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 km², the Springfield covers 73,500–81,000 km², and the Herrin spans 73,900 km². Each has correlatives in the Western Interior Basin, such that their entire regional extent varies from 116,000 km² to 200,000 km². 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 source) 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.
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 km² (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 stable 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 palaeochannels 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 km² (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 palaeomire.

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 km² (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 km² (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 km² (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
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).
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. Midecontinent 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 cyclothem 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 Midecontinent cyclothems and bundles of cyclothem 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.
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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; Cecil 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 peats 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 the basin (Hatch and Affolter, 2002). The Herrin Coal covers an area of 73,900 km² (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 km².

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.
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 km² (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 km²). 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 km². It reaches...
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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.

G Galatia paleochannel  L Leslie Cemetery paleochannel
H Henderson paleochannel W Walshville paleochannel
Dm DuQuoin Monocline

Figure 10. Isopach map of Galatia paleochannel. The Galatia paleochannel has 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 km² (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.
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 splayform 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.
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 contains 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 *Anacanthotrites 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 *Anacanthotrites 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,
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, 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 km². Hence, the combined peatland complex covered an area of 91,500–99,000 km². If the basins were connected, the Springfield-Summit paleocomics may have covered an area of 121,500 km². 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. 15A; 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 (Westphalian D) boundary with the Whitebreast coal of Iowa, and thereby its equivalents, the Croweburg and Colchester. These coals all occur within the Shopfites colchestsens-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 km² (Fig. 16A). If continuous with the Colchester, as inferred by Wanless and Wright (1978), the total original peatland area exceeded 200,000 km² (Fig. 16A). Correlative coals do not occur west of the Nemaha Uplift, where marine and marginal marine facies dominate (Fig. 16A).

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**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 overlain 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 Lepidodendron, 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 lycopsids 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 resinorum, 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. Vitritine dominance in each of the Desmoinesian coals also suggests topogenous to soligenous mires as vitritine 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, Lycopsodora-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 areas 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 km², could have constituted the upper Herrin paleomire.

There was undoubtedly some lateral transition 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 in 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 km² in the Eastern Interior Basin alone. The Colchester and equivalent paleomires may have covered an area of more than 200,000 km² 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 km² in northern Canada (Zoltai and Pollett, 1983) and 1.39 million km² in West Siberia (Yefremov and Yefremova, 2001).

In terms of individual peatlands, Ziegler et al. (1987) reported a 300,000 km² area of peat on the southwest margin of Hudson Bay, Canada (Fig. 17A), as the largest continuous area...
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 correlate 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 cyclothem (discussed in Heckel, 1994).

Although cyclothem 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
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 glacioeustacy, 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, Dunbarrella, and conodonts. These shales represent widespread condensed sections (Heckel, 1986, 1999). The Herrin Coal is overlain by the Anna Shale and the Breton 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 (Kylyyski, 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 interbasinal peatland development.

**Topographic and Hydrologic Controls**

Another important reason for the broad extent of the Colchester 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, glaciated-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 (Martin 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
Desmoinesian coal beds of the Eastern Interior

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.

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 fast 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 syn-depositional channel system of the three coals. Higher water tables across larger areas could have inhibited the proliferation 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 syn-depositional 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 subjacent 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.
of the Pennsylvanian, there was a general decrease in tectonic accommodation from the Moron 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.

Intrabasin 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 km².

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


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


