) and by the forces that subsequently acted upon it (diagenesis and coalification).

### *Precursor Plant Material*

There are many factors that control plant growth, accumulation, and preservation in peat-forming environments. These include nutrients, topography, subsidence rates, hydrologic conditions, and climate. Climatic factors, in particular, influence rates of plant growth and decomposition, swamp types, and the formation of peat. In modern settings, tropical and subtropical climates are more favorable than temperate-zone climates for the growth of forest swamps with high densities of large trees. In tropical and subtropical areas, rates of plant accumulation and degradation are high, and rates of peat accumulation may range from one to several millimeters per year. In temperate regions, plant degradation is slower, but so is accumulation, and the rate of peat deposition is usually less than one millimeter per year. In perennially wet climates, conditions are favorable for the development of raised bogs, while climates having seasonality can produce a variety of wetlands, ranging from low-lying swamps, through mixed types, to raised bogs.

In the tropical Pennsylvanian forest swamps of the northern hemisphere (280 to 320 million years ago), the flora was dominated by tree forms and herbaceous plants of five major groups—lycopods, ferns, pteridosperms, cordaites, and sphenopsids—of lower vascular plants (Phillips and others, 1976). Lycopod trees, such as *Lepidodendron* and *Sigillaria*, were the dominant form of biomass. Sphenopsids (horsetails), such as *Calamites*, and Pteridosperms (primitive conifers), such as *Neuropteris* and *Mariopteris*, were abundant; gymnosperms, such as Cordaites, developed and also contributed to the peat-forming organic mass. The tree forms were composed mostly of periderm (barklike tissue with thick lignified cell walls), which became the major constituents of most coals. The plant materials also included foliage, spores, pollen, stems, and rootlets.

Chemically, plants consist of carbohydrates (cellulose, sugars, and polysaccharides), proteins, lipids (fats, waxes, and related compounds), lignins, and tannins. In higher plants, cellulose and lignin can account for up to 75 percent of the organic matter, of which 30 to 50 percent is cellulose, and 15 to 25 percent is lignin. Protein accounts for about 5 percent. The lipid content of higher plants is relatively low and is mainly concentrated in fruits and cuticular leaf waxes. Cellulose and lignin build cell walls of woody tissue, while proteins and sugars form cell fillings. Some of these components, such as sugars and cellulose, are very prone to degradation, but lignin is more resistant than cellulose, and waxes and resins are extremely resistant to degradation.

Coal balls are nodular masses of plant debris that became petrified (primarily by calcite and pyrite and, to a much lesser extent, by dolomite and silica) before the transformative processes of compression and degradation were much advanced. These are an important source of information about the types of plant materials that accumulated in coal swamps. In some coal balls, the preservation of cellular detail is excellent (Phillips and others, 1976), allowing identification (by the use of thin sections and peels) of tissues and organs and recognition of plant genera. This, in turn, permits reconstruction of plant communities and helps establish controls on their evolution.

### *Phases of Coal Formation*

There are two main phases in the formation of coals: peatification and coalification. Coalification can be divided into a biochemical stage and geochemical stage. The main factor during peatification and early coalification is microbial activity, whereas temperature, pressure, and time are the main factors during the geochemical stage. The evolution of organic matter with increasing temperature and burial is termed maturation; for coal, however, another term, rank, is commonly used instead. In order of increasing rank, the main stages of humic coal[1] formation are: peat, lignite, subbituminous coal, bituminous coal, and anthracite. Some of the changes that occur between these stages can be determined from inspection of Table 1. In general, carbon content, percent vitrinite reflectance, and calorific value increase as rank increases, while the content of water and volatiles decrease.

Peatification begins with mechanical fragmentation of plant material on a wetland. The fragmented plant material—particularly cellulose—is vigorously attacked by microorganisms. Degradation of lignin (a more resistant biopolymer than cellulose) takes place mostly in aerobic conditions due to fungal and bacterial activity. With progressive peatification, gradual biochemical transformation of lignin takes place. The products of these processes are: (1) peat, which is essentially the solid residue, having lignin content up to 35 percent and only a few percent (if any) of cellulose, and (2) gases such as: $CH_4$, $NH_3$, $N_2O$, $N_2$, $H_2S$, and $CO_2$. Peat has a high water content (commonly about 95 percent), relatively low carbon content, relatively high volatile matter content, and very low calorific value (Table 1). Peat formation is an inefficient process; less than 10 percent of plant production in a typical peat-forming environment accumulates as peat. The rest is recycled by the associated microbial community or lost from the system due to mineralization and leaching.

Organic matter that enters the biochemical stage of coalification contains little or no cellulose, but it still contains about 35 percent lignin. It also contains lipid materials (spores, pollens, resins) that are fairly resistant to degradation. In the biochemical stage, there is relative enrichment in carbon and hydrogen. Bacterial activity is still an important factor. This stage results in the formation of lignite, which usually contains 60 to 70 weight percent carbon and 5 to 7 weight percent hydrogen, more than 28 percent water, and usually less than 8,000 BTU per pound (Table 1). The biochemical stage of coalification ends with the termination of biologically mediated transformations.

The geochemical stage of coalification begins when temperature and pressure become critical factors. During this stage, carbon content increases and oxygen content decreases; hydrogen content remains constant for most of the geochemical stage but decreases substantially in the advanced phase of this stage. Methane, carbon dioxide, and water are the main volatile products. Compaction increases with increasing burial, resulting in decreased porosity and increased density; estimates of the compaction ratio (namely, ratio of peat thickness to coal thickness) range from less than 2:1 to more than 30:1 (most often 6:1 to 12:1 for bituminous coal) (Teichmuller, 1955; Ryer and Langer, 1980). Water content decreases to one percent in anthracite (from typically more than 90 percent in peat) (Table 1).

Temperature is the determining factor in the geochemical stage of coalification. The formation of lignite appears to be associated with a temperature range of 10° to 40°C, bituminous coal 40° to 100°C, and anthracite 100° to 150°C. These ranges are generalizations only, and they will depend on pressure, duration of elevated temperature, and volcanic activity in the area, and they may vary significantly between basins.

There are several coal-rank parameters in use, the most common of which is vitrinite reflectance. This parameter is a measure of the amount of light that is reflected from the polished surface of a vitrinite maceral (see definition of "vitrinite" in the next section). Vitrinite reflectance increases with increasing rank (Table 1), and it is particularly suitable for rank classification of bituminous coals.

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[1] Humic coals are formed mainly from vascular plants, as a result of humification, which is the dominant process of degradation of organic matter on a wetland. They exhibit stratification, usually with a high proportion of bright bands. Most coals of economic importance are humic coals. Sapropelic coals contain varying amounts of degradation products of vascular plants, algal remains, and mineral matter. They are dull, nonstratified, and relatively uncommon.

Table 1. Summary of changes in characteristics of coal with increasing rank. This is a compilation of standard ASTM classification by rank, German classification by rank (DIN, see Teichmuller, 1982), and Ward (1984) classification.

| **Rank** | | **Carbon Content** | **Volatile Matter** | **Water** | **Vitrinite Reflectance** | **Calorific Value** |
|---|---|---|---|---|---|---|
| | | weight percent; dry, mineral-matter-free basis | | percent | | Btu/lb; moist, mineral-matter-free basis |
| **Peat** | | <60 | | >75 | <0.25 | <6300 |
| **Lignite** | | ~ 60 - 70 | >49 | 28 - 75 | 0.25 - 0.37 | 6300 - 8300 |
| **Subbituminous** | C | ~ 70 - 77 | 42 - 49 | 10 - 28 | 0.37 - 0.47 | 8300 - 9500 |
| | B | | | | | 9500 - 10500 |
| | A | | | | | 10500 - 11500 |
| **High-volatile Bituminous** | C | ~ 77 - 83 | 31 - 42 | <10 | 0.71 - 1.1 | 11500 - 13000 |
| | B | | | | 0.57 - 0.71 | 13000 - 14000 |
| | A | | | | 0.47 - 0.57 | >14000 |
| **Medium-volatile Bituminous** | | ~ 83 - 88 | 22 -31 | | 1.1 - 1.5 | |
| **High-volatile Bituminous** | | ~ 88 - 90 | 14 - 22 | | 1.5 - 2.05 | |
| **Semianthracite** | | ~ 90 - 91 | 8 - 14 | | 2.05 - 3 (approx) | |
| **Anthracite** | | >91 | 2 - 8 | ~ 0 | 3.0 - 4.5 | |
| **Meta-anthracite** | | | <2 | 0 | >4.5 | |

## COAL COMPOSITION AND QUALITY

Visual inspection of undisturbed bituminous coalbeds—even without the aid of a microscope—reveals that the coal is typically banded. These megascopically recognizable bands are called *lithotypes*. Four lithotypes of bituminous coals are distinguished on the basis of luster: vitrain, also known as "bright coal"; durain, also known as "dull coal"; clarain, which consists of thin intercalated bright and dull bands; and fusain, which is fibrous and friable, and which is the constituent of coal that marks and blackens objects. Subdivisions of clarain can be megascopically recognized on the basis of proportions between dull and bright bands. Coal lithotypes represent changes in the original plant community and in the conditions under which the precursor peats were formed, including changes that affected peat preservation, as well as accumulation. The various lithotypes possess different physical and chemical properties and, consequently, have different effects on coal quality.

Under a microscope, the organic components of coal appear as individually recognizable constituents having distinctive physical and chemical properties. These microscopically recognizable constituents are referred to as *macerals*. For bituminous ranks, three groups of macerals are distinguished: the vitrinite group, the liptinite (exinite) group and the inertinite group.

Vitrinite macerals originate from woody material; liptinite macerals from spores, resins, cuticles, and algae; and inertinite macerals from all types of plant material that underwent rapid enrichment in carbon during peatification (for example, as a result of wildfires in the Pennsylvanian swamps). Inertinite group macerals are generally nonreactive (inert), and as such, are undesirable in most coal usages. The liptinite (exinite) group is characterized by high hydrogen content and is very reactive during conversion processes. The vitrinite group usually has a lower hydrogen content than macerals of the liptinite group, is reactive during carbonization, and together with the liptinite group constitutes a good quality material that can be utilized for many purposes.

The suitability of a particular coal for various usages is determined by the character of the coal's organic constituents (macerals), its mineral matter content, and its rank. For some uses, a single coal type may suffice, but for other uses, several coals may need to be blended.

In simple terms, coal can be regarded as a mixture of pure coal, mineral matter, and moisture. Coal properties are often reported as proximate and ultimate analyses. Proximate analysis includes moisture, volatile matter, fixed carbon, and ash contents. Ultimate analysis includes the concentration of chemical elements such as carbon, hydrogen, nitrogen, sulfur, and oxygen. To determine the combustion properties of coal, the determination of calorific value and ash-fusion temperature is made. Sulfur and ash content are also very important for combustion purposes. To determine coking properties of coal, the determination of free swelling (crucible) index and a set of coking tests are performed. Physical properties of coal, such as hardness and grindability, abrasion index, or float-sink content, also influence its utilization and beneficiation. Coal density is essential for obtaining reliable calculation of coal reserves. Detailed explanation of how chemical and physical properties of coal influence its utilization is beyond the scope of this report and the reader is referred to Ward (1982) and Thomas (1992).

## DISTRIBUTION OF INDIANA COAL

### *Stratigraphy*

Coal-bearing strata of Indiana are divided into three major intervals: the Raccoon Creek Group, the Carbondale Group, and the McLeansboro Group. Each of these groups consists dominantly of shales and sandstones, interbedded with thinner layers of limestone, claystone, and coal. Figure 2 presents the stratigraphy of coal seams in Indiana and possible correlations with coal seams of western Kentucky and southern and eastern Illinois. Some of the correlations shown in figure 2 may be subject to change by the Tri-State Correlation Committee, which is made up of personnel of the Illinois State Geological Survey, the Indiana Geological Survey, and the Kentucky Geological Survey.

The Raccoon Creek Group extends from the base of the Pennsylvanian System to the top of the Seelyville Coal Member.[2] This group consists of three formations; in ascending order, these are the Mansfield Formation (bounded on the top by the base of the Lower Block Coal Member and ranging in thickness from 50 to more than 800 feet [15 to 245 m]), the Brazil Formation (bounded on the top by the top of the Minshall or Buffaloville Coal Member and ranging in thickness from less than 30 to as much as 90 feet [9 to 27 m]) (Hutchison, 1960), and the Staunton Formation (ranging in thickness from 75 to 150 feet [23 to 45 m]) (Shaver and others, 1986). Six coal seams of this group—Blue Creek, Mariah Hill, Lower Block, Upper Block, and Minshall/Buffaloville Coal Members, and an unnamed coal in the Staunton Formation referred to informally as the "Holland coal"—are of some economic interest because of their locally low content of sulfur. None of them are thick (greater than 4.5 ft [1.4 m]) across extensive areas, however. The croplines of these and other coalbeds of the group are referred to in figure 3 as coalbeds in the lower part of the Pennsylvanian.

Coalbeds of the Carbondale Group account for most of the large-scale mining operations in Indiana. The Carbondale Group comprises the Linton Formation (upper boundary at the top of the Survant Coal Member and ranging in thickness from 43 to 162 feet [13 to 49 m]) (Shaver and others, 1986), the Petersburg Formation (upper boundary at the top of the Springfield Coal Member and ranging in thickness from 70 to 190 feet [21 to 58 m]) (Wier, unpub. data, 1965), and the Dugger Formation (upper boundary at the top of the Danville Coal Member and ranging in thickness from 73 to 185 feet [22 to 56 m]) (Wier, unpub. data, 1965).Within this group, there are four coalbeds that have been of great commercial importance— the Danville, Hymera, Springfield, and Survant Coal Members. Within each coalbed, there are deposits of thick coal (greater than 4.5 feet [1.4 m]) that extend across many square miles. The croplines of coalbeds of this group, together with the cropline of a minor coalbed (Hazelton Bridge Coal Member) in the overlying McLeansboro Group, are referred to in figure 3 as coalbeds in the middle part of the Pennsylvanian. The average sulfur content of the coalbeds of the Carbondale Group is generally somewhat higher than that of the coals of the Raccoon Creek Group.

The McLeansboro Group includes the Pennsylvanian strata above the Danville Coal. This is primarily a barren sequence having no thick, extensive, or low-sulfur coals and having undergone no significant mining. The group comprises four formations (Shelburn, Patoka, Bond, and Mattoon Formations) (fig. 2).

Except for some coalbeds, paleosols, limestones, and black shales, most rock strata within the Pennsylvanian System of Indiana are too variable in thickness and character to be mappable across broad areas. Consequently, the formations discussed above have been effectively defined as intervals between particular mappable coalbeds, limestones, and (or) black shales. In most cases, the coalbeds that were chosen as formational boundaries were the commercially important coals. Problems of mapping remain, however, because only three coalbeds (Springfield, Houchin Creek, and Colchester coals) are present in a relatively unsplit condition across the entire coal-bearing area. Thus, the base of the Linton Formation (Carbondale Group) has been defined as the top of the commercially important Seelyville Coal Member.[3] But in many places, the Seelyville is split into multiple benches that are difficult to recognize and correlate. For purposes of subsurface mapping, the commercially insignificant Colchester Coal might make a better bound-

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[2] The upper boundary of this group will soon be moved to the *base* of the Seelyville Coal Member by the Tri-State Correlation Committee.

[3] The base of this formation will soon be moved to the *base* of the Seelyville Coal Member by the Tri-State Correlation Committee.

ary, because it is readily recognized on most geophysical logs. Other such mapping difficulties exist elsewhere in the stratigraphic section.

As in other coal basins, the recognition of Pennsylvanian lithostratigraphic stages and series in the Eastern Interior Basin, of which Indiana is a part, is based to a large extent on the occurrences and abundances of floral remains, including microflora as well as macroflora. Studies of spores (both microspores and megaspores) and pollen have been extensively used in biostratigraphic classification. Several spore assemblage zones have been distinguished and are being used to subdivide the Pennsylvanian System into the Morrowan, Atokan, Desmoinesian, and Missourian Series. For example, the transition from Atokan to Desmoinesian is marked by the boundary between the *Radiizonates difformis* zone and the *Cadiospora magna* and *Mooreisporites inusitatus* zone, and the transition from Desmoinesian into the overlying Missourian Series is marked by the boundary between the *Lycospora granulata* and *Granasporites medius* zone and the *Punctatisporites minutus* zone (Peppers and Popp, 1979).

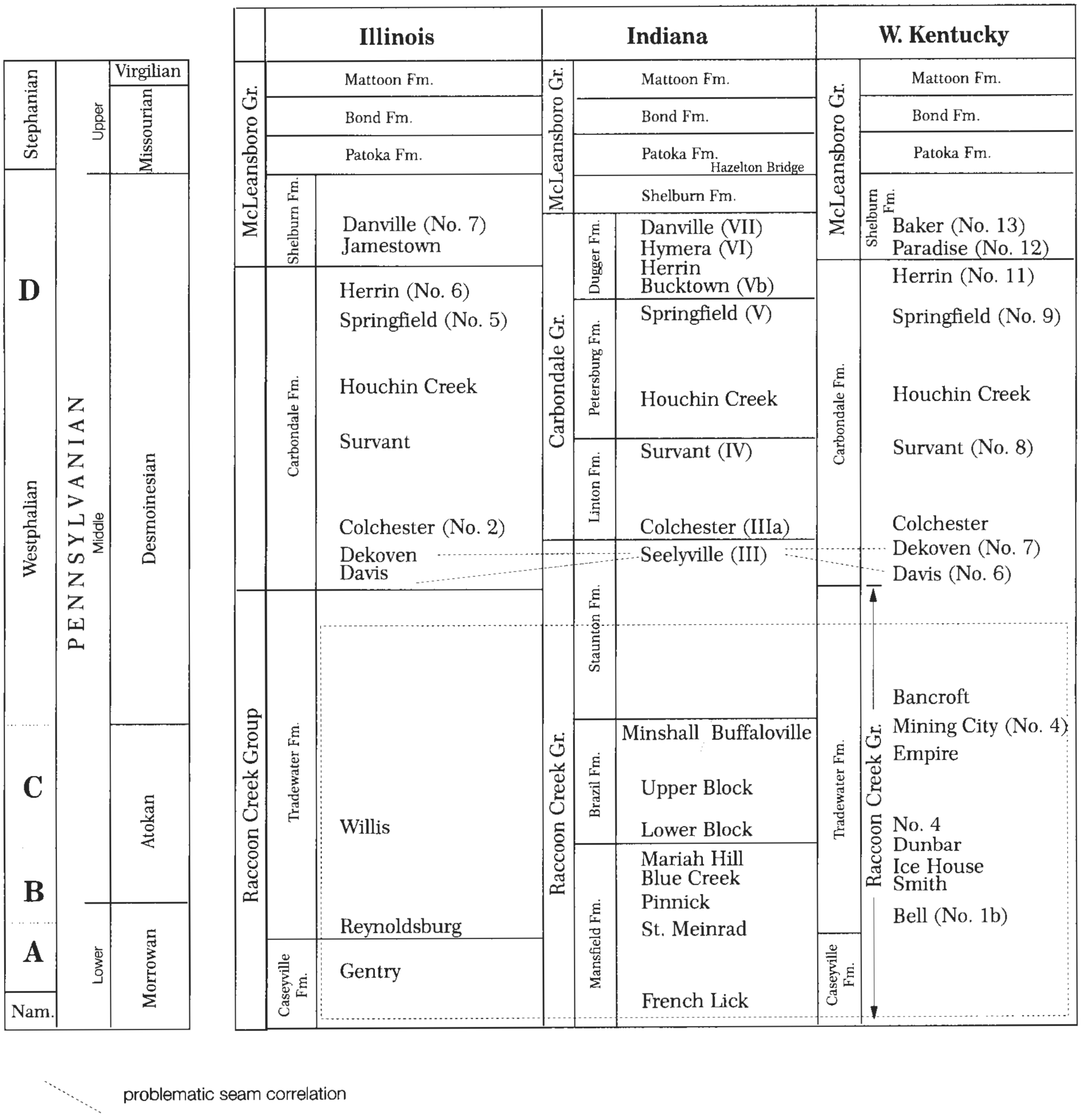

Figure 2. Lithostratigraphy of the Pennsylvanian System in the Eastern Interior Basin, showing major coalbeds; compiled and modified from Kosanke (1950), Peppers (1970), Willman and others (1975), Jacobson and others (1985), Shaver and others (1986), Peppers (1988), and Greb and others (1992).

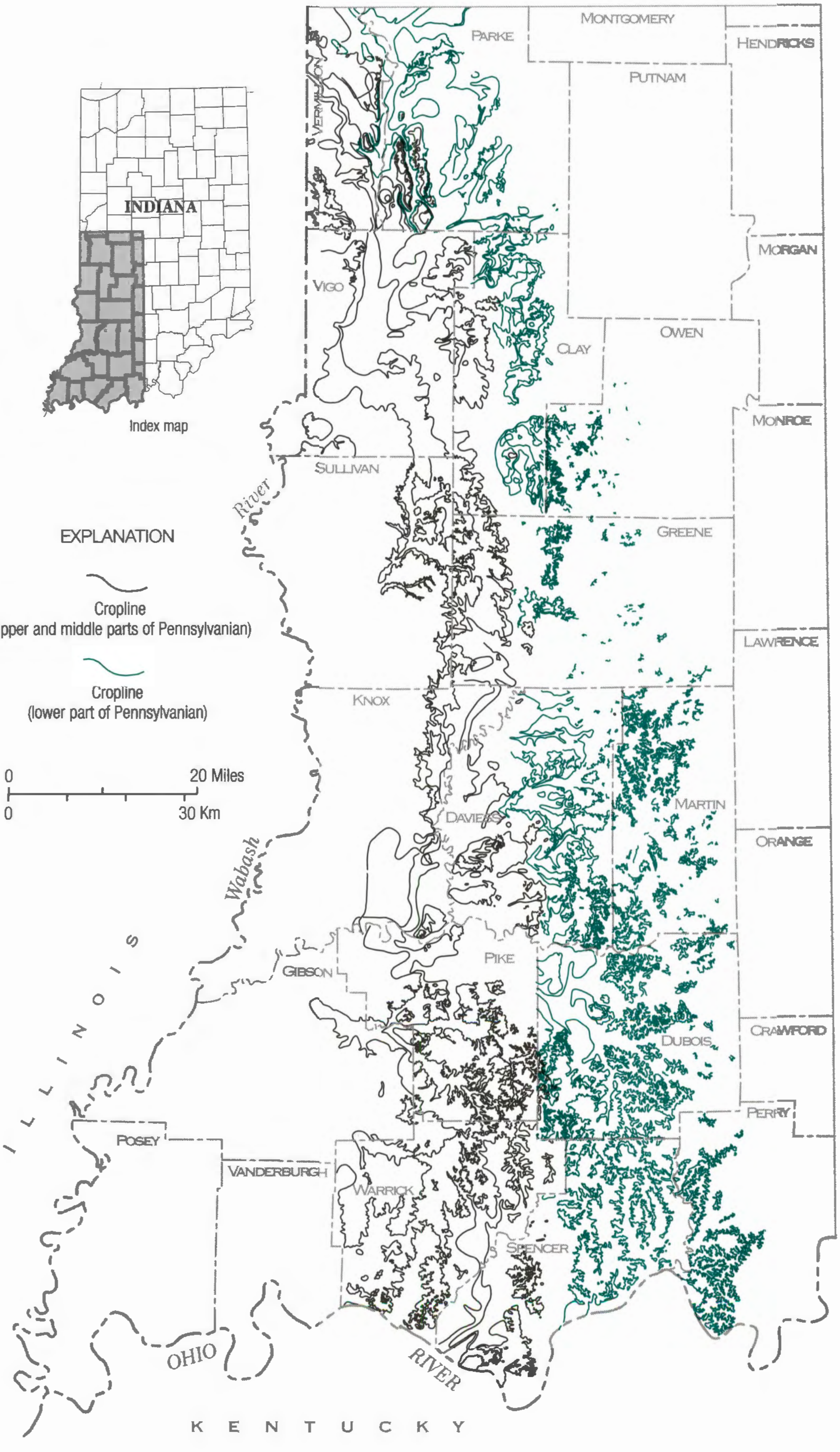

Figure 3. Map showing croplines of coalbeds in Indiana, as compiled from published maps. The Hazelton Bridge Coal Member (referred to informally as the "Vigo coal") is in the upper part of the Pennsylvanian Series (Missourian Series, fig. 2). Coalbeds in the middle part of the Pennsylvanian (upper Desmoinesian Series, fig. 2) include the Bucktown, Colchester, Danville (including that which has been referred to informally as "Millersburg coal"), Houchin Creek, Hymera (including that which has been referred to informally as "Lower Millersburg coal"), Seelyville, Springfield, and Survant Coal Members; coalbeds in the lower part of the Pennsylvanian (Morrowan, Atokan, and lower Desmoinesian Series, fig. 2) include the Blue Creek, Buffaloville, French Lick, Lower Block, Minshall, Mariah Hill, Pinnick, St. Meinrad, and Upper Block Coal Members, and undifferentiated or unnamed coalbeds in the Brazil, Mansfield, and Staunton Formations. Compiled from the Preliminary Coal Map series (Wier, 1952, 1953; Wier and Stanley, 1953; Friedman, 1954a, 1954b; Hutchison and Hamilton, 1956; Hutchison, 1959, 1961, 1964, 1967, 1971a, 1971b; Powell and Wier, 1967; Powell, 1968; Hill, 1980; Hutchison and Hasenmueller, 1988; and Hasenmueller, 1993) and the Coal Investigation Map series (Friedman, 1961; Hutchison, 1958; Kottlowski, 1954, 1959, 1960; Waddell, 1954; Wier, 1950, 1951, 1954, 1958) of the Indiana Geological Survey. This map is also available in digital form.

### *Coalbed Thickness and Structure*

The economic feasibility of mining a coal deposit depends upon many factors, one of the foremost being the coalbed's thickness. For example, underground mining of coal in Indiana has been conducted almost exclusively in areas where the thickness of the coalbed exceeded 4.5 feet [1.4 m].

The Indiana Geological Survey (IGS) has produced maps showing thicknesses of several middle Pennsylvanian coalbeds, including the Seelyville, Survant, Springfield, Hymera, and Danville coals. A compilation of some of these maps, which are also available in electronic digital form, are shown in figures 4 through 6. These maps, which include parts of Gibson, Knox, Sullivan, and Vigo Counties, are based on three types of publicly available data: drilling records, interpretations of geophysical logs, and mine-map notations. The accuracy, precision, and distribution of these three types of data vary greatly. Mine-map notations are probably the most accurate, followed by drilling records of good quality. Interpretations of geophysical logs have been used where no other publicly available data exist.

Harper and Olyphant (1991) noted that superjacent deposits of thick coal tend to be located in three geographically restricted parts of west-central Indiana. Namely, thick deposits of the Seelyville, Survant, and Springfield coals occur in southern Vermillion and northern Vigo Counties; thick deposits of the Survant, Springfield, and Hymera coals occur in eastern Sullivan and western Greene Counties; and thick deposits of the Springfield and Hymera coals occur in central Knox County. This geological circumstance led to the development of underground mining districts within which multiple coalbeds were exploited (fig. 7). Elsewhere, the coalbeds are either all thin, or only one coalbed is thick enough to have been mined by underground methods.

Local and regional variations in the thickness of a coalbed may result from a variety of depositional and post-depositional processes, and such variations are often observed to be related to structural features. Relatively thick deposits of coal, for example, are sometimes associated with local structural features such as basins and troughs, and, conversely, relatively thin deposits may occur across structural domes. Maps have been published by the IGS showing the structure (namely, elevation above sea level) of several middle Pennsylvanian coalbeds, including the Seelyville, Survant, Springfield, Hymera, and Danville coals. An example of such a map is shown in figure 8. These maps, which include parts of Vermillion, Vigo, Sullivan, Knox, Gibson, Pike, Warrick, Vanderburgh, and Posey Counties, are based on drilling records and interpretations of geophysical logs. While it can be difficult to map coalbed thicknesses using some types of geophysical logs, they are quite adequate for determining coalbed elevations. There are two mine maps (Blackhawk and Thunderbird Mines) in the files of the IGS that provide highly detailed data concerning coalbed elevations. As with the thickness maps, the maps of coalbed structure are now available in digital form.

The mechanisms that give rise to structural features and the causes of the relationships between thickness and structure have been the subject of debate. A detailed study of coalbed structure in Sullivan County by Adams and Kullerud (1987) suggested that structure in that area was controlled by a combination of differential compaction, the presence of underlying Silurian reefs, and the nature of the surface of the underlying Mississippian-Pennsylvanian unconformity. Harper and Olyphant (1991) surveyed a variety of features that may be correlated with spatial variations in the thicknesses of middle Pennsylvanian coalbeds in southern Vigo and northern Sullivan Counties. These features include the La Salle Anticlinal Belt (a regional structural feature), variations in the thicknesses of lower and middle Pennsylvanian sandstones, and local domal features associated with Silurian reefs. They suggested that these features may have exerted an influence on coalbed thickness by complex, interrelated processes of differential volumetric changes, depositional compensation, and tectonism.

Furer (1996), who discusses basement tectonics and its effect on Paleozoic sedimentation, states that "there is no direct relation between the [Marts] reef and the thickness of the Pennsylvanian Springfield Coal Member." On the other hand, he suggests that subtle movements of a basement fault influenced the thicknesses of sandstones, and thereby indirectly affected the thicknesses of coalbeds. Harper and Olyphant (1991) previously suggested that the causal relationship between Silurian reefs and the thickness of the Springfield Coal is indirect, but they also demonstrated a physical relationship between the coalbed's thickness and the positions of reefs, based on thickness maps that include several hundred data points (including notations from mine maps). Furer's conclusion that such a physical relationship does not exist may arise from the fact that his thickness map of the Springfield Coal is based on fewer than 15 data points. In the near future, the advent of electronic digital databases may make it possible to apply statistical analyses to stratigraphic attributes and thereby recognize chains of causation and quantify their direct and indirect effects on the thicknesses of coalbeds.

There are relatively few maps showing structure or thickness of lower Pennsylvanian coalbeds, and the existing maps cover relatively small areas. This results, in part, from the variability of those coalbeds and the difficulty of correlating them across broad areas (Droste and Furer, 1995). A study of the Mansfield and Brazil Formations has recently been completed by Kvale and others (1996), providing detailed correlation of lithostratigraphic units, as well as a series of structural and isopach maps of coalbeds in Daviess County. Despite the complexity of stratigraphic relationships, units were correlated using a combination of mapping with geophysical logs and sedimentologic, palynologic, and geochemical techniques.

In addition to digital maps showing the thickness and elevation of various coalbeds, several other computerized databases and geographic information systems (GIS) exist

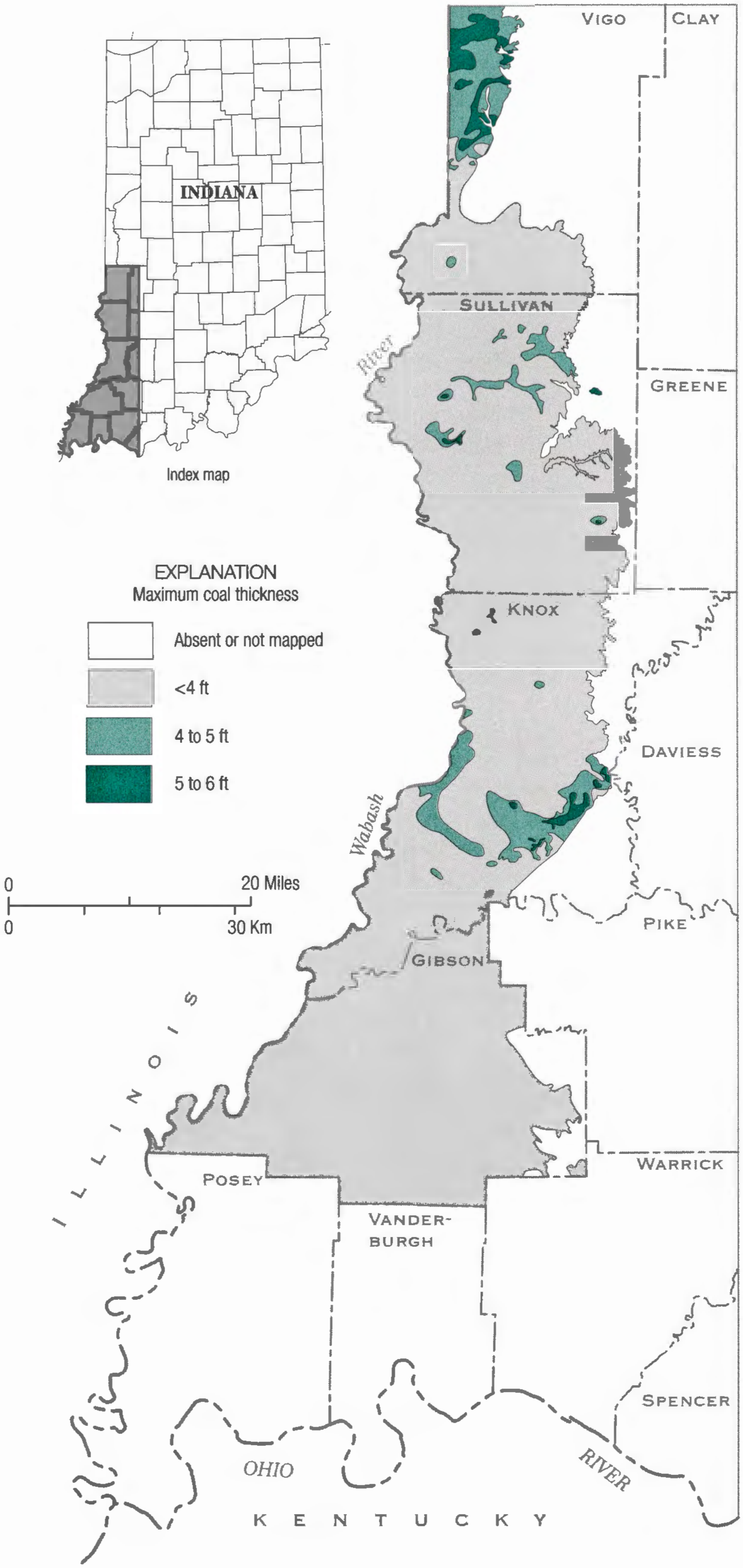

Figure 4. Map showing the thickness of the Danville Coal Member; modified from Harper (1985b, 1988a), Harper and Eggert (1995), and Eggert (1994). This map is also available in digital form.

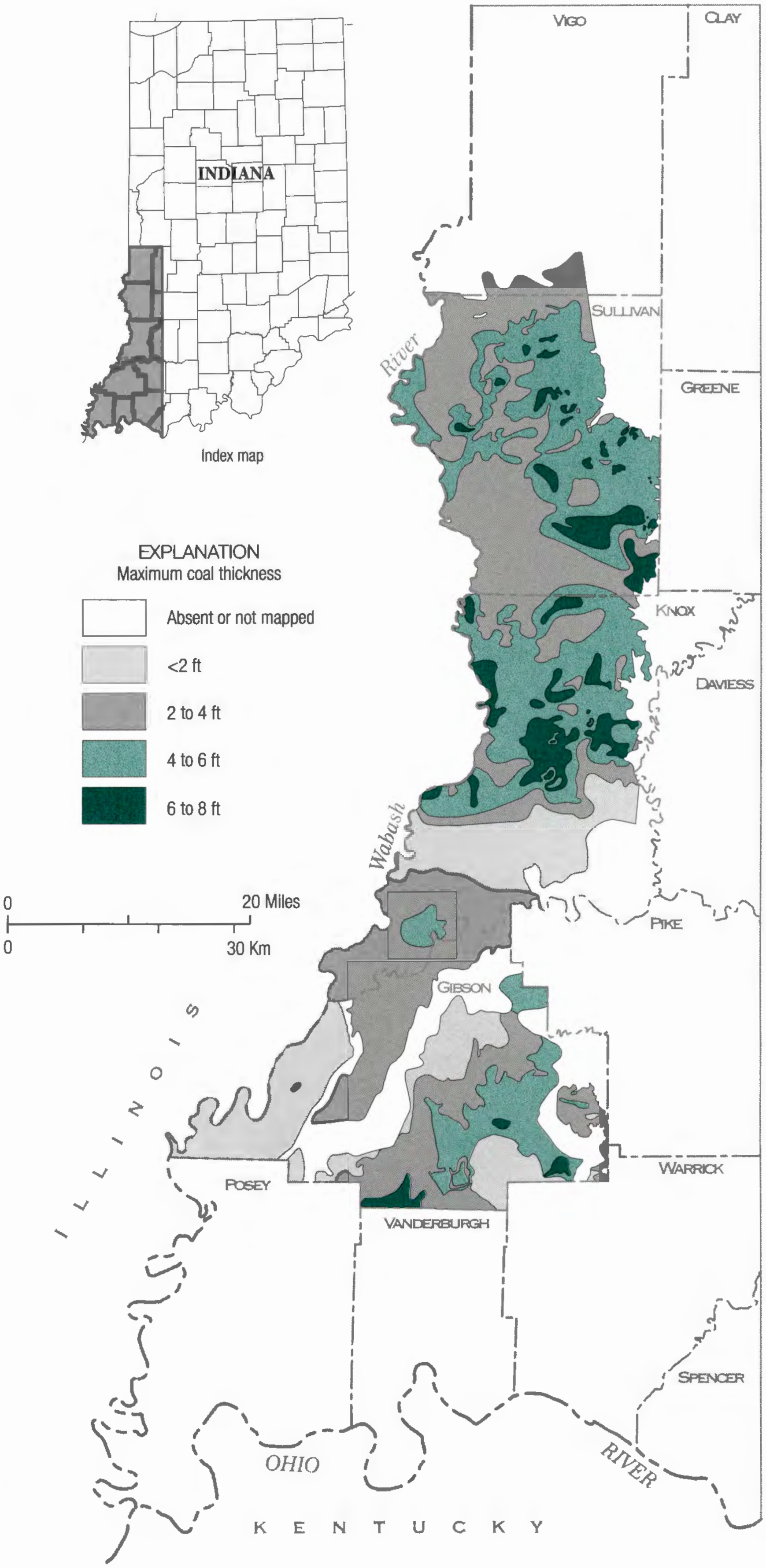

Figure 5. Map showing the thickness of the Hymera Coal Member; modified from Harper (1985b, 1988a), Harper and Eggert (1995), and Eggert (1994). This map is also available in digital form.

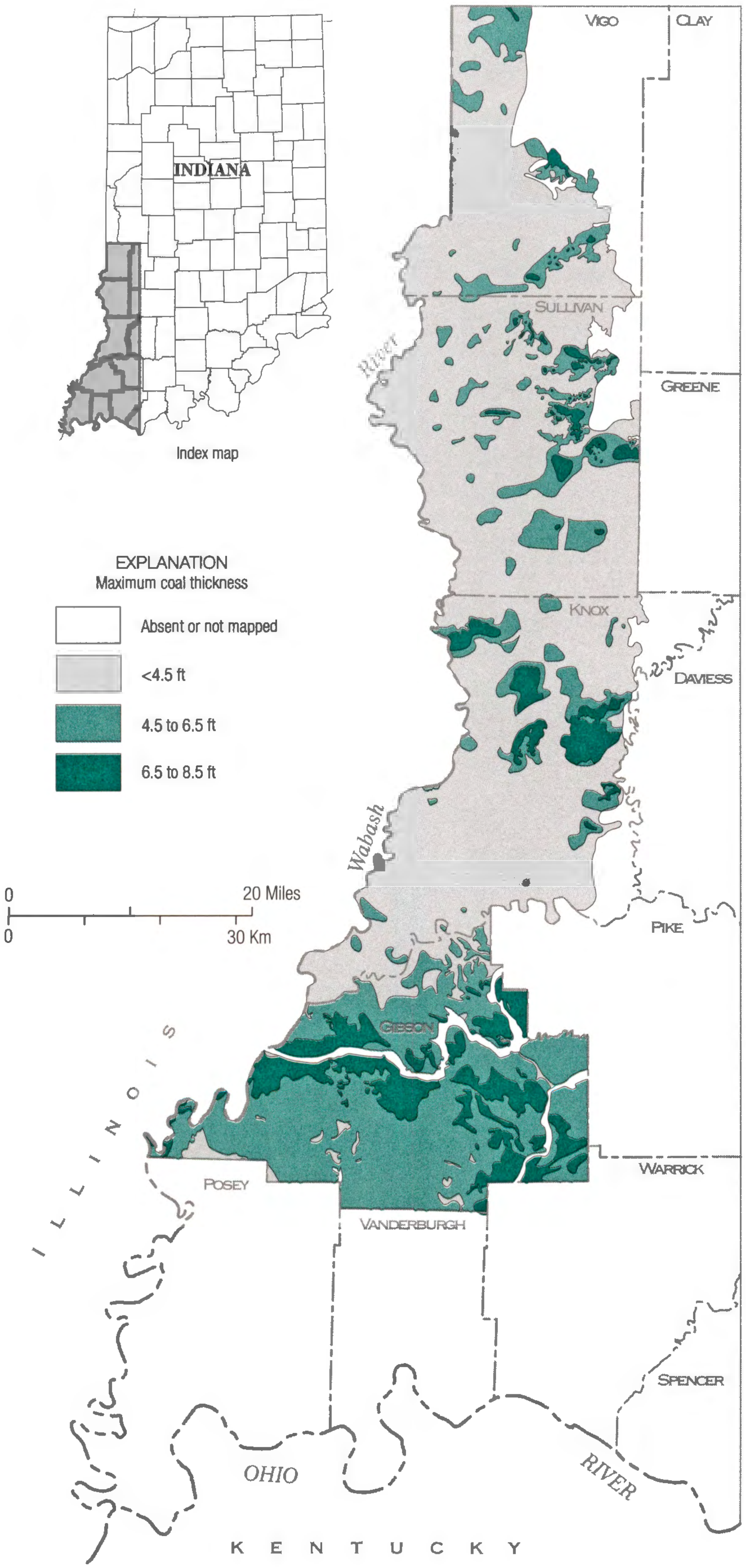

Figure 6. Map showing the thickness of the Springfield Coal Member in southwestern Indiana, modified from Harper (1985b, 1988a), Harper and Eggert (1995), and Eggert (1994). This map is also available in digital form.

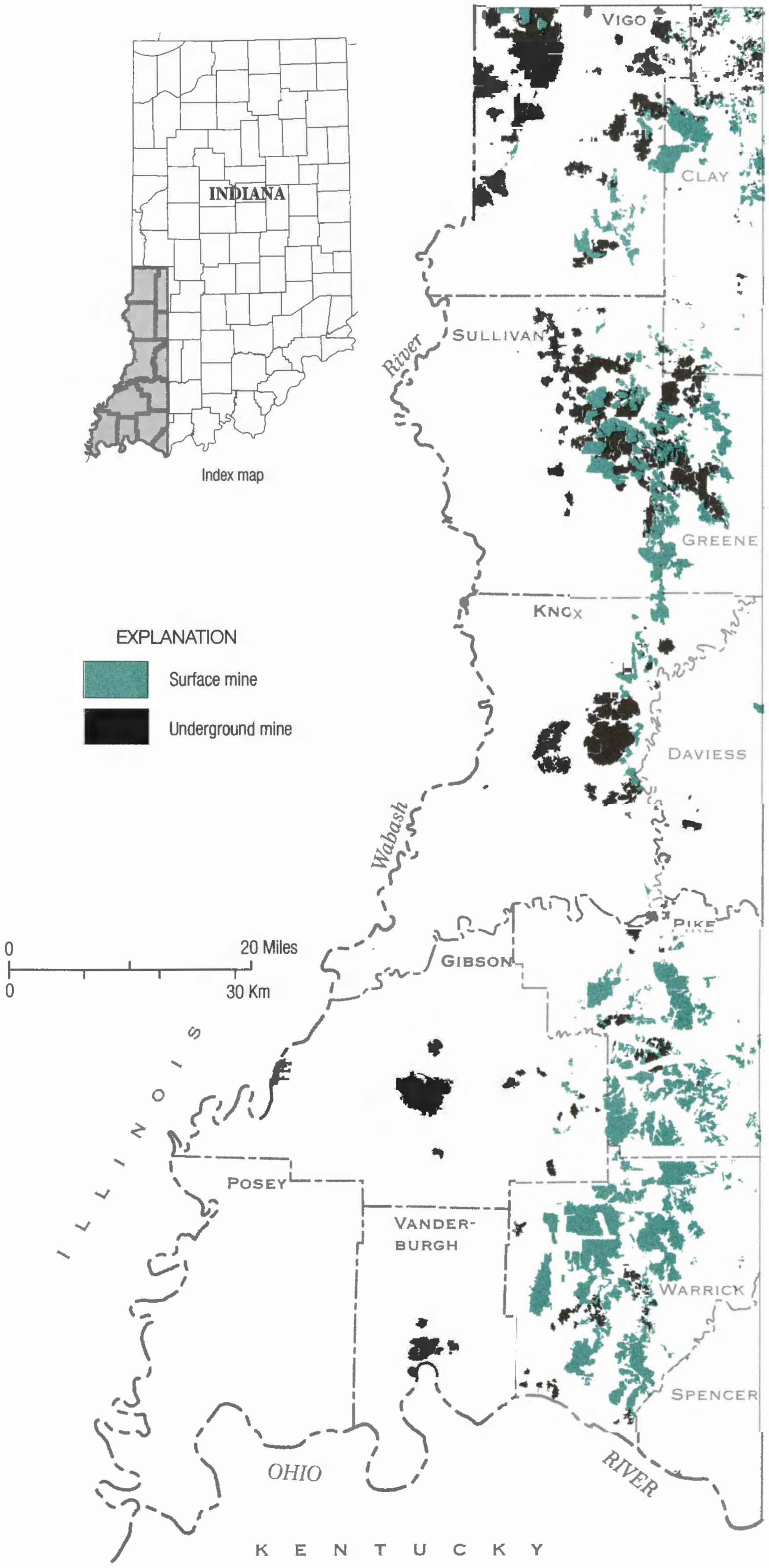

Figure 7. Map showing the distribution of underground and surface coal mines (active and abandoned) in southwestern Indiana; modified from the Indiana Coal Mine Database of the Indiana Geological Survey (Licia Weber and Paul Irwin, Indiana Geological Survey). This map is also available in digital form.

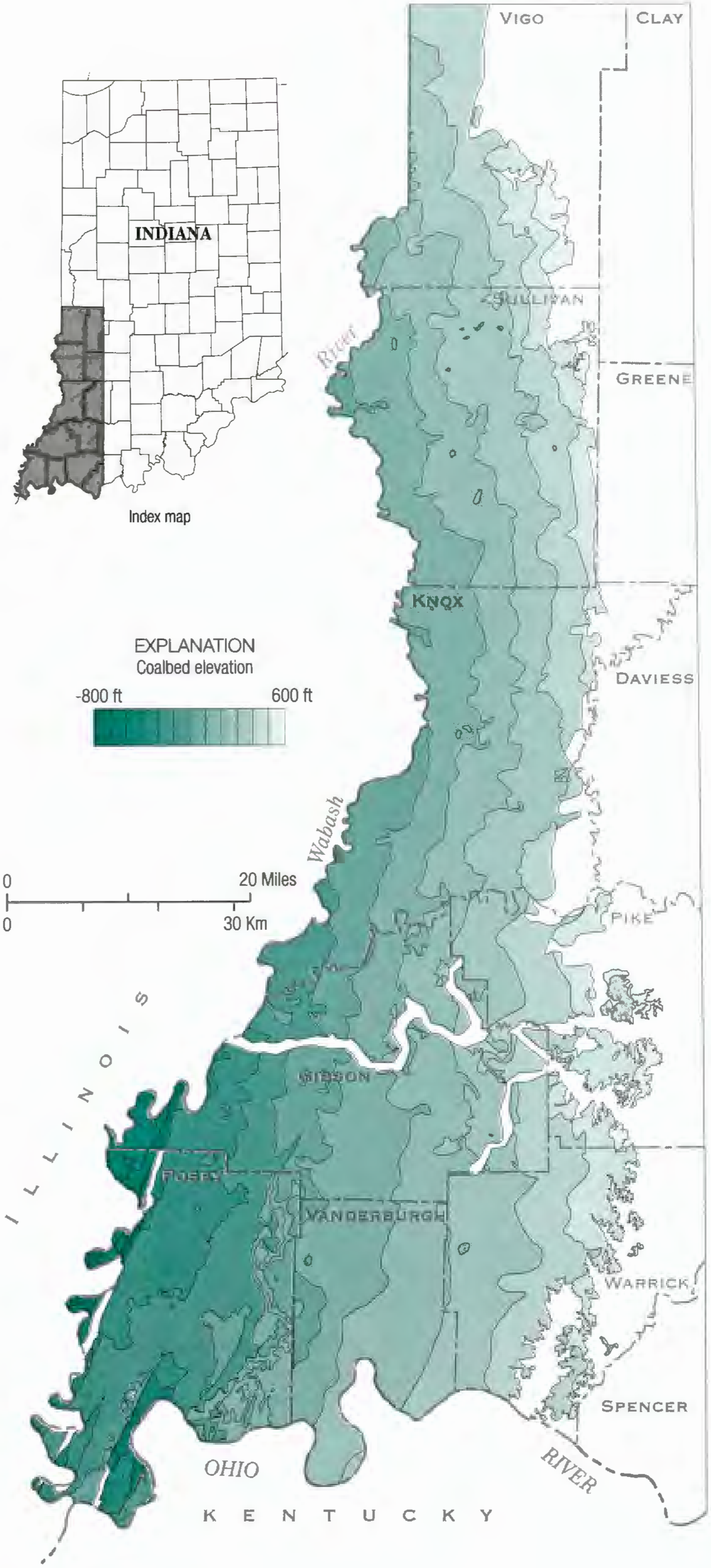

Figure 8. Map showing the elevation of the Springfield Coal Member in southwestern Indiana; modified from Harper (1985b, 1988a), Harper and Eggert (1995), Eggert (1994), Ault (in preparation), Wier and Stanley (1953), Friedman (1954a, 1954b), and Wier (1958). Various maps exhibit discrepancies across county lines; where the disagreements are small, contour lines were adjusted to create continuous lines across the county boundaries, but where the differences are large (for example, between Posey and Vanderburgh Counties), the discrepant contour lines were left unadjusted. For clarity, the contour interval is 100 feet, but a map is available with a contour interval of 20 feet. This map, and similar maps for the Hymera and Danville Coal Members, are available in digital form.

or are currently being developed. A computer database is being compiled that catalogs published and unpublished maps within the Indiana Geological Survey. For example, a search for maps showing thickness of coal with the stratigraphic designation of Springfield yields references to 249 different maps (110 published and 139 unpublished) at scales ranging from 1:5,997 to 1:1,267,200. The database also provides information regarding the location within the Survey of the unpublished maps. Other computer databases that contain stratigraphic information on coalbeds (for example, thickness, depth, and [or] elevation) include the Indiana Coal Analysis Database (ICAD) of Hasenmueller and Miller (1992) and the National Coal Resource Data System (NCRDS). However, some recent attempts to use the NCRDS data indicate that there may be numerous misidentifications of coalbeds within that dataset, particularly in the Mansfield and Brazil Formations. The Indiana Coal Mine Database (ICMD), compiled by Paul Irwin and Licia Weber of the Indiana Geological Survey, contains a variety of information about underground and surface coal mines in the state (for example, mine name, company name, depth to coal, and thickness of coal at selected sites such as mine shafts). The boundaries of mines are already available as GIS coverages, and coverages showing the detailed workings of underground mines, based upon historical maps prepared by the coal companies, are currently in production.

### *Depositional Environments*

Pennsylvanian rocks in Indiana are part of the Pennsylvanian System of the Eastern Interior Basin. The Eastern Interior Basin is a broad, shallow, trough-like structural depression. During various periods, sediment was transported into the basin from the northeast, and from the northwest in western Illinois (Potter, 1962, 1963). The source of sediment is generally thought to have been the southern part of the Canadian Shield, and possibly highlands of the Northern Appalachians. For many decades, the depositional environment of the Pennsylvanian Period in Indiana was conceptualized as a dominantly fluvial-deltaic setting with short-term marine transgressions and regressions. Such an interpretation was the basis for the so-called "cyclothem" concept, developed for the Pennsylvanian System in the Eastern Interior Basin by H. R. Wanless and numerous coworkers (Wanless and others, 1969; Wanless and Wright, 1978). More recently, a tidally dominated coastal setting has been proposed. Arguments between adherents of various models continue today.

The presence of channel-fills in the Pennsylvanian System has been of central importance in a variety of the fluvial-deltaic models. Numerous channels have been documented in the Eastern Interior Basin, and they are considered to be parts of a drainage system established by the so-called "Michigan River System" in Late Mississippian time (Swann, 1963; Trask and Palmer, 1986). Coal in the vicinity of these channels—where clastic sediments were deposited penecontemporaneously with peat—is usually low in sulfur, especially when it is covered by a sequence of fine-grained sediments, referred to as "clastic wedges." In the fluvial-deltaic model, these clastic wedges, which are comprised of gray-shale sequences, have been interpreted as nonmarine, fluvial (for example, crevasse splays and levees), or lacustrine deposits (Johnson, 1972; Eggert, 1982, 1987). It is widely believed that much of the sulfur in coal is derived from sulfates in seawater, so that fine-grained, nonmarine roof-sediments above coalbeds of Indiana may have isolated peat from marine waters during subsequent submergence beneath the sea, preventing penetration of the seawater's sulfates into the peat. The distribution of channels and their associated gray-shale roofs was influenced by differential compaction of underlying sediments. In accord with such fluvial-deltaic models, many persons exploring for (and developing) thick deposits of low-sulfur coal have concentrated their efforts in recent decades on the mapping of channels and flanking deposits of gray shale that are believed to have been deposited penecontemporaneously with the commercially important coalbeds of the Carbondale Group (for example, Hopkins, 1968; Eggert, 1982, 1984, 1994).

Recently, tidal influence has been documented in some fine-grained Pennsylvanian sequences in Indiana (Kvale and Archer, 1990, 1991; Archer and Kvale, 1993). Such tidally influenced sediments (referred to as "rhythmites") have been documented extensively from the Mansfield and Brazil Formations (Fishbaugh and others, 1989; Kvale and Archer, 1991), but tidal lamination has also been observed near the base of the gray shale strata (that have long been recognized as indicators of low-sulfur coal deposits) above the Colchester, Springfield, Herrin, and Danville coals. Other lines of evidence also indicate that the channel fills and their associated gray shale wedges are, in fact, composed of both coarse- and fine-grained clastic sediments that are nonfluvial in origin (Archer and others, 1994). Archer and Kvale (1993) have suggested a coastal-plain, rather than a fluvial-deltaic, setting for Indiana's coal seams. They suggested rapid deposition of roof rocks in tidally controlled, brackish to fresh water estuarine settings as the major control on the sulfur content in coal. Burial beneath tidal deposits—rather than fluvial crevasse splays and levees—provided protection from prolonged exposure of peat to seawater sulfates. Current studies of the petrology and geochemistry of organic matter in roof rocks above selected low-sulfur coals in the Mansfield and Brazil Formations suggest that these rocks were deposited under fresh-water (rather than saline) conditions, even though tidal-like lamination is present (Mastalerz and others, in press; Kvale and Mastalerz, 1996). Perhaps laminated shales above low-sulfur coals represent a freshwater environment that was relatively distant from the seaway but still strongly influenced by tides. It has been documented from modern peat-forming environments that tidal influence can extend as far as 50 km from the shore landward (Staub and Esterle, 1993); alternatively, they may represent low-salinity marine deposits.

Thus, even though several different conceptual models have been proposed to explain deposition of clastic sediments during Pennsylvanian time, most of these models share the notion that coal tends to be low in sulfur where peat deposits were rapidly buried beneath thick fresh-water sediments. The presence of such fresh-water rocks does not guarantee that the underlying coal is low in sulfur, however. Even though there are examples of low-sulfur peats and coals covered by marine sediments in other parts of the world (Neuzil and others, 1993), the presence of marine horizons in the immediate roof is usually associated with high sulfur in underlying coals in the Eastern Interior Basin.

While much attention in the Eastern Interior Basin has been focused on the environments of deposition of roof strata, it may be that processes operating within the peat-forming environments themselves were of decisive importance in determining the sulfur distribution within coals. As indicated by many studies of both coalbeds and modern wetlands throughout the world, the nature of the sources of moisture (for example, precipitation *vs.* ground water) within living mires is known to be an important factor in determining coal quality in fresh-water settings. In rain-fed bogs, less iron and sulfur are available than in surface- and ground-water-influenced swamps. Also, conditions of pH and microbial activity are chemically unfavorable for the fixation of the iron and sulfur in the form of pyrite, resulting in lower total sulfur and ash contents. Petrographic and geochemical studies indicate that some coal seams of the Mansfield and Brazil Formations may be derived from rain-fed domed peat deposits, while the extensive coalbeds of the Carbondale Group (with their clastic partings) may be derived from surface- and ground-water-influenced, flat-lying peats.

Sulfur content commonly varies vertically through any given coalbed. Careful inspection of coal lithotypes, which can be observed visually without a microscope, can be used to assess chemical variations within a coalbed. The distribution of sulfur, for example, may be related to the placement and arrangement of bright and dull layers (lithotypes) within the coalbed.

## PROPERTIES OF INDIANA COALS

The bituminous coalbeds of Indiana are of high-volatile C to A rank (Table 1). On an as-received basis, fixed carbon ranges from 39 to 44 percent (namely, for mean values of individual coalbeds), volatile matter ranges from 33 to 38 percent, and calorific value is typically between 10,500 and 12,000 Btu/lb but is as much as 14,000 Btu/lb in places. Moisture content is commonly within the range of 5 to 15 percent, ash content within 5 to 20 percent, and sulfur content usually within the range of 0.5 to 5 percent. The petrographic composition of the coal varies; coalbeds dominated by bright coal are common in the Petersburg and Dugger Formations (fig. 2), whereas duller coal dominates many of the Brazil Formation coalbeds.

### *Sources of Information*

Currently, the single best source of publicly available information on the quality of Indiana's coals is the Indiana Coal Analysis Database (ICAD) (Hasenmueller and Miller, 1992). This database includes analytical data for 1,416 coal samples analyzed by the Coal Laboratory of the Indiana Geological Survey between 1954 and the late 1980s. Results of proximate analyses, as well as selected ultimate and sulfur-form analyses, are included, but the database does not contain any petrographic information on coal, vitrinite reflectance data, or trace-element analyses. Statistical analyses of coal quality of complete channel samples from the ICAD database are presented in Hasenmueller (1994). Table 2 summarizes the number of coal analyses in the ICAD that are available for various coalbeds. The ICAD contains analyses of samples taken from trucks and railroad cars, coal piles, tipples (usually taken from conveyor belts), drill cuttings, grab samples taken from within coalbed benches, and channel samples (both partial and complete). Figure 9 shows the locations of sample points where complete channel samples were obtained; samples such as these are considered to be the most truly representative of the entire thickness of a particular coalbed. Complete channel samples are samples that are collected by carefully excavating a groove of constant width and depth from the bottom to the top of the coalbed, and thereby minimizing the disproportionate inclusion of any given layer within the coalbed. As such, channel samples and complete cores provide the most accurate samples of a coalbed. The ICAD is available to the public on computer disks, accompanied by a short complementary written report, and can be obtained from the Indiana Geological Survey. The database also includes stratigraphic information for the samples.

Information on the chemistry of Indiana's coals is also included in the U.S. Geological Survey (USGS) Coal Quality (COALQUAL) Database. This database can be considered a subset of ICAD, because it reports analyses that were performed on splits of the same coal samples that were analyzed by the Indiana Geological Survey and included in ICAD. However, the analyses in COALQUAL were performed by the U.S. Bureau of Mines, and, consequently, the values that are reported are not the same as those in ICAD, even though they represent the same samples at the same locations.[4] Proximate and ultimate analyses, heat content, ash-fusion temperature, free-swelling index, and air-drying loss

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[4] Even though the samples in COALQUAL are splits of the samples in ICAD, coordinate values of locations may differ somewhat, because personnel of the IGS subsequently revised the locational information in ICAD by reference to mine maps. Also, several coordinate values in COALQUAL are known to have serious errors, probably because of typographical errors during data entry.

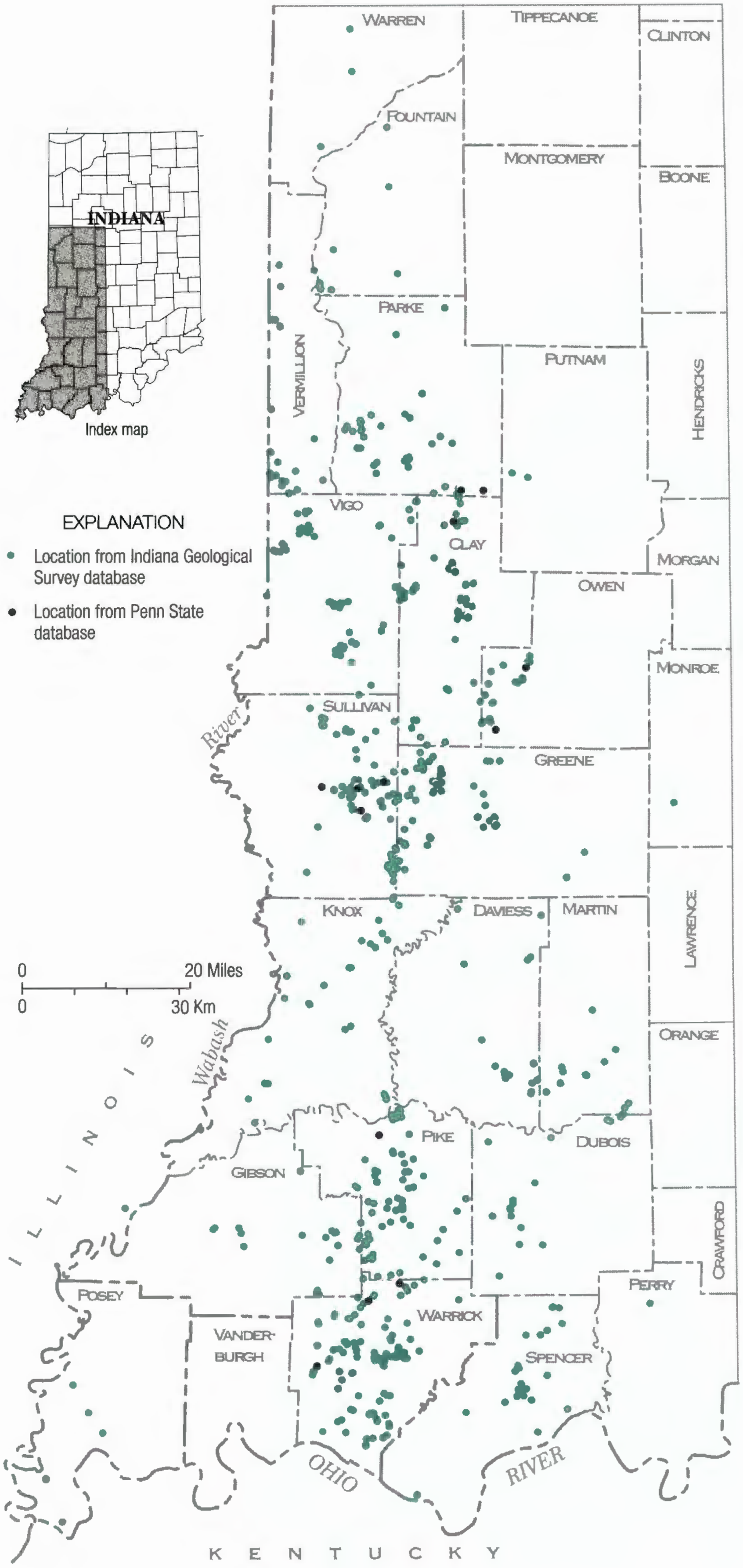

Figure 9. Map showing the locations of selected points where coal samples have been collected for chemical analysis. The points shown for the IGS database include only those samples that are described as "complete channel samples" in the Indiana Coal Analysis Database (ICAD) (Hasenmueller and Miller, 1992). The Penn State database is from Penn State Coal Sample Bank and Database, Version 8.1.

Table 2. Distribution of coal samples with chemical analyses in the Indiana Coal Analysis Database (Hasenmueller and Miller, 1992). All samples were "complete channel samples." The nomenclature of the "unnamed" and "undifferentiated" coals are taken from Hasenmueller and Miller (1992).

| Stratigraphic Name | Number of Samples | Principal Counties |
|---|---|---|
| Springfield Coal Member | 271 | Warrick, Pike, Greene, Knox |
| Danville Coal Member | 103 | Warrick, Sullivan, Knox |
| Hymera Coal Member | 99 | Warrick, Sullivan, Knox |
| Seelyville Coal Member | 64 | Greene, Knox, Clay, Parke |
| unnamed coals in Staunton Formation | 64 | Parke, Fountain, Daviess |
| Upper Block Coal Member | 64 | Clay, Owen, Parke, Greene |
| undifferentiated coals in Mansfield Formation | 52 | Martin, Dubois, Putnam |
| Minshall or Buffaloville Coal Member | 49 | Spencer, Parke |
| Survant Coal Member | 44 | Greene, Clay, Pike |
| Lower Block Coal Member | 33 | Clay, Owen, Parke, Greene |
| undifferentiated coals in Brazil Formation | 33 | Clay, Parke, Spencer |
| Mariah Hill Coal Member | 27 | Spencer, Dubois |
| Bucktown Coal Member | 24 | Sullivan, Knox |
| undifferentiated coals in McLeansboro Group | 24 | Vigo, Sullivan |
| Colchester Coal Member | 21 | Parke |
| Blue Creek Coal Member | 13 | Dubois, Martin |
| St. Meinrad Coal Member | 10 | Perry |
| Houchin Creek Coal Member | 8 | Vigo, Warrick, Posey |
| **TOTAL** | **1,003** | |

of 179 coal samples from Indiana were determined by the U.S. Bureau of Mines. COALQUAL contains fewer coal analyses than ICAD because it includes only channel samples having ash contents that are less than or equal to 33 percent. In addition to proximate and ultimate analyses of coal, the COALQUAL database includes analyses of major and minor oxides in the ash, as well as trace elements in the coal, presented on whole-coal, as-received basis. This database does not include any petrographic or vitrinite reflectance information, however, and coal rank is calculated from parameters of proximate and ultimate analyses.

Another source of information on the coal of Indiana is the Pennsylvania State University (Penn State) Coal Database. This database includes analyses of 48 samples of Indiana coal. In addition to sample location and depth, information is provided on moisture content (as-received), ash content (dry basis), sulfur content (dry basis), calorific value (dry basis), vitrinite reflectance, and trace-element contents (whole-coal, as-received basis).

### *Coalification Patterns*

Bituminous coalbeds of the Eastern Interior Basin range in rank from high-volatile C to high-volatile A (Table 1). This contrasts with coal from competing regions, such as the Appalachian Basin, where there are large reserves of medium-volatile and low-volatile bituminous coal, as well as major deposits of anthracite (northern Pennsylvania), and the western United States, which contains all ranks of coal, with the majority of resources being of lignite and subbituminous ranks.

There are at present no maps representing detailed coalification trends (namely, variations in rank) within Indiana. Such maps have been drawn, however, for the Illinois portion of the Eastern Interior Basin. Cady (1948) presented a coalification map of the Herrin seam in Illinois, expressed in terms of calorific values (on a moisture- and mineral-matter-free basis) for selected counties. Damberger (1971) revised that map, adding numerous new data. These maps indicate an increase in maturation from the northwest towards the southeast, with the highest maturation in south-central and southeastern Illinois. For the Herrin Coal, the rank varies from high-volatile C bituminous coal in the northwestern part of Illinois to high-volatile A bituminous coal in the southern part (Damberger, 1974: Thomas and Damberger, 1976). Recalculation of calorific values and moisture contents into equivalent vitrinite reflectance gives a range of 0.5 percent in the northwestern part of Illinois to 0.75 percent in the southern part (Cluff and Byrnes, 1989). The coalification pattern observed in Illinois results from depth of burial, except in the southern part of the state, where increased heat flow, as well as burial, contributed to the elevated rank (Damberger, 1971).

The actual depth of burial of coal seams during coalification and the effects of post-Permian erosional events in the Eastern Interior Basin are still controversial topics. Estimates of the maximum depth of burial vary considerably: 2.2 to 4.8 km (Cobb, 1981), 3.3 to 5.2 km (Ambers, 1993), 4500 ft (1.4 km) (Damberger, 1971), and 0 to 2000 ft (0.6 km) (Cluff and Byrnes, 1989, based on thermal maturation modeling, using the Lopatin method).

Coal-bearing strata in Indiana occupy the eastern part of the Eastern Interior Basin, and the depth of burial was probably less to the east. Extrapolating the coalification trend from Illinois into Indiana, the highest rank coals should be found in Posey County. Elsewhere in Indiana, iso-rank lines should be parallel to the present-day extent of the Pennsylvanian System. Reflectance of the Herrin seam in Indiana should be 0.6 to 0.7 percent (Cluff and Byrnes, 1989). Vitrinite reflectance data are very sparse, although in general, they corroborate the trends observed in Illinois.

### *Summaries of Coal Quality*

Histograms showing moisture contents (as-received basis), total sulfur and ash contents, and heating values (reported on a dry basis) of selected coalbeds in Indiana are presented in figures 10 through 13. Statistical values are summarized in Table 3. Maps showing the distributions of values of moisture content, total sulfur, and heat value are shown in figures 14 through 28. These histograms and maps are based on data from the ICAD and Penn State databases, and include only complete channel samples. These data indicate that a substantial portion of Indiana's coal resources are of high quality. For example, although most of Indiana's coal resources have more than 11 percent moisture, there is a high percentage of coal with lower moisture content. The Lower and Upper Block seams have low sulfur contents, and seams such as the Hymera and Danville have substantial percentages of low-sulfur coal resources (fig. 11).

### *Trace Elements*

Since the Clean Air Act of 1970, the content and distribution of trace elements in coal has assumed great importance. The 1990 Amendments to this act focused attention on environmentally hazardous elements in coal. Of 189 hazardous air pollutants (HAPs), the following thirteen are considered to be the most hazardous: antimony, arsenic, beryllium, cadmium, chlorine, chromium, cobalt, lead, manganese, mercury, nickel, phosphorus, and selenium. Strict $SO_2$ emissions are already in effect, and regulation of trace-element emissions will probably occur in the near future. One way to reduce the emission of these elements is to remove them from the coal prior to combustion. Some elements (for example, arsenic and antimony) occur in pyrite and other sulfides, and physical cleaning can efficiently reduce their concentration. Some others (for example, selenium and chlorine) are associated primarily with organic matter, so that physical cleaning may only concentrate them in the clean coal. A good understanding of the occurrence and distribution of trace elements will contribute greatly to their efficient reduction.

The only trace-element analyses of coals of Indiana are provided by the USGS and Penn State databases. The distribution of trace elements in analyses of Indiana coal is presented in figures 29 and 30. The largest number of analyses is available from the Springfield, Hymera, and Upper Block Coal Members, but even for these coalbeds, the number of analyses is too small to allow mapping of trace-element distributions. Statistics on individual trace elements in Indiana coal are available in Oman and others (1994). The number of trace-element analyses for individual seams of Indiana varies greatly, and as a result, it is difficult to compare trace-element variations between the seams. The Springfield Coal shows wide concentrations of all elements, and of arsenic, chromium, and lead, in particular. The Danville and Hymera Coals have lower selenium content than other coals, and higher lead and arsenic contents than the Springfield Coal (fig. 29). Mean mercury content is highest in the Springfield Coal (figs. 29 and 30). The Danville Coal is similar to the Hymera, and the most significant difference is lower mercury content in the Danville. The Upper Block Coal appears to be somewhat more uniform with regard to trace-element variations. The comparisons here are based on a limited number of analyses, and much more information is needed before valid conclusions can be drawn regarding trace-element occurrences and distributions.

Table 3. Characteristics of selected coal seams in Indiana (moisture on as-received basis, other parameters on dry basis). These statistics are the same as those from Hasenmueller (1994), except for the Upper Block, Seelyville, Springfield, Hymera, and Danville coalbeds, for which additional analyses from the Penn State databases were added. (Note: n = number of analyses.)

| PARAMETER | MEAN | STD. DEVIATION | MIN. | MAX. |
|---|---|---|---|---|
| *BLUE CREEK COAL n = 13* | | | | |
| Btu | 13,220 | 861 | 11,592 | 14,061 |
| Moisture | 14.9 | 3.0 | 7.8 | 21.6 |
| Vol. matter | 39.4 | 1.9 | 35.3 | 44 |
| Fixed carbon | 52.9 | 4.9 | 42.7 | 568 |
| Sulfur | 1.7 | 1.6 | 0.5 | 7.4 |
| Ash | 7.7 | 4.9 | 2.8 | 17.7 |
| *MARIAH HILL COAL n = 27* | | | | |
| Btu | 12,727 | 686 | 11,109 | 13,729 |
| Moisture | 13.0 | 4.9 | 3.0 | 27.2 |
| Vol. matter | 38.9 | 2.7 | 33.7 | 465 |
| Fixed carbon | 49.9 | 5.5 | 35.5 | 59.5 |
| Sulfur | 1.7 | 1.4 | 0.7 | 8.2 |
| Ash | 11.1 | 6.3 | 3.3 | 31 |
| *LOWER BLOCK COAL n = 33* | | | | |
| Btu | 12,664 | 1,041 | 9,677 | 13,887 |
| Moisture | 14 | 5.0 | 0.7 | 27.1 |
| Vol. matter | 38.9 | 3.3 | 33.5 | 47.5 |
| Fixed carbon | 49.8 | 5.5 | 35.5 | 59.5 |
| Sulfur | 1.7 | 1.4 | 0.7 | 8.2 |
| Ash | 11.1 | 6.3 | 4.1 | 31 |
| *UPPER BLOCK COAL n = 67* | | | | |
| Btu | 12,722 | 1,671 | 3,645 | 13,887 |
| Moisture | 15.4 | 6.1 | 1.3 | 52.8 |
| Vol. matter | 39.1 | 2.9 | 27.9 | 47.0 |
| Fixed carbon | 51.2 | 7.0 | 13.6 | 59.0 |
| Sulfur | 1.7 | 1.2 | 0.1 | 4.9 |
| Ash | 9.6 | 6.7 | 4.4 | 58.5 |

| PARAMETER | MEAN | STD. DEVIATION | MIN. | MAX. |
|---|---|---|---|---|
| *MINSHALL AND BUFFALOVILLE COAL n = 49* | | | | |
| Btu | 12,454 | 1,740 | 4,773 | 14,053 |
| Moisture | 10.5 | 4.5 | 0.7 | 25.8 |
| Vol. matter | 40.9 | 5.2 | 21.3 | 49.9 |
| Fixed carbon | 47.2 | 1.6 | 17.1 | 60.2 |
| Sulfur | 3.7 | 1.6 | 0.9 | 7.1 |
| Ash | 11.9 | 11.5 | 3.0 | 61.6 |
| *SEELYVILLE COAL n = 65* | | | | |
| Btu | 12,404 | 1,054 | 8,494 | 13,271 |
| Moisture | 9.6 | 4.0 | 0.8 | 29.2 |
| Vol. matter | 41.6 | 3.7 | 31.2 | 65.4 |
| Fixed carbon | 43.5 | 5.7 | 19.0 | 61.1 |
| Sulfur | 5.0 | 1.8 | 1.0 | 10.5 |
| Ash | 14.5 | 5.7 | 7.3 | 35.6 |
| *COLCHESTER COAL n = 21* | | | | |
| Btu | 12,084 | 1,218 | 9,879 | 13,667 |
| Moisture | 10.8 | 5.9 | 1.9 | 26.9 |
| Vol. matter | 43.7 | 2.5 | 36.9 | 47.4 |
| Fixed carbon | 43.8 | 3.7 | 37.4 | 57.2 |
| Sulfur | 4.1 | 2.2 | 0.7 | 11.0 |
| Ash | 13.0 | 5.0 | 5.9 | 22.3 |
| *SURVANT COAL n = 44* | | | | |
| Btu | 12,636 | 904 | 9,754 | 13,943 |
| Moisture | 11.4 | 3.8 | 1.0 | 22.2 |
| Vol. matter | 40.7 | 3.1 | 25.2 | 4.9 |
| Fixed carbon | 48.7 | 4.4 | 32.2 | 68.3 |
| Sulfur | 2.9 | 1.5 | 0.6 | 6.7 |
| Ash | 11.2 | 3.9 | 5.5 | 24.2 |

Table 3 (cont.). Characteristics of selected coal seams in Indiana (moisture on as-received basis, other parameters on dry basis). These statistics are the same as those from Hasenmueller (1994), except for the Upper Block, Seelyville, Springfield, Hymera, and Danville coalbeds, for which additional analyses from the Penn State databases were added. (Note: n = number of analyses.)

| PARAMETER | MEAN | STD. DEVIATION | MIN. | MAX. |
|---|---|---|---|---|
| *SPRINGFIELD COAL n = 277* | | | | |
| Btu | 12,580 | 739 | 8,744 | 14,025 |
| Moisture | 10.0 | 3.7 | 0.5 | 34.7 |
| Vol. matter | 41.4 | 4.1 | 19.9 | 49.9 |
| Fixed carbon | 47.2 | 1.6 | 29.0 | 70.7 |
| Sulfur | 3.7 | 1.4 | 0.7 | 7.7 |
| Ash | 11.5 | 4.0 | 4.9 | 30.1 |
| *HYMERA COAL n = 121* | | | | |
| Btu | 12,069 | 2,694 | 2,520 | 13,734 |
| Moisture | 10.5 | 3.2 | 0.8 | 23.5 |
| Vol. matter | 38.8 | 4.3 | 15.6 | 45.8 |
| Fixed carbon | 46.7 | 5.2 | 11.7 | 56.6 |
| Sulfur | 3.2 | 1.3 | 0.3 | 6.2 |
| Ash | 14.2 | 7.7 | 6.7 | 72.7 |
| *DANVILLE COAL n =109* | | | | |
| Btu | 12,406 | 766 | 7,651 | 13,889 |
| Moisture | 11.2 | 4.0 | 1.9 | 28.2 |
| Vol. matter | 39.7 | 3.2 | 26.9 | 46.1 |
| Fixed carbon | 47.9 | 3.7 | 32.0 | 57.8 |
| Sulfur | 2.8 | 1.5 | 0.4 | 6.0 |
| Ash | 12.5 | 4.3 | 4.9 | 41.1 |

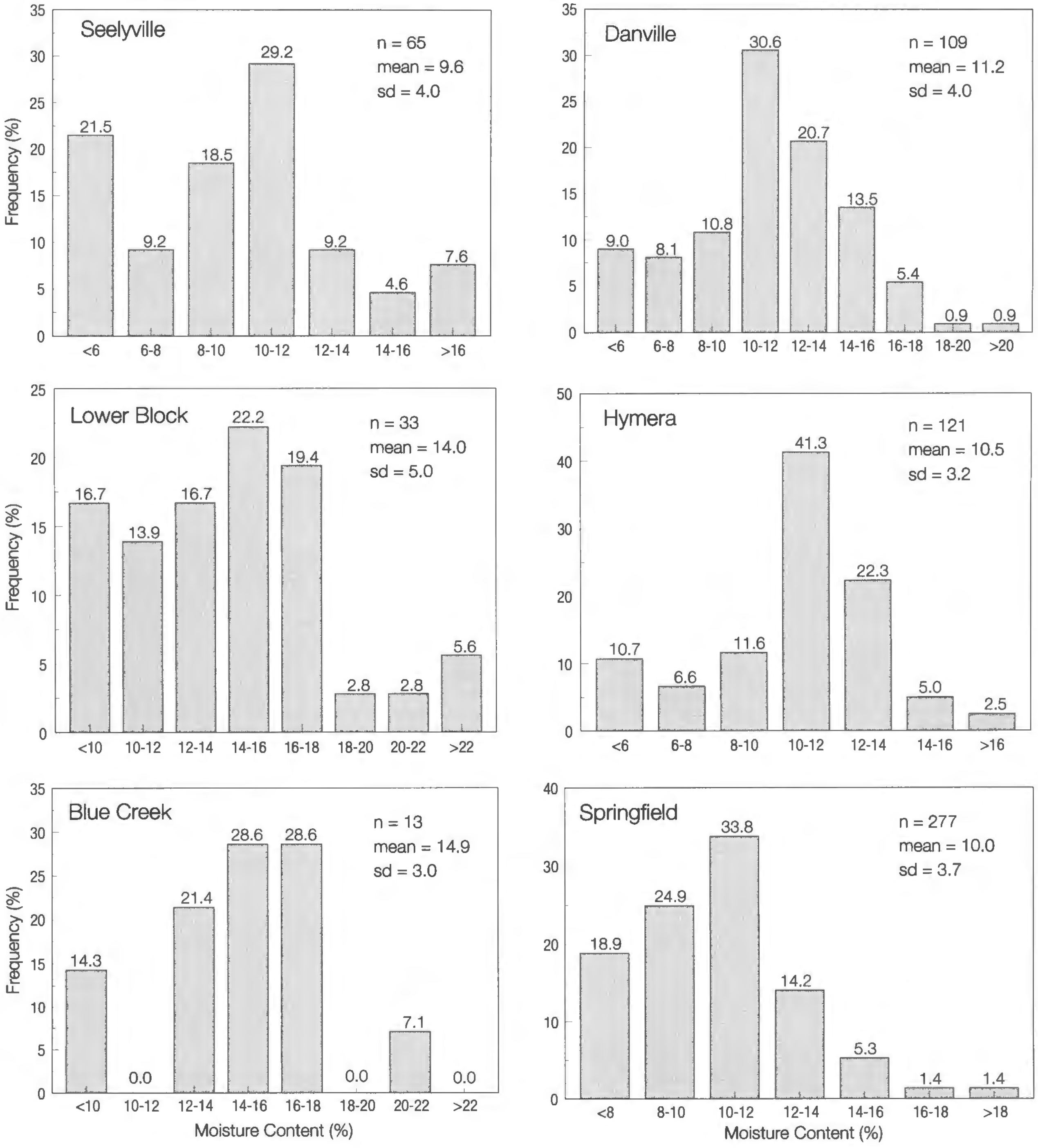

Figure 10. Histograms (frequency distribution, in percent) showing moisture content (weight percent, as-received basis, of samples with less than 33 percent ash) of selected coalbeds in Indiana. Data are derived from the IGS and Penn State databases (see fig. 9). All samples are "complete channel samples."

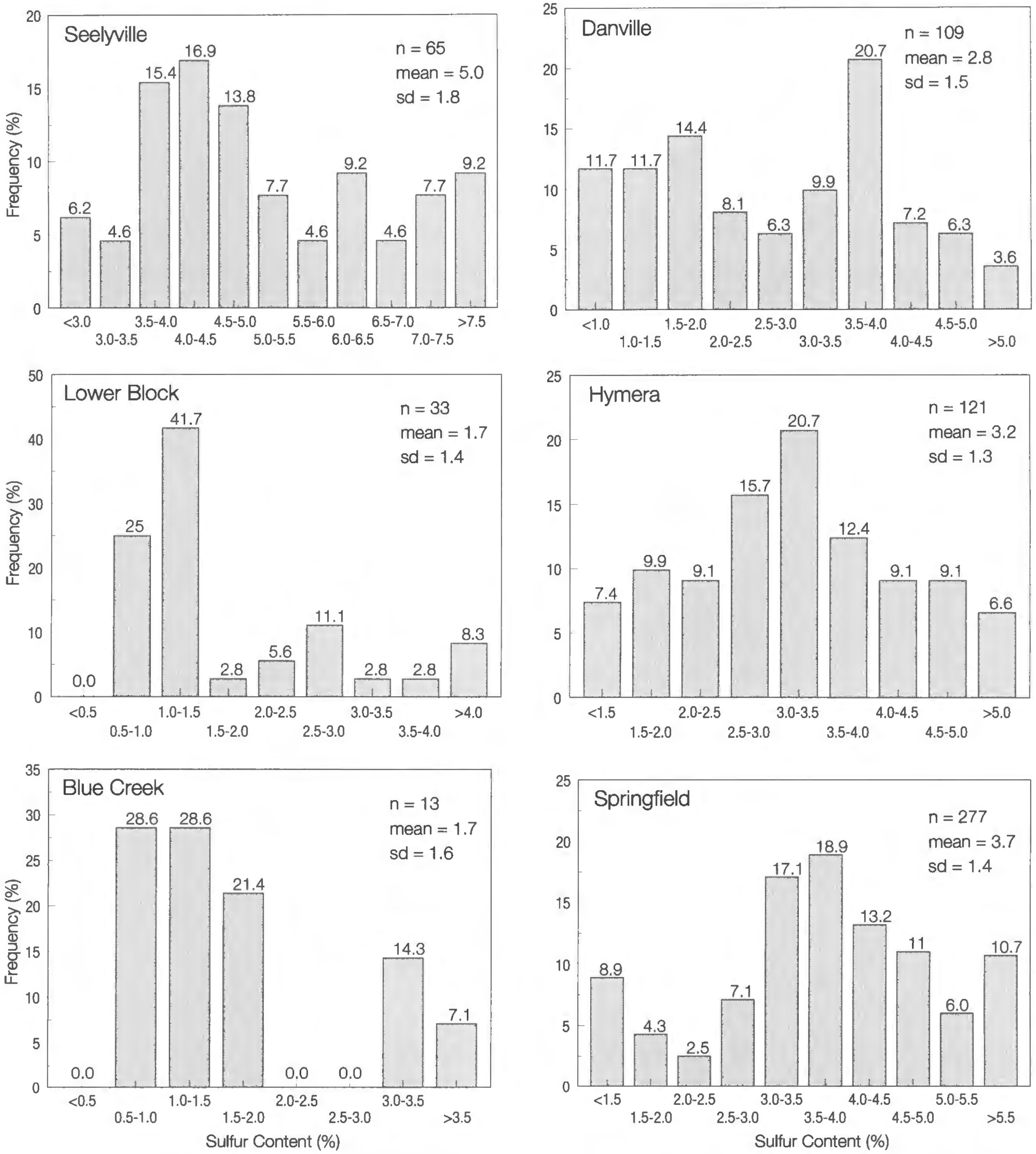

Figure 11. Histograms (frequency distribution, in percent) showing total sulfur content (weight percent, dry basis, of samples with less than 33 percent ash) of selected coalbeds in Indiana. Data are derived from the IGS and Penn State databases (see fig. 9). All samples are "complete channel samples."

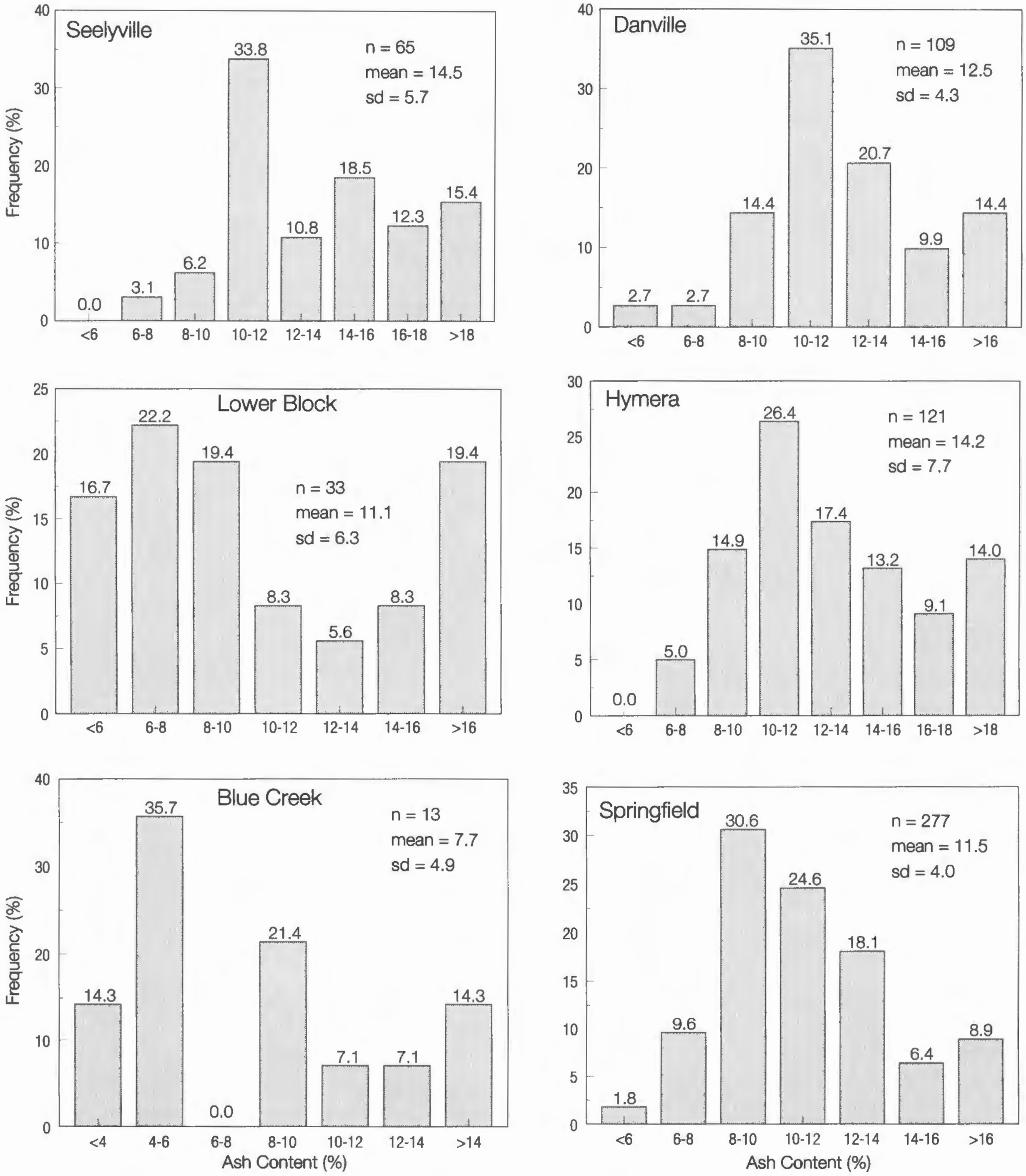

Figure 12. Histograms (frequency distribution, in percent) showing ash content (weight percent, dry basis, of samples with less than 33 percent ash) of selected coalbeds in Indiana. Data are derived from the IGS and Penn State databases (see fig. 9). All samples are "complete channel samples."

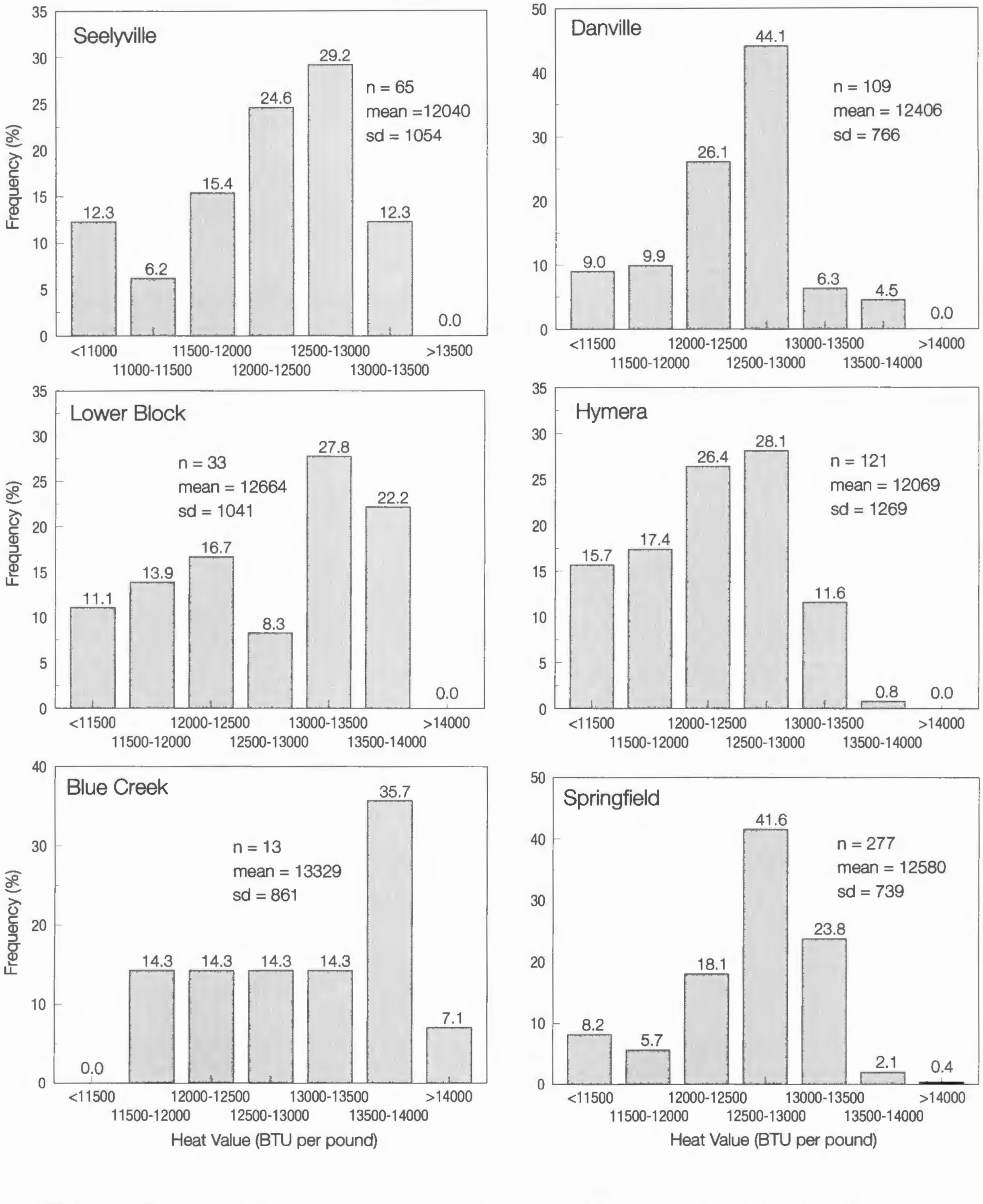

Figure 13. Histograms (frequency distribution, in percent) showing heating value (Btu per pound, dry basis, of samples with less than 33 percent ash) of selected coalbeds in Indiana. Data are derived from the IGS and Penn State databases (see fig. 9). All samples are "complete channel samples."

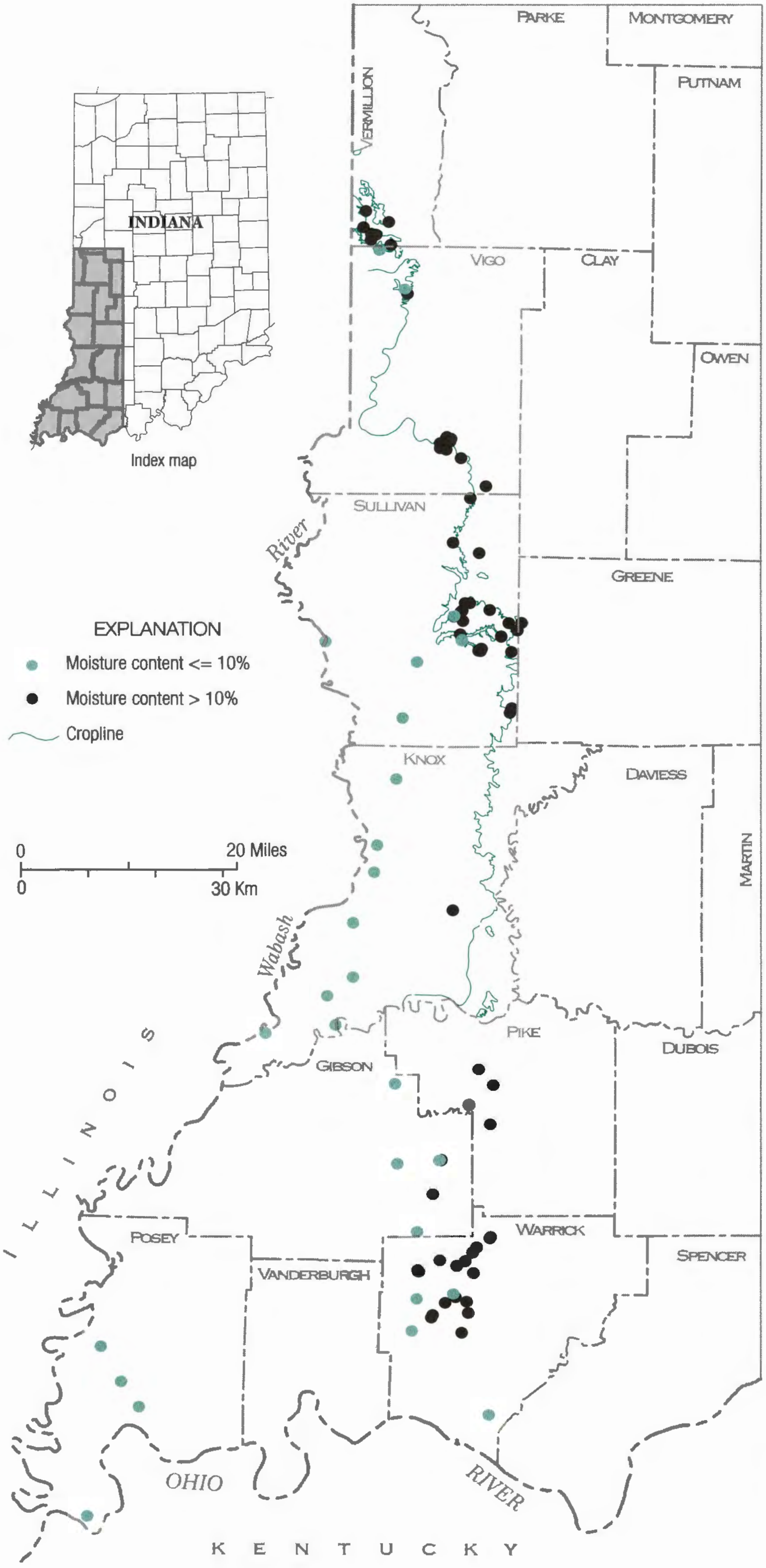

Figure 14. Map showing the moisture content (weight percent, as-received basis) of the Danville Coal Member. Data are derived from the IGS and Penn State databases (see fig. 9). All samples are "complete channel samples."

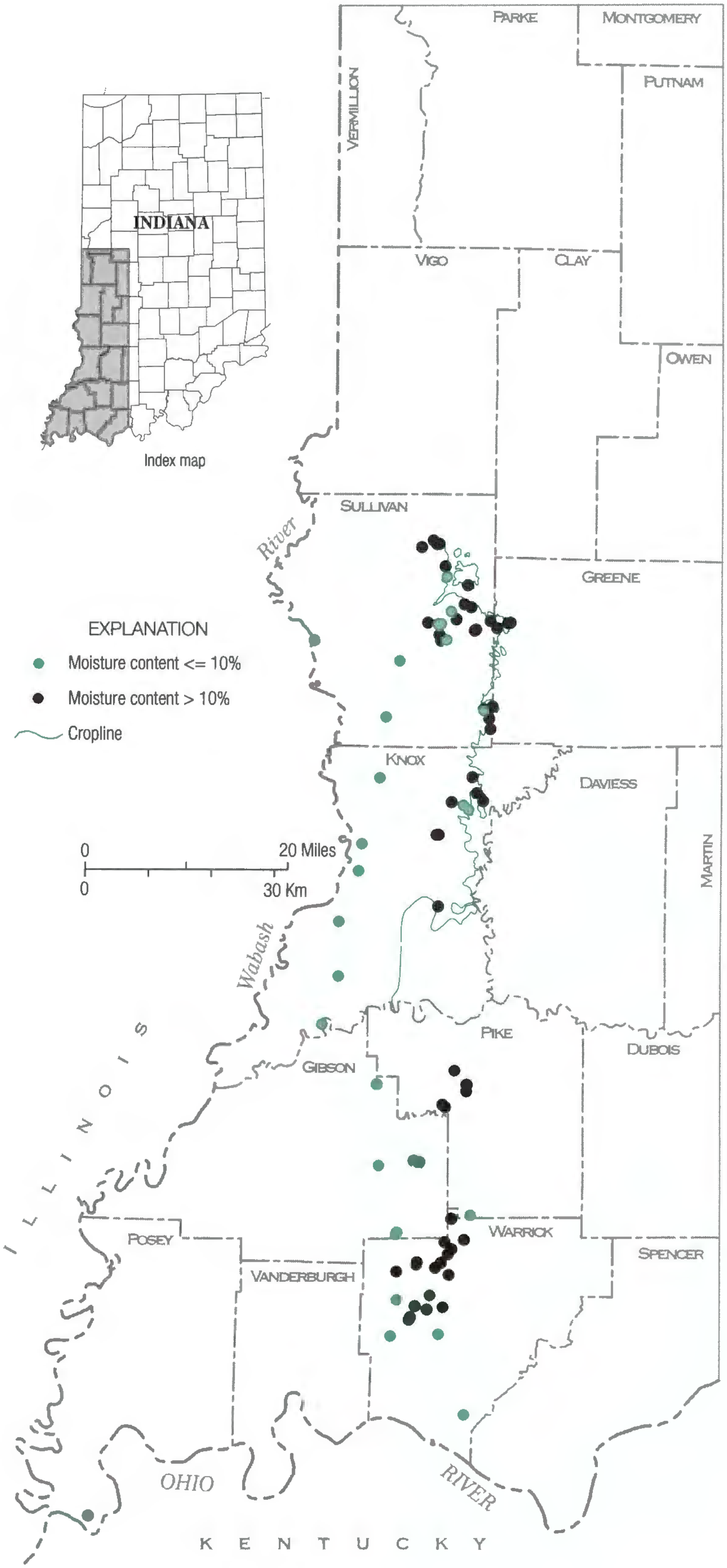

Figure 15. Map showing the moisture content (weight percent, as-received basis) of the Hymera Coal Member. Data are derived from the IGS and Penn State databases (see figure 9). All samples are "complete channel samples."

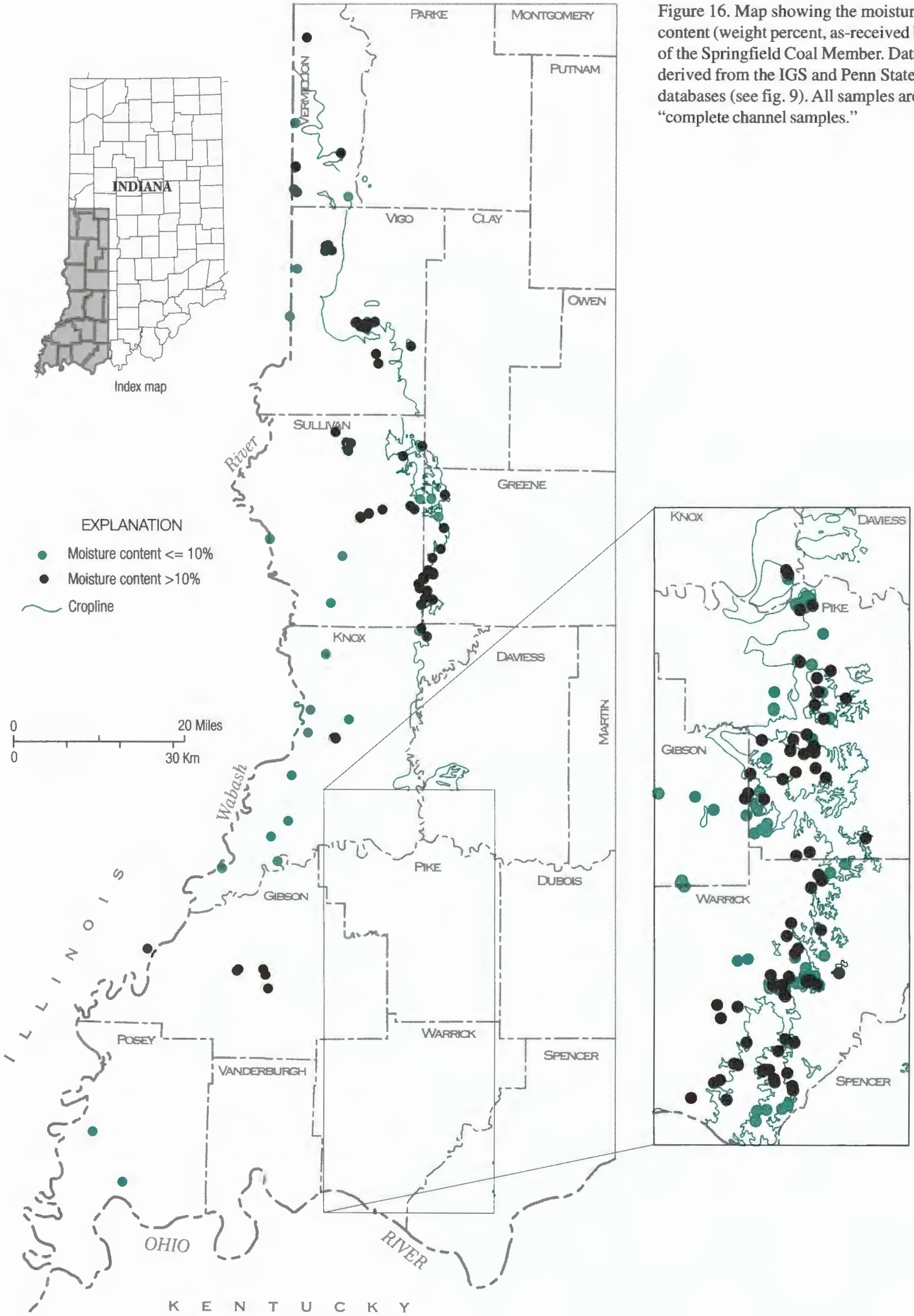

Figure 16. Map showing the moisture content (weight percent, as-received basis) of the Springfield Coal Member. Data are derived from the IGS and Penn State databases (see fig. 9). All samples are "complete channel samples."

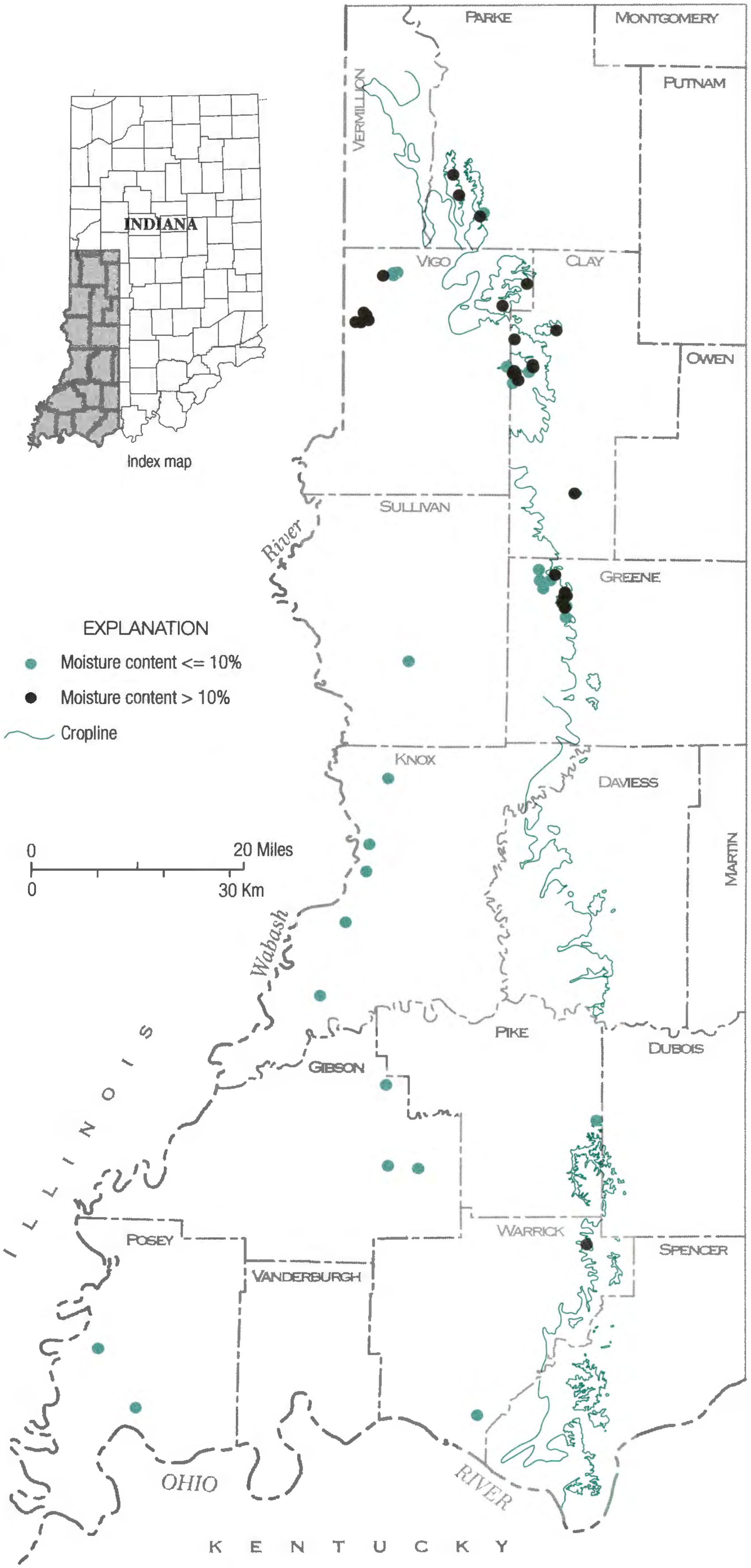

Figure 17. Map showing the moisture content (weight percent, as-received basis) of the Seelyville Coal Member. Data are derived from the IGS and Penn State databases (see fig. 9). All samples are "complete channel samples."

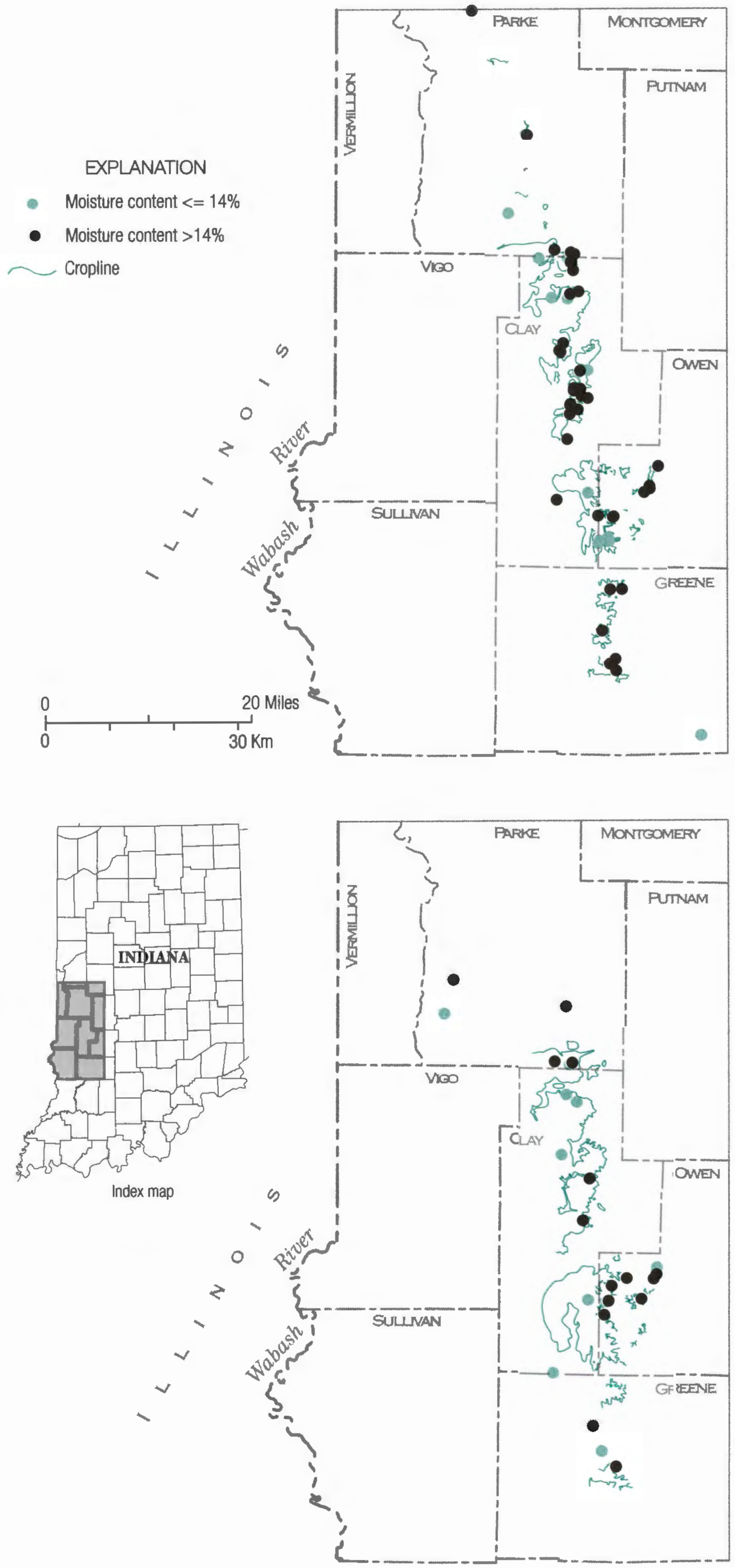

Figure 18. Maps showing the moisture content (weight percent, as-received basis) of the Upper Block and Lower Block Coal Members. Data are derived from the IGS and Penn State databases (see fig. 9). All samples are "complete channel samples."

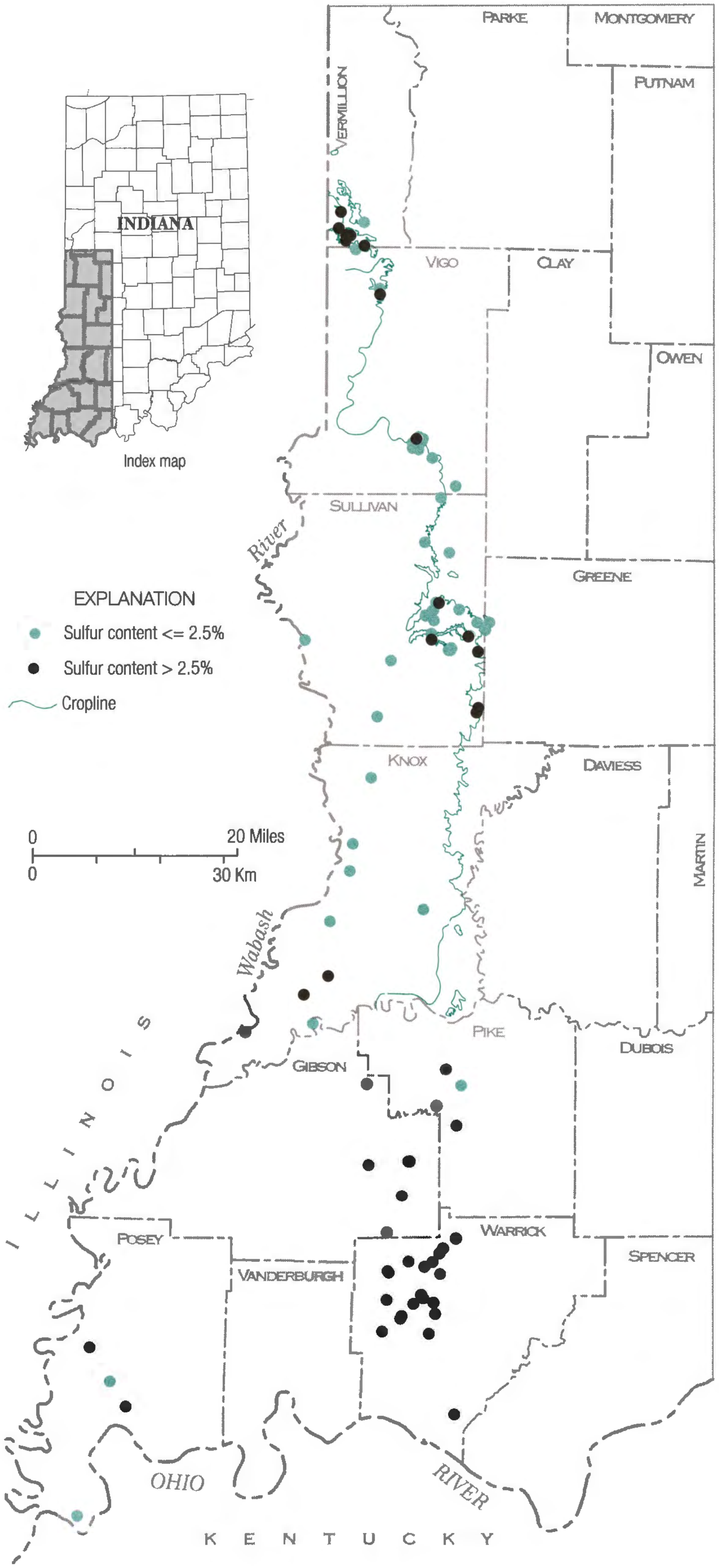

Figure 19. Map showing the sulfur content (weight percent, dry basis) of the Danville Coal Member. Data are derived from the IGS and Penn State databases (see fig. 9). All samples are "complete channel samples."

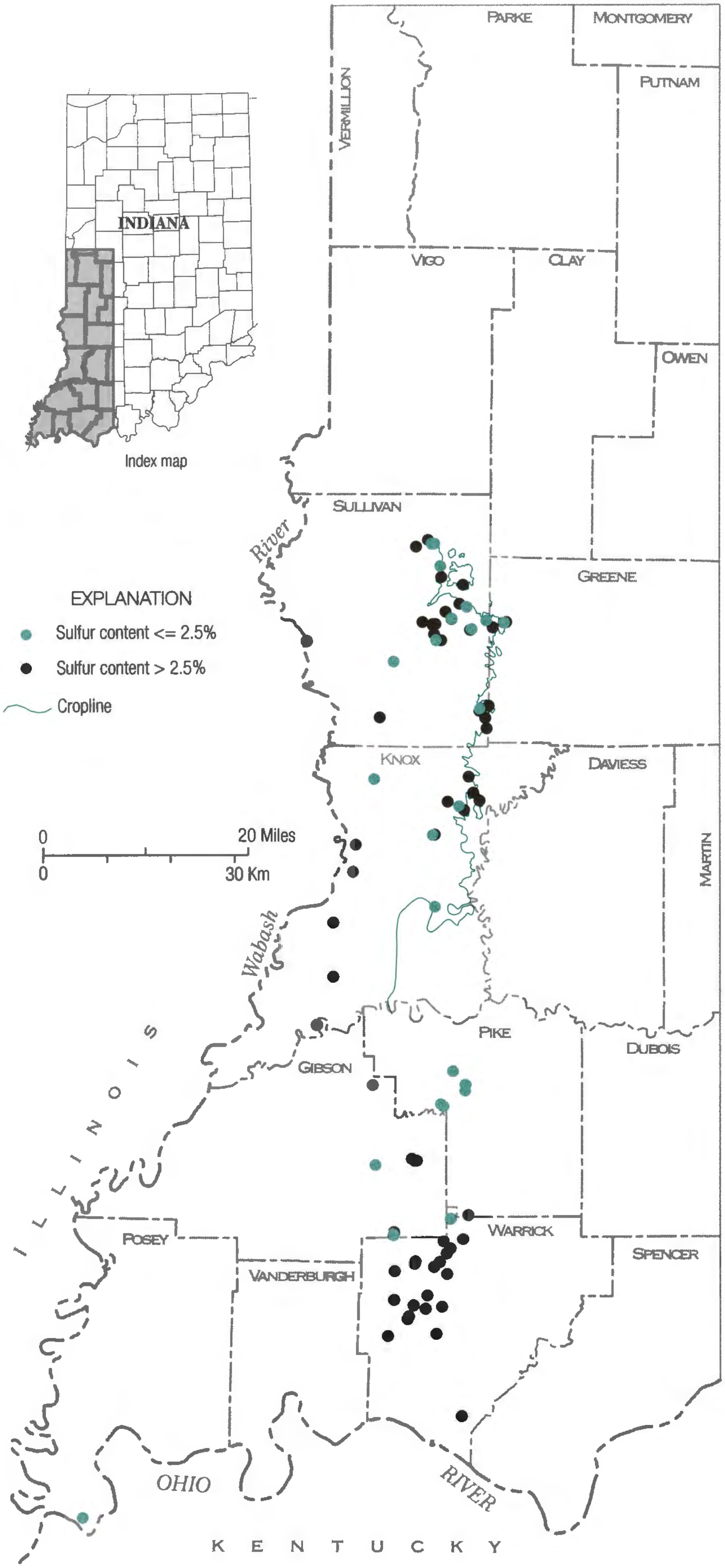

Figure 20. Map showing the sulfur content (weight percent, dry basis) of the Hymera Coal Member. Data are derived from the IGS and Penn State databases (see fig. 9). All samples are "complete channel samples."

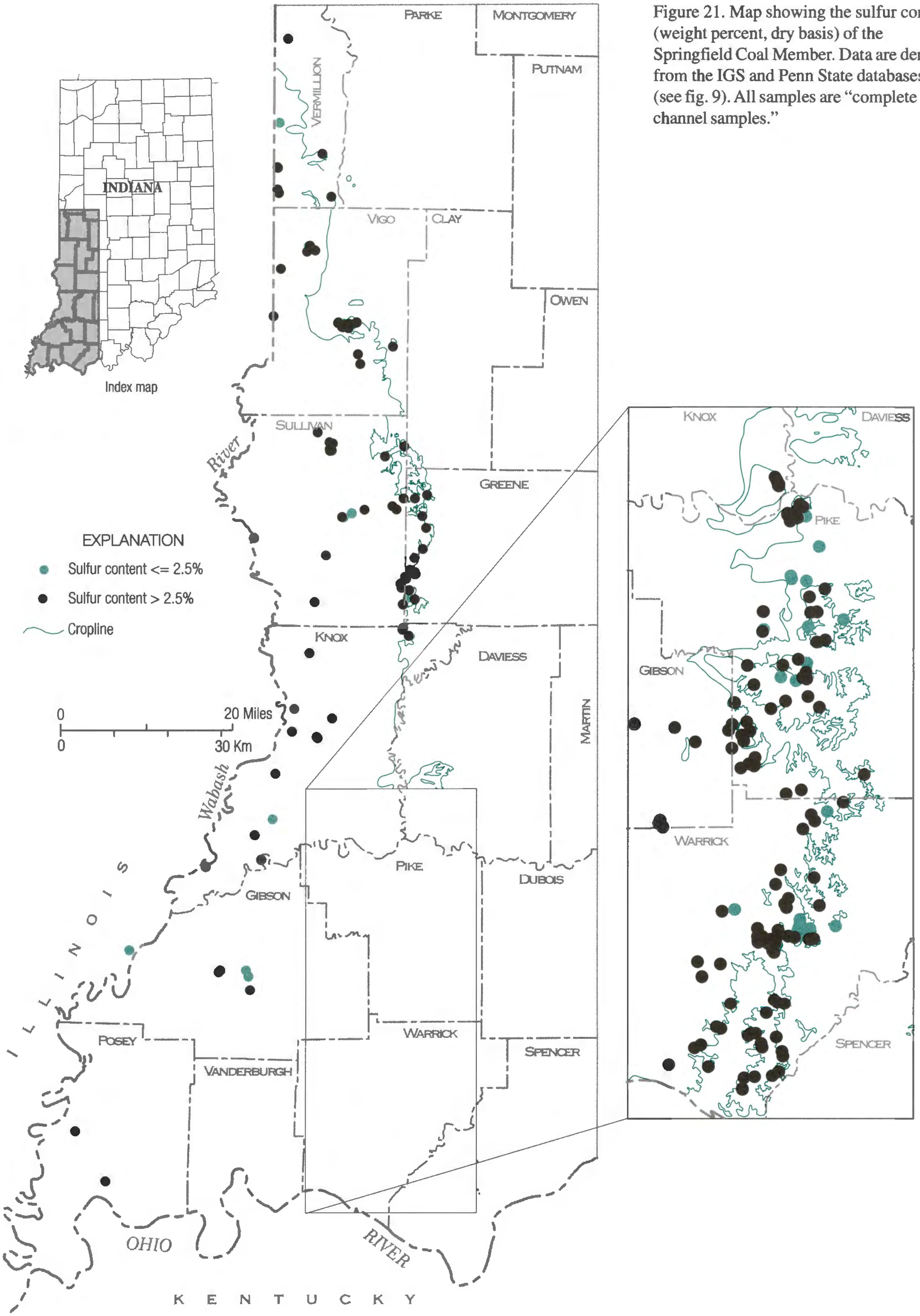

Figure 21. Map showing the sulfur content (weight percent, dry basis) of the Springfield Coal Member. Data are derived from the IGS and Penn State databases (see fig. 9). All samples are "complete channel samples."

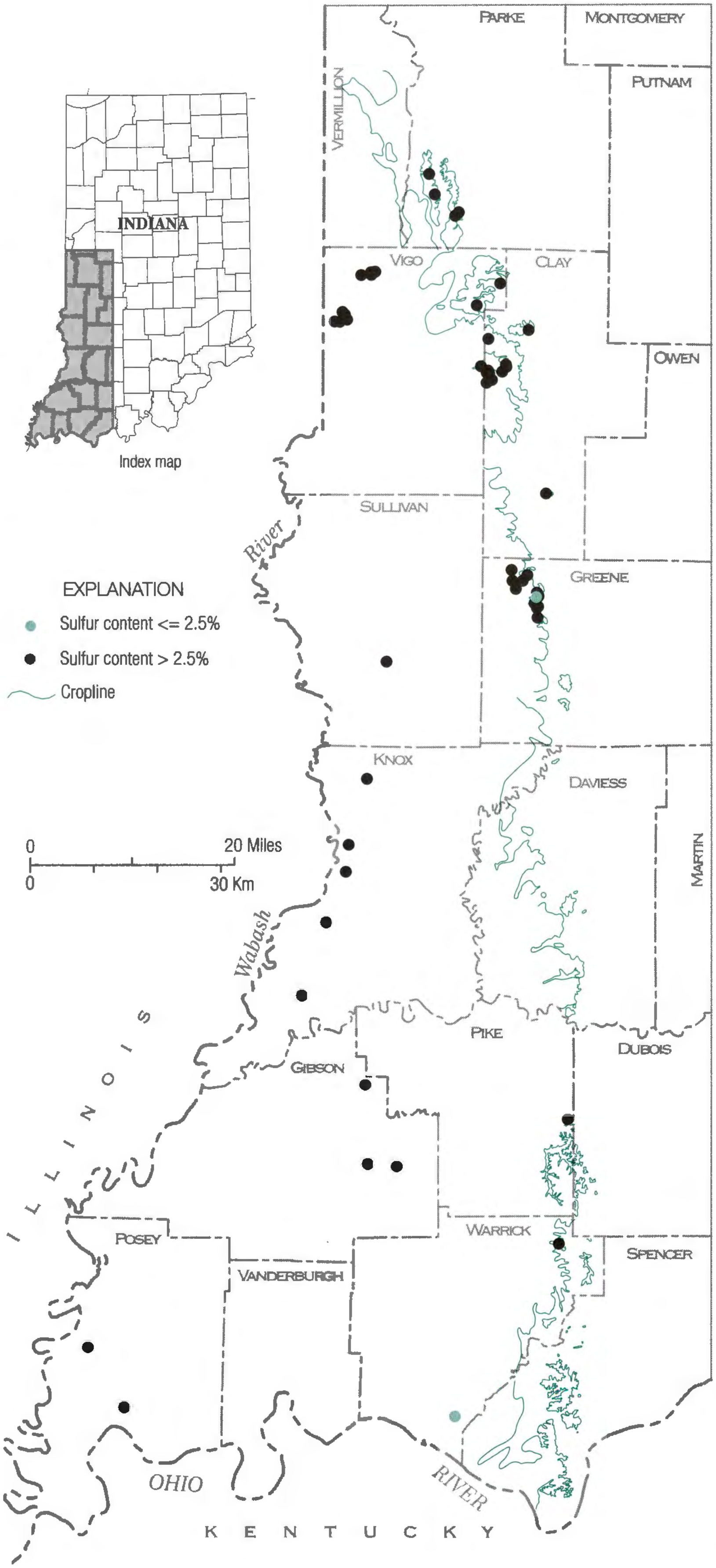

Figure 22. Map showing the sulfur content (weight percent, dry basis) of the Seelyville Coal Member. Data are derived from the IGS and Penn State databases (see fig. 9). All samples are "complete channel samples."

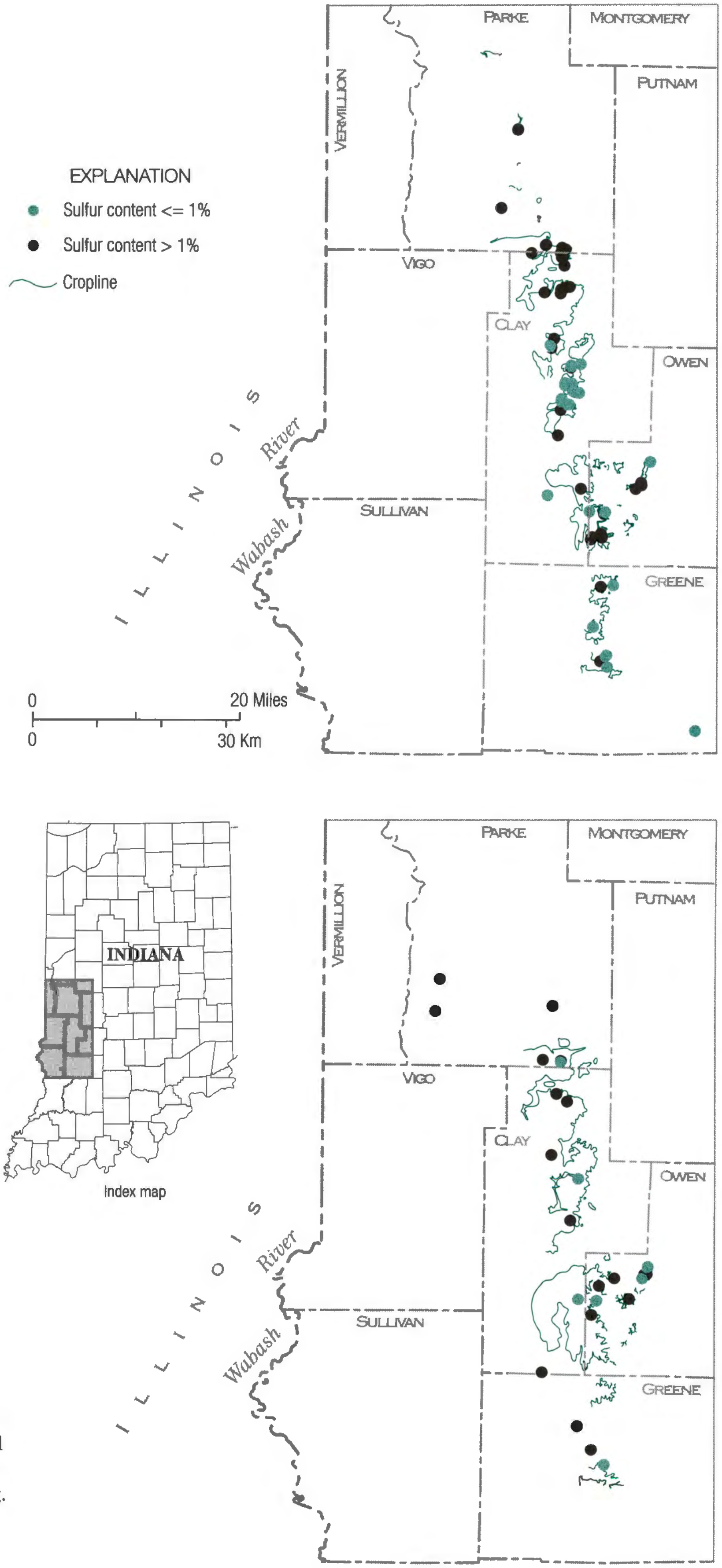

Figure 23. Maps showing the sulfur content (weight percent, dry basis) of the Upper Block (top) and Lower Block Coal (bottom) Member. Data are derived from the IGS and Penn State databases (see fig. 9). All samples are "complete channel samples."

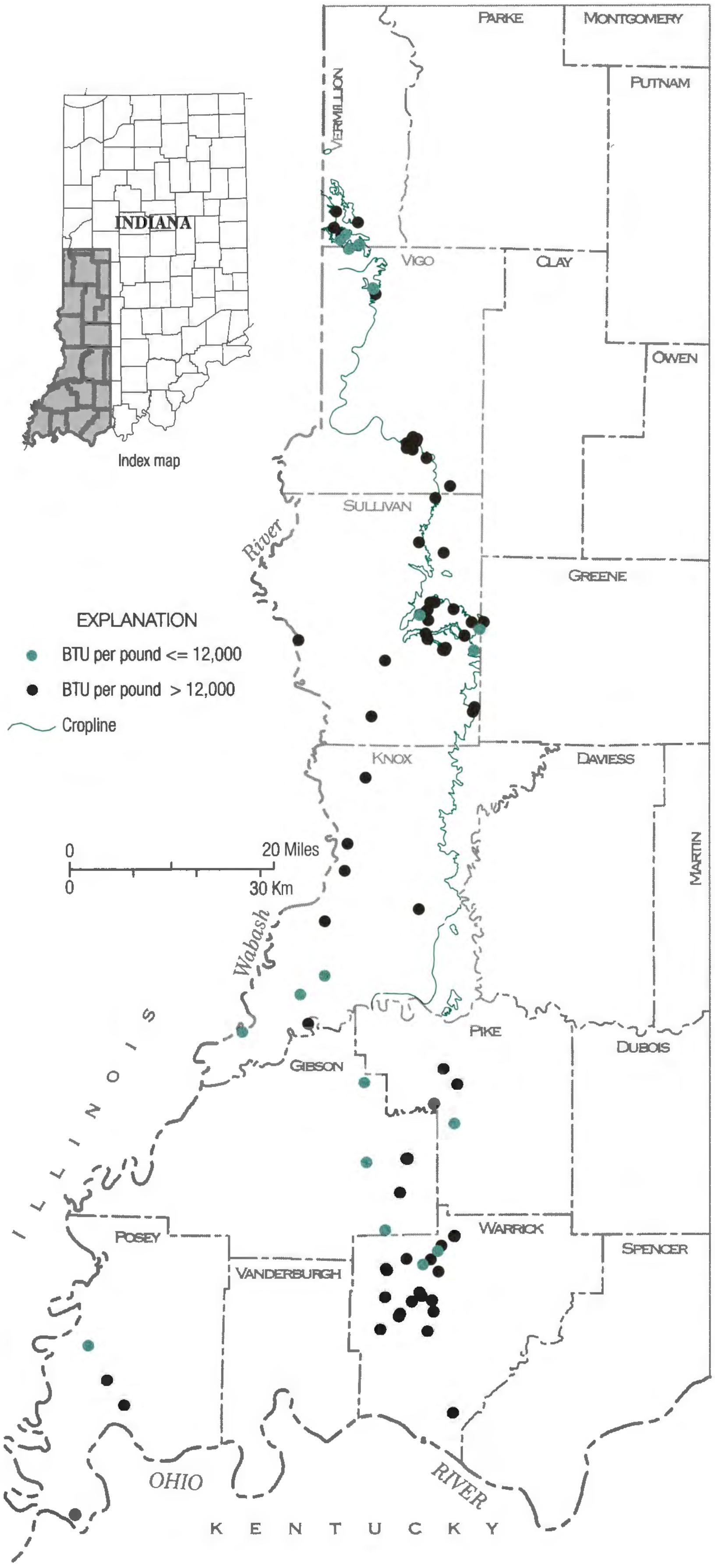

Figure 24. Map showing the heating value (Btu per pound, dry basis) of the Danville Coal Member. Data are derived from the IGS and Penn State databases (see fig. 9). All samples are "complete channel samples."

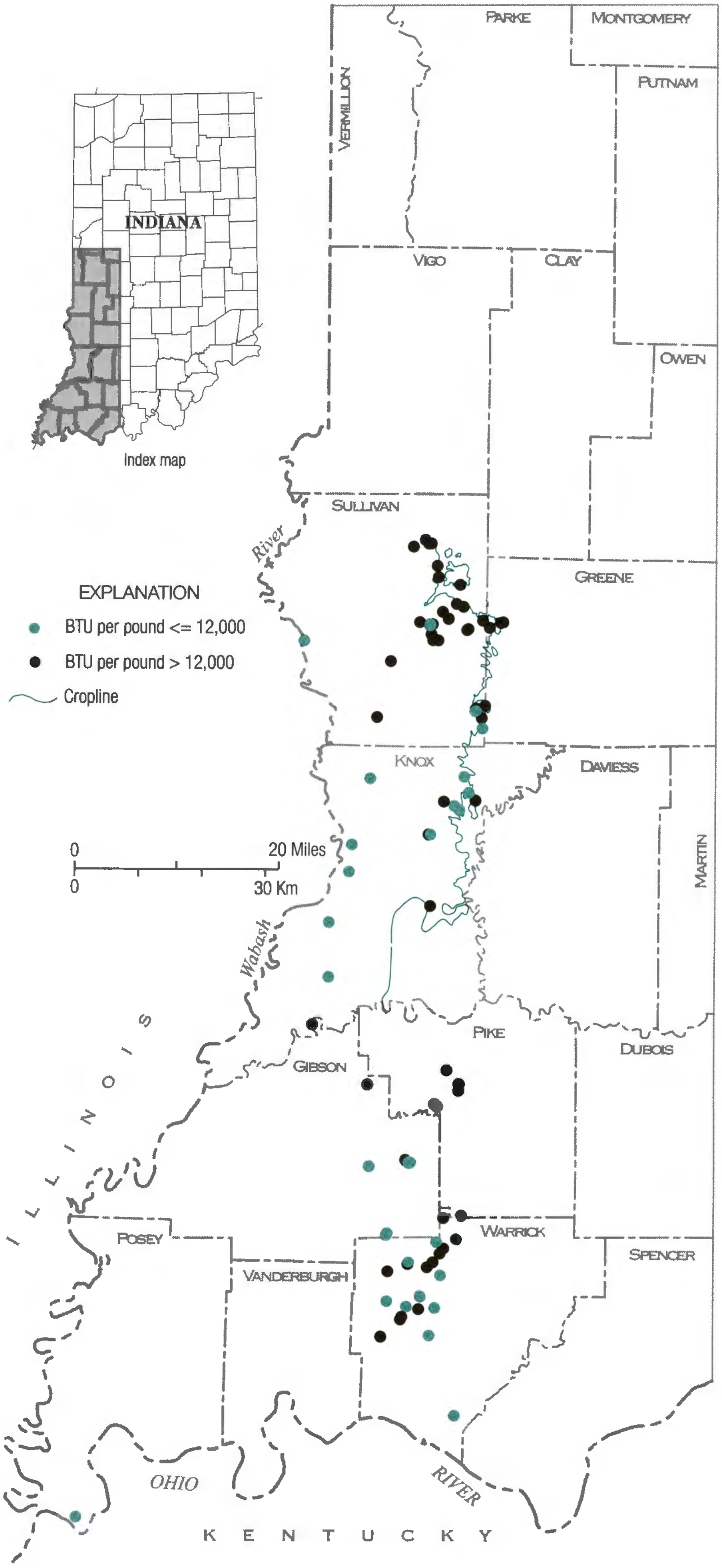

Figure 25. Map showing the heating value (Btu per pound, dry basis) of the Hymera Coal Member. Data are derived from the IGS and Penn State databases (see fig. 9). All samples are "complete channel samples."

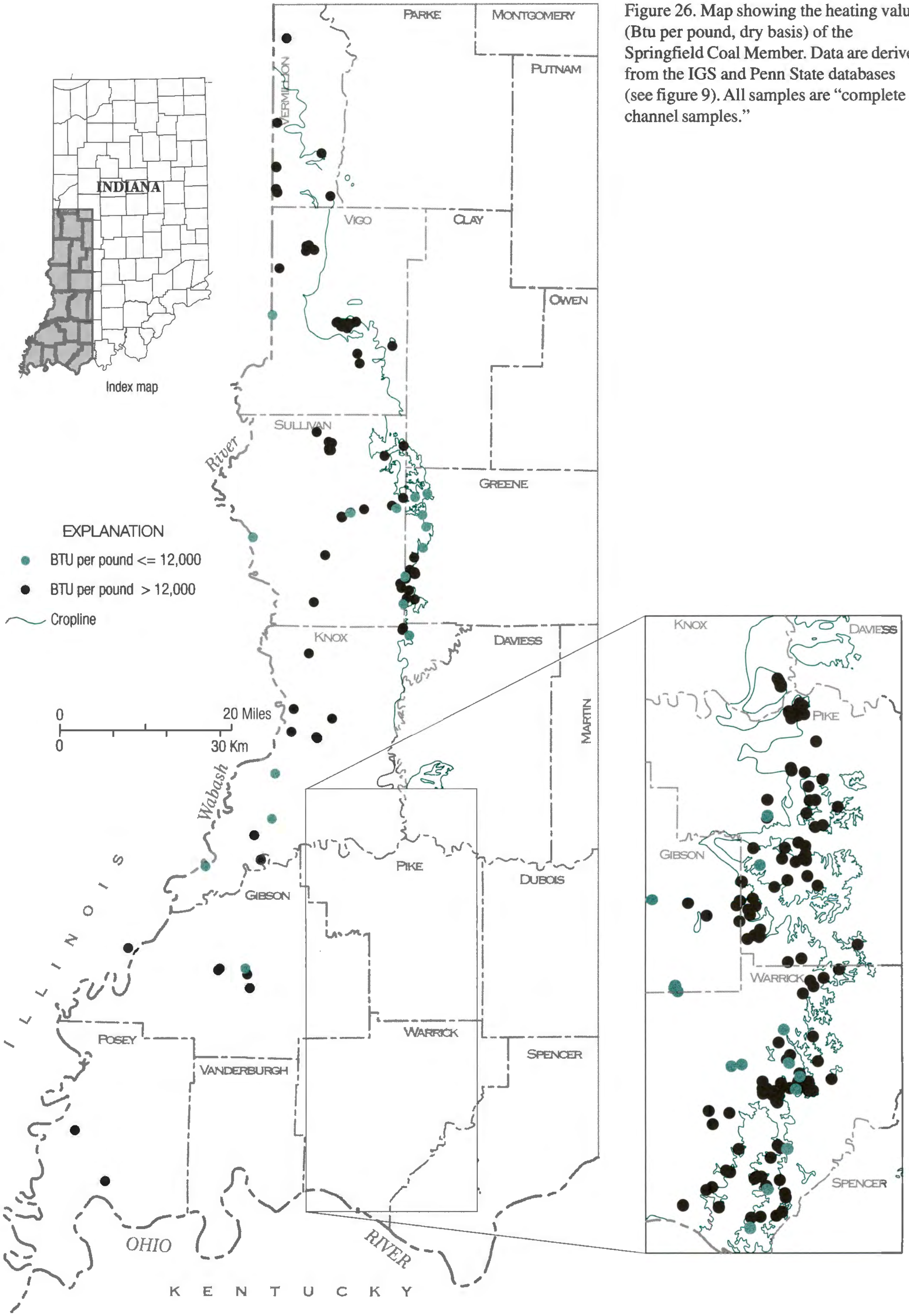

Figure 26. Map showing the heating value (Btu per pound, dry basis) of the Springfield Coal Member. Data are derived from the IGS and Penn State databases (see figure 9). All samples are "complete channel samples."

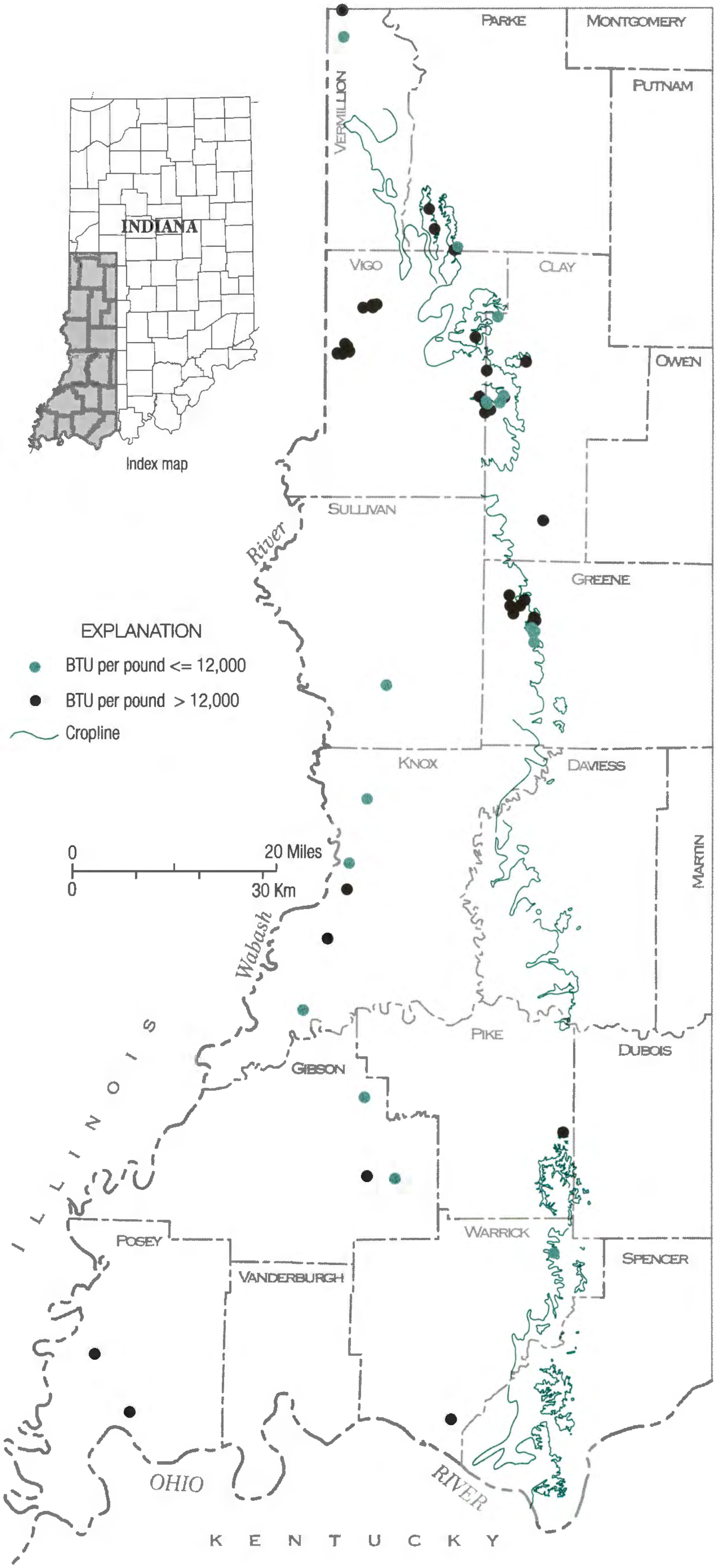

Figure 27. Map showing the heating value (Btu per pound, dry basis) of the Seelyville Coal Member. Data are derived from the IGS and Penn State databases (see fig. 9). All samples are "complete channel samples."

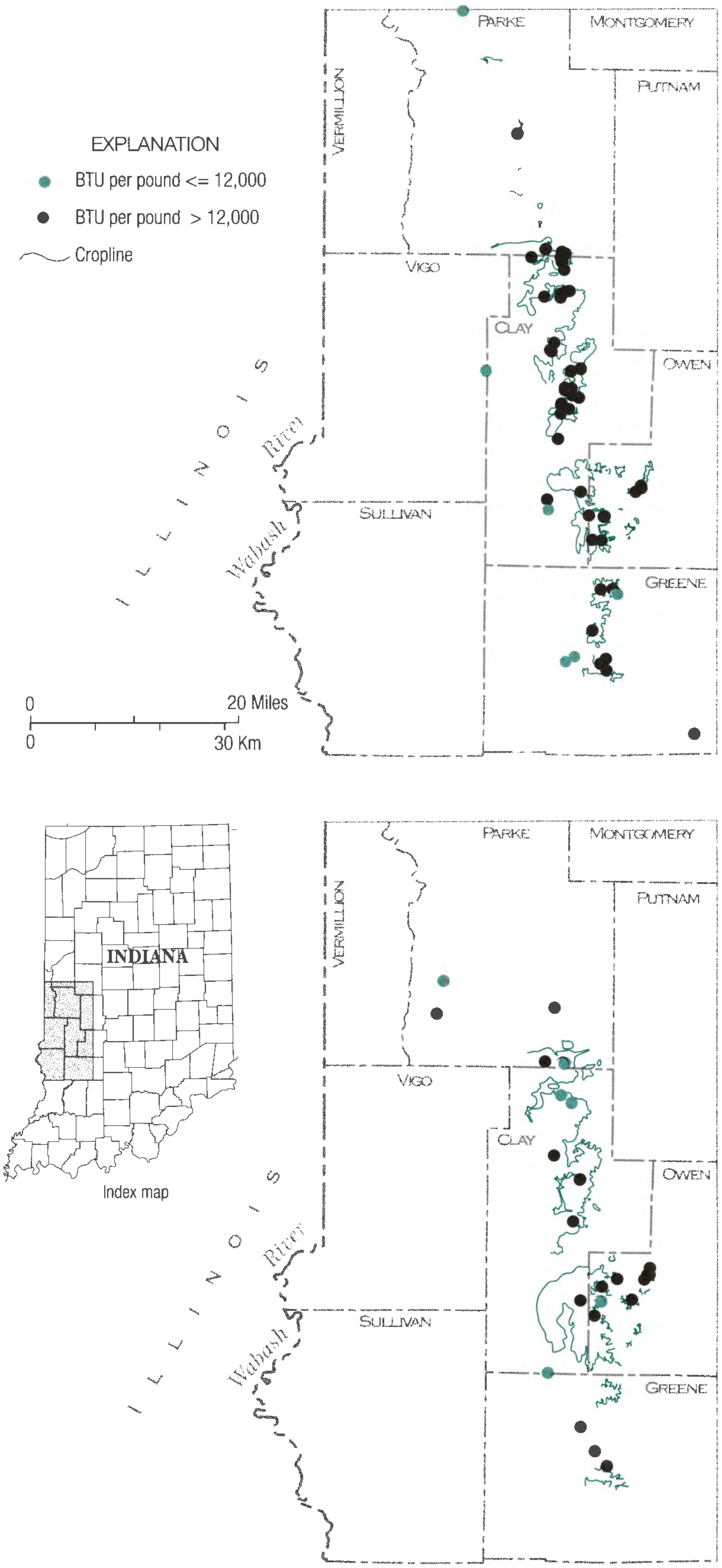

Figure 28. Maps showing the heating value (Btu per pound, dry basis) of the Upper Block (top), and Lower Block Coal (bottom) Members. Data are derived from the IGS and Penn State databases (see fig. 9). All samples are "complete channel samples."

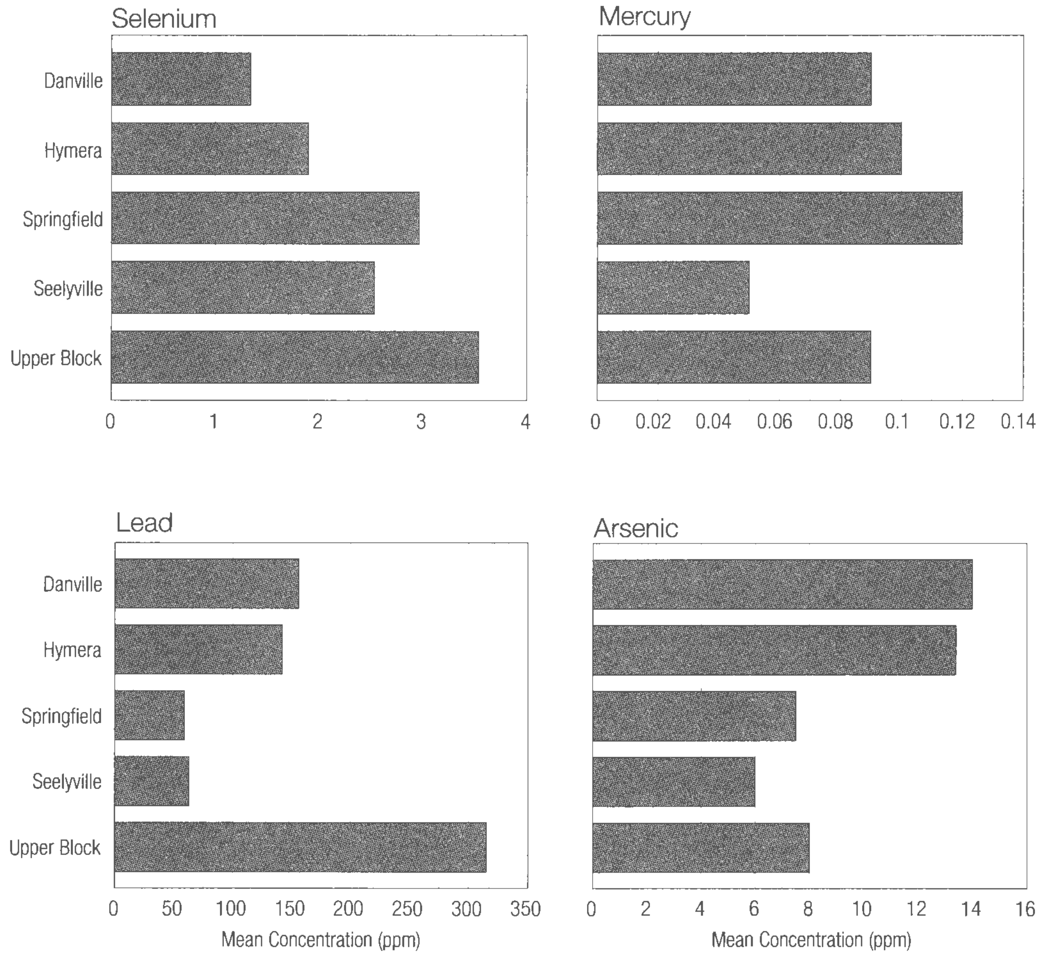

Figure 29. Diagrams showing mean concentrations (ppm, as-received basis, of samples with less than 33 percent ash) of trace elements in selected coalbeds in Indiana. Data are derived from the USGS and Penn State databases (see figure 6). All samples are "complete channel samples." Number of analyses: Upper Block (17), Seelyville (7), Springfield (46), Hymera (23), and Danville (15) Coal Members.

## SUMMARY AND CONCLUSIONS

Harper (1981, 1985a) has sketched the history of surface and underground mining in Indiana and provides graphs of annual coal production through time, and the Indiana Coal Council, Inc., publishes annual summaries of the state's coal production. It has been estimated that there are 34 billion tons of coal resources remaining in Indiana, of which seven percent are accessible using surface-mining methods and 93 percent using underground methods. Whether this great resource will continue to be exploited in the future depends upon many complex factors of minability, transportation, and utilization. Several of these factors—the depths and thicknesses of the coalbeds, the areal extents of minable tracts, and the qualities of the coals—are geological in nature.

The feasibility of mining a coal deposit requires detailed knowledge of the coal's thickness and chemical characteristics. Such knowledge is gained primarily by analysis of samples and cores that are obtained by drilling. Detailed examination of cores in the field (including recognition of such geological features as paleosols, bioturbation, tidal rhythmites, and coal lithotypes) can provide indications of coal quality, thereby reducing the number of expensive analyses that are subsequently needed for assessment of reserves. A recent publication of the Indiana Geological Survey, *Corebook of Pennsylvanian Rocks in the Illinois Basin* (Barnhill and Zhou, 1996), is designed to help drillers, mining engineers, and geologists standardize rock descriptions and to recognize features that are important for coal exploration and subsequent mining.

Even fewer expensive drill holes will be needed when depositional models and (or) statistical relationships between coal and associated clastic rocks are developed to the point where they can predict which areas are most likely to be underlain by coal of suitable thickness, quality, and uniformity. Recognition of statistical relationships between the thickness of a coalbed and other variables (for example, the thickness of certain underlying sandstones) may also reduce the need for exploratory drilling by allowing greater utilization of other already existing sources of data (for example, logs from petroleum exploration holes).

Detailed sedimentological analysis of clastic sediments and geochemical analysis of organic matter, including that dispersed in clastic rocks as well as that concentrated in coal, might shed light on how the paleogeography of Indiana changed during the Pennsylvanian Period. Although some petrographic data on Indiana coal were gathered 35 years ago (Neavel, 1961), there have been only a few more recent publications, and those have dealt with the petrology, paleoecology, and organic geochemistry of the Springfield seam and Indiana paper coal (Crelling and Bensley, 1980; Willard and others, 1995). When sedimentologic data can be supplemented by petrographic data, it may become possible to reconstruct peat-forming depositional conditions (for example, domed *vs.* planar peats) and to better understand the factors that have influenced the distribution of ash and sulfur. Such efforts might result in more effective exploitation of low-sulfur deposits in the Springfield, Hymera, and Danville coals, as well as coalbeds in the Mansfield and Brazil Formations. Particularly in the Mansfield and Brazil Formations, there is a need for additional stratigraphic work to improve the reliability of coalbed identification and correlation. In that part of the geologic column, more palynological data would be of great value.

Because of Clean Air Act restrictions, there is also an urgent need to acquire more data on the distribution of trace elements in Indiana's coalbeds and, in particular, to gain a better understanding of the factors that control the distribution of mercury, lead, selenium, and chlorine in the coals. Such efforts might result in the identification of zones that are low in trace-element content, which together with monitoring of coal-combustion by-products, would assist utility companies in their efforts to comply with provisions of the Act.

In addition to the search for thick deposits of low-sulfur coal with suitable trace-element contents, there is a need to determine controls on moisture content in Indiana coal and to delineate low-moisture zones. Coal from such zones could be utilized in steelmaking, thereby allowing greater substitution of Indiana coal for coking coal from other states. The Springfield, Hymera, Danville, and Brazil Formation coals, which have been of largest interest to the steelmaking industry to date, are the most promising targets for such research. These seams comprise large resources, and abundant data are already available. Augmented by petrographic analyses, these data could be used to determine controls on moisture content and identify low-moisture zones.

Other opportunities exist for increased use of Indiana coal, including increased use of coalbed methane (Harper, 1991). Indiana coal may contain significant resources of coalbed gas that could be used commercially. But exploitation of that resource would require determination of coal-rank variations (expressed as vitrinite reflectance) and studies of the properties of coalbed gas (for example, isotopic composition), as well as by investigations of seam pressure and hydrodynamics. Trends of vitrinite reflectance for individual seams will provide a broader view of coalification trends and may help to identify areas having greater potential for generation of coalbed gas and gas storage. It would also be a valuable addition to thermal maturation modeling for gas exploration in the New Albany Shale (Devonian and Mississippian).

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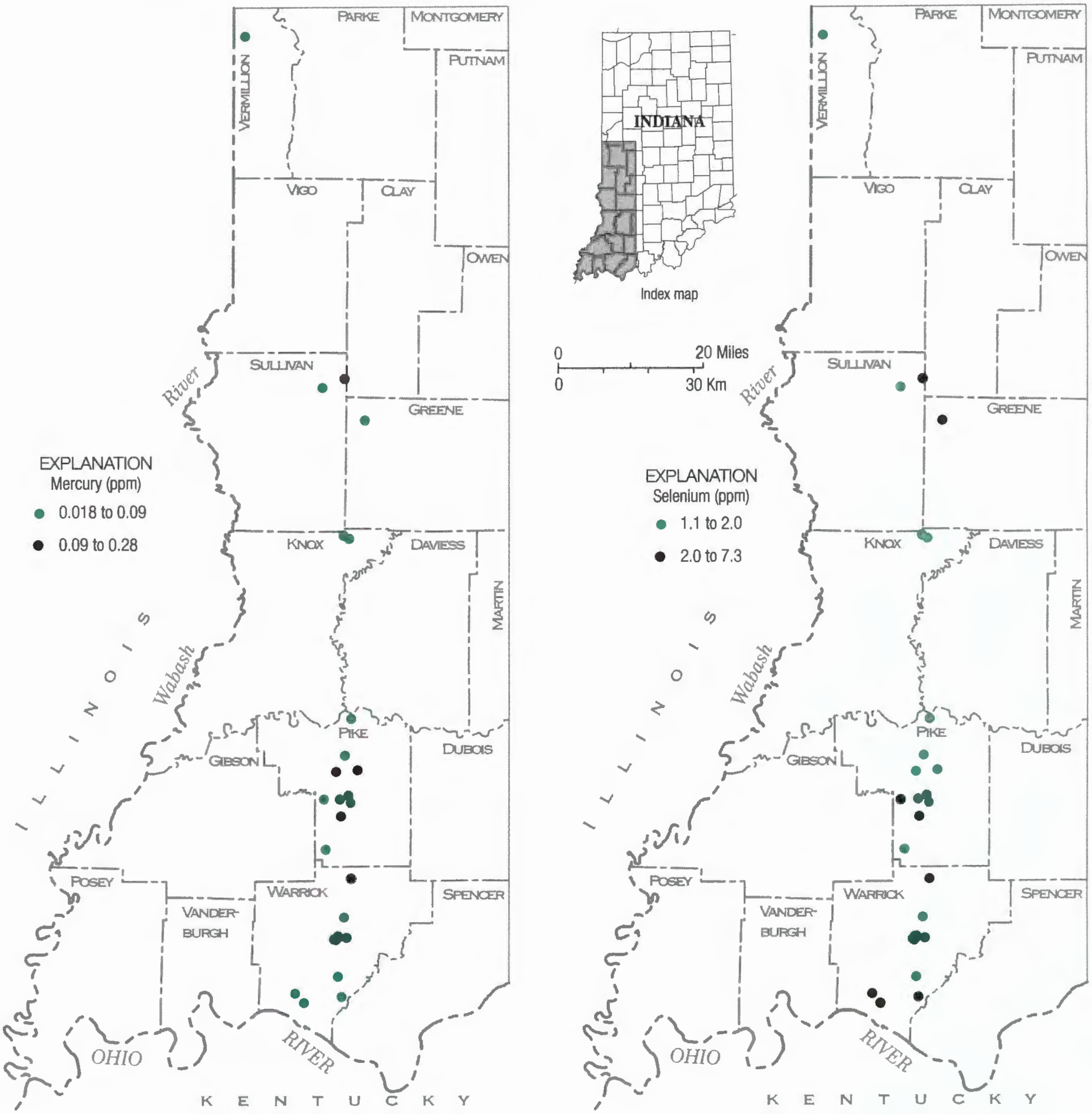

Figure 30. Maps showing the concentrations (ppm, as-received basis) of selected trace elements (mercury and selenium) in the Springfield Coal Member. The data are derived from the USGS and Penn State databases.

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Mastalerz & Harper - **COAL IN INDIANA: A Geologic Overview** Indiana Geological Survey Special Report 60

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