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Desmoinesian coal beds of the Eastern Interior and surrounding basins: The largest tropical peat mires in Earth history

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ABSTRACT

The Colchester, Springfield, and Herrin Coals of the Eastern Interior Basin are some of the most extensive coal beds in North America, if not the world. The Colchester covers an area of more than 100,000 km^2, the Springfield covers 73,500–81,000 km^2, and the Herrin spans 73,900 km^2. Each has correlatives in the Western Interior Basin, such that their entire regional extent varies from 116,000 km^2 to 200,000 km^2. Correlatives in the Appalachian Basin may indicate an even more widespread area of Desmoinesian peatland development, although possibly slightly younger in age. The Colchester Coal is thin, but the Springfield and Herrin Coals reach thicknesses in excess of 3 m.

High ash yields, dominance of vitrinite macerals, and abundant lycopsids suggest that these Desmoinesian coals were deposited in topogenous (groundwater fed) to soligenous (mixed-water sourcc) mires. The only modern mire complexes that are as widespread are northern-latitude raised-bog mires, but Desmoinesian Midcontinent paleomires were topogenous and accumulated within 10° of the paleo-equator.

The extent and thickness of Desmoinesian paleomires resulted from the coincidence of prime peat-forming factors, including a seasonally wet paleoclimate; cyclothemic transgressions and base-level rise above extensive, low-relief cratonic areas floored by vast, impermeable paleosols; broad floodplains along large rivers with a groundwater table high enough to hydrologically link peatlands and keep them wet; low, relatively uniform rates of tectonic subsidence; and accumulation in a basin surrounded by low relief, which led to minimal sediment input.

Keywords: Carboniferous, Carbondale Formation, Illinois Basin, Midcontinent, topogenous, peatlands.

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INTRODUCTION

Wanless (1975a) noted that the Colchester Coal of the Eastern Interior (Illinois) Basin, and its correlatives in the Western Interior Basin, combined to form the most widespread coal bed in North America and possibly the world. Currently there is no database or central source area for comparing global coal areas on a bed basis, but for the purpose of determining the most widespread coals of all time, basin size can be used as an initial limiting extent. Some of the largest coal basins in the world are the Bowen (Queensland) Basin of Australia; Karoo Basin of South Africa; and the Powder River, Williston, Appalachian, Western Interior, and Eastern Interior Basins of the United States (Fig. 1).

Many Bowen Basin coal seams split into multiple beds or benches, rather than occurring as single, widespread beds (Hower et al., 1995; Diessel, 1998). At least one Permian coal bed contains a tuff, which is extensive along the outcrop margin of the coal, suggesting coeval, basin-wide peat accumulation (Michaelsen et al., 2000). The Leichardt and Vermont "superseams" are extensive for 200 km along strike and may have areal distributions of 20,000 km^2 (Mallett et al., 1995; Michaelsen et al., 2000), which is vast, but less extensive than the most extensive Desmoinesian coals of the Eastern Interior Basin.

Permian coals are also extensive in the Karoo Basin of South Africa, but are restricted to three coal fields on the northern stablc platform of the basin. The number 4 and 5 seams of the Ecca Group can be correlated for more than 250 km along the outcrop margin of the coal fields, but they are bisected by numerous paleochannels and split into multiple subseams across part of the Natal Coal Field (Cadle et al., 1993).

In North America, the Wyodak-Anderson coal, a Paleocene coal of the Powder River Basin (Fig. 1), is currently the largest coal producer in the United States, producing 320 million short tons in 2001 (U.S. Department of Energy, 2001). It has a total area of 24,000 km^2 (Ellis et al., 1999), which is less than the extent of the most extensive coals in the Eastern Interior Basin. Additionally, the Wyodak-Anderson is actually a zone of as many as 11 separate beds (Hardie and Van Gosen, 1986) in a coal zone rather than a single bed, such that it may be difficult to discern the distribution of any single coeval palcomire.

The Pittsburgh coal is the second largest producer in the United States, producing 81 million short tons in 2001 (U.S. Department of Energy, 2001). This Upper Pennsylvanian bed of the Northern Appalachian Basin (Fig. 1) covers an area of more than 21,450 km^2 (Northern and Central Appalachian Basin Coal Regions Assessment Team, 2001). Another extensive coal from the Northern Appalachian Basin is the upper Middle Pennsylvanian Upper Freeport coal. This coal produced 10.3 million short tons in 2001, and ranked nineteenth nationally (Northern and Central Appalachian Basin Coal Regions Assessment Team, 2001). The Upper Freeport coal covers an area of at least 27,000 km^2 (Northern and Central Appalachian Basin Coal Regions Assessment Team, 2001). Some of the top-producing coals of the Central Appalachian Basin (Fig. 1), such as the Fire Clay (Hazard No. 4) coal (18.5 million short tons, eleventh nationally, Northern and Central Appalachian Basin Coal Regions Assessment Team, 2001), cover areas of less than 17,000 km^2 (Northern and Central Appalachian Basin Coal Regions Assessment Team, 2001), and most of these Appalachian Basin coals split or develop into zones toward the foreland basin axis.

Eastern Interior Basin Coals

The largest producing coals in the Eastern Interior (Illinois) Basin are the Desmoinesian coals of the Carbondale Formation (Fig. 2). These coal beds have member status in Illinois and Indiana, but bed status in Kentucky. For the purposes of this report, Eastern Interior Basin coal beds will be treated as members for

Figure 1. Map of coal fields in conterminous United States (after Tully, 1996).

Series	Stage	Illinois formation	Illinois (coals are members)	Indiana formation	Indiana (coals are members)	Kentucky formation	Kentucky (coals are beds)	Tri-state	Tri-state nomenclature (2001)
Middle Pennsylvanian (part)	Desmoinesian (part)		Danville (No. 7)		Danville (VII)	McLeansboro Group (part)	Wheatcroft	*	Danville
		Carbondale Formation	———	Carbondale Formation	———		Western Ky. No. 13		Baker
			Jamestown *Brereton Ls.*		Jamestown *Providence Ls.*		Western Ky. No. 12 *L. Providence Ls.*	**	Paradise/ Jamestown
			Herrin (No. 6)		**Herrin (VI)**	Carbondale Formation	**Western Ky. No. 11**	Carbondale Formation	**Herrin**
			Briar Hill (No. 5A)		Bucktown (Vb)		Western Ky. No. 10		Briar Hill
			Springfield-Harrisburg (No. 5)		**Springfield (V)**		**Mulford-W. Ky. No. 9**		**Springfield**
			Summum (No. 4)		Houchin Creek (IVa)		Western Ky. No. 8b		Houchin Creek
			Survant		Survant (IV)		Western Ky. No. 8		Survant
			Colchester (No. 2)		**Colchester (IIIa)**		**"S" coal**		**Colchester**
		Tradewater Formation	Dekoven		———		Western Ky. No. 7		Dekoven
			Seelyville		Seelyville (No. III)		Western Ky. No. 6		Davis

Figure 2. Stratigraphic column for Eastern Interior Basin showing nomenclature for the basin's three states. Tri-state Committee on Correlation of the Pennsylvanian System in the Illinois Basin nomenclature (2001) is used in this report. Ls—limestone.

consistency. The two largest producers are the Springfield and Herrin Coals. The Springfield is the third largest producer in the nation at 42 million short tons in 2001, and the Herrin ranked tenth nationally, with 19.1 million short tons (U.S. Department of Energy, 2001). Figure 3 is a cross section of the Eastern Interior Basin showing the stratigraphic position and extent of the Carbondale Formation coals. More coals are preserved beneath the Colchester Coal in the deeper, southern part of the basin above depocenters called the Fairfield Basin (Fb in Fig. 3) and Moorman Syncline (Ms in Fig. 3). Only three coals, the Herrin, Springfield, and Colchester, have basin-wide extent. Extensive and uniform distribution of strata and facies are typical of Desmoinesian and younger Pennsylvanian strata in the basin (Wanless and Weller, 1932; Kosanke et al., 1960; Wanless et al., 1963; Wanless, 1975b; Wanless and Wright, 1978; Greb et al., 1992). In general, coal bed extent and uniformity decreases beneath the Colchester and above the Herrin Coal. Increasingly extensive coals in the basin seem to parallel a trend toward decreasing tectonic accommodation in the basin from Morrowan into Desmoinesian time (Greb et al., 2002).

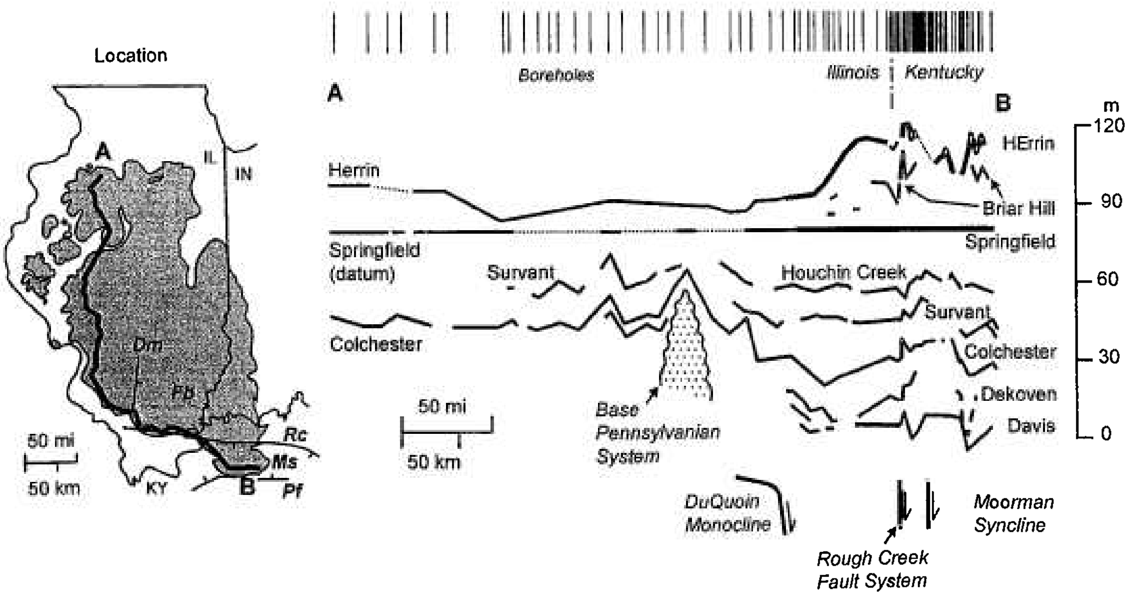

Figure 3. Cross section of Carbondale Formation (Davis to Herrin Coals) from the northern (A) to southern (B) margin of the Eastern Interior Basin (Borehole data from Smith, 1958, 1961; Smith and Berggren, 1963; and the Kentucky Geological Survey database). Dm—DuQuoin monocline, Fb—Fairfield Basin, Ms—Moorman Syncline, Pf—Pennyrile fault system, Rc—Rough Creek fault system, IL—Illinois, IN—Indiana, IA—Iowa, KY—Kentucky.

Cyclothems

Cyclothems are vertically repetitive successions of strata, including coals, clastics, and carbonates, which were named and first investigated in the Desmoinesian of the Eastern Interior Basin (Udden, 1912; Wanless and Weller, 1932). Similar groupings were also noted in the Western Interior Basin of the U.S. Midcontinent and eastward into the Appalachian Basin (Wanless and Weller, 1932; Wanless and Shepard, 1936; Wanless, 1939). Basin comparisons indicate a greater percentage of carbonate deposition in the Western Interior Basin and a greater percentage of clastic deposition in Appalachian Basin cyclothems (Wanless and Shepard, 1936; Wanless, 1975a, 1975b, 1975c, 1975d; Heckel, 1986, 1995, Heckel et al., 1998).

Figure 4 is a cross section of part of the Desmoinesian Carbondale Formation in the southern part of the Eastern Interior Basin. The only persistent marine carbonate in this part of the section, and in this part of the basin, is the Brereton (Providence) Limestone above the Herrin Coal. Most cycles consist of coarsening-upward sequences above the coals. Cyclothems, as defined by Wanless and Weller (1932), extend upward from the base of each scour-based sandstone to the next scour-based sandstone. These sand bodies, however, are not as continuous as the coals or underclays, which represent paleosols, in this part of the section; informally, it is easier to visualize the cyclicity as bounded by successive coal beds. In sequence analyses, (1) sequence boundaries are generally defined at paleosols within each cycle to mark lowstand surfaces of fourth-order sequences, or (2) in a genetic analysis, the base of marine-fossil bearing dark gray to black shales above coals is used to mark marine-flooding surfaces for delineation of transgressive-regressive (TR) cycles (e.g., Weibel, 1996).

Desmoinesian and younger cyclothemic deposition has been attributed to tectonic controls (e.g., Weller, 1930), delta switching (e.g., Ferm, 1970), glacio-eustacy (e.g., Wanless and Shepard, 1936), and combinations of glacio-eustacy and tectonics (e.g., Klein and Willard, 1989). Eustatic controls are most commonly inferred (Kosanke et al., 1960; Heckel, 1977, 1986, 1994, 1995; Ross and Ross, 1985). Using a mean duration for the Late Pennsylvanian, Heckel (1986) estimated that Midcontinent cyclothems and bundles of cyclothemic sequences fell within Milankovitch orbital parameters of 44 to 393 ka. Durations of 400 ka have been inferred for Appalachian Basin cyclothem-scale units (Chesnut, 1992), which have been analyzed as fourth-order sequences (Aitken and Flint, 1994).

Coalification

Coal is formed from peat, which accumulates in mires, where large amounts of plant material can accumulate and be buried without significant transport, degradation, or dilution by sedimentation. When peat is buried it undergoes physical and chemical changes during the process of coalification. One of the results of coalification is compaction of the peat. Compaction ratios of peat to bituminous coal generally range from 20:1 to 7:1 (Stach et al., 1982), although the degree of compaction may be minimal for some coals, or at least may have happened at or near the surface, prior to deep

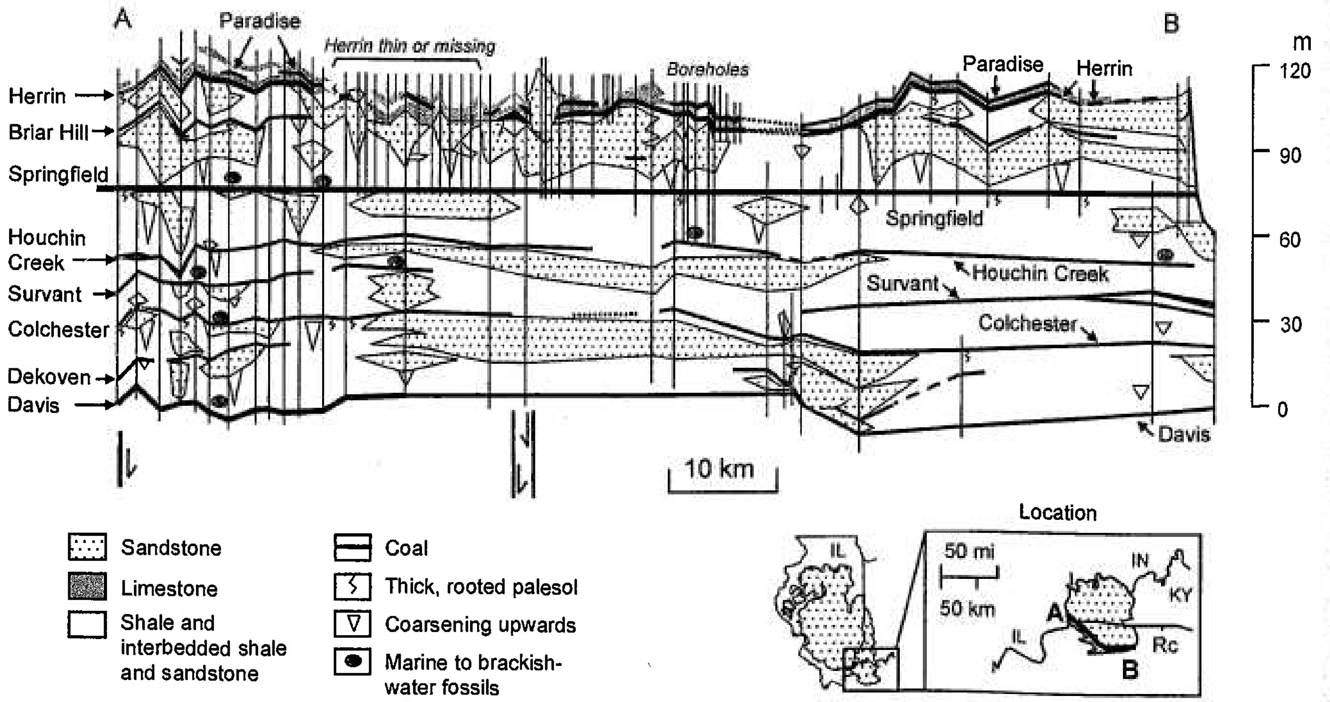

Figure 4. Detail of cross section shown in Figure 3 in southern part of the Eastern Interior Basin, showing characteristic Desmoinesian depositional cycles (cyclothems) of Carbondale Formation. Rc—Rough Creek Fault System. IL—Illinois, IN—Indiana, IA—Iowa, KY—Kentucky.

burial (Nadon, 1998). At a 10:1 compaction ratio, which is commonly used for Carboniferous coals, a 10-m-thick peat would be required to produce 1 m of bituminous coal. Likewise, not all peats become coals. Coals must have less than 50% mineral matter, and most economic deposits have less than 20% mineral matter. Different types of peats have characteristic amounts of mineral matter, water cover, and plant successions, which can be preserved and interpreted in coal beds. Understanding modern peat environments is important for interpreting analogues for coal beds.

Peat mires can be classified in many ways, but they are commonly classified based on the manner in which water enters the mire or by the nutrient content of the mire. Topogenous mires (also sometimes referred to as planar) get their water mostly from surface and ground water, soligenous mires get their water from mixed sources, and ombrogenous (also sometimes referred to as domed or raised) mires get their water from rainwater. Eutrophic mires are high-nutrient mires, mesotrophic mires have mixed nutrients, and oligotrophic mires are low-nutrient mires (Gore, 1983; Cccil et al., 1985; Moore, 1989).

Topogenous mires tend to fill depressions, while most ombrogenous mires dome upward above the groundwater table and receive all of their water from rain water. Mires may pass through a succession from topogenous (swamps, forest peats) to ombrogenous (bogs) stages (Gore, 1983; Clymo, 1987; Moore, 1989).

The broadest modern peats occur in northern-latitude mires of Siberia and Canada (Fig. 5; Walter, 1977; Gore, 1983; Clymo, 1987; Ziegler et al., 1987). The thickest pcats occur in ombrogenous mires of equatorial Indonesia (Fig. 5; Anderson, 1983; Esterle et al., 1992; Cecil et al., 1993). Mire type, latitude, and climate are important considerations when interpreting analogues for coal beds.

PURPOSE

The purpose of this report is to summarize salient attributes of three extensive Desmoinesian coal beds of the Eastern Interior Basin, to compare those attributes with modern extensive peatlands, and then to demonstrate that the coals and their correlatives represent the largest tropical peatlands in Earth history. Aspects of Desmoinesian paleoclimate, eustacy, sedimentation, topography, and tectonics are examined to better understand the controls on these ancient giant paleomires.

DESMOINESIAN COALS OF THE EASTERN INTERIOR BASIN

Herrin Area and Thickness

Recent mapping of resources in the Herrin and Springfield Coals allows for accurate determination of the area and thickness of these coals in thc basin (Hatch and Affolter, 2002). The Herrin Coal covers an area of 73,900 km^2 (Fig. 6). It is extensive across most of the basin and is the principal mined seam in Illinois. It reaches a maximum thickness of more than 4.3 m adjacent to the Walshville paleochannel (W in Fig. 6) in southern Illinois. The coal is thick in a belt 25–30 km wide on either side of the paleochannel for a distance of at least 350 km. The coal is more than 1.7 m thick across most of the present southwestern limit of the bed. The coal is at least 1.1 m thick across 32,950 km^2.

The Herrin Coal contains a 4–5-cm-thick claystone parting called the "blue band" in the lower third of the coal. Wanless (1939) noted the consistency of the parting throughout much of

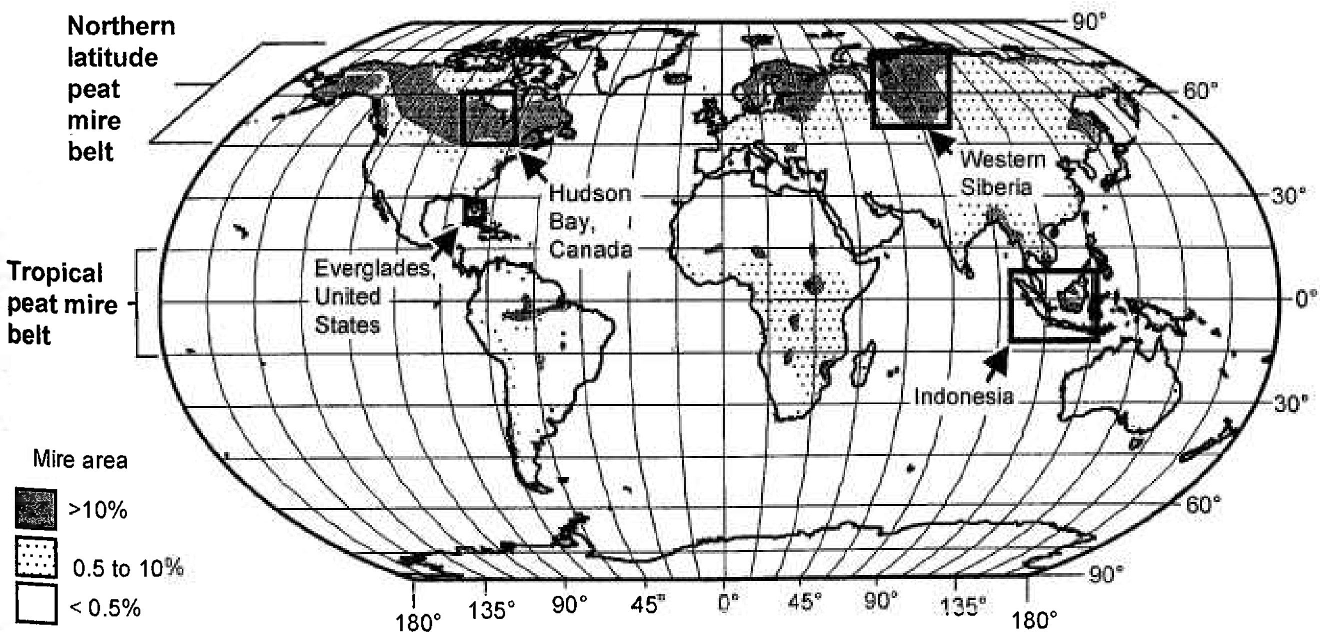

Figure 5. Peatlands of the world (modified from Gore, 1983). Specific areas outlined in diagram are shown in more detail in Figure 17.

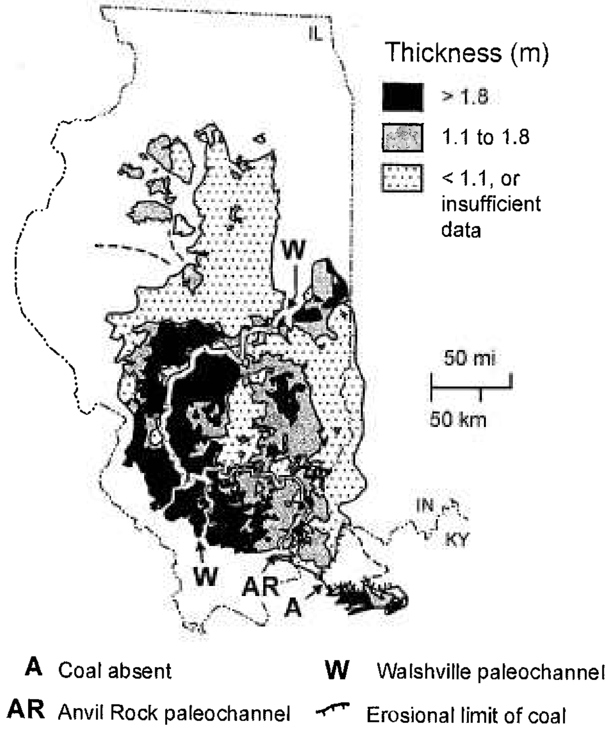

Figure 6. Isopach map of Herrin Coal (modified from Hatch and Affholter, 2002). A–Area where coal is absent in the southern part of the basin, AR—Anvil Rock paleochannel, W—Walshville paleochannel, IL—Illinois, IN—Indiana, IA—Iowa, KY—Kentucky. Dashed lines show possible trends of thicker coal beyond preserved basin margin.

the basin (Fig. 7). The parting locally thickens toward the Walshville paleochannel (W in Figs. 6 and 7) (Johnson, 1972). Several studies have also noted the consistency of smaller partings in the coal bench above the parting (e.g., Nelson, 1987).

The Herrin Coal thins to the north and northeast but thickens again on the northwest margin of the basin (Fig. 6). The coal splits and is truncated along the Walshville paleochannel (Fig. 8A; Hopkins, 1968; Gluskoter and Simon, 1968; Krausse et al., 1979; Hopkins et al., 1979; Nelson, 1983, 1987). Another elongate paleochannel, mapped as the Anvil Rock Sandstone (AR in Figs. 6 and 7), truncates the coal along an elongate belt in southern Illinois (Potter and Simon, 1961; Krausse et al. 1979; Nelson, 1983).

The Herrin Coal is overlain across much of its extent by thin black shale, the Anna Shale, and the Brereton (Providence) Limestone. The shale contains the bivalve *Dunbarella* and the inarticulate brachiopod *Orbiculoidea.* The limestone contains a more diverse marine assemblage, including brachiopods, bryozoans, crinoids, corals, and fusulinids (Utgaard, 1979). In the area of western Kentucky where the coal is absent (A in Figs. 6 and 7), the limestone thickens (Fig. 4). The coal has a sharp "ragged edge" or margin where it is missing (Fig. 8B). This ragged edge is accompanied by brecciation of the overlying limestone and, in some cases, a conglomeratic mudstone (Hower et al., 1987; deWet et al., 1997). The limestone is overlain by the Paradise Coal across much of western Kentucky, where the two coals are commonly mined together (Greb et al., 1992). South of the area of absent coal, the Herrin again thickens southward to the present outcrop margin of the basin (Figs. 6 and 7).

Springfield Area and Thickness

The Springfield Coal covers an area of 73,500 to 81,000 km^2 (Fig. 9). Uncertainty in the estimate is caused by thinning and possible nondeposition west of the Du Quoin Monocline (Dm in Fig. 9; maximum area of 7,500 km^2). The Springfield thickens eastward from the monocline and along the margins of the Galatia paleochannel (G in Fig. 9). The coal is uniformly more than 1.1 m across much of the southern basin, where it is the principal mined seam in western Kentucky. The Springfield averages more than a meter in thickness across an area of nearly 20,000 km^2. It reaches

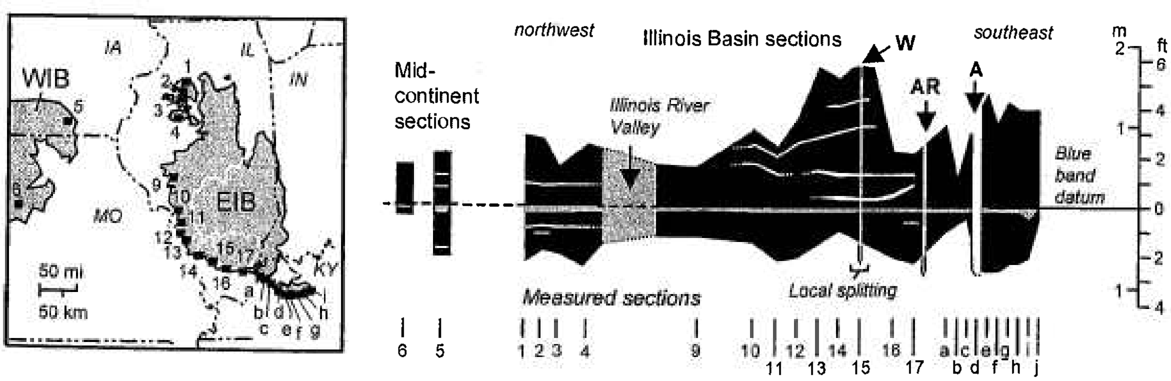

Figure 7. Cross section of Herrin Coal showing consistency of "blue band" parting across the Eastern Interior Basin (EIB) and westward into the Western Interior Basin (WIB). Numbered data from Wanless (1939), Figure 3, but adjusted to show spatial distribution and using blue band parting as datum. Data a through i are from Kentucky Geological Survey data. A—Area where coal is absent in southern part of the basin, AR—Anvil Rock paleochannel, W—Walshville paleochannel, IL—Illinois, IN—Indiana, IA—Iowa, KY—Kentucky, MO—Missouri.

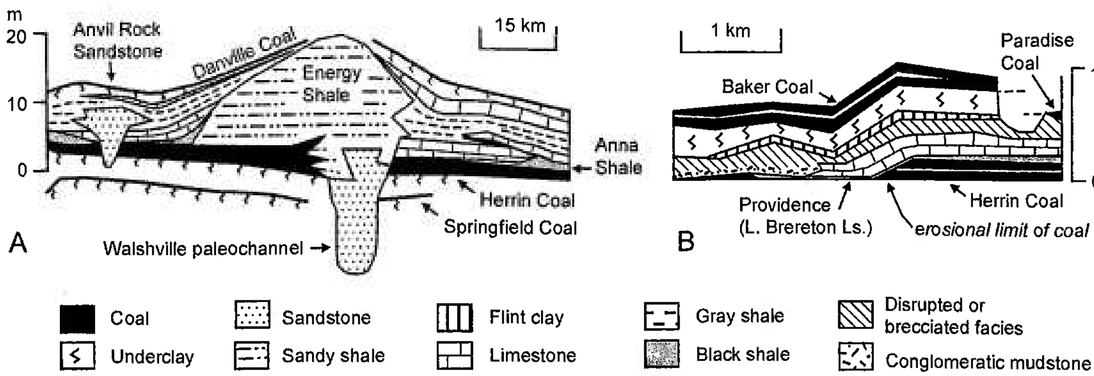

Figure 8. Interruptions in Herrin Coal continuity. A: Generalized diagram showing splitting of Herrin Coal and truncation beneath Walshville paleochannel in southern Illinois (after Nelson, 1987, Fig. 4, p. 7). B: Ragged edge of Herrin Coal in the barren area of western Kentucky (A in Fig. 6) showing truncation by carbonates and disrupted lithofacies (after deWet et al., 1997).

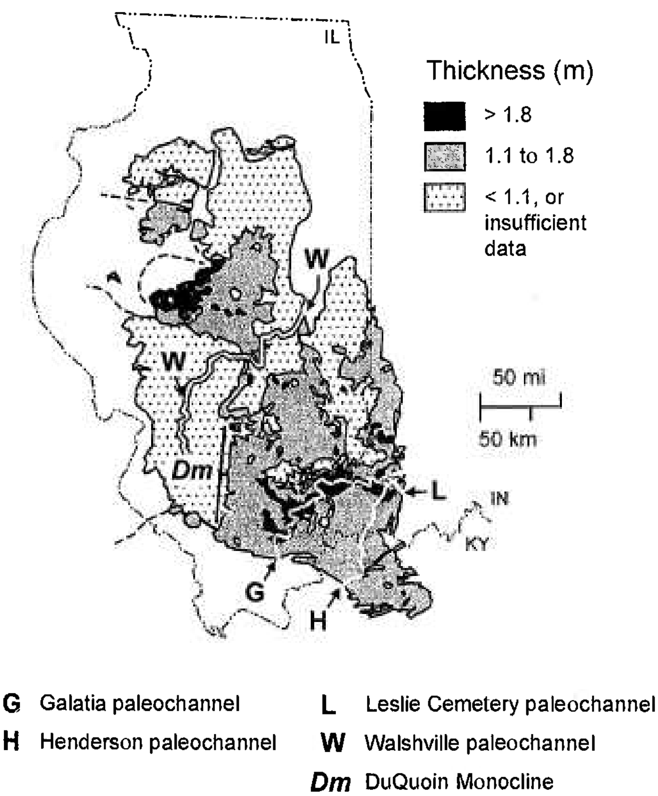

Figure 9. Isopach map of Springfield Coal (modified from Hatch and Affholter, 2002). IL—Illinois, IN—Indiana, KY—Kentucky. Dashed lines show possible trends of thicker coal beyond preserved basin margin.

a maximum thickness of more than 3 m along the Galatia paleochannel. The Springfield is thick in a belt 160 km-long along the paleochannel and is locally split and truncated along the margin of the channel (Hopkins et al., 1979; Nelson, 1983). On the eastern margin of the basin, a channel that is secondary to the Galatia paleochannel has been called the Leslie Cemetery paleochannel (L in Fig. 9). The Springfield is split along the Leslie Cemetery channel as well (Eggert, 1984, 1987). The coal is also truncated by overlying paleochannels, including the previously mentioned Walshville (W in Fig. 9) paleochannel in Illinois (Krausse et al., 1979; Nelson, 1983, 1987) and the Henderson (H in Fig. 9) paleochannel in western Kentucky (Beard and Williamson, 1979).

Colchester Area and Thickness

The Colchester Coal is generally thin (< 1 m), so it has not been the subject of regional resource analyses as were the previous two coals. It was historically mined in northern Illinois during the early 1900s because of its shallow depth. The Colchester appears to cover a slightly larger area than the Springfield Coal, perhaps more than 107,000 km^2 (Fig. 10). The coal reaches a maximum thickness of 1 m along the northern outcrop margin in Illinois (Hopkins et al., 1979). The thickness of the bed in the subsurface is uncertain because it is mostly known from geophysical well logs, although it appears to be thin across much of its extent. The Colchester is distinctive on subsurface geophysical logs because it is underlain by a thick underclay/paleosol and overlain by a carbonaceous dark gray to black shale, the Mecca Quarry Shale. The fact that the coal crops out along much of the basin's northern, western, and southern margins suggests that it is probably continuous into the deeper part of the basin, similar to the Herrin and Springfield Coals.

Coal Composition

The Herrin, Springfield, and Colchester Coals are all highly volatile bituminous coals. Each of the coals exhibits mean ash yields of 9%–12% and mean sulfur contents of 3%–5% (dry basis, Indiana Geological Survey, Illinois State Geological Survey, and Kentucky Geological Survey data). Each of the coals is dominated by vitrinite macerals (generally more than 80%), but some compositional differences are noted within and among coals. These differences are discussed in the following paragraphs.

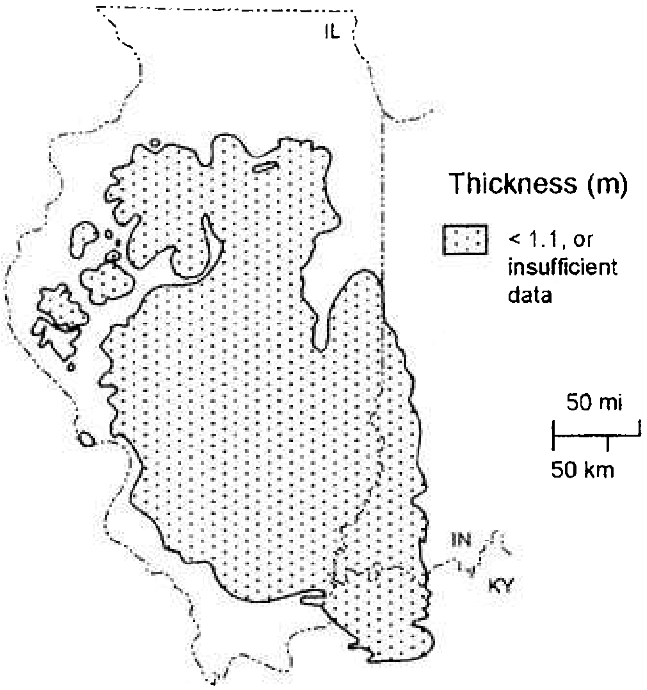

Figure 10. Isopach map of Colchester Coal (modified from Treworgy and Bargh, 1984). IL—Illinois, IN—Indiana, KY—Kentucky.

Herrin Coal

Of the three coals studied, the Herrin is probably the most uniform in composition. Austin (1979) noted that the lower bench of the Herrin, below the "blue band," was duller than the upper bench at sites in Muhlenberg County, Kentucky, but even these are still high in vitrinite content. At sites in Ohio and Hopkins County, Kentucky, Hower et al. (1987) found brecciated and oxidized coal, which was inferred to have oxidized in situ shortly after deposition of the peat. Further examples of the so-called "ragged edge" of the coal were found in western Hopkins County (de Wet et al., 1997; Schultz et al., 2002) and central Webster County, Kentucky (Hower and Williams, 2000). In western Hopkins County, lateral and vertical transitions from "normal," high-vitrinite to brecciated, inertinite-rich Herrin Coal occur along the southeastern limit of the coal (de Wet et al., 1997).

Another exception to the uniformity of Herrin composition is locally lower sulfur content (<2.5%) in the vicinity of the Walshville paleochannel (Fig. 8A; Hopkins, 1968; Gluskoter and Simon, 1968; Nelson, 1983, 1987). Low sulfur values occur beneath splay-form gray shale wedges (Energy Shale) that thicken toward the paleochannel. The Brereton Limestone, which overlies the Herrin Coal distal to the paleochannel, rises to more than 10 m above the coal where the Energy Shale is thick, resulting in low-sulfur coal beneath (Hopkins, 1968; Gluskoter and Simon, 1968; Krausse et al., 1979; Treworgy and Jacobson, 1979; Nelson, 1987). The Herrin Coal is also truncated by the Henderson paleochannel (H in Fig. 6) in western Kentucky (Beard and Williamson, 1979), but the coal retains high sulfur content adjacent to the Henderson paleochannel.

Springfield Coal

The Springfield Coal exhibits a dulling-upward trend, corresponding to an upward decrease in vitrinite content (Ault et al., 1979; Hower and Wild, 1982; Hower et al., 1990a), although even dull lithotypes have more than 65% vitrinite. Similar to the Herrin Coal, the Springfield shows a decrease in sulfur content beneath gray shale wedges (Fig. 11). These low-sulfur values occur beneath the Dykersburg Shale along the Galatia paleochannel (G in Fig. 9) and the Folsomville Shale adjacent to the Leslie Cemetery paleochannel (L in Fig. 9). The gray shale wedges formed a barrier to the downward percolation of sulfates from the marine-fossil bearing black shale and Alum Cave Limestone, which occur directly above the coal laterally (Hopkins, 1968; Treworgy and Jacobson, 1979; Eggert, 1984, 1987; Willard et al., 1995).

The Springfield also exhibits a generally higher rank and high chlorine (Cl) content in parts of southern Illinois and western Kentucky. The high Cl content is interpreted, at least in part, as a remnant of hydrothermal fluids that passed through the coal during diagenesis (Hower et al., 1990b, 1991). Similarly, enrichment of vanadium, zinc, nickel, and other trace metals near the top of the Springfield Coal in the same region may be a function of the same passage of Cl-rich, hydrothermal fluids through the coal (Zubovic, 1966; Hower et al, 1990a, 1990b, 1991; Hower and Gayer, 2002; Rowan et al., 2002). Some of the elements may have been remobilized from the overlying black shale.

Paleobotany

Palynological and coal-ball analyses indicate that all three coals contain similar arborescent lycopsids and tree ferns, although they differ in proportion (Phillips and Peppers, 1984; Phillips et al., 1985; DiMichele et al., 2002). The dominant lycopsid species is *Lepidophloios*, with lesser *Paralycopodites* (producers of *Lycospora* miospores), *Sigillaria* (producer of *Crassispora*), and *Diaphorodendron* and *Synchysidendron* (producers of *Granasporites* miospores). Tree ferns of several kinds were present, especially those producing the miospores *Thymospora*, *Laevigatosporites*, and *Punctatosporites*.

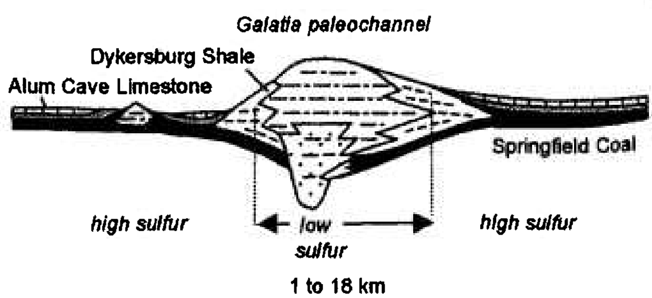

Figure 11. Generalized diagram of splits in Springfield Coal and areas of lower sulfur coal beneath gray shale wedges in Illinois and Indiana (modified from Eggert, 1987). See Figure 8 for explanation of symbols.

Most of the Desmoinesian coals of the Carbondale Formation, including the Herrin and Colchester Coals, are dominated by the lycopod tree spore *Lycospora* (Kosanke, 1950; Phillips et al., 1985; DiMichele and Phillips, 1988; Phillips and Cross, 1991). Analysis of Springfield Coal samples (Kosanke, 1950; Peppers, 1970; Mahaffy, 1988; Willard, 1993) shows that it exhibits greater palynologic diversity. Mahaffy (1988) studied bench samples of the Springfield Coal from three locations in Illinois and Indiana and established four miospore phases based on vertical abundance trends. Palynological studies of the Springfield Coal (Willard, 1993) from 10 locations in Illinois, Indiana, and Kentucky found most locations to be dominated by tree fern spores (47–69%) with subdominant lycopsid tree miospores (18–44%). Profiles collected in proximity to the Leslie Cemetery and Galatia paleochannels exhibited a greater diversity in miospore abundance among tree fern species and generally higher amounts of *Lycospora*. For example, profiles collected near the Leslie Cemetery paleochannel contained 54–62% lycopsid tree spores and 28–32% tree fern spores. Coal-ball studies indicate that the Springfield Coal near paleochannels exhibits larger ash values and is enriched in lycopsids rarely encountered in other late Westphalian coals of the basin, including *Lepidodendron hickii*, *L. mannabachense*, and *Sublepidophloios* (DiMichele and Nelson, 1989; Willard et al., 1995; Phillips and DiMichele, 1998). In contrast, *Thymospora* and *Anacanthotriletes spinosus*, additional types of lycopod spores, were found to be more abundant at localities distal to the paleochannels. In addition, *Granasporites medius, Crassispora kosankei*, and *Anacanthotriletes spinosus* were all found to be more abundant at northern locations (Willard, 1993).

Correlative Desmoinesian Coal Beds

Correlations and paleogeography of the Herrin, Springfield, and Colchester Coals across the Eastern and Western Interior Basins are discussed to demonstrate their possible extent. Figure 12 shows the correlation of the Colchester, Springfield, and Herrin Coals, as well as significant intervening units, with equivalents in surrounding basins. Coal correlations are based on palynology (Peppers, 1996; Eble, 2002). These correlations have been collaborated by correlations of conodonts in overlying marine black shales (Heckel, 1986, 1999). Many of the correlations have not changed significantly since interbasinal correlations were first attempted by Wanless and Weller (1932). Correlations between the Eastern and Western Interior Basins may indicate temporally equivalent units or slightly time-transgressive facies. Temporal equivalence versus lateral time-transgressive facies is more difficult to demonstrate between the Eastern Interior and Northern Appalachian Basins (discussed later).

Possible limits to the extent of individual facies include regional tectonic structures (Fig. 13). During the Desmoinesian,

Series	Stage	Eastern Interior Basin (Peppers, 1996)	Western Interior Basin (Wanless and Wright, 1978; Peppers, 1996; Ravn et al., 1984)			Northern Appalachian Basin	
			Oklahoma	Missouri and Kansas	Iowa	Peppers (1996)	Eble (2002)
Middle Pennsylvanian (part)	Desmoinesian (part)	Brereton/Providence Ls	Upper Oologah Ls	Myrick Station Ls	Myrick Station Ls		
		Anna Sh	Anna Sh.	Anna Sh	Anna Sh		
		Herrin c.	**Lexington c.**	**Lexington c.**	**Mystic c.**	Upper Kittanning c.	**Lower Freeport c.**
		Briar Hill c.	——	——	——	——	Upper Kittanning c.
		St. David/Alum Cave Ls	Higginsville Ls	Higginsville/Houx Ls.	Houx Ls		
		Unnamed black shale	Little Osage Sh	Little Osage Sh	Little Osage Sh		
		Springfield c.	——	**Summit c.**	**Summit c.**	**Middle Kittanning c.**	**Middle Kittanning c.**
		Hannover Ls	Blackjack Creek Ls	Blackjack Creek Ls	Blackjack Creek Ls		
		Excello Sh.	Excello Sh	Excello Sh	Excello Sh		
		Houchin Creek c.	Mulky c.	Mulky c.	Mulky c.	——	——
		——	Breezy Hill Ls ?	Breezy Hill Ls	Breezy Hill Ls		
		Survant c.	Bevier? c.	Bevier c.	Bevier c.	——	——
		Oak Grove Ls	Verdigris Ls	Verdigris/Ardmore Ls	Ardmore Ls		
		Mecca Quarry Sh.	Oakley Sh.	Oakley Sh	Oakley Sh.		
		Colchester c.	**Croweburg c.**	**Croweburg c.**	**Whitebreast c.**	**Lower Kittanning c.**	**Lower Kittanning c.**

Figure 12. Correlation of coals (bold) and other significant rock units between Eastern Interior, Western Interior, and northern Appalachian Basins (based on data from Donaldson and Eble, 1991; Peppers, 1996; Eble, 2002). Ls—limestone, Sh—shale.

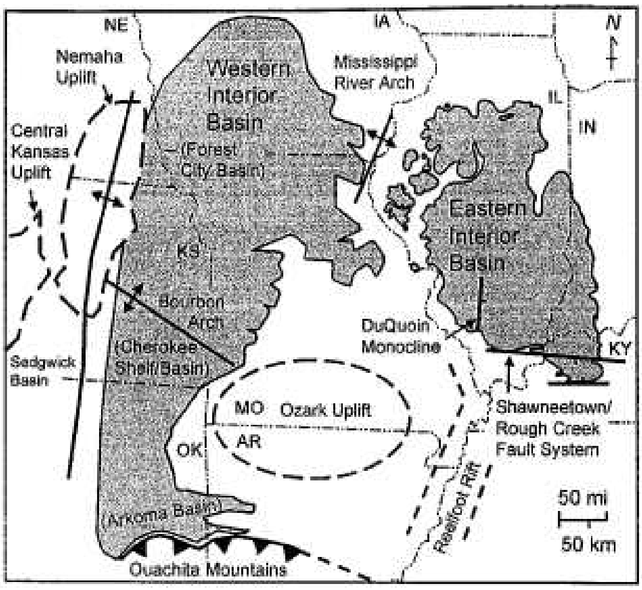

Figure 13. Structural features of U.S. Midcontinent. AR—Arkansas, IL—Illinois, IN—Indiana, IA—Iowa, KY—Kentucky, KS—Kansas, MO—Missouri, NE—Nebraska, OK—Oklahoma.

the Ouachita Mountains were uplifting along the southern margin of the craton. The Arkoma Basin was a foreland basin north of the Ouachitas (Rascoe and Adler, 1983; Houseknecht, 1986; Johnson et al., 1988; Thomas, 1989). The Ozark, Nemaha, and Central Kansas Uplifts (Fig. 13) are all inferred to have been positive, low-relief features (Wanless and Wright, 1978; Bunker et al., 1988; Johnson et al., 1988).

Herrin Correlation

The Herrin Coal is equivalent to the Lexington coal in Kansas, Missouri, and Oklahoma; and the Mystic coal in Iowa (Figs. 12 and 14A; Wanless and Weller, 1932; Wanless et al., 1969; Heckel, 1986, 1995; Peppers, 1996). These coals were the first to be correlated between basins on the basis of spores (Schopf, 1938). The Lexington contains a claystone "blue band" parting in the lower part, and it underlies the Anna Shale, the black and fissile marine shale that is named for a village in Kansas and traced eastward through the Eastern Interior Basin above the Herrin Coal. The Lexington coal is one of Missouri's most important coal resources, but it thins and becomes discontinuous westward (Robertson, 1971) into Oklahoma and Kansas (Friedman, 1977, Fig. 14A). The Lexington and Mystic coals cover a combined area of approximately 30,000 km^2. The combined area of these coals and the Herrin Coal is 73,900 km^2. Correlative coals do not occur west of the Nemaha Uplift, where marine and marginal marine facies dominate (Wanless and Wright, 1978, Fig. 14A).

The black, phosphatic, carbonaceous Anna Shale overlies the Herrin, Lexington, and Mystic coals from Illinois to Kansas (Wanless and Weller, 1932; Wanless et al., 1969), and southward into Oklahoma (Heckel, 1999). The shale is interpreted as a condensed section (Heckel, 1986, 1994, 1999). It is overlain by the Brereton (Providence) Limestone in the Eastern Interior Basin (Fig. 12) and the Myrick Station Limestone in the Midcontinent (Fig. 14B; Wanless and Wright, 1978; Thompson, 1995). Southward, the Myrick Station Limestone may pinch out into deeper-water, black shale facies, or it may be replaced by the overlying Labardie Limestone. The Myrick Station and Labardie Limestone are equivalent to the Oologah Limestone in Oklahoma (Heckel, 1999). The continuity of marine facies across the region indicates connection between basins during deposition of marine facies. If there was connection between basins during deposition of marine facies, it seems possible that there was also connection during initial base level rise when peat was accumulating. If peat accumulation was continuous between basins (dashed lines in Fig. 14A), the total area of Herrin-equivalent peatlands may have exceeded 116,000 km^2.

Marine connection appears likely to have occurred northward across the Mississippi River Arch, and possibly from the south and east of the Ozark Uplift. Paleocurrents from inferred fluvial paleochannels throughout the Carboniferous of the Eastern Interior Basin show southwesterly flow toward the present-day Mississippi River Embayment (Fig. 14A; Siever, 1957; Potter and Simon, 1961; Sedimentation Seminar, 1978; Greb, 1989). The embayment occurs above a Precambrian rift called the Reelfoot Rift (Soderberg and Keller, 1981; Hildenbrand et al., 1982). Subsidence above the rift during the Pennsylvanian caused lowstand valleys to trend along the valley before ultimately depositing their sediments in the Arkoma Basin (Sedimentation Seminar, 1978; Greb, 1989; Thomas, 1989; Donaldson and Eble, 1991). The Herrin Coal is thickest in a belt along the Walshville paleovalley, which drained southward into the embayment area. The Herrin is still thick at the present outcrop margin of the coal, and it is possible that this trend continued southward into the embayment (dashed lines in Fig. 6). During transgression, it is likely that these valleys would have been converted to estuaries and transgression would have moved up-dip into the Eastern Interior Basin. Also, tidal facies have been noted in gray-shale wedges that followed peat accumulation and preceded Anna Shale deposition in parts of the Galatia paleochannel (Archer and Kvale, 1993). It seems likely that rising base level in the floodplains of these valleys would have led to additional peat accumulations that were not preserved because they accumulated outside of the basin.

Eastward from the Eastern Interior Basin, Peppers (1996) correlated the Herrin Coal to the Upper Kittanning coal in the Northern Appalachian Basin (Fig. 12). Locally in Ohio, the Upper Kittanning may contain a parting in the lower part, similar to the parting in the Herrin Coal (J. Nelson, 2002, personal commun.). It has also been suggested that the Herrin Coal may correlate with the Lower Freeport coal (Fig. 12), just above the Upper Kittanning coal (Eble, 2002).

Springfield Correlation

The Summit coal of the Western Interior Basin in Missouri and eastern Kansas is the probable equivalent of the Springfield Coal (Figs. 12 and 15A; Heckel, 1994; Peppers, 1996). The

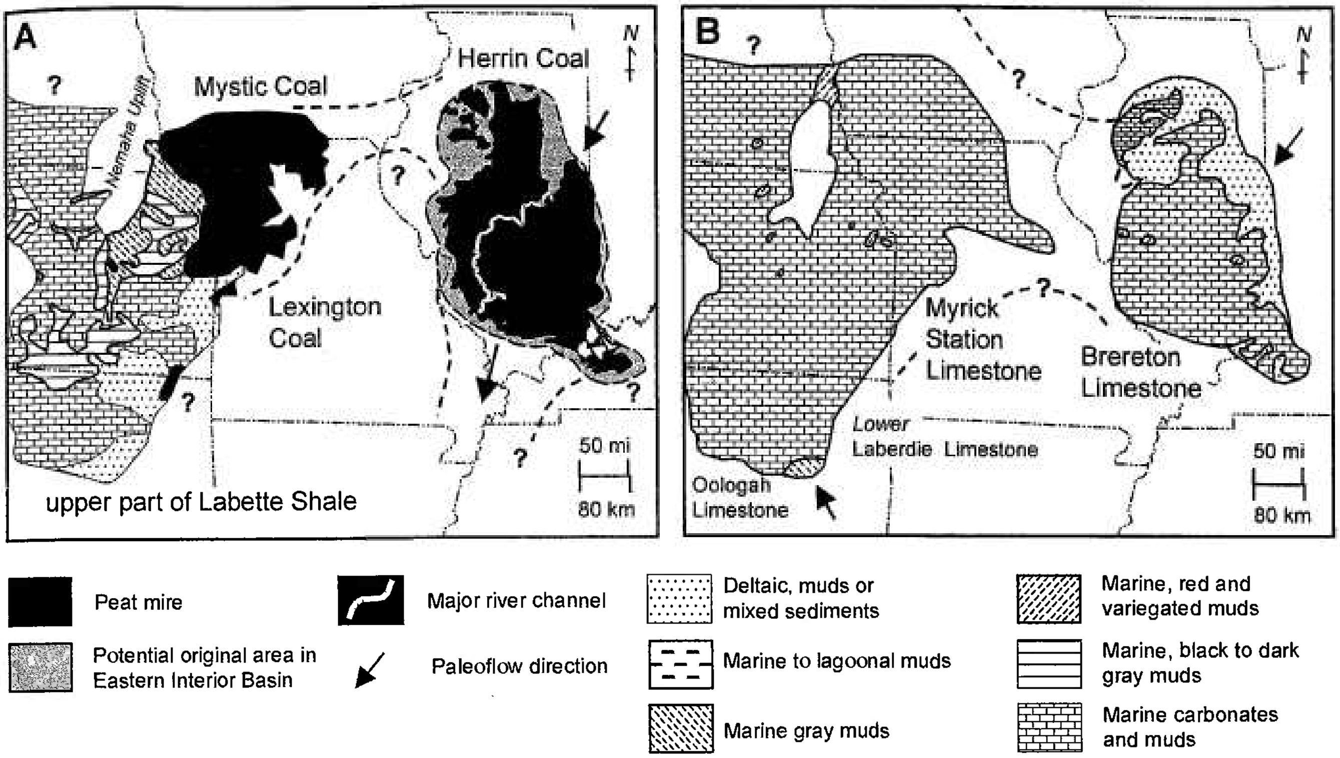

Figure 14. Generalized paleogeographic maps of key Desmoinesian beds across U.S. Midcontinent. A: Herrin Coal and its correlatives. Dashed lines show trend of possible original connections of coal/peat between preserved basins (modified from Wanless and Wright, 1978, Fig. 48, with outcrops from Robertson, 1971; Hatch and Affholter, 2002). B: Brereton Limestone and its correlatives. Dashed lines show possible limit of limestone between preserved basins (modified from Wanless and Wright, 1978, Fig. 51, with correlations from Heckel, 1994, 1999).

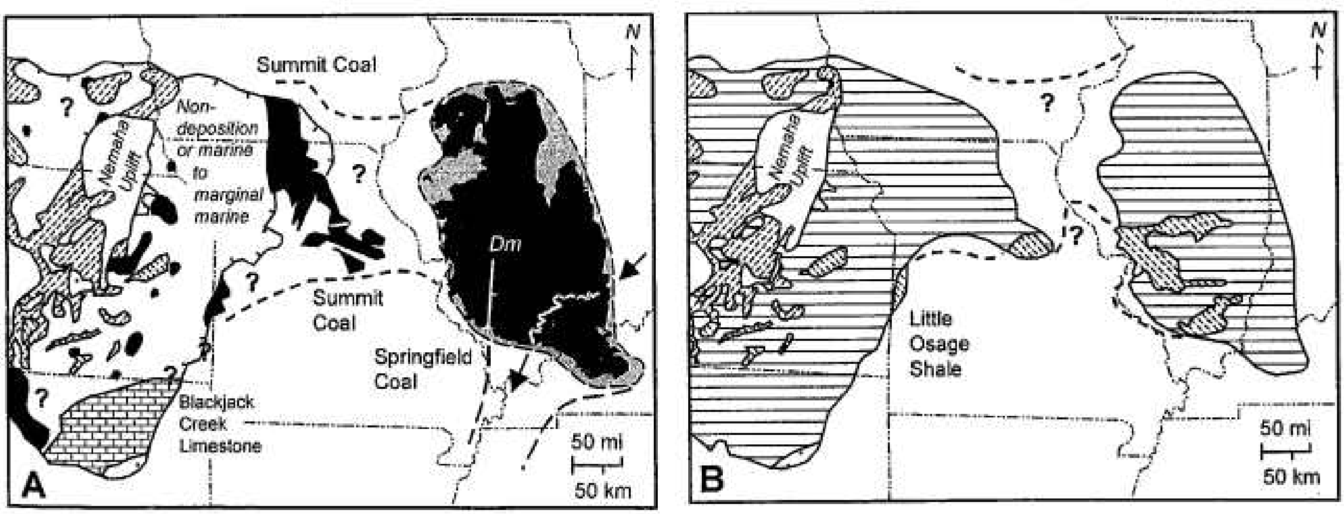

Figure 15. Generalized paleogeographic maps of key Desmoinesian beds across U.S. Midcontinent. A: Springfield Coal and its correlatives. Dashed lines show trend of possible original connections of coal/peat between preserved basins (modified from Wanless and Wright, 1978, Fig. 34, with outcrops from Robertson, 1971; Hatch and Affholter, 2002). B: Little Osage Shale and its correlatives. Dashed lines show possible path of connection between preserved basins (modified from Wanless and Wright, 1978, Fig. 35).

correlation is based on palynology (Peppers, 1996) and regional tracing of key beds that bracket the Summit coal, including the black, phosphatic Excello Shale and the Little Osage Shale above (Heckel, 1986, 1994). The Little Osage Shale in the western interior is correlated with the unnamed black shale above the Springfield (Fig. 15B; Wanless and Wright, 1978). The Little Osage Shale represents transgression of the Desmoinesian seas north and westward, again indicating connection between the Eastern and Western Interior Basins during transgression.

In Missouri, the Summit is best developed in the east-central part of the state and thins into a 1–2-cm-thick "smut zone" or rash above its underclay across much of the rest of the state (Robertson, 1971). The Summit is generally not a significant economic resource, and it is missing across large parts of the Western Interior Basin where nondeposition has been inferred (Wanless and Wright, 1978). Some of the area of inferred nondeposition includes area in which rashy layers above the underclay may indicate wetland, although non-peat-forming, environments. It is also possible that marine shales above the paleosol were partly coeval with lateral peat accumulations. In Oklahoma, Heckel (1999) inferred that the sequence from the Blackjack Creek Limestone to the overlying Little Osage Shale is entirely marine.

Regional estimates of areas for these correlative coals are more uncertain than for the Springfield Coal, but they appear to cover an area of 18,000 km^2. Hence, the combined peatland complex covered an area of 91,500–99,000 km^2. If the basins were connected, the Springfield-Summit paleomires may have covered an area of 121,500 km^2. Correlative coals do not occur west of the Nemaha Uplift, where marine and marginal marine facies dominate (Fig. 15A).

Eastward in the Appalachian Basin, Peppers (1996) correlated the Springfield Coal (Harrisburg, No. V) to the Middle Kittanning coal of Ohio and Pennsylvania and the Princess (No. 7) coal bed of eastern Kentucky based on spores (Fig. 12). This correlation is supported by preliminary correlation of ammonoid fauna between the Washingtonville shale above the Middle Kittanning coal and the Little Osage Shale above the Summit coal in the Midcontinent (D.M. Work, 2002, personal commun.).

Colchester Correlation

Wanless and Weller (1932) noted that the Croweburg coal of Kansas, Missouri, and Oklahoma occupies a similar stratigraphic position and shared a geophysical signature similar to that of the Colchester (No. 2) Coal in the Eastern Interior Basin (Fig. 12). Wanless (1975a) inferred that the Colchester-Croweburg coal may have formed a peat mire 960 km across as part of the Liverpool cyclothem (Fig. 16A; Wanless and Wright, 1978). The Croweburg extends across large areas of northern and western Missouri (Robertson, 1971), southeastern Kansas, and northeastern Oklahoma. Reserves in Oklahoma include coal containing less than 1% sulfur and ranging from 0.3 to 1.1 m thick (Friedman, 1977). The Croweburg occurs within the cyclothem containing the Verdigris Limestone, which can be correlated northward with lithologies above the Whitebreast coal (Heckel, 1986, 1995, 1999). Ravn (1986) correlated the upper Atokan (Westphalian C, Bolsovian)–Desmoinesian (Wesphalian D) boundary with the Whitebreast coal of Iowa, and thereby its equivalents, the Croweburg and Colchester. These coals all occur within the *Shopfites colchesternsis-Thymospora pseudothiessenii* (CP) spore assemblage zone (Peppers, 1996), in which one of the spores is named after the Colchester Coal. The Whitebreast and Croweburg coals may have covered an area of 105,000 km^2 (Fig. 16A). If continuous with the Colchester, as inferred by Wanless and Wright (1978), the total original peatland area exceeded 200,000 km^2 (Fig. 16A). Correlative coals do not occur west of the Nemaha Uplift, where marine and marginal marine facies dominate (Fig. 16A).

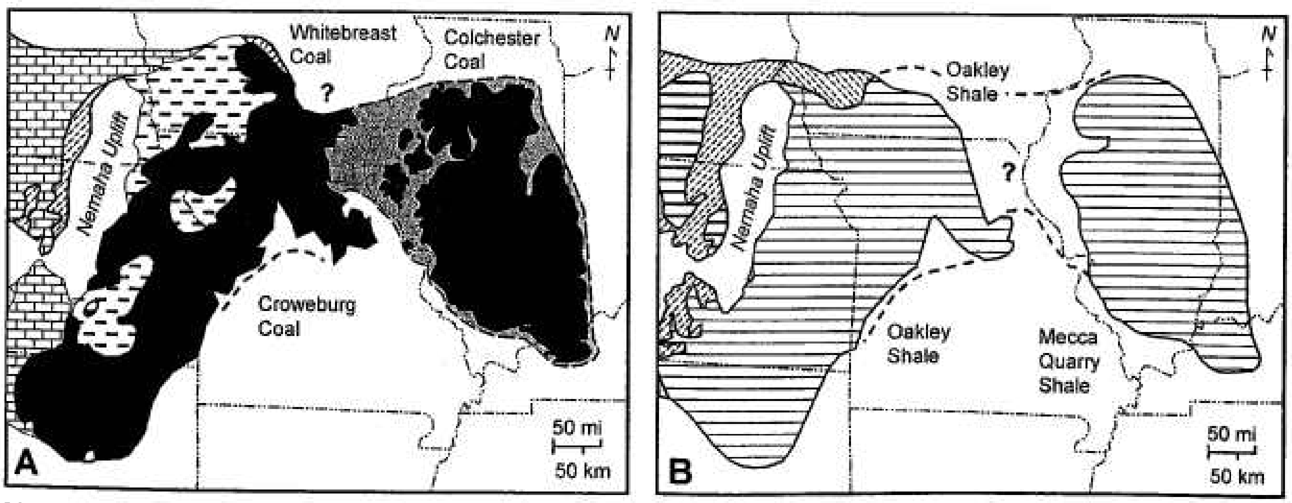

Figure 16. Generalized paleogeographic maps of key Desmoinesian beds across U.S. Midcontinent. A: Colchester Coal and its correlatives. Shaded area shows trend of likely original connections of coal/peat between preserved basins (modified from Wanless and Wright, 1978, Fig. 9, with outcrops from Robertson, 1971; Treworgy and Bargh, 1984). B: Mecca Quarry Shale and its correlatives. Dashed lines show possible path of connection between preserved basins (modified from Wanless and Wright, 1978, Fig. 11).

Each of the coals is overlain by a thick, brackish-water to marine unit: the Mecca Quarry and equivalent black shales in the Eastern Interior Basin, and the Oakley Shale (Raven et al, 1984) and Ardmore Limestone of the Verdigris cyclothem in the Western Interior Basin (Fig. 16B; Wright, 1975; Wanless and Wright, 1978; Heckel, 1986, 1999). Correlations of these marine to marginal-marine units were confirmed by conodont studies (see references in Heckel, 1986, 1999). In northern Illinois, the Colchester Coal is locally overlain by the Francis Creek Shale, which contains the famous Mazon Creek fossils, a mixed terrestrial, marginal marine, and marine fauna (Nitecki, 1979; Baird et al., 1985). Much of the Mazon Creek biota was buried in tidal environments, with evidence for increasing marine conditions to the west and southwest (Kuecher et al., 1990).

Eastward in the Appalachian Basin, the Colchester was first correlated with the Lower Kittanning coal by Wanless (1939). Subsequent spore analysis confirms that correlation in Ohio and Pennsylvania, as well as with the Princess No. 6 coal in eastern Kentucky and the No. 6 Block coal in West Virginia (Fig. 12; Peppers, 1996). Each of these coals is underlain by a thick paleosol across part of its extent. In fact, the paleosols may be more extensive than the coal beds. Spodosols, Ultisols, and gleyed Vertisols are interpreted for the claystone beneath the Lower Kittanning coal in the Northern Appalachian Basin (Cecil and Dulong, 2003). The paleosol beneath the Colchester Coal shares characteristics with gleyed Vertisols. The paleosol beneath the Croweburg coal of the Western Interior Basin is a moderately gleyed Vertisol. Mid-Desmoinesian Aridosols were also noted in several western basins, which may be equivalent to the paleosols beneath the Croweburg-Colchester coal but are not overlain by coal (Cecil et al., 2003).

INTERPRETATION

Types of Paleomires

For the purpose of interpreting modern analogues of comparable scale to the Desmoinesian coals studied, interpretations of the types of paleomires are required. Additionally, care is needed in interpreting Desmoinesian paleomires because of the strong diagenetic overprint, which resulted in locally high rank, chlorine, and trace metals in some areas (e.g., Hower et al., 1990b) and low-sulfur values beneath gray shale wedges in others (e.g., Gluskoter and Simon, 1968).

Comparison of available palynologic and coal-ball studies suggests that the Desmoinesian coals of the Eastern Interior Basin accumulated in three principal plant assemblages (DiMichele and Phillips, 1988, 1996). The first assemblage is very common and is enriched in species of the lycopsid tree *Lepidophloios*, particularly *L. hallii*. This assemblage exhibits low species richness, with few ground cover plants and vines or tree ferns. These features are consistent with an interpretation of a flooded peat surface. In addition, the vegetative and reproductive attributes of arborescent lycopods are distinctive and suggestive of semi-aquatic life-habitats, particularly the aerenchymatos (air-chambered) tissues in the roots and dispersal units that appear to be adapted to flotation and dispersal in water (Phillips et al., 1977; DiMichele and Phillips, 1985, 1988, 1994).

A second common assemblage is also rich in lycopsids, especially *Diaphorodendron scleroticum* and *Synchysidendron resinosum*, but contains abundant tree ferns of the genus *Psaronius*, many species of which produced a variety of miospore types; variable amounts of medullosan pteridosperms; and many kinds of small, ground-cover ferns and vines associated with limited amounts of clastic matter and fusain. *Diaphorodendron* has been interpreted as occupying saturated peat substrates that were occasionally covered with water (DiMichele and Phillips, 1994). Likewise, ferns require some period of substrate exposure to complete their life cycles (DiMichele and Phillips, 1994).

A third type of assemblage, rich in medullosans and the small lycopsid tree *Paralycopodites brevifolius*, is only locally abundant in habitats rich in clastics and, in some cases, fusain. Such environments were likely in ecotonal (not conducive to diverse flora) areas, intermediate between peat and clastic substrates. Other types of rare, but distinctive, assemblages also have been encountered. These include assemblages dominated almost entirely by the small shrubby or scrambling plant *Sphenophyllum*, or mixed assemblages of *Sphenophyllum* and the small lycopsid *Chaloneria*. Such assemblages have been interpreted as characteristic of disturbed or marsh-like vegetation (DiMichele et al., 1979). Each of these assemblages suggests topogenous to possibly soligenous mires.

Tree ferns in the late Middle Pennsylvanian were largely small, opportunistic weedy forms, contrasting with the large trees of the Late Pennsylvanian (Lesnikowska, 1989). These plants had little woody tissue and would not have been unexpected in low-nutrient habitats with exposed peat surfaces. Although the basic species pool of the Springfield Coal is similar to that of the Herrin, Baker, and Danville coals (DiMichele et al., 1996), tree-fern enrichment, in some areas associated with *Sigillaria* (a lycopsid associated with highly decayed, possibly exposed peats) (Willard, 1993), is a distinctive attribute of the Springfield paleomires.

In the area of the Galatia (G in Fig. 9A) and Leslie Cemetery (L in Fig. 9A) channels, lycopsid spores are more prominent than in other parts of the Springfield Coal (Willard, 1993). A number of these trees have been associated with either standing water or periodically inundated habitats, areas likely to have been associated with topogenous peat deposits. In areas of split coal, especially where clastic enrichment in the coal is significant, coal-ball (Phillips and DiMichele, 1998) and palynological (Willard et al., 1995) studies reveal dominance by medullosan pteridosperms and the small lycopsid tree *Paralycopodites brevifolius*. This same combination of dominant taxa has been identified in the Herrin Coal (DiMichele and Phillips, 1988) and Secor coal of Oklahoma (DiMichele et al., 1991) and in the Hamlin coal of eastern Kentucky (Phillips et al., 1985) in association with mineral matter and fusain. Such assemblages may have preferred organic mucks and other environments transitional between peats and oxygenated clastic environments. Vitrinite dominance in each of the Desmoinesian coals also suggests topogenous to soligenous mires as vitrinite preservation is enhanced in aqueous conditions (Teichmüller, 1989). Relatively high ash contents in each of the coals suggest that mineral matter periodically flooded the mires, which is also suggestive of topogenous mires.

Mahaffy (1988) noted the greater diversity of palynomorphs in the Springfield compared to the younger, *Lycospora*-dominant Herrin Coal. It was suggested that this may have been the result of the Springfield paleomire having more area with exposed substrates (if even temporary), which potentially could support a more diverse flora, versus those with mostly standing water cover that would be dominated by lycopsid trees. The Colchester paleomire shows similar high diversity and presumably had large areas of at least temporarily (possibly seasonally) exposed substrates (Eble et al., 2001).

Likewise, the Springfield shows some distinct spatial patterns in average plant compositional variation, based both on coal-ball and palynological data (Mahaffy, 1988; Willard, 1993; Willard et al., 1995). Palynological analyses suggest that areas near contemporaneous paleochannels differed from areas distal to paleochannels. Tree fern composition of the two areas differed, and in the channel areas, the proportion of lycopsid trees was elevated. These differences represent the influence of contemporaneous flooding and standing water near channels and are common in topogenous to soligenous mires. These are also the areas of thickest peat accumulations (Figs. 6 and 9).

DISCUSSION

Extent of Desmoinesian Midcontinent Mires

In some thick coal deposits, the coal represents a succession of different peat stages and in some cases entirely different mires, each succeeding the previous to form a thick peat, and thereby coal. Stacked mires produce vertical successions of changing petrography and palynology within coals. These successions are often bound by regionally extensive partings or high-ash layers (Shearer et al., 1994; Greb et al., 1999, 2002). No extensive partings or durains have been noted within the Colchester Coal, such that the coal at any of the locations sampled may represent the accumulation of a single, temporally extensive mire rather than stacked mires through time. Likewise, the Springfield Coal does not contain a persistent parting or durain layer, although it is more variable in composition, especially near contemporaneous paleochannels (DiMichele and Nelson, 1989; Willard, 1993; Willard et al., 1995; Phillips and DiMichele, 1998).

The Herrin Coal consists of two benches, but the benches are extremely uniform in petrographic, palynologic, and paleobotanical composition so that at least the upper bench could represent a single paleomire developed above the "blue band" detrital incursion. The extent and uniformity of the parting (Fig. 7) indicates that it was deposited in water above a relatively flat surface. This flat surface was formed when the underlying lower bench peat filled in the pre-Herrin peat paleotopography. Relative uniformity in the composition of the upper bench of the Herrin suggests an extensive, interconnected topogenous mire rather than individual mires separated by local paleotopography and wide drainages. Likewise, the persistence of several thin partings in the upper bench across much of the western margin of Illinois indicates that the upper bench may have been a persistent coeval peat on either side of the Walshville paleochannel. The paleochannel divides the coal area roughly in half, such that two peat mires, each possibly in excess of 35,000 km^2, could have constituted the upper Herrin paleomire.

There was undoubtedly some lateral translation of the mires as the Desmoinesian seas transgressed, but the persistence of partings in the Herrin Coal suggests that the bed was not wholly time transgressive. If the Herrin paleomire was a narrow coastal deposit that shifted laterally with transgression, partings in the coal would occur at different positions in the seam concurrent with that transgression. The extent of the blue band and overlying partings indicates that whatever paleotopographic variation existed in the pre-peat surface was infilled during the blue band clastic incursion. Post blue-band peat accumulation was broadly blanketform. Additionally, a similar parting in the coeval Mystic coal of the Western Interior Basin suggests exceptionally widespread, coeval peat accumulation in at least the northern part of the Western Interior Basin.

If the Herrin and Mystic coals represent an extensive, coeval mire complex, it is possible that the other widespread Desmoinesian coals of the Eastern Interior Basin also may have comprised one. Moreover, all three coals were extensive beyond the limits of the present basin. Wanless and Wright (1978) inferred continuity across the Mississippi River Arch between the Colchester and equivalent coals in the Western Interior Basin. The Springfield Coal was not drawn as continuous, but outliers in western Illinois are still more than 1-m thick, and so it must have extended beyond the present limit of the basin (Figs. 9 and 15A). Likewise, the Herrin is very thick along almost the entire southwestern margin of the basin (Figs. 6, 7, and 14A) and obviously was greater in extent than is presently preserved. Even where the coal is missing is western Kentucky (B in Fig. 14A), brecciation and conglomerates in overlying strata (Fig. 8B) indicate that the Herrin Coal may have been removed by post-peat erosion, rather than absence due to nondeposition (Hower et al., 1987; deWet et al., 1997).

The extent of these coals shows that the paleomire complexes that formed them may have covered areas of more than 70,000 km^2 in the Eastern Interior Basin alone. The Colchester and equivalent paleomires may have covered an area of more than 200,000 km^2 across the Midcontinent. The Springfield and Herrin Coals can be demonstrated to have covered slightly smaller areas, but they may have covered total areas much greater than are presently preserved. The Desmoinesian paleomires may have continued southward for an unknown extent above the Reelfoot Rift (Figs. 14A and 15A). The rift area was probably a broad lowland connecting the Illinois Basin southward to the Ouachita foreland.

Comparison to Modern Vast Peatlands

In the modern world, the most widespread peatlands occur in northern, cold-temperate to subpolar latitudes (Fig. 5), and are dominated by *Sphagnum* moss, but they also contain sedges, heath, and pines (e.g., Gore, 1983). Peatlands composed of topogenous to ombrogenous peats cover more than 1.29 million km^2 in northern Canada (Zoltai and Pollctt, 1983) and 1.39 million km^2 in West Siberia (Yefremov and Yefremova, 2001).

In terms of individual peatlands, Ziegler et al., (1987) reported a 300,000 km^2 area of peat on the southwest margin of Hudson Bay, Canada (Fig. 17A), as the largcst continuous area

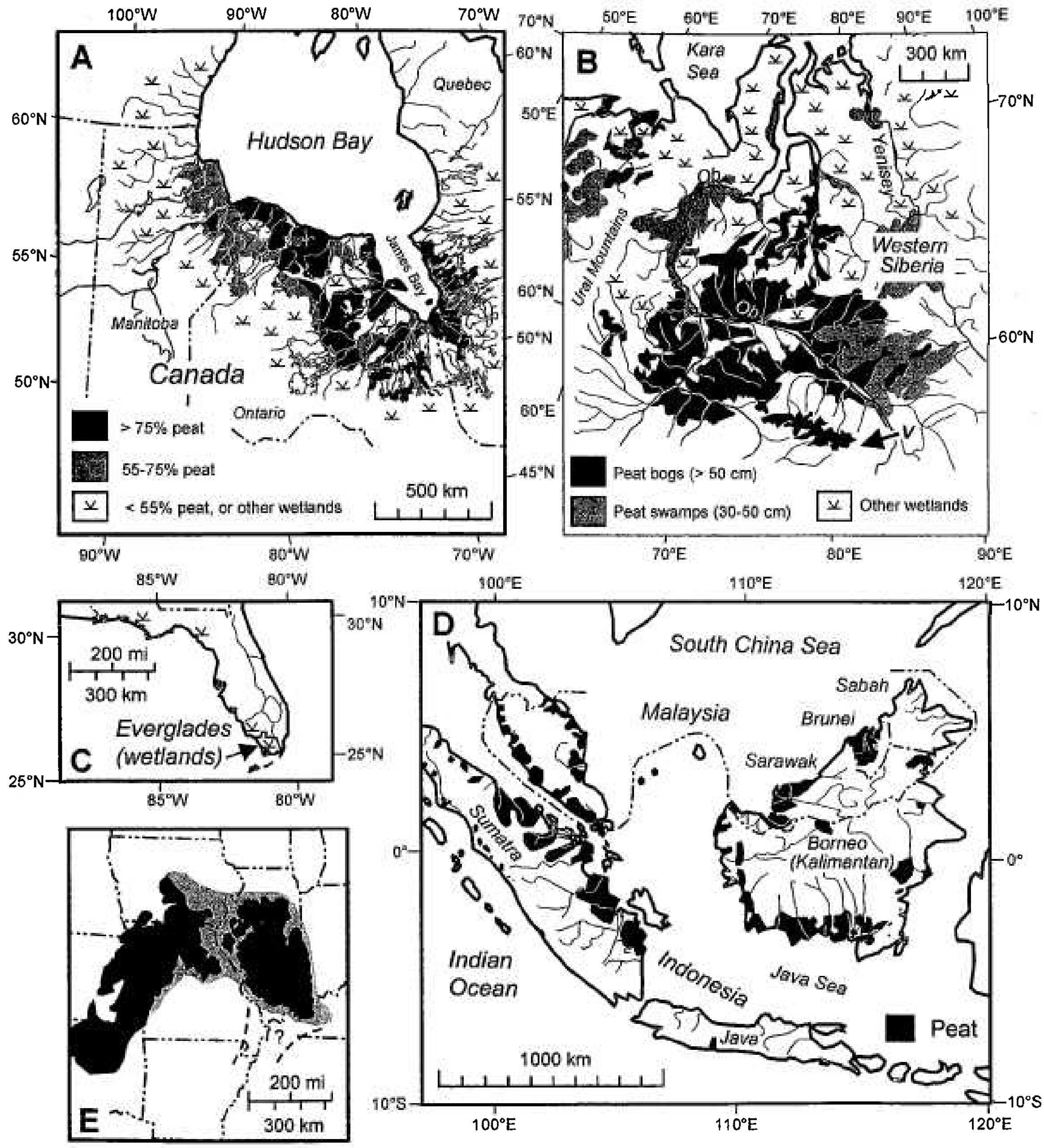

Figure 17. Comparison of scales of modern peatlands (see Fig. 5 for locations) with Desmoinesian peatlands. A: Hudson Bay Lowlands, Canada. Not all of black area is one continuous peat body (modified from Tarnocai et al., 2000, 2002). B: West Siberian peatlands (after Stolbovoi and McCallum, 2002). V—Vasyugan bog complex. C: Everglades area. Very little of this area is actually peatland; most is non–peat-accumulating wetland. D: Indonesian peatlands (after Anderson, 1983, Fig. 6.1). E: Desmoinesian peatlands of U.S. Midcontinent. All to same approximate scale.

of peat accumulation in the world. The Hudson Bay Lowland consists of a complex of coastal marshes, swamps, vast fens, and raised bogs (Martini and Glooschenko, 1985; Martini, 1989; Tarnocai et al., 2000, 2002). Walter (1977) inferred that a 1.4 million km^2 area of western Siberia, including raised peat bogs, hollows, and thousands of lakes, was joined into a single hydrological system during seasonal flooding of the Ob River (Fig. 17B). One of the bogs along this drainage is the Vasyugan bog complex (V in Fig. 17B). It covers 51,000 km^2 and may be the largest individual, undrained peat bog in the world (Botch and Massing, 1983; Bleuten et al., 2000; Lapshina et al., 2001). The total potential area of preserved Desmoinesian Midcontinent peatlands (Fig. 17E) is similar in scale to the main areas of thickest peat in the Hudson Bay Lowland and West Siberian peatlands (Fig. 17, A and B). These modern peatlands illustrate that ancient peatlands need not have been confined to individual basins. If the Desmoinesian peatlands were connected between basins, their total area may have rivaled these modern giant peatlands. In fact, individual mires during Colchester and Herrin peat accumulation may have been similar in size or even exceeded the Vasyugan bog complex.

Extensive, warm-temperate climate mires also occur in the modern world and include two of the most-studied modern mires, the Okefenokee and Everglades of North America (Hofsetter, 1983). The Okefenokee covers an area of 1600 km^2, and the Everglades 10,000 km^2 (Fig. 17C), both significantly less than the area covered by the Desmoinesian coals of the Eastern Interior Basin. Additionally, the Everglades are dominated by non-peat accumulating wetlands, and the peats that do exist are thin, discontinuous, and high in ash content.

Comparison to Modern Thick Peatlands

Although the most widespread modern peats occur in northern latitudes, the thickest modern peats occur at low latitudes. Plant production and net primary productivity is greater in tropical climates than in temperate (Clymo, 1987; Ziegler et al., 1987). Tropical forest peats may accumulate at rates of 3 to 4.8 mm/yr (Anderson, 1983), whereas raised bogs of northern latitudes accumulate at 1–2 mm/yr, and temperate climate topogenous peats accumulate at only 0.5–1 mm/yr (Stach et al., 1982). Most northern latitude peatlands have average thicknesses of 1 to 5 m, with maximum local thicknesses of 7 to 11 m in peats of west Siberia (Kazakov, 1954; Botch and Masing, 1983). Some of these thick northern latitude peats are valley fills, but the thickest are raised bogs (soligenous to ombrogenous peats), like the Vasyugan bog complex (Bleuten et al., 2000; Lapshina et al., 2001). Ombrogenous peatlands of Indonesia (Fig. 17D) may exceed 10 m in thickness for areas of hundreds of square kilometers, and may reach thicknesses of more than 15 m toward the center of peat domes (Anderson, 1983; Esterle et al., 1992; Cecil et al., 1993). These low-latitude peat domes are the thickest peats in the modern world. Individual peat domes are mostly coastal peats and are not as extensive as their northern latitude counterparts. Indonesian peatlands are limited in extent by the width of the coast and the distances between streams, estuaries, and marine straits (Fig. 17D).

The Desmoinesian coals of the Eastern Interior Basin accumulated at tropical latitudes (Witzke, 1990; Heckel, 1994, 1995) and appear to have consisted of widespread topogenous to soligenous mires or mire complexes, relatively undivided by extrabasinal secondary and tertiary drainages. If a 10:1 peat-to-coal compaction ratio is assumed, the only modern peats with comparable thicknesses to these Desmoinesian paleomires are the ombrogenous mires of Indonesia. Like the Desmoinesian paleomires, Indonesian peats occur within 10° of the equator. As stated previously, however, there is no evidence that the Desmoinesian peats were domed, as are modern Indonesian peats. Even if ombrogenous conditions were indicated, the maximum thickness of modern Indonesian peats is less than that indicated for the decompacted thickness of the Springfield peat, which could have been more than 30 m thick, and Herrin peat, which could have been more than 40 m thick (at a 10:1 peat-to-coal compaction ratio). The Desmoinesian coals studied herein not only represent more continuous, widespread, topogenous tropical paleomires than modern tropical mires, but they possibly were thicker.

Extent of Desmoinesian Mires in North America

If examined in terms of total peatland area, the Eastern Interior Basin coals can be looked at not solely by their present extent, but relative to the total potential peat-covered area of adjacent basins, in essence, as a vast Desmoinesian peatland (Fig. 18). The interconnection of peatlands and roof facies between the Eastern and Western Interior Basins has been previously discussed. Likewise, each of the coals has a correlative in the Northern Appalachian Basin, and each is underlain by a thick paleosol. In addition, highstands and lowstands appear to have been near-contemporaneous between basins, as indicated by available biostratigraphy and correlation of cyclothems (discussed in Heckel, 1994).

Although cyclothems appear to be near-contemporaneous, it is difficult to confirm temporal equivalence of coals between basins versus temporal shifts, within the limits of biostratigraphic control, accompanying transgression of the Desmoinesian seas. Correlative coals in the Northern Appalachian Basin cover areas of 20,000 to 30,000 km^2. If Desmoinesian peatlands in the Northern Appalachian Basin accumulated at the same time as those in the Eastern Interior Basin, then the combined peatlands area could have been more than 100,000 km^2 in the basins alone, and if connected by wetlands and peatlands, much more.

Although possibly coeval accumulations, there is evidence to suggest a broad, ramp-like Desmoinesian paleoslope between the Eastern Interior and Northern Appalachian Basins because the number of marine units increases westward from the Appalachians to Iowa, and then southward from Iowa into Oklahoma (Heckel, 1995; Heckel et al., 1998). Also, Ting (1989) provided evidence for a change in coal lithotypes within the upper parts of the Lower Kittanning coal related to the inferred salinity of the roof fauna. This suggests lateral translation of at least the late stages of

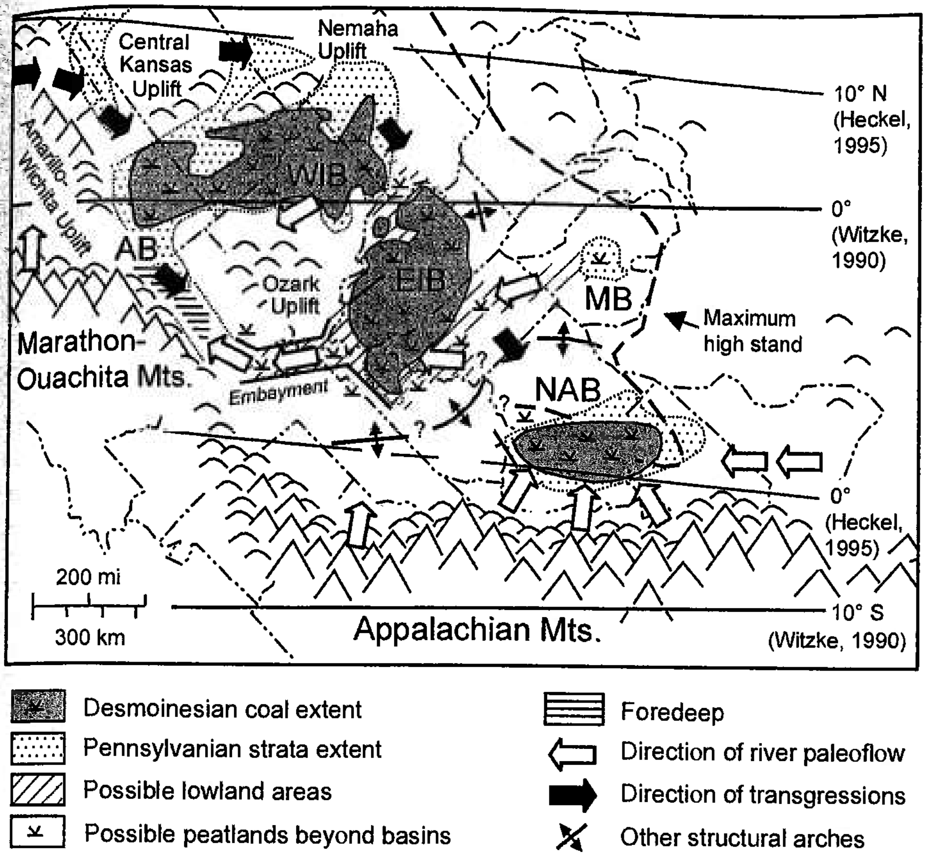

Figure 18. Paleogeography of Desmoinesian peatlands in eastern and middle United States (modified from information in Heckel, 1980; Thomas, 1989; Johnson et al., 1988; Donaldson and Eble, 1991). Peats may not have been completely coeval. Westphalian (Morrowan-Early Desmoinesian) paleoequator from Witzke (1990). Desmoinesian–Virgilian paleoequator from Heckel (1995). AB—Arkoma Basin, EIB—Eastern Interior Basin, MB—Michigan Basin, NAB—Northern Appalachian Basin, WIB—Western Interior Basin.

the northern Appalachian paleomires directly related to rising sea level. Ultimate drowning of the mires reflects the easternmost extent (highstands) of the Desmoinesian Midcontinent seas (Wanless et al., 1969; Heckel, 1995; Heckel et al., 1998). If transgression were needed for the base-level rise that initiated Appalachian peat accumulation, then Appalachian Basin peats would have been slightly younger than "correlative" Eastern and Western Interior Basin peats.

In the modern world, extensive peatlands can form between basins along low-lying coastal plains (Fig. 5). In west Siberia, peats are extensive 1000 km inland from the coast. Since (1) giant-peat-forming conditions seem to have existed in each of the Desmoinesian basins, and (2) extensive interbasinal paleosols indicate widespread exposure and weathering between basins, it seems probable that the areas between the present outcrop limits of the Desmoinesian coals would also have been low-relief, heavily-weathered areas. If low relief areas were extensive between basins, then Desmoinesian peatlands could have been extensive beyond the present limit of the basins, especially in low-lying areas such as might have existed in the embayment above the Reelfoot rift (Fig. 18). It seems likely that coastal mires could also have developed along much of the coast as the Desmoinesian seas transgressed to their maximum highstands (dashed line in Fig. 18), even if outside the present outcrop limit of the basins.

Controls on Desmoinesian Peatlands

Eustatic Controls

The extent of Desmoinesian coals in Midcontinent and eastern North American basins is generally attributed to glacio-eustacy, as previously noted (see discussion in Heckel, 1994). Coals occur in well-developed cyclothems and are overlain by dark shales that are attributed in part to condensed sections of marine transgressions and then overlying regressive deposits. The most laterally and vertically consistent coal-bearing cyclothems in the Desmoinesian of the Eastern Interior Basin occur in the stratigraphic interval between the Colchester and Herrin Coals, including the Springfield Coal (Fig. 4). The similarity of cyclothemic deposition across the central and eastern United States strongly supports eustatic controls on Desmoinesian coals. Heckel (1995) and Heckel et al. (1998) inferred that eustatic rise could have created the accommodation space for the development of the thick late Middle and Upper Pennsylvanian coals.

Not all of the Desmoinesian coals are widespread. The Davis, Dekoven, Houchin Creek, Survant, and Briar Hill Coals (Figs. 3 and 4) are not as extensive as the Colchester, Springfield, and Herrin. A consistent difference between the three coals studied and the other coals mentioned is that the three coals studied are underlain by widespread paleosols and overlain by more marine-influenced (at least stenohaline) roof strata than the other coals are. Each is also overlain by gray shale wedges that locally contain tidal stratification (Kuecher et al., 1990; Archer and Kvale, 1993). Marine strata and tidal facies accumulated during fourth-order transgressive systems tracts. The Mecca Quarry, Little Osage, and Anna Shales (Fig. 12) are all marine carbonaceous shales across much of their extent, containing orbiculoids, *Dunbarella*, and conodonts. These shales represent widespread condensed sections (Heckel, 1986, 1999). The Herrin Coal is overlain by the Anna Shale and the Brereton Limestone (Figs. 12 and 14B); the Colchester Coal is overlain by the Mecca Quarry Shale and Oak Grove Limestone. That these marine zones are more extensive than the marine facies above less extensive Desmoinesian coals illustrates the importance of the extent of transgression to Desmoinesian peat extent, and possibly their importance to thickness.

The correlation between the extent of post-peat marine influences and peat extent may reflect greater relative height of base-level rise and a more widespread base-level rise. It may also represent a longer duration of base-level rise or an optimal rate of base-level rise in which peats could accumulate and keep pace with the transgression.

Climatic Controls

A critical factor in modern peat accumulation is climate. In modern, extensive peat-forming mires, humid climates are important for rapid growth of vegetation and peat formation (Kylcyński, 1949; Pearsall, 1950; Clymo, 1987). The extensive west Siberian peatlands (Semenova and Lapshina, 2001; Lapshina et al., 2001) and Hudson Bay Lowland (Zoltai and Pollett, 1983; Martini and Glooschenko, 1985; Martini, 1989) show north-south vegetational gradients related to climate and coastal proximity, as well as temporal changes in vegetation related to Holocene climate changes. The thickest modern peats occur within the Intertropical Convergence Zone within 10° of the equator. It has been postulated that when the Intertropical Convergence Zone is narrow, as it is today, rain forests occur at tropical latitudes (Ziegler et al., 1987). During the Desmoinesian, the coals of middle and eastern North America accumulated within the Intertropical Convergence Zone, within 10° of the equator (Fig. 18).

Desmoinesian paleoclimates in the Eastern Interior Basin are inferred to have had a long wet season and short dry season (Cecil and Dulong, 2003). Comparison of mid-Desmoinesian paleosols suggests a westward change from humid to arid paleoclimates west of the Western Interior Basin. Spodosols, Ultisols, and gleyed Vertisols beneath the Lower Kittanning coal in the Appalachian Basin are soil types that indicate humid to perhumid climates (Retallack, 1990). Gleyed Vertisols beneath the Colchester Coal in the Eastern Interior Basin also suggest humid conditions. Moderate gleying of the paleosol beneath the Croweburg coal of the Western Interior Basin suggests a moist, subhumid paleoclimate. Mid-Desmoinesian Aridosols in western basins demonstrate more arid climates westward in the Desmoinesian (Cecil et al., 2003). A lack of correlative coals in the western United States north of 10° from the paleoequator may also suggest a narrow Intertropical Convergence Zone during the Desmoinesian.

Since Desmoinesian coal beds are found only east of the Nemaha Uplift (Fig. 18) it can be concluded that at least seasonally humid paleoclimates were critical to the establishment of vast mid-Desmoinesian peatlands (Cecil et al., 2003). Some seasonality was also probably needed to preclude development of ombrogenous mires. Indonesian equatorial peats receive rain all year, allowing domed peat to accumulate. Precipitation continuity is critical to establishing tropical ombrogenous peats (Ziegler et al., 1987).

Additional evidence for the importance of climate controls on the regional development of Desmoinesian peatlands is that cyclothemic sedimentation patterns continued into the Late Pennsylvanian in middle and eastern North America (e.g., Heckel, 1986; Greb et al., 1992), but coal beds became less widespread in the Western and Eastern Interior Basins. There is also a sharp change in palynology from Middle to Upper Pennsylvanian coals. Upper Pennsylvanian coals contain more fern-dominated mires, which is suggestive of increased seasonality and drying (Cecil et al., 1985; 2003; Phillips and DiMichele, 1985; Cecil, 1990; DiMichele and Phillips, 1996; Eble et al., 2001). Seasonality and drying climate would have precluded widespread inter-basinal peatland development.

Topographic and Hydrologic Controls

Another important reason for the broad extent of the Colchester and later coals is related to infilling of the last remnants of the sub-Pennsylvanian unconformity along the margins of the Midcontinent and Eastern Interior Basins (Wanless and Wright, 1978). Older coals were restricted to a smaller area, and the unconformity was still an exposure surface along the basin margins with topographic relief. The Colchester Coal and younger deposits formed above that surface, across a broader possible area for deposition (Wright, 1975; Wanless and Wright, 1978).

Wanless et al. (1969) inferred that Desmoinesian peats accumulated on widespread, low-relief delta platforms of the Eastern Interior (Illinois) Basin. These platforms and correlative environments were mapped across the Eastern and Western Interior Basins (Wright, 1975; Wanless and Wright, 1978). The widespread Desmoinesian coals of middle and eastern North America are underlain by well-developed underclays, which are typically more extensive than the coals themselves. These underclays represent widespread paleosols, which formed due to weathering of sediments from underlying paleoenvironments rather than just weathering of the delta platforms. As extensive paleosols, they most likely represent fourth-order lowstands (e.g., Weibel, 1996).

The extensive northern-latitude peats of our modern world have developed on widespread low-relief, glacially-scoured, coastal plains with little topographic relief. The Hudson Bay Lowland peats (Fig. 17A) are developed on a vast, essentially flat, marine platform that has isostatically rebounded since the last glacial retreat (Martini and Glooschenko, 1985; Ziegler et al., 1987; Martini, 1989). In the Hudson Bay Lowland, slopes average 0.5m/km (Martini et al., 1980). Likewise, the vast, low-relief cratonic setting of the West Siberian peatlands, has gradients between 0.5 to 1.5 degrees (Semenova and Lapshina, 2001). This type of setting is undoubtedly crucial for the development of widespread peatlands.

In west Siberia, cold, humid, maritime-influenced climates with low evapotranspiration because of cold average annual temperatures led to paludification of the extensive lowlands. Paludification involves the development of soil gleying or podzolization (Pearsall, 1950), which results in limited infiltration capacity and substrate permeability, impeded drainage, seasonal to permanent waterlogging of the impermeable substrates, and peat accumulation (Heinselman, 1963; Walter, 1977; Tallis, 1983). Frenzel (1983) inferred that modern flat-lying basins may be prone to mire formation through paludification and may become self-perpetuating ecosystems. Examination of key areas in the West Siberian peatlands indicates that peats began in topographic depressions (lake depressions and poorly drained basins) and then spread laterally, ultimately fusing into expansive peat massifs and bog complexes (Lapshina et al., 2001). Surplus water running from the growing mires, either superficially or as groundwater, resulted in downslope paludification and lateral extension of the peat. This resulted in impeded water flow and ponding of the water table, which allowed upslope expansion of the peat (Heinselman, 1963; Walter, 1977; Tallis, 1983). In fact, Romanova (1967) and Frenzel (1983) inferred that geomorphic and geologic conditions may have been more important to paludification and extensive mire development in west Siberia than climate.

The widespread paleosols that developed prior to the Colchester, Springfield, and Herrin peats probably formed a vast, low-relief surface that would have been susceptible to paludification and peat accumulation. These paleo-peats were significantly more expansive than modern tropical peats, such as the mires in Indonesia. One of the reasons that tropical mires in Indonesia are not greater in expanse is that they occupy relatively narrow coastlines on a series of volcanic islands (Fig. 17D). In fact, coastal position is not necessary for the development of peatlands. Widespread northern-climate peatlands are more extensive and thicker away from the coast. In the Hudson Bay Lowland, the thickest and most extensive peats occur 50–300 km inland (Fig. 17A; Martini and Glooshenko, 1985; Martini, 1989). The largest West Siberian peatlands are essentially vast floodplain deposits developed in flat, cratonic settings, and they are extensive for more than 800 km inland from the coast.

Much of the West Siberian peatlands is drained by a single large anastomosing to sinuous river, the Ob (Fig.17B), along which the peatlands are most continuous. The Springfield and Herrin Coals are likewise bisected by single, large contemporaneous paleochannels and are best developed on either side of these paleochannels in a cratonic floodplain setting (Figs. 6, 8, and 9), inland from the encroaching Desmoinesian seaway (Fig. 18). Seasonal flooding from the large paleochannels that bisected each of the Desmoinesian paleomires supplied nutrients and water to adjacent peatlands. Seasonal floods may have been impeded by peat infilling of some secondary and tertiary drainage pathways, as happens along the modern Ob River. Because of resulting poor drainage, individual mire complexes are linked into single hydrological systems across broad areas. This is significant because the modern analogue indicates that Desmoinesian peats could develop and become widespread independent of a eustatic rise. The combination of water table rises along the floodplain may have reinforced regional base-level rise and widespread peat saturation, leading to extremely thick and widespread topogenous peats. The major water sources of the ancient peatlands also greatly affected their botanical makeup. The Herrin exhibits greater palynologic diversity than the Springfield and Colchester Coals, and it is associated with the Walshville paleochannel, which is the largest syndepositional channel system of the three coals. Higher water tables across larger areas could have inhibited the prolifcration of ferns and thereby decreased average plant diversity in the Springfield and Colchester peatlands (Eble et al., 2001).

Too much flooding from fluvial sources can lead to oxidation and preclude peat accumulation in tropical settings (Ziegler et al., 1987). In both the Hudson Bay Lowland and West Siberian peatlands, winter freezing restricts sedimentation during parts of the year. The Hudson Bay Lowland is drained only by small rivers, which carry small sediment loads (Martini and Glooshenko, 1985). Too much clastic influx would preclude peat accumulation and result in deposition of carbonaceous shales rather than coals. Since widespread peats developed, it can be inferred that the Desmoinesian rivers did not excessively flood the adjacent mires with coarse clastics but did keep water tables high enough for thick peat accumulation. Coarse clastics were confined to narrow zones along the margins of syndepositional channels in the Herrin and Springfield peatlands. Because the Herrin and Springfield mires were only bisected by single large contemporaneous river systems, much of the peatlands may have been protected from coarse clastic influx during flooding. Multiple rock partings in the coals in channel areas (see Fig. 7) attest to periodic flooding. Widespread, high ash yields (9%–12%) in the coals also partly resulted from flooding and may attest to the regional extent of flooding influences.

The relative lack of additional drainages in each of the three Desmoinesian coal beds studied in the Eastern Interior Basin indicates not just poor drainage and low relief, but also low relief in subadjacent areas. Low relief outside of the depositional basin would have contributed to poor drainage within the basin and to the lack of dissected topography. Additionally, extra-basinal low relief might have led to a much lower total detrital sediment volume, which would aid in widespread peat accumulation. In contrast, the splitting and zoning of correlative coals in the Appalachian Basin indicates more influx of detrital clastics and more relief adjacent to the basin in the Appalachian orogen.

Tectonic Controls

A comparison of the Western Kentucky Coal Field (southern Eastern Interior Basin) and Eastern Kentucky Coal Field (central Appalachian Basin) shows that although tectonic accommodation was greater in the Appalachian Basin throughout most of the Pennsylvanian, there was a general decrease in tectonic accommodation from the Morrowan to Desmoinesian in both basins (Greb et al., 2002). Minimal tectonic subsidence coincided with mid-Desmoinesian cyclothem development. Areas of thick Herrin Coal away from the Walshville paleochannel correspond to the Fairfield Basin depocenter in Illinois (Fig. 6), suggesting at least small tectonic influences. Earlier in the Pennsylvanian, increased tectonic subsidence toward basin depocenters in both the Eastern Interior and Appalachian Basins led to splitting, changes in coal thickness, and diversions of paleodrainages due to structural influences (Greb et al., 2002), which probably precluded widespread giant paleomire development.

Intrabasinal tectonics were also primary controls on limiting the extent of pre-Colchester peatlands in the Eastern Interior Basin, especially along the Du Quoin monocline (Fig. 3). Updip thinning of the Springfield Coal and concomitant thinning of the interval between the Springfield and Herrin Coals (Figs. 3 and 8A) suggest that the monocline created a low accommodation area on the western shelf of the basin, which negatively influenced peat accumulation. The Walshville paleochannel (W in Fig. 6) was apparently deflected southward toward the Reelfoot rift by the monocline. Stacking of channel sandstones, informally termed the "highlands fluvial complex," has been attributed to subsidence along the structure (Palmer et al., 1979). Hence, tectonics indirectly affected the accumulation of thick Herrin peat mires by influencing the position of the dominant paleodrainage and, thereby, the pathways for sedimentation. The absence of the Herrin Coal along part of the Rough Creek Graben (B in Fig. 6), and correspondence of part of the mire to local faults (Hower et al., 1987; deWet et al., 1997), may indicate that tectonics influenced the trend of post-Herrin transgression as well.

SUMMARY

Wanless (1975a) inferred that the Colchester Coal of the Eastern Interior (Illinois) Basin and its correlatives in the Western Interior Basin formed the most widespread coals in Earth's history. The Springfield and Herrin Coals and their correlatives in the Western Interior Basin also represent vast Desmoinesian peatlands. These coal beds all have correlatives, although possibly slightly younger, in the Northern Appalachian Basin as well. Herein, the coals were examined as part of vast paleopeatlands. Petrography, palynology, and ash contents of the coals indicate that each was deposited in topogenous to soligenous mires or mire complexes, which may have covered areas in excess of 200,000 km^2.

Desmoinesian giant-topogenous mire complexes were deposited in an equatorial setting and were thicker and much more extensive than modern tropical topogenous mires. They may represent the most extensive tropical topogenous mires in Earth history. The only modern peatlands similar in extent to the Desmoinesian peatlands are the northern-latitude peatlands of the Hudson Bay Lowland and west Siberia. Although these modern peatlands accumulated under a much colder climatic regime, some of the controls on their extent are applicable to understanding the development of giant Desmoinesian paleomires. Paludification above vast paleosols, infilling and damming of early peat paleotopography, and widespread seasonal flooding that links separated mire complexes into single hydrological systems, all may be applicable to the development of the tropical Desmoinesian paleomires.

The superposition of favorable Desmoinesian humid paleoclimates, broad cratonic and impermeable paleosol substrates, strong eustatic influences, basin-wide decreased tectonic subsidence, low relief and low-sediment yield in areas updip of the peat mires all combined to form some of the most widespread peats in Earth history.

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REFERENCES CITED

Aitken, J.F., and Flint, S.S., 1994, High-frequency sequences and the nature of incised-valley fills in fluvial systems of the Breathitt Group (Pennsylvanian), Appalachian foreland basin, eastern Kentucky, *in* Dalrymple, R., Boyd, R., and Zaitlen, B., eds., Incised valley systems–Origin and sedimentary sequences: SEPM (Society for Sedimentary Geology) Special Publication 51, p. 353–368.

Anderson, J.A.R., 1983, The tropical pet swamps of western Malesia, *in* Gore, A.J.P., ed., Mires: Swamps, bog, fen, and moor: Ecosystems of the World: New York, Elsevier, v. 4B, p. 181–199.

Archer, A.W., and Kvale, E.P., 1993, Origin of gray-shale lithofacies ("clastic wedges") in U.S. Midcontinental coal measures (Pennsylvanian), *in* Cobb, J.C., and Cecil, C.B., eds., Modern and ancient coal-forming environments: Geological Society of America Special Paper 286, p. 181–192.

Ault, C.H., Carr, D.D., Chen, P.Y., Eggert, D.L., Hassenmueller, W.A., and Hutchinson, H.C., 1979, Geology of the Springfield Coal Member (V) in Indiana–A review, *in* Palmer, J.E., and Dutcher, R.R., eds., Depositional and structural history of the Pennsylvanian system in the Illinois Basin. Part 2: Invited papers: Field trip 9, 9th International Congress of Carboniferous Stratigraphy and Geology, Urbana, Illinois: Illinois State Geological Survey, p. 43–49.

Austin, S.A., 1979, Depositional environment of the Kentucky No. 12 coal bed (Middle Pennsylvanian) of western Kentucky, with special reference to the origin of coal lithotypes [Ph.D. thesis]: University Park, The Pennsylvania State University, 390 p.

Baird, G.C., Shabica, C.W., Anderson, J.L., and Richardson Jr., E.S., 1985, Biota of a Pennsylvanian muddy coast; habitats within the Mazonian delta complex, northeast Illinois: Journal of Paleontology, v. 59, p. 253–281.

Beard, J.G., and Williamson, A.D., 1979, A Pennsylvanian channel in Henderson and Webster Counties, Kentucky: Kentucky Geological Survey, ser. 11, Information Circular 1, 12 p.

Bleuten, W., Vasilev, S.V., and Lapshina, E.D., 2000, The scientific relevance of the greatest raised bog of the world: Vasuganskoe bog (west Siberia): Quebec, Canada, 11th International Mire Conservation Group Peat Congress, Program and Abstracts, p. 251.

Botch, M.S., and Masing, V.V., 1983, Mire ecosystems in the USSR, *in* Gore, A.J.P., ed., Mires: Swamps, bog, fen, and moor: Ecosystems of the World: New York, Elsevier, v. 4B, p. 95–152.

Bunker, B.J., Witzke, B.J., Watney, W.L., and Ludvigson, G.A., 1988, Phanerozoic history of the central Midcontinent, U.S., *in* Sloss, L.L., ed., Sedimentary cover—North American craton: Boulder, Colorado, Geological Society of America, The Geology of North America, v. D-2, p. 243–260.

Cadle, A.B., Cairncross, B., Christie, A.D.M., and Roberts, D.L., 1993, The Karoo Basin of South Africa: Type basin for thc coal-bearing deposits of southern Africa: International Journal of Coal Geology, v. 23, p. 117–157.

Cecil, C.B., 1990, Paleoclimate controls on stratigraphic repetition of chemical and siliciclastic rocks: Geology, v. 18, p. 533–536.

Cecil, C.B., Stanton, R.W., Neuzil, S.G., Dulong, F.T., Ruppert, C.F., and Pierce, B.S., 1985, Paleoclimate controls on Late Paleozoic sedimentation and peat formation in the central Appalachian Basin (U.S.A.): International Joumal of Coal Geology, v. 5, p. 195–230.

Cecil, C.B., Dulong, F.T., Cobb, J.C., and Supardi, S., 1993, Allogenic and autogenic controls on sedimentation in the central Sumatra basin as an analogue for Pennsylvanian coal-bearing strata in the Appalachian basin, *in* Cobb, J.C., and Cecil, C.B., eds., Modem and ancient coal-forming environments: Geological Society of America Special Paper 286, p. 3–22.

Cecil, C.B., and Dulong, F.T., 2003, Precipitation models for sediment supply in warm climates, *in* Cecil, C.B. and Edgar, N.T., eds., Climate Controls on Stratigraphy: Society of Sedimentary Petrology, SEPM (Society for Sedimentary Geology) Special Publication 77.

Cecil, C.B., Dulong, F.T., West, R.R., Stamm, R., Wardlaw, B., and Edgar, N.T., 2003, Climate controls on the stratigraphy of a middle Pennsylvanian cyclothem in North America, *in* Cecil, C.B. and Edgar, N.T., eds., Climate Controls on Stratigraphy: Society of Sedimentary Petrology, SEPM (Society for Sedimentary Geology) Special Publication 77.

Chesnut, D.R., Jr., 1992, Stratigraphic and structural framework of the Carboniferous rocks of the central Appalachian Basin in Kentucky: Kentucky Geological Survey, Bulletin 3, Series 11, 42 p.

Clymo, R.S., 1987, Rainwater-fed peats as a precursor of coal, *in* Scott, A.C., ed., Coal and coal-bearing strata—Recent advances: Geological Society of America Special Publication 32, p. 7–23.

de Wet, C.B., Moshier, S.O., Hower, J.C., de Wet, A.P., Brennan, S., Helfrich, C.T., and Raymond, A.L., 1997, Disrupted coal and carbonate facies within two Pennsylvanian cyclothems, Southern Illinois Basin, USA: Geological Society of America Bulletin, v. 109, p. 1231–1248.

Diessel, C.F.K., 1998, Sequence stratigraphy applied to coal seams: Two case histories, in Shanley, K.W., and McCabe, P.J., eds., Relative role of eustacy, climate, and tectonism in continental rocks: SEPM (Society for Sedimentary Geology) Special Publication 59, p. 151–173.

DiMichele, W.A., and Nelson, W.J., 1989, Small-scale spatial heterogeneity in Pennsylvanian-age vegetation from the roof-shale of the Springfield Coal: PALAIOS, v. 4, p. 276–280.

DiMichele, W.A., and Phillips, T.L., 1985, Arborescent lycopod reproduction and paleoecology in a coal-swamp environment of late Middle Pennsylvanian age (Herrin Coal, Illinois, U.S.A): Reviews Palaeobotany and Palynology, v. 44, p. 1–26.

DiMichele, W.A., and Phillips, T.L., 1988, Paleoecology of the Middle Pennsylvanian-age Herrin Coal swamp near a contemporaneous river system, the Walshville paleochannel: Review of Palaeobotany and Palynology, v. 56, p. 157–176.

DiMichele, W.A., and Phillips, T.L., 1994, Paleobotanical and paleoecological constraints on models of peat formation in the Late Carboniferous of Euramerica: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 106, p. 39–90.

DiMichele, W.A., and Phillips, T.L., 1996, Climate change, plant extinctions, and vegetational recovery during the Middle-Late Pennsylvanian transition: The case of tropical peat-forming environments in North America, *in* Hart, M.L., ed., Biotic recovery from mass Extinctions: London, Geological Society Special Publication 102, p. 201–221.

DiMichele, W.A., Mahaffy, J.F., and Phillips, T.L., 1979, Lycopods of Pennsylvanian age coals: *Polysporia*: Canadian Journal of Botany, v. 57, p. 1740–1753.

DiMichele, W.A., Phillips, T.L., and McBrinn, G.E., 1991, Quantitative analysis and paleoecology of the Secor coal and roof-shale floras (Middle Pennsylvanian, Oklahoma): PALAIOS, v. 6, p. 390–409.

DiMichele, W.A., Phillips, T.L. and Nelson, W.J., 2002, Place vs. time and vegetational persistence: a comparison of four tropical mires from the Illinois Basin during the height of the Pennsylvanian Ice Age: International Journal of Coal Geology, v. 50, p. 43–72.

DiMichele, W.A., Pfefferkom, H.W., and Phillips, T.L., 1996, Persistence of Late Carboniferous tropical vegetation during glacially driven climatic and sea-level fluctuations: Paleoclimatology, Paleogeography, and Paleoecology, v. 125, p. 105–128.

Donaldson, A.C., and Eble, C.F., 1991, Pennsylvanian coals of central and eastern United States, *in* Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., Economic geology, U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. P-2, p. 523–546.

Eble, C.F., 2002, Palynology of late-Middle Pennsylvanian coal beds in the Appalachian Basin: Intemational Joumal of Coal Geology, v. 50, in press.

Eble, C.F., and Grady, W.C., 1990, Paleoecological interpretation of a Middle Pennsylvanian coal bed in the central Appalachian Basin, U.S.A.: International Joumal of Coal Geology, v. 16, p. 255–286.

Eble, C.F., Greb, S.F., and Williams, D.A., 2001, The geology and palynology of Lower and Middle Pennsylvanian strata in the Western Kentucky coal field: International Joumal of Coal Geology, v. 47, p. 189–205.

Eggert, D.L., 1984, The Leslic Cemetery and Francisco distributary fluvial channels in the Petersburg Formation (Pennsylvanian) of Gibson County, Indiana, U.S.A., *in* Rahmnai, R.A., and Flores, R.M., eds., Sedimentology of coal and coal-bearing sequences: Special Publications of the International Association of Sedimentologists, v. 7, p. 309–315.

Eggert, D.L., 1987, Earlier differential compaction in Gibson County, Indiana: Intemational Joumal of Coal Geology, v. 8, p. 305–334.

Ellis, M.S., Gunther, G.L., Ochs, A.M., Roberts, S.B., Wilde, E.M., Schuenemeyer, J.H., Power, H.C., Stricker, G.D., and Blacke, D., 1999, Coal resources, Powder River basin, *in* Fort Union Coal Assessment Team, 1999 resource assessment of selected tertiary coal beds and zones in the northern Rocky Mountains and Great Plains region: U.S. Geological Survey Professional Paper 1625 A, Chapter PN, version 1.2, disc 1.

Esterle, J.S., Gavett, K.L., and Ferm, J.C., 1992, Ancient and modern environments and associated controls on sulfur and ash in coal, *in* Platt, J., Price, J.P., Miller, M., and Suboleski, S., eds., 1.2–New perspectives on central Appalachian low-sulfur coal supplies: Fairfax, Virginia, Techbooks, Coal Decisions Forum Publication, p. 55–76.

Ferm, J.C., 1970, Allegheny deltaic deposits, *in* Morgan, J.P., ed., Deltaic sedimentation, modem and ancient: Society of Economic Paleontologists and Mineralogists Special Publication 15, p. 246–255.

Frenzel, B., 1983, Mires—Repositories of climatic information or self-perpetuating ecosystems?, *in* Gore, A.J.P., ed., Mires: Swamp, bog, fen and moor: Ecosystems of the world: New York, Elsevier, p. 35–66.

Friedman, S.A., 1977, Investigation of the coal reserves in the Ozarks section of Oklahoma and their potential uses: Final report to the Ozarks Regional Commission, July 10, 1974, Norman, Oklahoma, Oklahoma Geological Survey Special Publication 74-2, 117 p.

Gluskoter, H.J., and Simon, J.A., 1968, Sulfur in Illinois coals: Illinois State Geological Survey Circular 432, 28 p.

Gore, A.J.P., ed., 1983, Mires: Swamp, bog, fen and moor: Ecosystems of the world: New York, Elsevier, 440 p.

Greb, S.F., 1989, Structural controls on the formation of the sub-Absaroka unconformity in the U.S. Eastern Interior Basin: Geology, v. 17, p. 889–892.

Greb, S.F., Williams, D.A., and Williamson, A.D., 1992, Geology and stratigraphy of the western Kentucky coal field: Kentucky Geological Survey Bulletin 2, 77 p.

Greb, S.F., Eble, C.F., and Hower, J.C., 1999, Depositional history of the Fire Clay coal bed (late Duckmantian), eastern Kentucky, USA: International Journal of Coal Geology, v. 40, p. 255–280.

Greb, S.F., Eble, C.F., and Chesnut Jr., D.R., 2002, Comparison of the eastern and western Kentucky coal fields, U.S.A—Why are coal distribution patterns and sulfur contents so different in these coal fields?: International Joumal of Coal Geology, v. 50, p. 89–118.

Greb, S.F., Eble, C.F., Hower, J.C., and Andrews, W.M., 2002, Multiple-bench architecture and interpretations of original mire phases–Examples from the

Middle Pennsylvanian of the central Appalachian Basin, U.S.A.: International Journal of Coal Geology, v. 49, p. 147–175.

Hardie, J.K., and Van Gosen, B.S., 1986, Fence diagram showing coal bed correlations within Upper Fort Union Formation in and adjacent to the eastern part of the Kaycee 30′ × 60′ quadrangle, Johnson and Campbell Counties, Wyoming: U.S. Geological Survey Coal Investigations Map C-107, 1 sheet.

Hatch, J.R., and Affolter, R.H., 2002, Resource assessment of the Springfield, Herrin, Danville, and Baker coals in the Illinois Basin: U.S. Geological Survey Professional Paper 1625-D, CD-ROM.

Heckel, P.H., 1977, Origin of black phosphatic shale facies in Pennsylvanian cyclothems of the Midcontinent, North America: American Association of Petroleum Geologists Bulletin, v. 61, p. 1045–1068.

Heckel, P.H., 1980, Paleogeography of eustatic model for deposition of Midcontinent Upper Pennsylvanian cyclothems, *in* Pouch, T.D., and Magathan, E.R., eds., Paleozoic paleogeography of the west-central United States: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, Rocky Mountain Paleogeography Symposium, p. 197–215.

Heckel, P.H., 1986, Sea-level curve for Pennsylvanian eustatic marine transgressive-regressive depositional cycles along Midcontinent outcrop belt, North America: Geology, v. 14, p. 330–334.

Heckel, P.H., 1994, Evaluation of evidence for glacio-eustatic control over marine Pennsylvanian cyclothems in North America and consideration of possible tectonic effects, *in* Dennison, J.M., and Ettensohn, F.R., eds., Tectonic and eustatic controls on sedimentary cycles: SEPM (Society for Sedimentary Geology) Concepts in Sedimentology and Paleontology, v. 4, p. 65–87.

Heckel, P.H., 1995, Glacial-eustatic base-level-climatic model for late Middle to Late Pennsylvanian coal-bed formation in the Appalachian basin: Journal of Sedimentary Research, v. B65, p. 348–356.

Heckel, P.H., 1999, Field Trip No. 8: Middle and Upper Pennsylvanian Cyclothem Succession in Midcontinent Basin, U.S.A.: Kansas Geological Survey Open-file Report 99-27, 236 p.

Heckel, P.H., Gibling, M.R., and King, N.R., 1998, Stratigraphic model for glacial-eustatic Pennsylvanian cyclothems in highstand nearshore detrital regimes: Journal of Geology, v. 106, p. 373–383.

Heinselman, M.L., 1963, Forest sites, bog processes, and peatland types in the glacial Lake Agassiz region, Minnesota: Ecology Monographs, v. 33, p. 327–374.

Hildenbrand, T.G., Kane, M.F., and Hendricks, J.D., 1982, Magnetic basement in the Upper Mississippi Embayment region and preliminary report: U.S. Geological Survey Professional Paper 1236, 53 p.

Hofsetter, R.H., 1983, Wetlands in the U.S., *in* Gore, A.J.P., ed., Mires: Swamps, bog, fen, and moor: Ecosystems of the World: New York, Elsevier, v. 4B, p. 201–244.

Hopkins, M.E., 1968, Harrisburg (No. 5) coal reserves of southeastern Illinois: Urbana, Illinois State Geological Survey Circular 431, 25 p.

Hopkins, M.E., Nance, R.B., and Treworgy, C.G., 1979, Mining geology of Illinois coal deposits, *in* Palmer, J.E., and Dutcher, R.R., eds., Depositional and structural history of the Pennsylvanian system of the Illinois Basin: Field trip 9, Ninth International Congress of Carboniferous Stratigraphy and Geology, Part 2: Invited Papers, p. 142–151.

Houseknecht, D.W., 1986, Evolution from passive margin to foreland basin—The Atokan Formation of the Arkoma Basin, south-central U.S.A., *in* Allen, P.A., and Homewood, P., eds., Foreland basins: Special Publications of the Industrial Association of Sedimentologists, v. 8, p. 327–345.

Hower, J.C., and Gayer, R.A., 2002, Mechanisms of coal metamorphism: Case studies from Paleozoic coalfields: International Journal of Coal Geology, v. 50, p. 215–245.

Hower, J.C., and Wild, G.D., 1982, Petrographic variation in the Springfield (No. 9) coal in western Kentucky: International Journal of Coal Geology, v. 2, p. 17–30.

Hower, J.C., Riley, J.T., Thomas, G.A., and Griswold, T.B., 1991, Chlorine in Kentucky coals: Journal of Coal Quality, v. 10, p. 152–158.

Hower, J.C., and Williams, D.A., 2000, Further examination of the ragged edge of the Herrin Coal bed, Webster County, western Kentucky coal field: International Journal of Coal Geology, v. 46, p. 145–155.

Hower, J.C., Trinkle, E.J., Graese, A.M., and Neuder, G.L., 1987, Ragged edge of the Herrin (No. 11) coal, western Kentucky: International Journal of Coal Geology, v. 7, p. 1–20.

Hower, J.C., Wild, G.D., Pollock, J.D., Trinkle, E.J., Bland, A.E., and Fiene, F.L., 1990a, Petrography, geochemistry, and mineralogy of the Springfield (Western Kentucky No. 9) coal bed: Journal of Coal Quality, v. 9, p. 90–100.

Hower, J.C., Rimmer, S.M., Williams, D.A., and Beard, J.G., 1990b, Coal rank trends in the western Kentucky coal field and relationship to hydrocarbon occurrence, *in* Nuccio, V.F., and Barker, C.E., eds., Applications of thermal maturity studies to energy exploration: Tulsa, Oklahoma, Rocky Mountain Section, SEPM (Society for Sedimentary Geology), p. 127–138.

Hower, J.C., Scott, A.C., Hutton, A.C., Pareleh, B.K., and Dowley, B., 1995, Coal: Availability, mining, and preparation, *in* Encyclopedia of energy technology and the environment: John Wiley and Sons, p. 603–684.

Johnson, D.O., 1972, Stratigraphic analysis of the interval between the Herrin (No. 6) coal and the Palsa limestone in southwestern Illinois [Ph.D. thesis]: Urbana, University of Illinois, 105 p.

Johnson, K.S., Amsden, T.W., Denison, R.E., Dutton, S.P., Goldstein, A.G., Rascoe Jr., B., Sutherland, P.K., and Thompson, D.M., 1988, Southern Midcontinent region, *in* Sloss, L.L., ed., Sedimentary cover–North American craton, U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. D-2, p. 307–359.

Kazakov, G., 1954, Soviet peat resources: A descriptive study: New York, Edwards Brothers, Research Program on the U.S.S.R., 201 p.

Klein, G.D., and Willard, D.A. 1989, Origin of the Pennsylvanian coal-bearing cyclothems of North America: Geology, v. 17, p.152–155.

Kosanke, R.M., 1950, Pennsylvanian spores of Illinois and their use in correlation: Illinois State Geological Survey Bulletin v. 74, 128 p.

Kosanke, R.M., Simon, J.A., Wanless, H.R., and Willman, H.B., 1960, Classification of the Pennsylvanian strata of Illinois: Urbana, Illinois State Geological Survey Report of Investigations 214, 84 p.

Krausse, H.-F., Damberger, H.H., Nelson, W.J., Hunt, S.R., Ledvina, C.T., Treworgy, C.C., and White, W.A., 1979, Roof strata of the Herrin (No. 6) Coal and associated rocks in Illinois—a summary report: Illinois State Geological Survey Illinois Minerals Notes 72, 54 p.

Kuecher, G.J., Woodland, B.G., and Broadhurst, F.M., 1990, Evidence of deposition from individual tides and tidal cycles from the Francis Creek Shale (host rock to the Mazon Creek Biota), Westphalian D (Pennsylvanian), northeastern Illinois: Sedimentary Geology, v. 68, p. 211–221.

Kylcyński, S., 1949, Peat bogs of Polesie: Memoirs of the Academy of Polish Science, B15, p. 1–356.

Lapshina, E.D., Mouldiyarov, E. Ya., and Vasilev, S.V., 2001, Analyses of key area studies, *in* Bleuten, W., and Lapshina, E.D., eds., Carbon storage and atmospheric exchange by West Siberian Peatlands: Utrecht, The Netherlands, Utrecht University, Department of Physical Geography, p. 23–37.

Lesnikowska. A.D., 1989, Anatomically preserved Marattiales from coal swamps of the Desmoinesian and Missourian of the mid-continent United States: Systematics, ecology, and evolution: [PhD dissertation] University of Illinois, Urbana, 227 p.

Mahaffy, J.F., 1988, Vegetational history of the Springfield Coal (Middle Pennsylvanian of Illinois) and distribution patterns of a tree-fern miospore, *Thymospora pseudothiessenii*, based on miospore profiles: International Journal of Coal Geology, v. 10, p. 239–260.

Mallett, C.W., Pattison, P., McLennan, C., Balfe, P., and Sullivan, D., 1995, Bowen Basin, *in* Ward, C.W., Harrington, H.J., Mallett, C.W., and Beeston, J.W., ed., Geology of Australian coal basins: Geological Society of Australia, Coal Geology Group, Special Publication 1, p. 299–339.

Martini, I.P, 1989, The Hudson Bay lowland: Major geologic features and assets: Geologie en Mijnbouw, v. 68, p. 25–34.

Martini, I.P., and Glooschenko, W.A., 1985, Cold climate peat formation in Canada and its relevance to Lower Permian coal measures of Australia: Earth-Science Reviews, v. 22, p. 107–140.

Martini, I.P, Morrison, R.I.G., Glooshenko, W.A., and Protz, R., 1980, Coastal studies in James Bay, Ontario: Geoscience Canada, v. 7, p. 11–21.

Michaelsen, P., and Henderson, R.A., 2000, Facies relationships and cyclicity of high-latitude, Late Permian coal measures, Bowen Basin, Australia: International Journal of Coal Geology, v. 44, p. 19–48.

Michaelsen, P., Henderson, R.A., Crosdale, P.J., and Mikkelsen, S.O., 2000, Facies architecture and depositional dynamics of the Upper Permian Rangal Coal Measures, Bowen Basin, Australia: Journal of Sedimentary Research, v. 70, p. 879–895.

Moore, P.D., 1989, The ecology of peat-forming processes—A review: International Journal of Coal Geology, v. 12, p. 89–103.

Nadon, G.C., 1998, Magnitude and timing of peat-to-coal compaction: Geology, v. 26, p. 727–730.

Nelson, W.J., 1983, Geologic disturbances in Illinois coal seams, Illinois State Geological Survey Circular 530, 47 p.

Nelson, W.J., 1987, The Hornsby District of low-sulfur Herrin Coal in central Illinois (Christian, Macoupin, Montgomery, and Sangamon Counties): Illinois State Geological Survey Circular 540, 40 p.

Nitecki, M.H., ed., 1979, Mazon Creek fossils: New York, Academic Press, 581 p.

Northern and Central Appalachian Basin Coal Regions Assessment Team, 2001, 2000 resource assessment of selected coal beds and zones in the northern and central Appalachian Basin coal regions: U.S. Geological Survey Professional Paper 1625-C, CD-ROM, Discs 1 and 2, Version 1.0.

Palmer, J.E., Jacobson, R.J., and Task, C.B., 1979, Depositional environments of strata of Late Desmoinesian age overlying the Herrin (No. 6) Coal Member in southwestern Illinois, *in* Palmer, J.E., and Dutcher, R.R., eds., Depositional and structural history of the Pennsylvanian system of the Illinois Basin, Ninth International Congress of Carboniferous Stratigraphy and Geology, Field Trip 9, p. 86–92.

Pearsall, W.H., 1950, Mountains and moorlands: London, Collins Publishing, New Naturalist Series, 32 p.

Peppers, R.A., 1970, Correlation and palynology of coals in the Carbondale and Spoon Formations (Pennsylvanian) of the northeastern part of the Illinois Basin: Illinois State Geological Survey Bulletin 93, 173 p.

Peppers, R.A., 1996, Palynological correlation of major Pennsylvanian (Middle and Upper Carboniferous) chronostratigraphic boundaries in the Illinois and other coal basins: Boulder, Colorado, Geological Society of America Memoir 188, 111 p.

Phillips, T.L. and Cross, A.T., 1991, Paleobotany and paleoecology of coal, *in* Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., Economic geology, U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. P-2, p. 483–502.

Phillips, T.L. and DiMichele, W.A., 1998, A transect through a clastic-swamp to peat-swamp ecotone in the Springfield Coal, Middle Pennsylvanian age of Indiana, U.S.A.: PALAIOS, v. 13, p. 110–125.

Phillips, T.L., and Peppers, R.A., 1984, Changing patterns of Pennsylvanian coal swamp vegetation and implications of climate control on coal occurrence: International Journal of Coal Geology, v. 3, p. 205–255.

Phillips, T.L., Kunz, A.B., and Mickish, D.J., 1977, Paleobotany of permineralized peat (coal balls) from the Herrin (No. 6) Coal Member of the Illinois Basin, *in* Given, P.H., and Cohen, A.D., eds., Interdisciplinary studies of peat and coal origins: Boulder, Colorado, Geological Society of America Microform Publication 7, p. 18–49.

Phillips, T.L., Peppers, R.A., and DiMichele, W.A., 1985, Stratigraphic and interregional changes in Pennsylvanian-age coal-swamp vegetation: Environmental inferences: International Journal of Coal Geology, v. 5, p. 43–109.

Potter, P.E., and Simon, J.A., 1961, Anvil Rock sandstone and channel cutouts of Herrin (No. 6) coal in west-central Illinois: Illinois State Geological Survey Circular 314, 12 p.

Rascoe, B., Jr., and Adler, F.J., 1983, Permo-Carboniferous hydrocarbon accumulations, Midcontinent, U.S.A.: American Association of Petroleum Geologists Bulletin 67, p. 979–1001.

Ravn, R.C., 1986, Palynostratigraphy of the Lower and Middle Pennsylvanian coals of Iowa: Iowa Geological Survey Technical Paper 7, 245 p.

Ravn, R.C., Swade, J.W., Howes, M.R., Gregory, J.L., Anderson, R.R., and Van Dorpe, P.E., 1984, Stratigraphy of the Cherokee Group and revision of Pennsylvanian stratigraphic nomenclature in Iowa: Iowa Geological Survey, Technical Information Series 12, 76 p.

Retallack, G.J., 1990, Soils of the past: Boston, Unwin Hyman Publishing, 520 p.

Robertson, C.E., 1971, Evaluation of Missouri's coal resources: Missouri Geological Survey, Report of Investigation 48, 92 p.

Romanova, E.A., 1967, Nekotorye morfologicheskie charakteristiki oligotrofnykh bolotnykh landshaftov zapadnosibirskoi nizmennosti kak osnova ikh tipologii I rayonirovannii, *in* Nítsenko, A.A., ed., Priroda bolot i metody ikh issledovaniya: Lenningrad, Nauka, p. 63–67.

Ross, C.A., and Ross, J.R.P., 1985, Late Paleozoic depositional sequences are synchronous and worldwide: Geology, v. 13, p. 27–30.

Rowan, E.L., Goldhaber, M.B., and Hatch, J.R., 2002, The role of regional fluid flow in the Illinois Basin's thermal history: Constraints from fluid inclusions and the maturity of Pennsylvanian coals: American Association of Petroleum Geologists Bulletin, v. 86, p. 257–277.

Schopf, J.M., 1938, Spores from the Herrin (No. 6) coal bed in Illinois: Illinois State Geological Survey Report of Investigations 50, 73 p.

Sedimentation Seminar, 1978, Sedimentology of the Kyrock sandstone (Pennsylvanian) in the Brownsville paleovalley, Edmonson and Hart Counties, Kentucky: Kentucky Geological Survey, ser. 10, Report of Investigations 21, 24 p.

Semenova, N.M., and Lapshina, E.D., 2001, Description of the West Siberian Plain, *in* Bleuten, W., and Lapshina, E.D., eds., Carbon Storage and Atmospheric Exchange by West Siberian Peatlands: FGUU Scientific Reports, The Netherlands, Utrecht University, Department of Physical Geography, Utrecht, p. 10-22.

Shearer, J.C., Staub, J.R., and Moore, T.A., 1994, The conundrum of coal bed thickness—A theory for stacked mire sequences: Journal of Geology, v. 102, p. 611–617.

Shultz, M., Klein, J., McKenzie, F.M., Rimmer, S.M., Hower, J.C., and Popp, J.T., 2002, On the road to Paradise: Depositional setting of the Herrin and Paradise coals, western Kentucky coalfield: Nineteenth Annual International Pittsburgh Coal Conference, University of Pittsburgh, Sept. 23-27, 2002, CD-ROM.

Siever, R., 1957, Pennsylvanian sandstones of the Eastern Interior Basin: Journal of Sedimentary Petrology, v. 27, p. 227–250.

Smith, W.H., 1958, Strippable coal resources of Illinois—Part 2, Jackson, Monroe, Perry, Randolph, and St. Clair Counties: Illinois State Geological Survey Circular 260, 35 p.

Smith, W.H., 1961, Strippable coal resources of Illinois—Part 3, Madison, Macoupin, Jersey, Greene, Scott, Morgan, and Cass Counties: Illinois State Geological Survey Circular 310, p. 3–40.

Smith, W.H., and Berggren, D.J., 1963, Strippable coal resources of Illinois—Part 5A, Fulton, Henry, Knox, Peoria, Stark, Tazewell, and parts of Bureau, Marshall, Mercer, and Warren Counties: Illinois State Geological Survey Circular 348, 59 p.

Soderberg, R.K., and Keller, G.R., 1981, Geophysical evidence for deep basins in western Kentucky: American Association of Petroleum Geologists Bulletin 65, p. 226–234.

Stach, E., Mackowsky, M.-Th., Teichmüller, M., Taylor, G.H., Chandra, D., and Teichmüller, R., 1982, Stach's textbook of coal petrology: Berlin, Gebrüder Borntraeger, 535 p.

Stolbovoi, V., and McCallum, I., 2002, Land resources of Russia: Laxenburg, Austria, International Institute for Applied Systems Analysis and the Russian Academy of Sciences, CD-ROM.

Tallis, J.H., 1983, Changes in wetland communities, *in* Gore, A.J.P., ed., Mires: swamps, bog, fen, and moor: Ecosystems of the World: New York, Elsevier, v. 4A, p. 311–318.

Tarnocai, C., Kettles, I.M., and Lacelle, B., 2000, Peatlands of Canada: Geological Survey of Canada, Open File 3834 (1:6,500,000 map).

Tarnocai, C., Kettles, I.M., and Lacelle, B., 2002, Peatlands of Canada Database: Geological Survey of Canada, Open File 4002 (Digital data).

Treworgy, C.G., and Jacobson, R.J., 1979, Paleoenvironments and distribution of low-sulfur coal in Illinois, *in* Cross, A.T., ed., Economic geology: Coal, oil, and gas: Carbondale, Southern Illinois Press, Compte Rendu of Ninth International Congress on Carboniferous Stratigraphy and Geology, v. 4, p. 349–359.

Teichmüller, M., 1989, The genesis of coal from the viewpoint of coal petrography: International Journal of Coal Geology, v. 12, p. 1–87.

Thomas, W.A., 1989, The Appalachian-Ouachita orogen beneath gulf coastal plain between thc outcrops in the Appalachian and Ouachita Mountains, *in* Hatcher Jr., R.D., Thomas, W.A., and Viele, G.W., eds., Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, Geology of North America, v. F-2, p. 537–553.

Thompson, T.L., 1995, The stratigraphic succession in Missouri: Missouri Department of Natural Resources, Division of Gcology and Land Survey, v. 40 (revised), 189 p.

Ting, F.T.C., 1989, Facies in the Lower Kittanning coal bed, Appalachian Basin (U.S.A.): International Journal of Coal Geology, v. 12, p. 425–442.

Treworgy, J.D., and Bargh, M.H., 1984, Coal resources of Illinois: Illinois State Geological Survey, 1:500,000, 5 map sheets.

Tri-state Committee on Correlation of the Pennsylvanian System in the Illinois Basin, 2001, Toward a more uniform stratigraphic nomenclature for rock units (formations and groups) of the Pennsylvanian system in the Illinois Basin: Illinois Basin Consortium Study 5: Illinois State Geological Survey, Indiana Geological Survey, and Kentucky Geological Survey, 26 p.

Tully, J., 1996, Coal fields of the conterminous United States: U.S. Geological Survey Open-File Report OF96–92, 1 map.

Udden, J.A., 1912, Geology and mineral resources of the Peoria quadrangle, Illinois: U.S. Geological Survey Bulletin 506, 103 p.

United States Department of Energy, 2001, Energy Information Administration Annual Coal Report, Web data tables, <www.eia.doe.gov/cneaf/coal/page/acr/acr_html_tabs.html>.

Utgaard, J., 1979, Paleoecology and depositional history of rock strata associated with the Herrin (No. 6) Coal Member, Delta Mine, southern Illinois, *in* Palmer, J.E., and Dutcher, R.R., eds., Depositional and structural history of the Pennsylvanian System of the Illinois Basin, Ninth International Congress of Carboniferous Stratigraphy and Geology, Field Trip 9: Urbana, Illinois State Geological Survey, p. 86–92.

Walter, H., 1977, The oligotrophic peatlands of western Siberia: The largest peino-heiobiome in the world: Vegetatio, v. 34, p. 167–178.

Wanless, H.R., 1939, Pennsylvanian correlation in the Eastern Interior and Appalachian coal fields: Boulder, Colorado, Geological Society of America Special Paper 17, 130 p.

Wanless, H.R., 1975a, Distribution of coals in the United States, *in* McKee, E.D., and Crosby, E.J. (coords.), Paleotectonic investigations of the Pennsylvanian system in the United States; Part II, Interpretive summary and special features of the Pennsylvanian system: U.S. Geological Survey Professional Paper 853, p. 33–47.

Wanless, H.R., 1975b, Illinois Basin region, *in* McKee, E.D., and Crosby, E.J. (coords.), Paleotectonic investigations of the Pennsylvanian system in the United States; Part I Introduction and regional analyses of the Pennsylvanian system: U.S. Geological Survey Professional Paper 853, p. 71–95.

Wanless, H.R., 1975c, Missouri and Iowa, *in* McKee, E.D., and Crosby, E.J. (coords.), Paleotectonic investigations of the Pennsylvanian system in the United States; Part I Introduction and regional analyses of the Pennsylvanian system: U.S. Geological Survey Professional Paper 853, p. 97–114.

Wanless, H.R., 1975d, Appalachian region, *in* McKee, E.D., and Crosby, E.J. (coords.), Paleotectonic investigations of the Pennsylvanian system in the United States; Part I Introduction and regional analyses of the Pennsylvanian system: U.S. Geological Survey Professional Paper 853, p. 17–62.

Wanless, H.R., and Shepard, F.P., 1936, Sea level and climatic changes related to Late Paleozoic cycles: Geological Society of America Bulletin, v. 47, p. 1177–1206.

Wanless, H.R., and Weller, J.M., 1932, Correlation and extent of Pennsylvanian cyclothems: Geological Society of America Bulletin, v 43, p. 1003–1016.

Wanless, H.R., and Wright, C.R., 1978, Paleoenvironmental maps of Pennsylvanian rocks, Illinois basin and northern Midcontinent region: Geological Society of America Map and Chart Series, MC-23, 1:3,937,000, 165 plates, 32 p.

Wanless, H.R., Tubb, J.B., Jr., Gednetz, D.E., and Weiner, J.L., 1963, Mapping sedimentary environments of Pennsylvanian cycles: Geological Society of America Bulletin, v. 74, p. 437–486.

Wanless, H.R., Baroffio, J.R., and Trescott, P.C., 1969, Conditions of deposition of Pennsylvanian coal beds: Geological Society of America Special Paper 114, p. 105–142.

Weibel, C.P., 1996, Applications of sequence stratigraphy to Pennsylvanian strata in the Illinois basin, *in* Witzke, B.J., Ludvigson, G.A., and Day, J., eds., Paleozoic sequence stratigraphy, Views from the North American Craton: Geological Society of America Special Paper 306, p. 331–339.

Weller, J.M., 1930, Cyclical sedimentation of the Pennsylvanian period and its significance: Journal of Geology, v. 38, p. 97–135.

Willard, D.A., 1993, Vegetational patterns in the Springfield Coal (middle Pennsylvanian): Comparison of miospore and coal-ball records, *in* Cobb, J.C., and Cecil, C.B., eds., Modern and ancient coal-forming environments: Geological Society of America Special Paper 286, p. 139–152.

Willard, D.A., DiMichele, W.A., Hower, J.C., Eggert, D.L., Rexroad, C.B., and Scott, A.C., 1995, Paleoecology of the Springfield Coal member (middle Pennsylvanian, Illinois Basin) near the Leslie Cemetery Paleochannel, southwestern Indiana: International Journal of Coal Geology, v. 27, p. 59–98.

Witzke, B.J., 1990, Paleoclimatic constraints for Paleozoic palaeolatitudes of Laurentia and Euramerica, *in* McKerrow, W.S., and Scotese, C.R., eds., Palaeozoic palaeogeography, and biogeography: Geological Society [London] Memoir 12, p. 57–73.

Wright, C.R., 1975, Environments within a typical Pennsylvanian cyclothem, *in* McKee, E.D., and Crosby, E.J., eds., Paleotectonic investigations of the Pennsylvanian system in the United States, Part II, interpretive summary and special features of the Pennsylvanian system: United States Geological Survey Professional Paper 853, p. 73–84.

Yefremov, S.P., and Yefremova, T.T., 2001, Present stocks of peat and organic carbon in bog ecosystems of west Siberia, *in* Bleuten, W., and Lapshina, E.D., eds., Carbon storage and atmospheric exchange by West Siberian peatlands: Utrecht University, The Netherlands, Department of Physical Geography, p. 23–37.

Ziegler, A.M., Scotese, C.R., McKerrow, W.S., Johnson, M.E., and Bambach, R.K., 1987, Paleozoic paleogeography: Annual Review of Earth and Planetary Science, v. 7, p. 473–502.

Zoltai, S.C., and Pollett, F.C., 1983, Wetlands in Canada: Their classification, distribution, and use, *in* Gore, A.J.P., ed., Mires: swamps, bog, fen, and moor: Ecosystems of the World: New York, Elsevier, v. 4B, p. 245–268.

Zubovic, P., 1966, Physico-chemical properties of certain minor elements as controlling factors in their distribution in coal, *in* P.H. Given, ed., Coal science: American Chemical Society Advances in Chemistry Series 55, p. 211–231.

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