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Petrography, palynology, and paleoecology of the Lower Pennsylvanian Bon Air coal, Franklin County, Cumberland Plateau, southeast Tennessee

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Abstract

Stratigraphy, palynology, petrography, and geochemistry of the Bon Air coal from the Armfield, Dotson, Rutledge, and Shakerag mine sites of Franklin County, Tennessee suggest that Bon Air seams at all sites were small (≤ 1.0 mile, 1.6 km), spatially distinct paleomires that evolved from planar to domed within the fluviodeltaic Lower Pennsylvanian Raccoon Mountain Formation. Of observed palynoflora, 88–97% are from lycopsids prevalent in the Westphalian. *Densosporites* palynomorphs of small lycopsids (e.g., *Omphalophloios*) dominate at the shale-hosted Armfield site, while *Lycospora* palynoflora of large arboreous lycopsids (especially *Lepidodendron*, with lesser *Lepidophloios harcourtii* and *Lepidophloios hallii*) dominate where intercalated siltstone/sandstone/shale hosts the coal (all other sites). Palynoflora of other lycopsids (*Sigillaria* and *Paralycopodites*), tree ferns, seed ferns, small ferns, calamites, and cordaites are generally minor. Genera of clastic-associated *Paralycopodites* are most common in Shakerag's coal (≥ 10%), yet quite rare in Rutledge or Dotson coals. Overall, the palynomorph assemblages suggest that the Bon Air paleomires were forest swamps, and Early Pennsylvanian in age (Westphalian A, Langsettian).

Dominant macerals at all sites are vitrinites, with fine collodetrinite (from strongly decomposed plant debris) more common than coarser collotelinite (from well-preserved plant fragments), and with lesser inertinites (fusinite and semifusinite) and liptinites (dominantly sporinite). Shakerag's coal has greatest abundance (mineral-matter-free) of collotelinite (up to 47%) and total vitrinite (74–79%) of any sites, but lowest liptinite (12–14.5%) and inertinite (7–11%). The Dotson and Rutledge seams contain moderate liptinite (21–23%) and highest inertinite (36–37%), lowest vitrinite (≤ 41%), and lowest collotelinite (13–15%). Armfield's seam has relatively high liptinite (26–28%) and vitrinite (56.5–62%), but rather low inertinite (12–15%). Moderately high ash (11.0–20.0%) and low to moderate sulfur (1.24% avg.) are typical, but ash may locally be up to 38% and sulfur up to 2.9%. Volatile matter (32.1–41.3%), calorific value (33.3–34.9 MJ/kg MAF), moisture (2.2–3.4%), and vitrinite reflectance (0.70–0.84% R_{max}; 0.64–0.79% R_{random}) place the Bon Air's rank as high-volatile-A bituminous (hvAb).

The Armfield coal was probably a channel-distal paleomire, perhaps an oxbow lake or floodplain depression, which domed and then subsided back to planarity prior to burial. Features of its basal and uppermost benches suggest low-lying, often-flooded (but periodically dry) mires marked by fluvial influxes and diverse lycopsid growth. These include variable inertinite, common palynoflora of both small lycopsids (*Omphalophloios*-like) and large arboreous ones (*Lepidophloios* and *Lepidodendron*), minor but significant palynoflora of subaerial levee or levee/mire transition species (especially *Paralycopodites*), moderate to high ash, variable sulfur, and elevated levels of commonly fluvial trace elements (e.g., Al, Cr, REEs, Rb, Sr, Th, V, Y, and Zr). These benches

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also contain high total vitrinite, high collotelinite/collodetrinite ratios, and clays with moderate to low kaolinite/quartz ratios, all consistent with the near-neutral pH and limited peat degradation that typify such planar mires. By contrast, middle benches at Armfield reflect mires domed above the land surface, less-often flooded, less-preservational, and of lower pH: coals have lower ash, vitrinite, and collotelinite, less palynoflora of both large arboreous lycopsids and *Paralycopodites*, and high proportions of kaolinite, liptinite, and *Densosporites*.

Similar data at Shakerag suggest that its mire also grew from planar to domed. However, more abundant *Paralycopodites*, a kaolinite-poor but quartz-and-illite-rich underclay, benches alternately ash-rich and ash-poor, and an upper bench truncated by channel sandstone, suggest that it was channel-proximal and prone to intermittent clastics. It is unclear if it returned to planarity prior to burial. The mires at Dotson and (especially) Rutledge, with more ferns, more inertinite, less *Paralycopodites* and less vitrinite, were probably topographically elevated or protractedly domed mires, more vulnerable to drought or fire.

Keywords: Bon Air bituminous coal; Sewanee, Tennessee; Palynology; Paleoecology; Lower Pennsylvanian; Geochemistry

1. Introduction and previous work

The Bon Air coal lies within the Lower Pennsylvanian Raccoon Mountain Formation (RMF) (Gizzard Group, lower Pottsville Series), and typically consists of one to four (locally six) seams discontinuously distributed along 60 miles (96 km) of RMF strike-length (Fig. 1). Previous Bon Air work includes quadrangle-scale mapping (Ferguson, 1969a,b; Garman, 1967, 1969a,b; Garman and Milici, 1967a,b; Luther, 1964; Luther and Swingle, 1964a,b; Luther and Hershey, 1964; Milici, 1967a,b, 1979a,b; Milici and Finlayson, 1979; Moore, 1983a,b; Swingle, 1963, 1964) and one proximate analysis (Luther and Swingle, 1964b). Some stratigraphic columns (Churnet, 1996; Clark et al., 1993) show the Bon Air only at the RMF top, but seams can also occur in its base and middle. Petrography on Raccoon Mountain basin coals (Kuehn et al., 1983) does not address the Bon Air.

The Bon Air was mined as early as 1836 (Goodspeed, 1887) between Bon Air and Sparta, Tennessee. Production, from both Cumberland Plateau western escarpment areas (Sewanee to Sparta, Tennessee) and the Sequatchie Valley and Walden's Ridge (Whitwell to Morgan Springs to Pennine, Tennessee) (Fig. 1), was important into the early 1900s. However, mining was scattered, intermittent, and small-scale because seams are laterally discontinuous (strike-length ≤ 100–2000 ft, 30–610 m, rarely to 8400 ft, 2560 m), locally argillaceous or parting-rich, crushed or offset by low-angle thrusts, and irregular in thickness (typically ≤ 20–48 in., 0.5–1.2 m, but pinched out completely or structurally thickened to 11.5 ft, 3.5 m, over short distances) (Phalen, 1911; Luther and Hershey, 1964).

The purpose of our study is to present petrologic, palynologic, and geochemical data from the Bon Air coal, and to use these data to discuss the Bon Air's paleoenvironment. Our study focused on exposures near Sewanee, Franklin County, Tennessee, where more workings occur than in any other area (Table 1).

2. Stratigraphic relations

Study area stratigraphy is comprised of two main sections, a lower section (~ 700 ft thick, 213 m) of Mississippian marine carbonates and lesser shales, and an upper section (150–230 ft thick, 46–70 m) of Lower Pennsylvanian terrestrial siliciclastics (sandstones, siltstones, conglomerates and minor shales) (Figs. 2 and 3a) (Knoll and Potter, 1998). The Raccoon Mountain Formation (0–150 ft thick, 0–46 m), which hosts the Bon Air, is the earliest of these siliciclastics, lying disconformably above carbonates and shales of the Upper Mississippian Pennington Formation (190–350 ft thick, 58–107 m), and disconformably below the Warren Point Sandstone (30–130 ft thick, 9–40 m). The Warren Point is a fine- to medium-grained sandstone, locally thick-bedded (up to 20 ft, 6 m), with ubiquitous southwest-dipping cross-beds, and thin coal stringers (<1 in. thick, 2.5 cm) and calamites, *Lepidodendron*, and *Sigillaria* impressions near its base. It contains local interbeds of coal-bearing, plant-fossil-rich, laminated clay and silt (Signal Point Shale), generally 0.1–30 ft thick, 0.02–9.0 m, but up to 60 ft thick, 18 m, when present at the top of the Warren Point (Hurd and Stapor, 1997). Disconformably overlying the Warren Point and/or its Signal Point Shale is the Sewanee Conglomerate, a quartz-rich (>98 vol.%), quartz pebble-bearing conglomeratic sandstone (up to 130 ft thick, 40 m) with trough and planar cross-beds, local shale beds 1–2 in. thick (2–5 cm), rare coal stringers (up to 1 in. thick, 2.5 cm), and local shale or siderite intraclasts up to 16 in. long (41 cm).

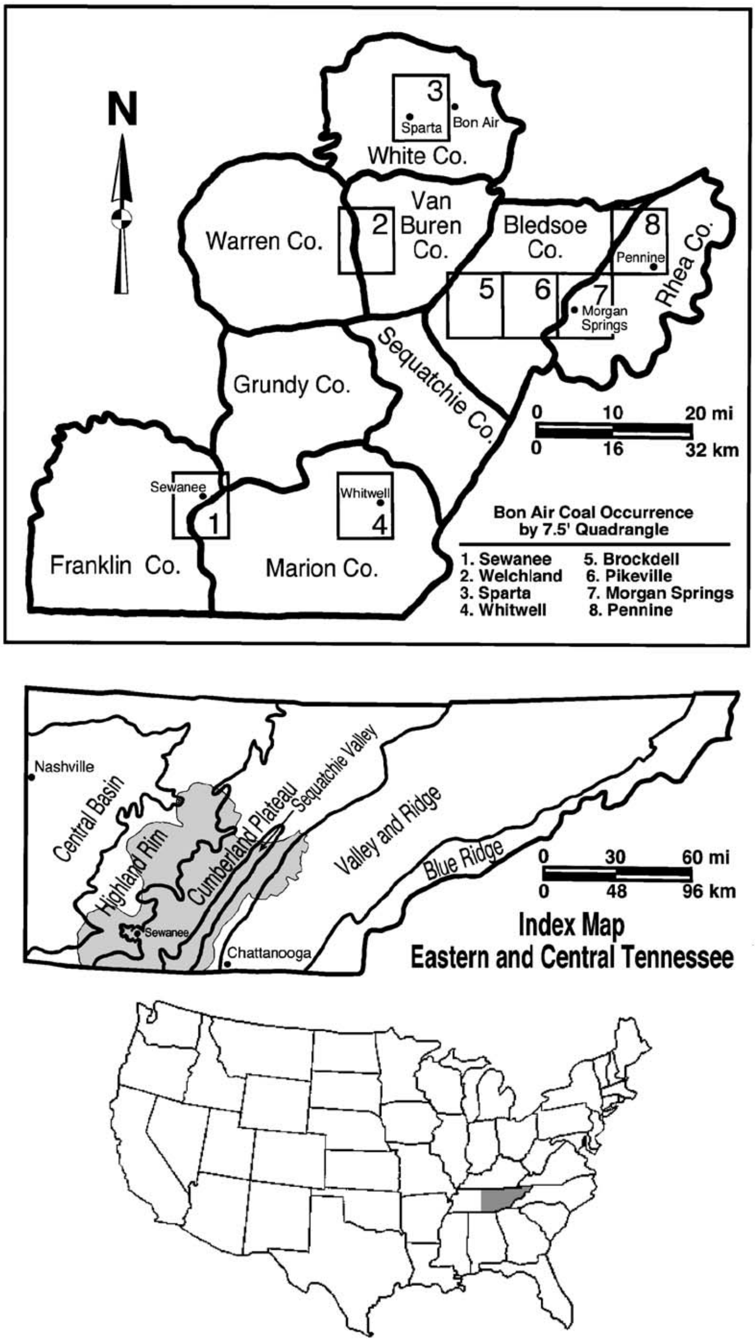

Fig. 1. Bon Air coal occurrence in Tennessee, USA, by county and 7.5′ quadrangle.

The siliciclastic units were deposited by Early Pennsylvanian, orogenically-sourced (Churnet, 1996), braided stream systems that flowed southwest along the rising Appalachians (Churnet and Bergenback, 1986; Archer and Greb, 1995; Hurd and Stapor, 1997). Local upward-coarsening of grains within units and disconformable to transitional boundaries between units suggest that the systems were broadly progradational. The change from shallow marine to fluvial was a striking one: the disconformity between the RMF and the underlying tidal flat-deposited Pennington Formation (Figs. 2 and 3a) is marked by paleokarst, paleosols, topographic relief up to 40 ft (12 m), and thick lag conglomerates (0.5–36 in. thick, 0.01–1.0 m) with

Table 1
Occurrences of the Bon Air coal, by Tennessee topographic quadrangle and county, showing adits, coal thicknesses, and total strike length of coal workings (in lieu of production data) as relative indicators of coal volume present or produced

Topographic quadrangle	County	Adits	Seam thickness, in. (cm)	Strike length of coal workings [a]	References
Sewanee [b]	Franklin	59	1–42 (1–107)	2.3 miles (3.7 km)	This study; Moore, 1983a; Killebrew, 1876
Welchland [b]	Van Buren	5	1–96 (1–244)	0.8 mile (1.2 km)	Garman, 1969a,b
Sparta [b]	White	9	1–38 (1–97)	1.1 miles (1.8 km)	Ferguson, 1969a,b
Whitwell [c]	Marion	15	1–36 (1–91)	2.3 miles (3.7 km)	Milici, 1979a,b
Brockdell [c]	Bledsoe	4	1–60 (1–152)	0.2 mile (0.3 km)	Garman and Milici, 1967b
Pikeville [c]	Bledsoe	2	1–48 (1–122)	1.7 miles (2.7 km)	Milici, 1967b; Butts and Charles, 1917
Pennine [c]	Rhea	2	unknown	100 ft (30 m)	Luther and Swingle, 1964a
Morgan Springs [c]	Rhea	9	1–138 (1–351)	3.2 miles (5.2 km)	Luther and Swingle, 1964b

[a] Total of all Bon Air segments sufficiently thick that they were mined (≥ 10 in., 25 cm).
[b] Bon Air coal along the western escarpments of the Cumberland Plateau.
[c] Bon Air coal in the Sequatchie Valley and Walden's Ridge areas of the Cumberland Plateau.

clasts up to 6 in. (15 cm) in size (Caudill et al., 1992; Knoll and Potter, 1998).

Features of the RMF suggest that it formed from the initial phase of these developing fluvial systems in a low-energy fluviodeltaic environment locally subjected to minor marine transgression. For example, its lower to middle parts contain delta channel, levee, and overbank deposits of silt and clay (Bergenback et al., 1992a), discontinuous Bon Air coal, and local marginal marine features such as tidal-flat shale, dark bay-fill shale, tidal channels, and rare brachiopods (Bergenback, 1993). Stratigraphically higher parts, which can also include Bon Air seams, are dominated by fluvial sands and silts with bedding features indicative of meandering channels (Bergenback et al., 1992b).

Within the study area, mineable Bon Air coal thicknesses (> 10 in., 25 cm) occur largely in four mine sites 1–1.5 miles (1.6–2.4 km) from one another: Armfield, Dotson, Rutledge, and Shakerag (Fig. 3a–b). The Armfield site contains a single Bon Air seam (1.2 ft thick, 0.36 m), in the top one-third of well-exposed RMF composed entirely of shale (Fig. 3b). At

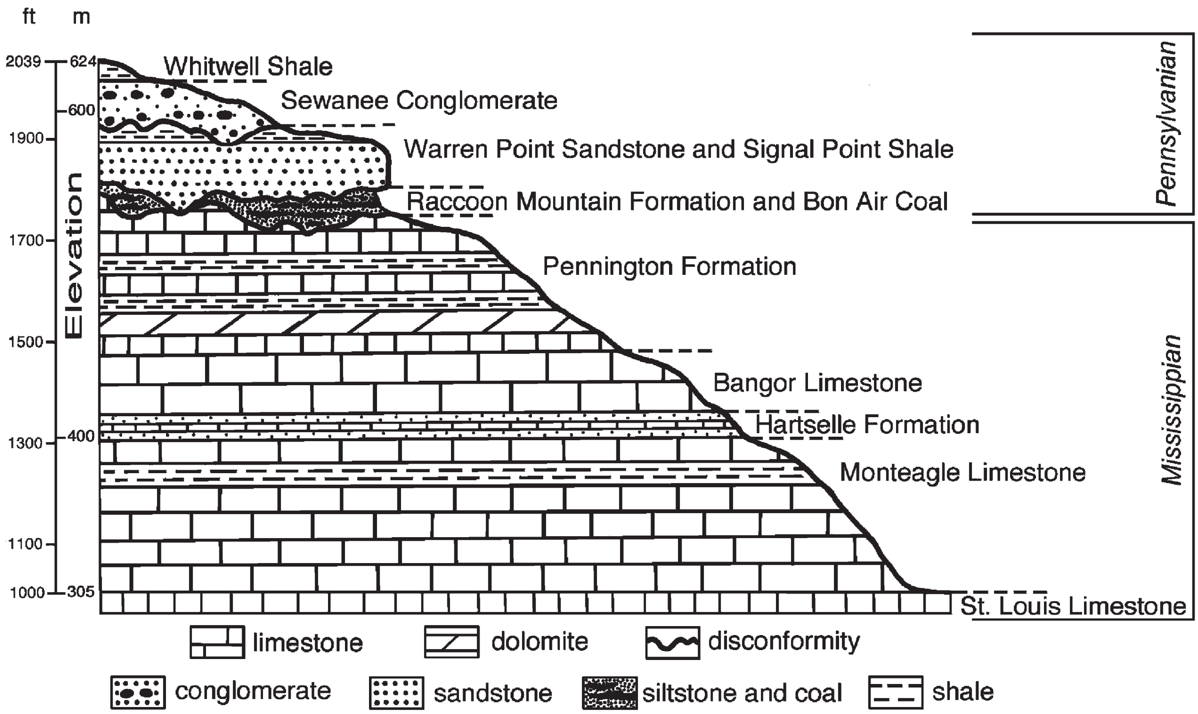

Fig. 2. Generalized stratigraphy of the Cumberland Plateau in the vicinity of Sewanee, Tennessee (modified after Knoll and Potter, 1998).

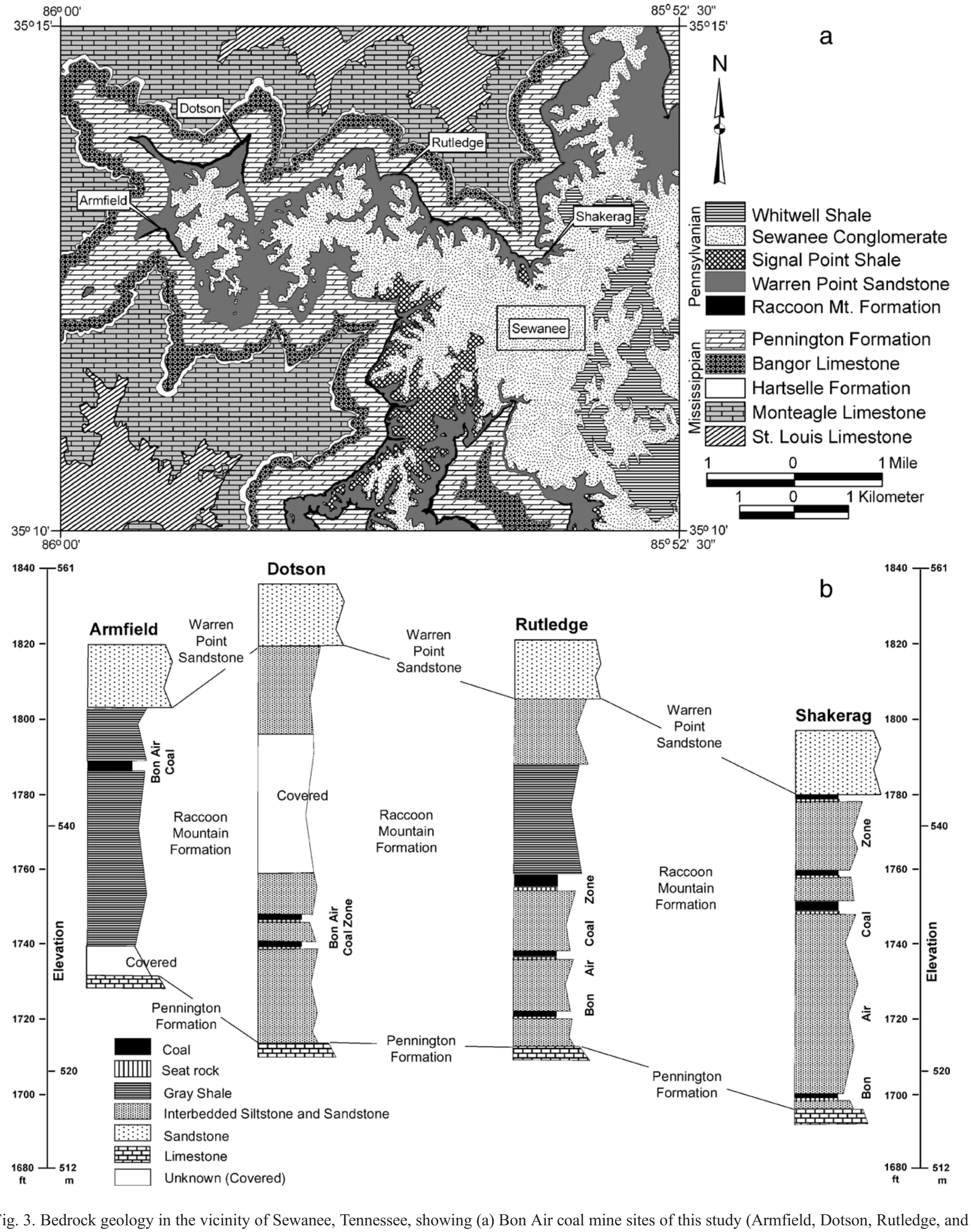

Fig. 3. Bedrock geology in the vicinity of Sewanee, Tennessee, showing (a) Bon Air coal mine sites of this study (Armfield, Dotson, Rutledge, and Shakerag) and (b) lithological profiles of the Bon Air coal and surrounding strata at each mine site. Seam thicknesses at Armfield and Shakerag were measured; those at Dotson and Rutledge were estimated from workings and dumps.

all other sites the RMF is composed of complexly interbedded shales, sandstones, and flaser-bedded siltstones, with two to four Bon Air seams in its top, middle, and/or bottom (Fig. 3b). In the few still-accessible Shakerag adits, the main seam is well-exposed, 1.5–2.0 ft thick (0.45–0.6 m), locally cut by low-angle to bedding-parallel thrusts, and abruptly overlain by intraclastic, coal-stringer- and calamites-bearing scour-and-fill channel sandstone up to 4.5 ft (1.4 m) thick. All adits at Dotson and Rutledge are collapsed. Historical records (Trustee Proceedings, 1872, 1874, 1884, 1917, 1922; Killebrew, 1876, 1881) suggest sites were mined largely from the 1870s to the early and mid-1900s, that Rutledge had the thickest seam (avg. 2.5 ft, 0.76 m, locally to 3.5 ft, 1.1 m), and that Dotson's seams were thin (<1.5 ft, 0.45 m). Generally poor exposures preclude thorough stratigraphic analysis of the RMF at mine sites, but poor seam correlation from site to site and lack of workings between sites suggest all seams were spatially and perhaps temporally distinct paleomires of quite small size (≤1.0 mile wide, 1.6 km, at Rutledge; <0.2 mile wide, 0.3 km, for all others). Relative ages of the different paleomires are not clear. While most seams are higher in the RMF section at Armfield and Shakerag than at Dotson or Rutledge (Fig. 3b), disconformities are common at both the top and bottom of the RMF, making temporal correlations between seams difficult.

3. Methods

Twenty 4-kg coal samples (4 channel and 9 bench samples from Armfield and Shakerag, 7 mine dump samples from Rutledge and Dotson) and six 8-kg seat- or roof-rock samples were collected. Sampling avoided clearly weathered coal and was from the main seam(s) mined in the past—the thickest seam at Rutledge and Shakerag, both Dotson seams, and the one Armfield seam.

Using standardized procedures (ASTM, 1999a) at the Center for Applied Energy Research, vitrinite reflectance was determined on three coal samples. Proximate analyses (moisture, ash, volatiles, fixed carbon), plus calorific value and sulfur, were conducted on 11 coal samples by CTE (Commercial Testing and Engineering Company, Birmingham, Alabama), following ASTM procedures (ASTM, 1990a, 2000). Sulfur forms (organic versus pyritic) were determined on five of these 11 samples, also by CTE, according to ASTM standards (ASTM, 1990b). Ash yields and sulfur contents reported in this paper are on a dry basis.

For the palynological study, each coal, seat- and roof-rock sample was crushed to −20 mesh (846 μm), and prepared according to ASTM standards (ASTM, 2000) in laboratories of the Kentucky Geological Survey to produce a representative 50 g subsplit, of which 5 g were isolated for palynological determination. A total of 250 spores in Canada balsam mounts were counted in each sample to determine relative percentages of palynomorph taxa. Parent plant groups (lycopsid, fern, etc.) were assigned to palynomorphs, based on compilations by Ravn (1986) and Eble (1988). Coal petrography and maceral analysis followed ASTM guidelines (ASTM, 1999b), with maceral abundances based on point counts of 1000 points, 500 from each of two polished pellets. Coarse vitrinite fragments (generally ≥20–30 μm) of moderate reflectance and without fine-grained mineral debris were counted as collotelinite; fine-grained matrix vitrinite (generally ≤3 μm), with lower reflectance and generally ubiquitous mineral inclusions, was counted as collodetrinite (ICCP, 1998).

For X-ray diffraction (XRD) analysis of clay mineral contents of the coal, seat- or caprock, one subsplit of Armfield roof shale and of each of the coal benches and underclays at Armfield and Shakerag were crushed to −60 mesh (250 μm). (The quartz sandstone caprock at Shakerag was not sampled for XRD-analysis.) To avoid any of the potential mineralogic alterations that low-temperature ashing has been shown to produce (Vassilev and Vassileva, 1996; Ward et al., 2001; Vassilev and Tascón, 2003), XRD analysis of coal samples was conducted on their −60 mesh whole-coal splits rather than on their ashes. To better quantify contents of seatrock and caprock, these samples were X-rayed in size fractions produced by sonic disaggregation and centrifugation (<0.5 μm, 0.5–0.75 μm, 0.75–1.5 μm, >1.5 μm). All XRD scans (air-dried, glycolated, and heated) utilized CuKα radiation on a Siemens D5000 diffractometer at the University of the South, using long count times (2–225 s) and small step sizes (0.008–0.020°) to enhance peak definition and intensity. While Rietveld-based methods have been shown useful in coal XRD analysis (e.g., Mandile and Hutton, 1995; Ward and Taylor, 1996; Ward et al., 2001), this study followed methods of sample preparation and clay identification (Reynolds and Hower, 1970; Russell and Rimmer, 1979) and internal standard quantification procedures (Brindley, 1980; Moore and Reynolds, 1997) which have produced consistent semi-quantitative mineral percentage estimations (±5–10%) in higher-ash whole coals like the Bon Air (Renton et al., 1984; Huggins, 2002; Vassilev and Tascón, 2003).

4. Results

4.1. Palynology

Lycopsid spores and pollen are by far the most common palynoflora in all Bon Air coal samples (channel, dump, and bench) (Table 2, Figs. 4–6), with large lycopsid trees and small lycopsids (Fig. 7) together accounting for 88–97% of all observed palynomorphs. In seams bounded by complexly intercalated siltstones, sandstones, and shales (Dotson, Rutledge, and Shakerag), lycopsid palynoflora are overwhelmingly those of large arboreous lycopsids. These include abundant *Lycospora pusilla* (26–61.2% of observed palynoflora, avg. 38.5%, representing the Westphalian *Lepidodendron hickii*), lesser *Lycospora granulata* (1.2–28.8%, avg. 14.1%, from the thicker-barked *Lepidophloios hallii* more common in the Early to Middle Pennsylvanian (late Westphalian)), and *Lycospora pellucida* (1.6–20.8%, avg. 9.8%, from the thinner-barked, and more commonly early Westphalian, *Lepidophloios harcourtii*) (DiMichele and Phillips, 1994).

In sharp contrast, palynoflora in the shale-hosted Armfield seam are dominated by *Densosporites* (52.4–61.2% of observed palynoflora, avg. 56.0%), and *L. harcourtii* palynoflora (15.2–27.6%, 22.2% avg.) are much more common than those of *Lepidodendron* (7.2–19.2%, 12.3% avg.) or *L. hallii* (2.6% avg.). *Densosporites* was produced prolifically by *Omphalophloios*, a wood-tissue-poor, small (≤10 ft, 3 m) lycopsid (Remy and Remy, 1975; Wagner, 1989; Wagner et al., 1992), with a generally unbranched stem ≤1 ft (30 cm) in diameter. White (1898, 1899) first described *Omphalophloios* from Missouri, USA, but well-preserved reproductive and vegetative remains from Puertollano, Spain, respectively denoted *Sporangiostrobus* (Bode, 1928) and *Bodeodendron* (Wagner and Spinner, 1976), created the name *Bodeodendron/Sporangiostrobus* for this *Densosporites* producer (e.g., Wagner, 1989). More recent work (Brouschmiche-Delcambre et al., 1995) has shown that *Sporangiostrobus* and *Bodeodendron* are the same *Omphalophloios* that White first described, and we have therefore used the name *Omphalophloios* in this paper. Importantly, the *Densosporites* palynomorphs this species produced are found in many different habitats in Appalachian coals, and it is not yet clear if they or other similar crassicingulate palynomorphs were produced only by *Omphalophloios* or rather by several small lycopsids (Eble and Hower, 1995; Eble, 1996).

Other Pennsylvanian palynoflora is less abundant. *Lycospora orbicula* and *Lycospora micropapillata* palynomorphs, from the moderate-sized Early- to Middle-Pennsylvanian lycopsid *Paralycopodites* (<33–50 ft tall, 10–15 m) (DiMichele, 1980; DiMichele and Phillips, 1985; Bateman et al., 1992), comprise 9.6% of Shakerag coal palynoflora and 3.2% of those in Armfield seatrock, but are otherwise uncommon except in individual benches (discussed below). Minor *Crassispora kosankei*, representing *Sigillaria*, is present at all sites.

All sites contain minor tree fern palynoflora (e.g., *Punctatisporites minutus*, produced by *Psaronius* sp.), and pteridosperm (seed fern) spores (e.g., *Schulzospora rara*). Small-fern spores (e.g., *Granulatisporites*, *Deltoidaspora*, and especially the *Lophotriletes* spores that seed ferns may also have produced; Brouschmiche, 1983) occur at all sites, but are most common in coal at Dotson and Rutledge and dominate the plants of Bon Air seatrock (sampled at Armfield). Minor *Calamospora*, from calamites, occurs at nearly all sites, while cordaites pollen (e.g., *Florinites*) is quite rare and occurs only in the Shakerag top bench.

Bench-column samples (Shakerag and Armfield) show distinct upward changes in Bon Air palynoflora from basal to upper benches (Table 2, Figs. 5 and 6). At Shakerag, palynoflora of large arboreous lycopsids (*Lepidodendron* and *Lepidophloios*) increase from basal bench to next bench, then decrease upwards to the seam top, accompanied by opposite trends (decreases, then increases) in *Densosporites* palynomorphs of small *Omphalophloios*-like lycopsids. Seed fern palynomorphs, and to some degree small fern and calamites palynoflora, are most abundant in the two lowest Shakerag benches, where both total large lycopsid palynoflora and those of *Lepidodendron* in particular are most abundant. At Armfield, while *Densosporites* is ubiquitously abundant and fern and calamites genera are generally low, the coal is least *Densosporites*-rich in the basal and two upper benches (where large-lycopsid genera are most abundant) and most *Densosporites*-rich in the two middle benches (where large-lycopsid genera are less abundant). Palynoflora of *Paralycopodites* are more common in Armfield's basal and uppermost benches (both 1.6%) than in intervening benches (0.4% average), but they are considerably more abundant in all benches at Shakerag, especially its upper two benches (≤10%, compared to 3.4% average in the lower two benches) (Figs. 5 and 6, Table 2). *Sigillaria* palynomorphs occur only in the top Shakerag bench and in the bench just below the top at Armfield, and cordaites palynoflora (*Florinites*) occur only in the top bench at Shakerag.

Overall, palynoflora suggest that Bon Air paleomires were quite different. The Shakerag mire (especially

Table 2
Spore taxa, listed according to affinity, from channel, dump, seat rock, and bench-column samples of the Bon Air coal, Sewanee Quadrangle, Tennessee

	Coal channel and dump samples				Seat rock	Coal bench column samples								
	Armfield	Dotson	Rutledge	Shakerag	Armfield	Shakerag				Armfield				
	4	# 1,2	AR-8	1		Base	Lower–Mid	Upper–Mid	Top	Base	Lower–Mid	Upper–Mid	Lower–Top	Upper–Top
Lycospora pellucida	15.2	20.8	11.2	1.6	13.2	10	9.6	10	5.6	27.6	24.4	26	18.8	21.2
L. pusilla	18.8	40	38.4	61.2	11.2	35.6	35.6	26	32.4	9.6	8.8	7.2	19.2	10
L. granulata	0.4	2	1.2	1.6		22.4	28.8	23.6	18.8	0.8	1.6	3.2	2.4	7.2
L. orbicula		0.4	0.4	6		3.6	3.2	10.8	10					0.8
L. micropapillata	0.8	1.2	1.2	3.6	3.2					1.6		1.2		1.6
L. rotunda		1.6	0.4	0.4										
L. torquifer		2.4	0.4											
L. cf. rugosa														0.8
Crassispora kosankei		0.4	0.4	1.2					0.4				1.2	
Total Lycopsid Trees	35.2	68.8	53.6	75.6	27.6	71.6	77.2	70.4	67.2	39.6	34.8	37.6	41.6	41.6
Densosporites lobatus	1.2		2		2.4					1.2	1.2	0.4	0.8	
D. sphaerotriangularis	56.4	16.4	35.6	19.6	0.8	2.8	6	17.2	17.2	47.6	52.4	42	45.2	42.4
D. covensis	0.4	0.8					0.4		0.4				0.8	
D. irregularis	0.4			1.2		13.2	3.6	1.2	0.4	2.4	3.2	2.8	2	4
D. tenui	1.2			0.8		0.8	0.4	1.6	2	3.2	4	4	1.2	6
D. annulatus		1.2					0.4		0.8	1.2	0.4	1.2	1.2	1.6
D. triangularis								0.8	0.8			2	2	
Radiizonates striatus	0.4													
R. aligerans											0.8	0.8		
Cingulizonates loricatus	0.8	0.8					0.4	0.8	1.2	2.4	0.4	6		
Anacanthotriletes spinosus		0.4			0.4							0.4		
Total Small Lycopsids	60.8	19.6	37.6	21.6	3.6	16.8	11.2	21.6	22.8	58	62.4	59.6	53.2	54
Punctatisporites minutus		0.4				0.8	0.4	0.8	0.8		0.4	0.4	0.4	1.2
Spinosporites exiguus														0.4
Total Tree Ferns	0	0.4	0	0	0	0.8	0.4	0.8	0.8	0	0.4	0.4	0.4	1.6
Schulzospora rara	0.4	0.4	0.8			4	2.8	0.4	1.2				0.4	0.8
Total Pteridosperms	0.4	0.4	0.8	0	0	4	2.8	0.4	1.2	0	0	0	0.4	0.8
Granulatisporites parvus						0.8	0.8	1.6	1.2		1.6	0.4	0.8	
G. granulatus		2.4												
G. piroformis		0.4	0.4											
G. adnatoides		0.4			0.4	2	1.2		0.4	1.2	0.4		0.4	

Lophotriletes microsaetosus					0.8		0.4			0.4		0.4		
L. granoornatus	0.8	2	0.8	1.2	2.4									0.8
L. commissuralis		2	4.4	0.4	22.4		0.8	0.4				0.4		
L. pseuadaculeatus						0.4			0.4					
Deltoidaspora subadnatoides	1.2	1.6	1.2	0.4	34.8							0.4	0.4	
D. sphaerotriangula				0.4	0.8									
D. subintorta	0.8													
D. pridyii					2									
Convolutispora tessellata					0.8									0.4
Raistrickia fulva						0.4	1.2	0.4	0.4				0.8	
Verrucosisporites donarii			0.4											
Punctatisporites aerarius									0.4					
P. sp.									0.4					
Total Small Ferns	2.8	8.8	7.2	2.4	64.4	3.6	4.4	2.4	3.2	1.6	2	1.6	2.4	1.2
Calamospora breviradiata	0.4	0.4					1.6		0.4	0.8		0.4	0.8	0.4
C. flexilis														0.4
C. microrugosa		0.4												
C. perrugosa				0.4										
C. hartungiana						0.4		0.4						
Reticulatisporites muricatus					0.4									
Total Calamites	0.4	0.8	0	0.4	0.4	0.4	1.6	0.4	0.4	0.8	0	0.4	0.8	0.8
Florinites florini									0.4					
Total Cordaites						0	0	0	0.4					
Retispora staplini	0.4												0.4	
Anaplanisporites baccatus						2.4	1.6	4	4				0.8	
Stenozonotriletes lycosporoides			0.4		0.4							0.4		
Ahrensisporites guerickei		0.8	0.4		1.2									
Tantillus triquetrus		0.4			2.4						0.4			
Secarisporites remotus							0.8							
Simozonotriletes intortus						0.4								
Total Unknown Affinity	0.4	1.2	0.8	0	4	2.8	2.4	4	4	0	0.4	0.4	1.2	0

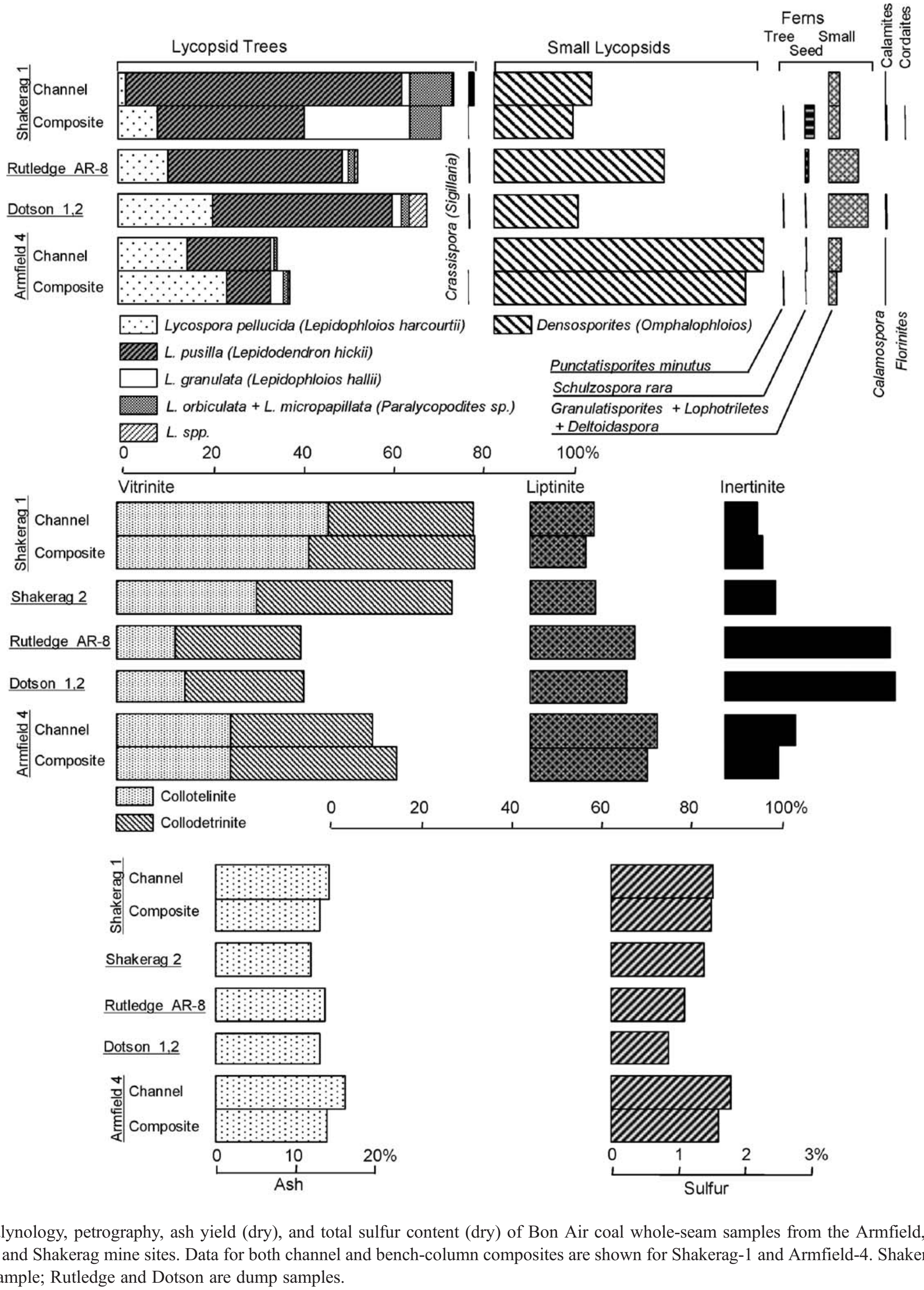

Fig. 4. Palynology, petrography, ash yield (dry), and total sulfur content (dry) of Bon Air coal whole-seam samples from the Armfield, Dotson, Rutledge, and Shakerag mine sites. Data for both channel and bench-column composites are shown for Shakerag-1 and Armfield-4. Shakerag-2 is a channel sample; Rutledge and Dotson are dump samples.

lower benches) was dominated by large lycopsids (*L. hickii*, and *L. harcourtii* and *L. hallii*), with moderately abundant small lycopsids like *Omphalophloios* (particularly in upper benches), significant *Paralycopodites* (especially in upper benches), minor cordaites and *Sigillaria* genera restricted to the seam top, and more

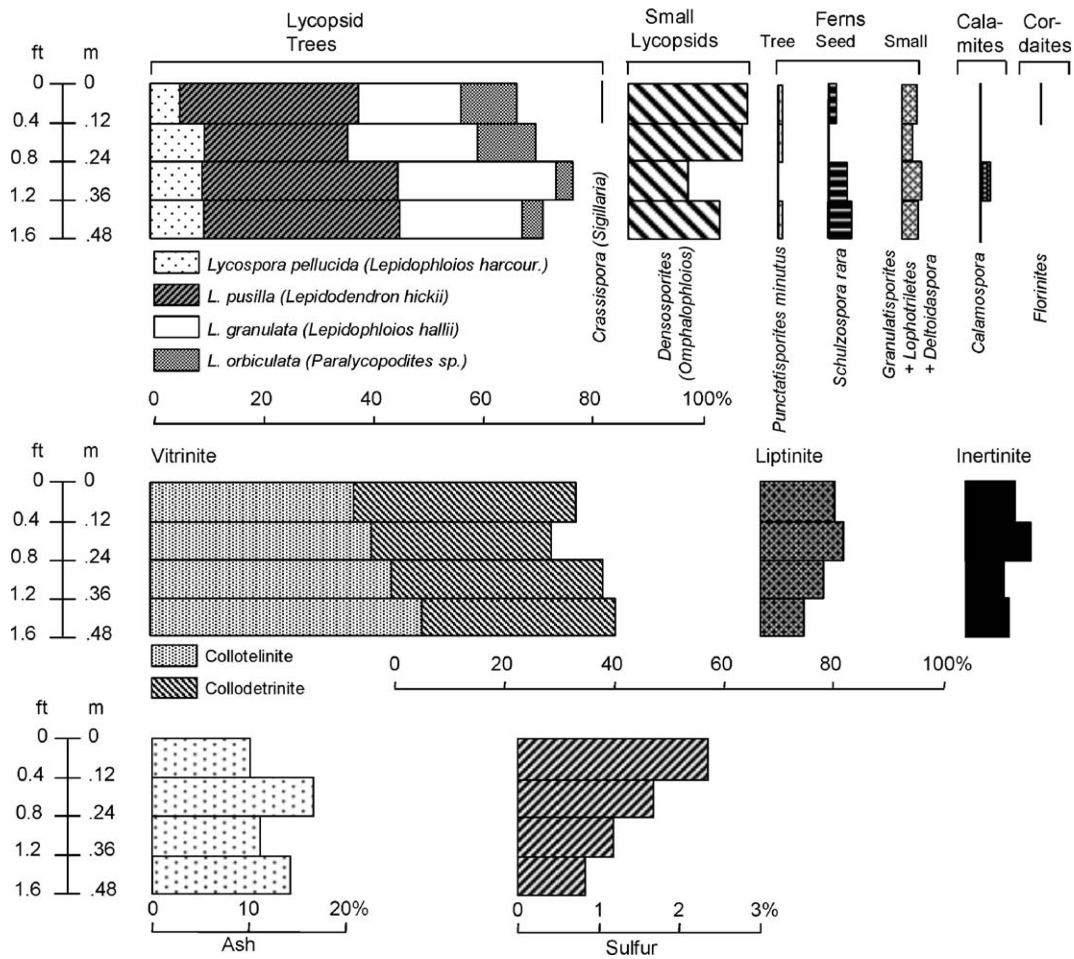

Fig. 5. Palynology, petrography, ash yield (dry), and total sulfur content (dry) profiles for bench-column samples of the Bon Air coal seam at Shakerag-1.

fern and calamites genera in lower benches than in the upper ones. The stratigraphically lower(?) Dotson and Rutledge mires, also large-lycopod dominant, were similar to Shakerag but had more ferns, somewhat different large-lycopod populations (less *Paralycopodites*, perhaps more early Westphalian *L. harcourtii* and less late Westphalian *L. hallii)*, and (at Rutledge) a much higher ratio of *Omphalophloios*-like lycopsids to large lycopsids (*Lepidodendron* and *Lepidophloios*). Taxa in the shale-hosted Armfield mire were strikingly different from those at all the other sites. Genera of *Omphalophloios*-like lycopsids dominate, with fewer large lycopsids (especially *Lepidodendron* and *L. hallii*) and few *Paralycopodites* genera. The collective palynoflora assemblages at all sites suggest that the Bon Air paleomires were forest swamps, and Early Pennsylvanian in age (Westphalian A, Langsettian).

4.2. Petrography, clay mineralogy, and geochemistry

The dominant macerals at all Bon Air sites are vitrinites, ranging from ~40% to over 80% (mineral matter free, Tables 3 and 4, Figs. 4–6). Fine-grained collodetrinite (Fig. 8a–f) (from strongly degraded plant debris) is more abundant overall than blocky collotelinite (Fig. 8m–n) (from well-preserved plant debris). Fusinite and semifusinite were the only inertinite macerals observed (Fig. 8j–p), and, while minor cutinite occurs in all samples, sporinite is by far the most common liptinite maceral (Fig. 8a–i). Maceral assemblages differ between sites, however. The Shakerag site's *Lepidodendron–Lepidophloios–Paralycopodites*-rich coal has the highest total vitrinite (74.2–79.2%) and collotelinite (up to 46.8%) of any site, and the lowest liptinite (12.3–14.5%) and inertinite (7.1–11.3%). The fern-rich, *Paralycopodites*-poor coal at Dotson and Rutledge contains

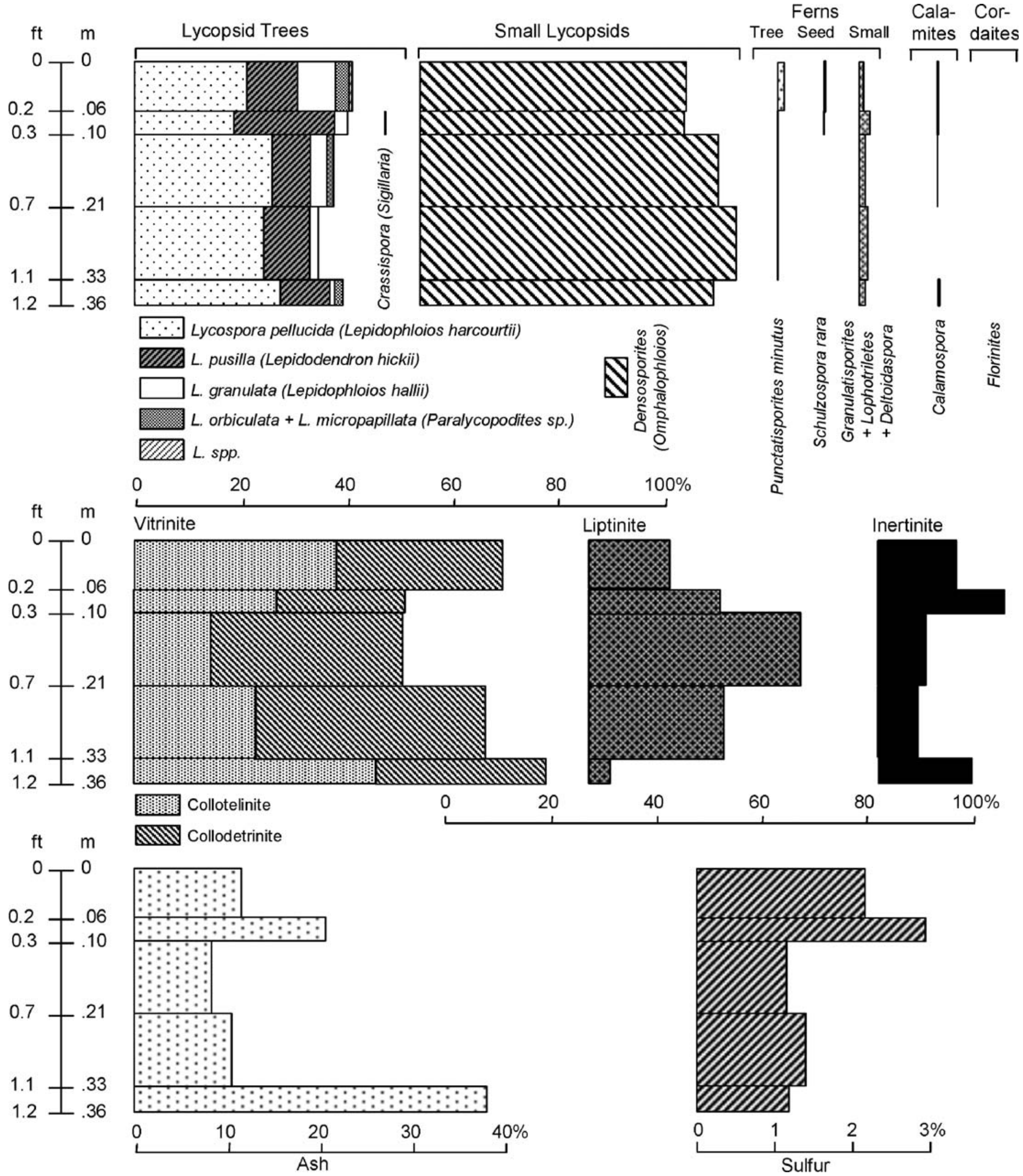

Fig. 6. Palynology, petrography, ash yield (dry), and total sulfur content (dry) profiles for bench-column samples of the Bon Air coal seam at Armfield-4.

moderate liptinite (21.3–23.0%), highest inertinite (36.3–37.4%), lowest vitrinite (40.7–41.4%), and lowest collotelinite (12.9–15.0%) of any site. The *Densosporites*-dominated coal at Armfield has more liptinite than other sites (25.9–28.2%), significant vitrinite (56.5–62.2%), and rather low inertinite (12.0–15.4%).

Within individual mine sites, bench-to-bench maceral variations are also significant (Table 4, Figs. 5 and 6). At Armfield, total vitrinite, collotelinite, and inertinite are high in basal and upper benches, but low in middle benches where liptinite and collodetrinite are high, and Armfield's opposing upward trends in liptinite and vitrinite are particularly symmetrical (Fig. 6). While Shakerag peat was scoured prior to burial, what remains now as coal has an upward maceral trend similar to that of the Armfield seam's lower half: a general decrease in total vitrinite and collotelinite and a general increase in liptinite and inertinite, although liptinite and inertinite are highest in the bench just below the top.

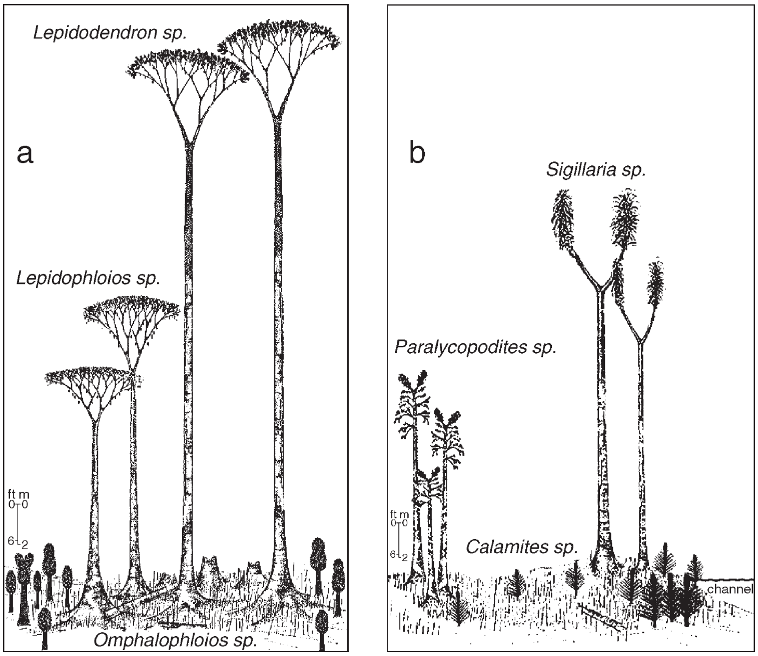

Fig. 7. Reconstructions of Early Pennsylvanian vegetation occurring in Bon Air paleomires, showing (a) species typical of more-flooded mire interiors and (b) those typical of more-subaerial, mire-marginal areas transitional to fluvial channels; modified from DiMichele and Phillips (1994) (*Calamites*), Wagner (1989) (*Omphalophloios*), and Bateman et al. (1992) (*Lepidophloios, Lepidodendron,* and *Sigillaria*).

Moderate to moderately-high ash yields (11.0–20.0%) (Table 5) are typical of the Bon Air coal throughout the study area, although average ash yield tends to increase slightly from east (Shakerag) to west (Armfield) (Fig. 9). Overall, the Bon Air has a higher ash yield (14.5% avg.) than the mean for Appalachian coal (9.6%) (COALQUAL database) (Bragg et al., 1998; Finkelman, 2003, personal communication). Ash yields of Shakerag benches (range 10.2–16.7%, 13.2% weighted avg.) alternate upwards, beginning with an ash-rich basal bench (Table 4, Fig. 5). The ash yield of each bench generally parallels its inertinite content (Fig. 5), although more perfect parallelism would predict slightly higher ash in Shakerag's top bench. In Armfield

Table 3
Macerals (vol.%), ash (wt.%), and sulfur (wt.%) in whole-seam channel, dump, or bench-composite samples of the Bon Air coal

	Armfield		Dotson	Rutledge	Shakerag		
	4		1,2	AR-8	2	1	
	Channel	Composite	Dump	Dump	Channel	Composite	Channel
Collotelinite	25.2	25.1	15.0	12.9	30.9	42.6	46.8
Collodetrinite	31.3	37.0	26.3	27.8	43.3	36.6	32.1
Sporinite	27.6	25.3	21.3	23.0	14.5	11.0	14.0
Alginite	0.1	0.2				0.1	
Resinite	0.1						
Fluorinite	0.1	0.1				0.1	
Cutinite	0.3	0.3				1.1	
Micrinite						0.5	
Fusinite	4.1	8.4	18.9	18.8	5.5	5.9	2.7
Semi-fusinite	11.3	3.6	18.4	17.5	5.8	2.0	4.4
Total Inertinite	15.4	12.0	37.4	36.3	11.3	8.5	7.1
Total Liptinite	28.2	25.9	21.3	23.0	14.5	12.3	14.0
Total Vitrinite	56.5	62.2	41.4	40.7	74.2	79.2	78.9
Ash Yield (dry)	16.52	14.03	13.26	13.85	12.20	13.23	14.34
Sulfur content (dry)	1.79	1.61	0.85	1.09	1.41	1.51	1.54

Table 4
Macerals (vol.%), ash (wt.%), and sulfur (wt.%) in individual benches of the Bon Air coal, Armfield and Shakerag sites

	Armfield					Shakerag			
	4					1			
	Basal	Lower Mid	Upper Mid	Lower Top	Upper Top	Basal	Lower Mid	Upper Mid	Top
Collotelinite	45.7	22.5	13.6	26.4	37.4	48.9	43.7	40.5	37.1
Collodetrinite	32.5	44.0	37.5	24.7	32.4	35.7	38.0	32.4	40.4
Sporinite	3.3	24.6	39.3	24.5	14.4	7.2	10.0	13.9	12.7
Alginite	0.5	0.4	0.2	0.1	0.4	0.1	0.2	0.1	0.2
Resinite				0.1	0.1		0.1		0.1
Fluorinite		0.1	0.1	0.1	0.2	0.1	0.1		0.1
Cutinite	0.1	0.5	0.3	0.1	0.2	0.7	1.5	1.7	0.7
Micrinite						0.6	0.6	0.7	
Fusinite	13.6	4.3	6.3	18.7	10.9	4.9	3.5	9.2	6.2
Semi-fusinite	4.1	3.4	2.8	5.4	4.0	1.8	2.2	1.5	2.5
Total Inertinite	17.7	7.8	9.1	24.1	14.9	7.4	6.3	11.5	8.7
Total Liptinite	3.8	25.5	39.9	24.8	15.3	8.1	11.9	15.7	13.8
Total Vitrinite	78.2	66.5	51.0	51.1	69.8	84.5	81.8	72.9	77.5
Collotelinite/Collodetrinite ratio	1.4	0.5	0.4	1.1	1.2	1.4	1.2	1.2	0.9
Ash Yield (dry)	38.0	10.7	8.4	20.6	11.7	14.2	11.2	16.7	10.2
Sulfur content (dry)	1.19	1.40	1.17	2.93	2.16	0.83	1.18	1.67	2.34

benches, ash yields (14.0% weighted avg.) also alternate upwards and even more closely parallel the inertinite contents, with a thin (1.5 in., 3.8 cm) basal bench very high in ash (38.0%), thicker middle benches of low to moderate ash (8.4–10.7%), and high ash again in the top two benches (20.6% and 11.7%, respectively) (Fig. 6). Megascopic inorganic partings are rare in all benches except in Armfield's ash-rich base.

Volatile matter (32.1–41.3%), calorific value (33.3–34.9 MJ/kg MAF), percent moisture (2.2–3.4%), and vitrinite reflectance (0.70–0.84% $R_{\max}$; 0.64–0.79% R_{random}) (Table 5) place the Bon Air coal's rank as high-volatile-A bituminous (hvAb) (ASTM, 1999c). Although individual benches contain up to 2.9% total sulfur, average sulfur content of Bon Air coal at each site (range 0.77–1.65%) (Table 5, this study; Table 1, Shaver et al., 2006-this volume) is moderate to low (1.24% avg. of all sites), similar to the mean sulfur content for Appalachian coals (1.54%) (COALQUAL database) (Bragg et al., 1998; Finkelman, 2003, personal communication). Sulfate contents are ubiquitously quite low (0.01%). There is no correlation between total sulfur and ash yield for a given site (Fig. 9), but bench-to-bench sulfur patterns are clear. Sulfur in Armfield benches is parallel to ash yield and inertinite content except in the basal bench (Fig. 6), and highest sulfur at both Shakerag and Armfield occurs in upper coal benches. Shakerag benches show a particularly steady upward increase in sulfur that closely parallels the site's upward-decreasing collotelinite trend (Fig. 5). Variations in total sulfur appear to be more related to pyritic sulfur variations (0.20–1.00%) than organic sulfur variations (0.53–1.01%), as evidenced by both sulfur form data (Table 5) and a strong geochemical correlation of total S with Fe and As, both of which occur dominantly in pyrite in the Bon Air coal (Shaver et al., 2006-this volume). Minor pyrite is petrographically visible in all samples (generally ≤2.5 vol.%, based on point counts), most commonly as small framboidal grains generally ≤2.0 mm in size (Fig. 8p–r), or rarely as cubic grains up to

Fig. 8. Photomicrographs of macerals and pyrite within the Bon Air coal. All photomicrographs taken on polished surfaces under oil immersion with field of view of 0.30 mm (300 μm). (a) Typical Shakerag site sample dominated by fine-grained matrix vitrinite (collodetrinite, medium gray) and sporinite (microspores, black), reflected light; (b) same view as (a) under blue light irradiation; (c) sporinite-rich zones (medium gray microspores) interlayered with vitrinite (black, collodetrinite and collotelinite) and one stringer of cutinite (white-gray), Armfield site, under blue light irradiation; (d) interlayered vitrinite (dominantly collodetrinite, medium gray) and sporinite (black) consisting of both microspores and megaspores, Shakerag site, reflected light; (e) same view as (d) under blue light irradiation; (f) sporinite-dominant coal typical of Armfield site, blue light irradiation; (g) sporangium (spore capsule) filled with immature microspores (black), Armfield site, reflected light; (h) same view as (g) under blue light irradiation; (i) cutinite layers (light to medium gray), Shakerag site, blue light irradiation); (j–l) typical fusinite (light gray-white) in the Bon Air coal, Armfield site, reflected light; (m) fusinite (light gray-white) and semifusinite (medium-light gray), Armfield site; (n–o) conspicuous fusinite rims (light gray white) on semifusinite (medium light gray), with (n) from Shakerag and (o) from Armfield, reflected light; (p) semifusinite (medium gray) showing growth of pyrite (bright white) in former cell interiors, Armfield site, reflected light; (q–r) typical framboidal pyrite in the Bon Air, with (q) from Armfield and (r) from Shakerag, reflected light.

0.3 mm in size. In rare cases of unusually high localized pyrite, weathered seams display white to yellow efflorescences of several Fe or Al sulfates, especially halotrichite [$Fe^{+3}Al_2(SO_4)_4 \cdot 22H_2O$] and ferricopiapite [$Fe^{+3}{}_5(SO_4)_6O(OH) \cdot 20H_2O$].

XRD analysis of coal, seat- and roof-rock at Shakerag and Armfield (Table 6, Fig. 10a,b) indicate that clay fractions of all samples are mixtures of kaolinite, illite, smectite, quartz, and chlorite, with much of the illite and smectite occurring as mixed-layer illite-

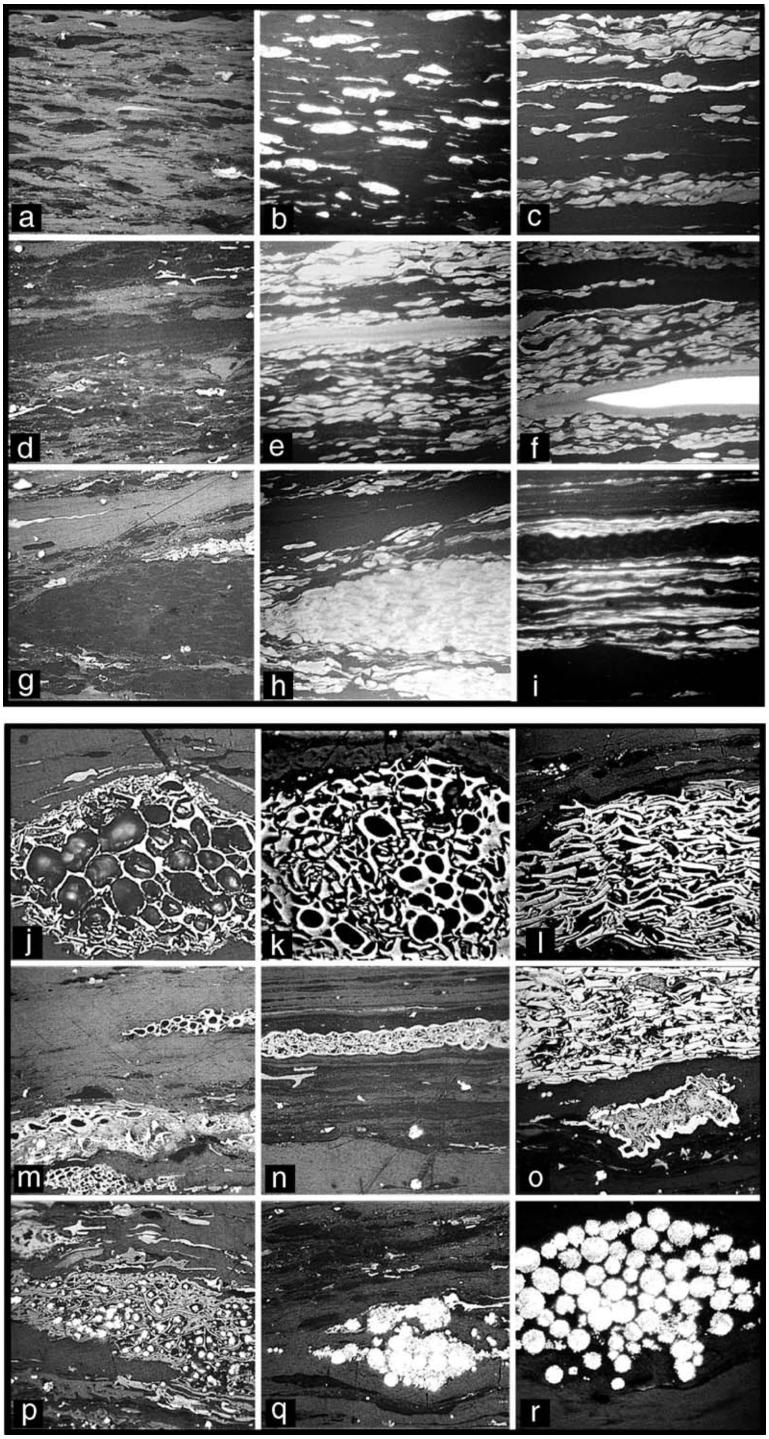

Table 5
Moisture, ash, volatiles, fixed carbon, calorific values (CV), vitrinite reflectance, and sulfur forms of selected Bon Air coal samples

	Armfield		Dotson			Rutledge				Shakerag	
	3	4	1	2	1, 2	CH-4	CH-2	AR-8	AR-5	2	1
	Channel	Channel	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Channel	Channel
% Moisture	2.16	2.20	2.90	3.32	3.03	3.38	2.70	3.05	3.10	2.68	2.44
% Ash (dry)	17.36	16.52	14.68	16.45	13.26	20.02	11.04	13.85	11.71	12.20	14.34
% Volatile (dry)	40.73	41.31	33.08	32.09	34.00	32.86	37.31	34.83	37.24	37.13	37.57
% Fixed C (dry)	41.91	42.17	52.24	51.46	52.74	47.12	51.65	51.32	51.05	50.67	48.09
CV (dry), MJ/kg (Btu/lb $\times 10^{-3}$)	28.6 (12.3)	29.1 (12.5)	29.2 (12.5)	28.2 (12.1)	29.7 (12.8)	26.6 (11.5)	30.2 (13.0)	29.3 (12.6)	30.3 (13.0)	30.2 (13.0)	29.8 (12.8)
CV (MAF), MJ/kg (Btu/lb $\times 10^{-3}$)	34.6 (14.9)	34.9 (15.0)	34.2 (14.7)	33.8 (14.5)	34.3 (14.7)	33.3 (14.3)	34.0 (14.6)	34.0 (14.6)	34.3 (14.8)	34.4 (14.8)	34.7 (14.9)
% Vitrinite Reflectance (Rmax)		0.70 ± .05						0.84 ± .05			0.77 ± .03
% Vitrinite Reflectance (Rrandom)		0.64 ± .04						0.79 ± .05			0.73 ± .04
% Total Sulfur (dry)	1.86	1.79	0.85	0.83	0.85	0.79	1.42	1.09	1.28	1.41	1.54
% Pyritic S (dry)		1.00			0.20		0.40	0.40			1.00
% Sulfate S (dry)		0.01			0.01		0.01	0.01			0.01
% Organic S (dry)		0.78			0.64		1.01	0.68			0.53

smectite. Illite + smectite contents are much lower in coal benches at both Armfield and Shakerag (8–15%) than in caprock (28%) or seatrock (23–28%), but it is noteworthy that total illite + smectite in most coal benches is relatively uniform (12–15%, except for 8–10% in the top two Armfield benches). Bench-to-bench kaolinite differences therefore largely reflect different ratios of quartz to kaolinite. While authigenically precipitated quartz is known in coal (observed as cell or pore infillings in organic matter, Sykes and Lindqvist, 1993; or interpreted from quartz cathodoluminescent responses not befitting detrital quartz, Ruppert et al., 1985), quartz in coals is dominantly detrital and quartz variations in the Bon Air coal most likely also reflect differences in detrital quartz. XRD analyses also indicate that the underclay at Shakerag contains much less kaolinite (34%) and much more quartz (36%) and illite (24%) than that at Armfield (60% kaolinite, 17% quartz, and 12% illite). Although their seams appear to show an opposite relationship, with a lower average ratio of quartz-to-kaolinite at Shakerag (66% kaolinite, 20% quartz) than at Armfield (56% kaolinite, 31% quartz), this is probably misleading since the high average at Armfield is due to terminal benches rich in quartz (59–63% of all clays) and the equivalent bench at Shakerag may have been removed by channel scouring.

Illite/smectite is the most common mixed-layer clay in sedimentary rocks and soils (Moore and Reynolds, 1997), and illitic clays are generally more detrital than authigenic in coals (Rimmer and Davis, 1986; Ward, 1989, 2002; Ward and Christie, 1994; Ward et al., 1999). By contrast, although some kaolinite in coal (generally poorly ordered) may be of clastic or volcanic origin, most kaolinite in coal (especially well-ordered polytypes) forms authigenically (Rimmer and Davis, 1986; Ward, 1989, 2002), and it is well known that acidic leaching of detrital clay and silica in peats and paleosols can lead to kaolinite-enriched and quartz- or illite/smectite/chlorite-depleted clay assemblages in both coals and underclays (Rimmer and Eberl, 1982; Hughes et al., 1987). Lateral clay mineral variations in coals have been useful in determining clastic source areas and coal basin paleogeography and paleobathymetry (Rimmer and Davis, 1986), but bench-to-bench correlations between clays (especially kaolinite) and other coal features (maceral types, ash yield, and sulfur content) have been shown particularly useful in paleoecological interpretations of paleomire doming or flattening (Eble and Grady, 1993).

Such bench-to-bench clay correlations are clearly present in the Bon Air coal: kaolinite-rich benches are typically moderate to low in ash, inertinite, and quartz, while kaolinite-poor benches are generally richer in

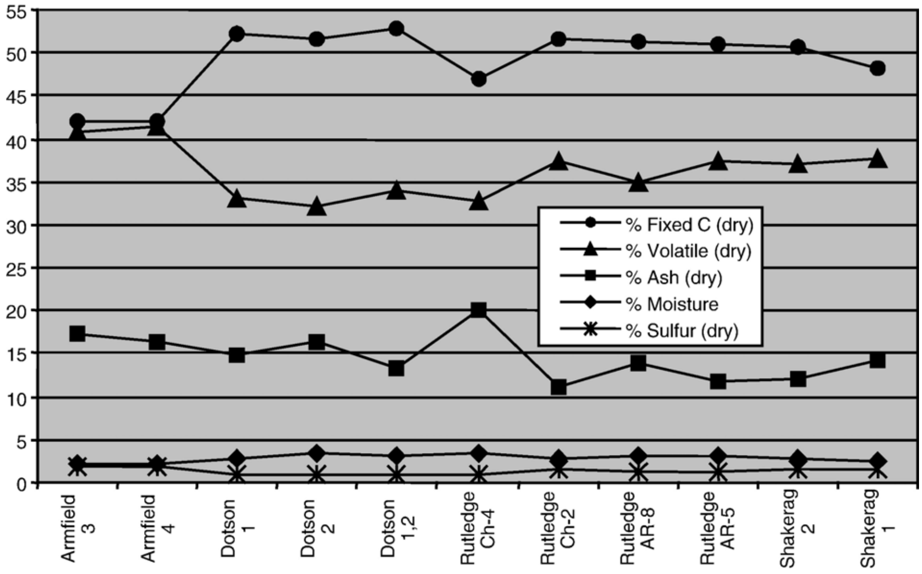

Fig. 9. Fixed carbon, volatile, ash, moisture, and total sulfur contents (wt.%) of the Bon Air coal from the Armfield, Dotson, Rutledge, and Shakerag mine site areas. All values except moisture reported on a dry basis.

these components (Table 6, Fig. 10b). At Armfield, for example, the basal bench is relatively kaolinite-poor, but ash/inertinite/quartz-rich. Kaolinite-rich middle benches are relatively ash/inertinite/quartz-poor. Top benches are again kaolinite-poor, but ash/inertinite/quartz-rich (Figs. 6 and 10b). In addition, kaolinite contents at Armfield closely follow both liptinite and collodetrinite contents, with all three showing the same upward pattern (less in lower and upper benches, more in middle benches) (Fig. 6). At Shakerag (Figs. 5 and 10b) kaolinite is also inversely related to ash/inertinite/quartz contents, but these contents alternate upwards: high ash/inertinite/quartz in the basal bench, lower in the next bench, and so on. These data, quartz/illite-rich underclay, and a sandstone-scoured upper bench, all suggest the Shakerag mire was channel-proximal and intermittently subjected to clastic influx. Kaolinite relationships with sulfur are complex at both sites (Tables 4 and 6). Low kaolinite (27–32% of all clays) typifies high-sulfur (2.16–2.93%) upper Armfield benches; moderate kaolinite (51–60%) occurs in low-sulfur (0.83–1.19%) basal benches at both Armfield and Shakerag; and high kaolinite (61–74%) occurs in the low-sulfur (1.17–1.40%) middle Armfield benches and variable-sulfur (1.18–2.34%) middle to top Shakerag benches.

Trace elements of paleoenvironmental importance also vary significantly between benches in the Bon Air coal, and these variations often correlate with other coal parameters (Tables 6–8; Figs. 5, 6 and 11). At Shakerag, Fe, S, and Sr are highest in the top two benches, yet Br is lower, and Ce, La, Nd, and V are quite high. Iron, Hg, S, and Sr generally increase upwards in Shakerag benches (with the uppermost bench particularly enriched in Sr, 231 ppm). The Shakerag bench just below the top, with

Table 6
Clay mineralogy (vol.%) of Bon Air coal benches, seatrock, and caprock, Shakerag and Armfield sites

	Quartz	Kaolinite	Illite	Smectite	Chlorite
Shakerag 1 Top	17	71	8	4	0
Shakerag 1 Upper Middle	25	61	7	6	0
Shakerag 1 Lower Middle	12	74	9	5	0
Shakerag 1 Basal	27	60	8	5	trace
Shakerag 1 Underclay	36	34	24	4	2
Weighted Average (coal only)	20	66	8	5	0
Armfield 4 Roof Shale	38	33	26	2	1
Armfield 4 Upper Top	63	27	6	4	1
Armfield 4 Lower Top	59	32	4	4	1
Armfield 4 Upper Middle	25	61	7	7	0
Armfield 4 Lower Middle	12	74	7	8	0
Armfield 4 Basal	35	51	6	8	trace
Armfield 4 Underclay	17	60	12	11	0
Weighted Average (coal only)	31	56	6	7	0.3

All values based on XRD analysis of −60 mesh (<250 μm) sample splits. Values for seatrock and caprock are composites of XRD analyses of four size fractions (<0.5 μm, 0.5–0.75 μm, 0.75–1.5 μm, and >1.5 μm).

sharply elevated *Paralycopodites* genera, increasing quartz in the clay fraction, the second highest sulfur (1.67%) and the highest inertinite and ash of any Shakerag bench, is marked by high levels of Al, Ba, Ce, Cr, K, Hg, La, Mn, Nd, Sm, Ni, Th, V, Y, and Zr. At Armfield, where *Paralycopodites* genera are enriched in the top bench, the pattern is similar, with high Fe, Hg, S, Mn, and Ba in both of the top two benches. Likewise, Sr and Hg generally increases upwards in Armfield coal, but highest concentrations of Sr (521 ppm) and Hg (635 ppb) occur in the

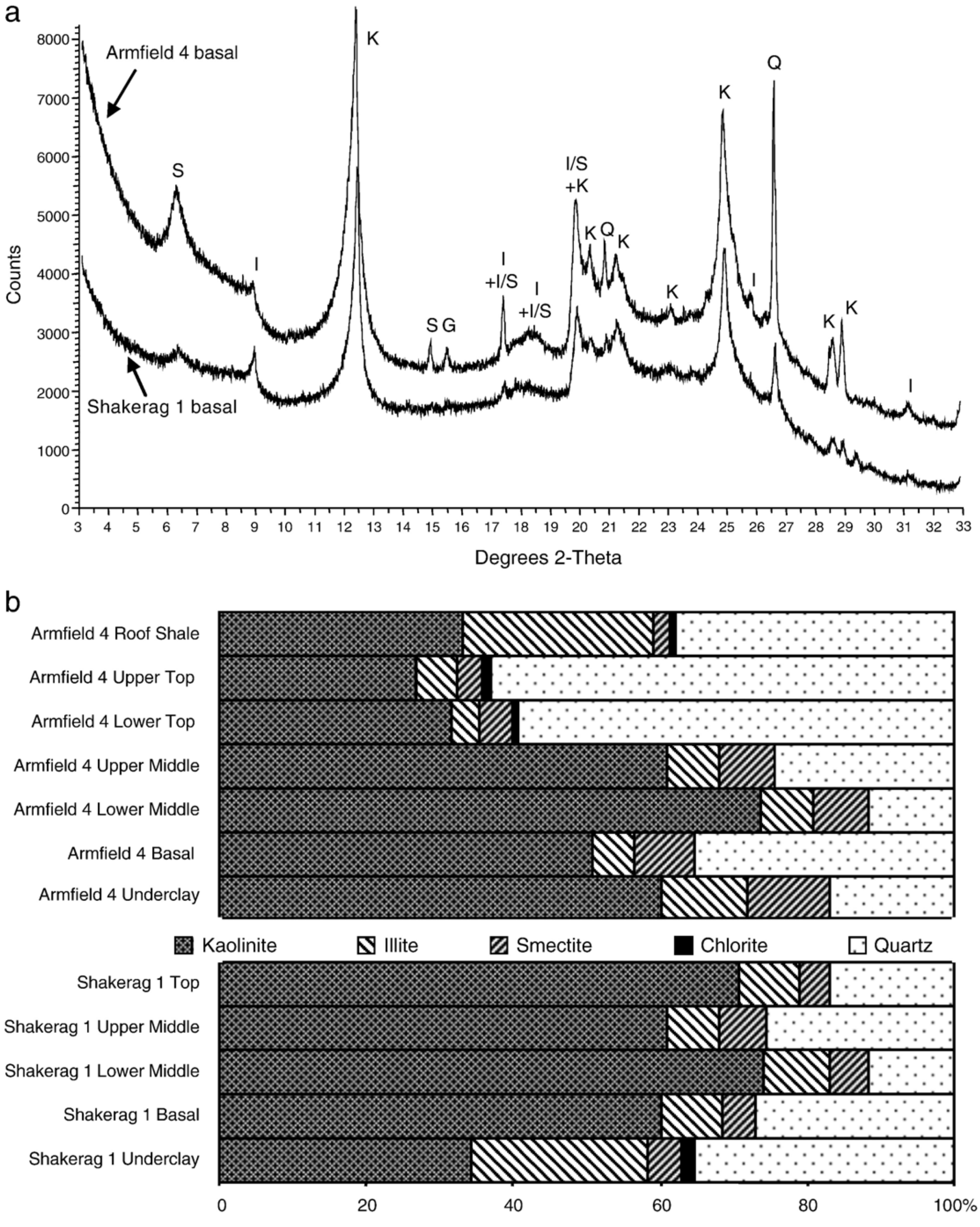

Fig. 10. X-ray diffraction results for Bon Air coal benches: (A) Typical raw-coal XRD traces. Bench samples: Shakerag 1 basal and Armfield 4 basal; CuKα radiation; 0.008° step size; count times 175 s (Shakerag) and 225 s (Armfield). Peaks for smectite (S), illite (I), illite/smectite (I/S), kaolinite (K), quartz (Q), and secondary Ba–Al phosphate (gorceixite) (G) are denoted. (B) Incremental variations (vol.%) in clay fraction mineralogy from seam underclay upwards to top coal bench and/or roof shale, for Shakerag-1 and Armfield-4 bench-column samples.

Table 7
Trace elements in Bon Air coal benches and under- or overlying beds, as determined by instrumental neutron activation analysis (INAA), except Hg (by cold vapor atomic absorption spectroscopy, AAS), S (by LECO combustion infrared spectrometry, IR), and Cd and Pb (by inductively coupled plasma emission spectroscopy (ICP/OES) after ashing the sample)

Sample	Type	As	Au	Ba	Br	Co	Cr	Cs	Fe	Hf	Hg	Ir	Mo	Na	Pb	Rb
		ppm	ppb	ppm	ppm	ppm	ppm	ppm	%	ppm	ppb	ppb	ppm	%	ppm	ppm
Armfield 4 Caprock	bc	16.4	−2	580	−0.5	21	124	11	6.39	4	17	−5	−1	0.13	13.9	148
Armfield 4 Overclay	bc	43.8	−2	570	−0.5	5	111	11	4.24	5	87	−5	3	0.12	67.8	151
Armfield 4 Upper Top	bc	70.5	−2	100	16.9	10	18	−1	2.28	−1	436	−5	6	0.02	4.1	−15
Armfield 4 Lower Top	bc	99.0	−2	370	11.5	6	33	−1	2.76	1	635	−5	7	0.03	7.5	−15
Armfield 4 Upper Middle	bc	13.6	−2	−50	17.7	10	17	−1	1.14	−1	591	−5	3	0.02	3.6	−15
Armfield 4 Lower Middle	bc	18.2	−2	−50	17.8	21	23	−1	1.35	−1	141	−5	5	0.02	6.7	−15
Armfield 4 Basal	bc	44.5	−2	−50	8.3	22	80	5	1.95	2	119	−5	6	0.05	37.0	42
Armfield 4 Underclay	bc	33.9	−2	630	−0.5	7	126	8	1.34	10	181	−5	3	0.14	27.7	102
Shakerag 1 Top	bc	66.0	−2	−50	18.0	7	14	−1	2.29	−1	188	−5	−1	0.02	8.1	−15
Shakerag 1 Upper Middle	bc	51.8	−2	110	19.0	11	33	1	2.03	−1	280	−5	−1	0.02	9.1	−15
Shakerag 1 Lower Middle	bc	43.7	−2	98	24.8	14	26	1	1.42	−1	206	−5	−1	−0.01	4.9	−15
Shakerag 1 Basal	bc	55.6	−2	110	20.7	17	34	2	1.42	−1	152	−5	−1	0.02	9.6	−15
Shakerag 1 Underclay	bc	16.5	−2	55	−0.5	11	118	7	4.16	7	13	−5	2	0.11	18.7	112

Sample	Type	S	Sb	Sc	Se	Ta	Th	U	W	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu
		%	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Armfield 4 Caprock	bc	0.14	0.9	21.6	1.2	1.3	14.8	3.1	−1	53.9	104	39	8.7	1.8	1.0	3.8	0.56
Armfield 4 Overclay	bc	0.73	2.5	16.9	1.4	1.0	10.4	3.0	−1	52.7	90	39	6.6	1.2	0.8	3.2	0.48
Armfield 4 Upper Top	bc	2.16	1.0	5.3	2.3	−0.5	1.2	0.3	−1	19.0	24	11	2.6	0.6	−0.5	1.4	0.22
Armfield 4 Lower Top	bc	2.92	0.6	6.7	3.9	−0.5	4.3	1.3	−1	100.0	105	50	8.7	1.8	0.9	2.2	0.31
Armfield 4 Upper Middle	bc	1.17	0.3	3.6	1.7	−0.5	1.8	1.1	−1	28.4	36	20	3.5	0.7	−0.5	1.4	0.22
Armfield 4 Lower Middle	bc	1.40	1.1	7.2	1.3	−0.5	2.1	0.6	−1	20.2	36	17	3.7	0.8	−0.5	1.5	0.24
Armfield 4 Basal	bc	1.19	4.1	21.6	2.3	0.6	7.1	3.0	−1	46.0	81	33	6.6	1.3	0.8	2.5	0.38
Armfield 4 Underclay	bc	0.16	1.0	17.3	1.8	1.6	18.3	4.5	−1	49.9	94	41	8.3	1.8	1.1	4.6	0.69
Shakerag 1 Top	bc	2.34	0.5	2.5	3.0	−0.5	0.8	−0.3	3	21.2	21	11	2.0	0.5	−0.5	1.0	0.15
Shakerag 1 Upper Middle	bc	1.67	0.3	4.8	3.5	−0.5	3.0	−0.3	−1	24.3	37	18	3.2	0.6	−0.5	1.3	0.20
Shakerag 1 Lower Middle	bc	1.18	0.4	3.4	1.6	−0.5	2.3	1.5	−1	10.3	18	8	1.5	0.4	−0.5	0.6	0.10
Shakerag 1 Basal	bc	0.83	1.0	5.4	2.1	−0.5	3.1	−0.3	−1	12.1	20	9	1.7	0.4	−0.5	1.1	0.16
Shakerag 1 Underclay	bc	0.06	0.8	17.6	−0.5	1.2	14.5	4.0	−1	54.5	110	51	9.7	1.9	1.0	4.4	0.68

All values are on a whole-coal basis (not ash basis).
Sample type: bc = bench column sample. Samples are coal unless otherwise noted as overclay, underclay, or caprock.
Negative values indicate less than the detection limit.

bench just below the top. Similar to the equivalent Shakerag bench, this is an ash-rich, sulfur-rich bench with elevated Al, Ba, Ce, K, La, Nd, P, Sm, Sr, Th, U, V, Y, and Zr concentrations, lower Br, increased quartz in the clay fraction, and the highest inertinite of any bench. Elevated levels of very similar suites of elements also occur in the ash-rich basal benches at Armfield and Shakerag: Al, K, Rb, Th, U, Ce, La, Nd, Sm, Eu, Ni, V, and Y (Armfield), Ba (Shakerag), and Co, Cr, Yb, Zr (both sites).

5. Discussion: Bon Air paleoecology

5.1. Fluvial versus volcanic inputs

Paleoecologically sensitive trace elements in coal (Al, Ba, Br, Ce, Cr, Fe, Hf, Hg, K, La, Mn, Nd, P, Pb, Rb, S, Sc, Sm, Sr, Th, U, V, Y, Zn, and Zr) are typical of heavy mineral detritus, clay minerals, and/or sulfides (Palmer and Wandless, 1985; Finkelman and Stanton, 1978; Finkelman, 1981, 1993; Davidson, 2000), and can be used to interpret relative inputs of fluvial, volcanic, and/or marine debris into paleomires (Harris et al., 1981; Palmer and Wandless, 1985; Dewison, 1989; Hickmott and Baldridge, 1995; Hower et al., 1999; Zhou et al., 2000).

It appears unlikely that the Bon Air paleomires received significant volcanic input. Trace elements commonly used to infer such inputs (particularly Hf, Sc, U, Th, Zr, Y, and the rare earths La, Ce, Nd, Sm, Eu, Tb, Yb, and Lu) are much less abundant in Bon Air coal, seat-, or caprock (Tables 7 and 8) than in known ash layers in coal (tonsteins) (typically an order of magnitude lower) (Dewison, 1989; Hower et al., 1999; Zhou et al., 2000;

Table 8
Trace elements in Bon Air Coal benches and under- or overlying beds, as determined by inductively coupled plasma emission spectroscopy (ICP/OES)

Sample	Type	Ag	Al	Be	Bi	Ca	Cu	K	Mg	Mn	Ni	P	Sn	Sr	Ti	V	Y	Zn	Zr
		ppm	%	ppm	ppm	%	ppm	%	%	ppm	ppm	%	ppm	ppm	%	ppm	ppm	ppm	ppm
Armfield 4 Caprock	bc	−0.2	1.34	1	−10	0.26	28	0.26	0.61	1116	61	0.044	−10	24	−0.01	28	16	97	11.1
Armfield 4 Overclay	bc	−0.2	0.64	−1	−10	−0.01	10	0.30	0.13	62	12	0.010	−10	19	−0.01	18	8	18	13.2
Armfield 4 Upper Top	bc	−0.2	0.13	−1	−10	0.11	11	0.03	0.01	28	9	0.005	−10	78	−0.01	7	4	7	1.9
Armfield 4 Lower Top	bc	−0.2	0.33	3	−10	0.07	22	0.04	0.01	20	10	0.059	−10	521	−0.01	18	9	4	4.5
Armfield 4 Upper Middle	bc	−0.2	0.14	1	−10	0.11	26	0.01	0.01	9	8	0.020	−10	199	−0.01	11	5	3	1.6
Armfield 4 Lower Middle	bc	−0.2	0.16	1	−10	0.09	22	0.02	0.02	8	19	0.003	−10	54	−0.01	14	5	7	2.1
Armfield 4 Basal	bc	−0.2	0.62	1	−10	0.03	28	0.08	0.03	7	37	0.006	−10	29	−0.01	52	10	59	7.5
Armfield 4 Underclay	bc	−0.2	0.80	−1	−10	−0.01	5	0.18	0.05	11	12	0.009	−10	18	−0.01	12	10	7	8.6
Shakerag 1 Top	bc	−0.2	0.10	−1	−10	0.20	18	0.02	0.02	24	10	0.012	−10	231	−0.01	21	2	4	1.5
Shakerag 1 Upper Middle	bc	−0.2	0.20	−1	−10	0.11	16	0.04	0.02	12	13	0.004	−10	68	−0.01	28	3	6	3.3
Shakerag 1 Lower Middle	bc	−0.2	0.17	−1	−10	0.12	9	0.03	0.02	9	11	0.002	−10	66	−0.01	14	1	7	2.1
Shakerag 1 Basal	bc	−0.2	0.17	−1	−10	0.10	11	0.03	0.02	7	11	0.003	−10	55	−0.01	19	2	9	2.6
Shakerag 1 Underclay	bc	−0.2	1.32	−1	−10	−0.01	17	0.17	0.54	285	31	0.020	−10	9	−0.01	26	10	66	14.3

All values are on a whole-coal basis (not ash basis).
Sample type: bc=bench column sample. Samples are coal unless otherwise noted as overclay, underclay, or caprock.
Negative values indicate less than the detection limit.

Sachsenhofer et al., 2003), coals overlain by tonsteins (up to three orders of magnitude lower) (Hower et al., 1999), tuffs interbedded with coals (up to an order of magnitude lower, especially for Zr) (Kramer et al., 2001; Grevenitz et al., 2003), or coals interpreted to contain significant volcaniclastic debris (Ward et al., 1999) (up to an order of magnitude lower, especially for Zr). Moreover, the Bon Air benches with highest concentrations of volcanic indicator elements are those with high ash yields and particularly low kaolinite contents (Shaver et al., 2006-this volume) unlike volcanically derived concentrations of these elements in coals (especially Ti, Zr, Y, Nd, and/or Nb), which are most common in kaolinite-enriched horizons derived from diagenetic alteration of volcanic ash (Dewison, 1989; Ward et al., 1999).

Instead, fluvial inputs appear to have been dominant, and marine inputs negligible, in the Bon Air mires. Ash-rich Bon Air benches (often higher in levee-related *Paralycopodites,* see Section 5.2 below), and seat- and caprocks, are enriched in elements typical of clays (Al, K, Rb, Co, Cr, Mn, Ni, and V) and/or heavy detritus (Co, Cr, Ce, La, Nd, Sc, Th, U, Y, and Zr) (Wedepohl, 1978; Harris et al., 1981; Palmer and Wandless, 1985), yet are depleted in Br, a marine indicator (Rimmer, 1991; Hickmott and Baldridge, 1995). Coals with significant marine influence also typically have much higher sulfur (up to 5–10%) (Williams and Keith, 1963; Shao et al., 2003) than the Bon Air (1.24% avg.). Altogether, the trace element data are consistent with stratigraphic work showing deposition of the Bon Air coal and RMF under fluvial conditions, with only local marine influence (Bergenback et al., 1992a,b; Bergenback, 1993; Knoll and Potter, 1998).

5.2. Bon Air plant communities

Collectively, the Bon Air paleomires were host to the large lycopsids *Lepidodendron hickii* and *Lepidophloios hallii* and *harcourtii*, the medium-sized lycopod *Paralycopodites*, the *Densosporites*-producing small lycopsid(s) (e.g., *Omphalophloios*), and minor to negligible amounts of small ferns, calamites, tree ferns, pteridosperms (seed ferns), and/or Sigilliarian lycopsids (Fig. 7). *Lepidodendron* and *Lepidophloios* were the tallest trees in Pennsylvanian forest swamps and were the dominant

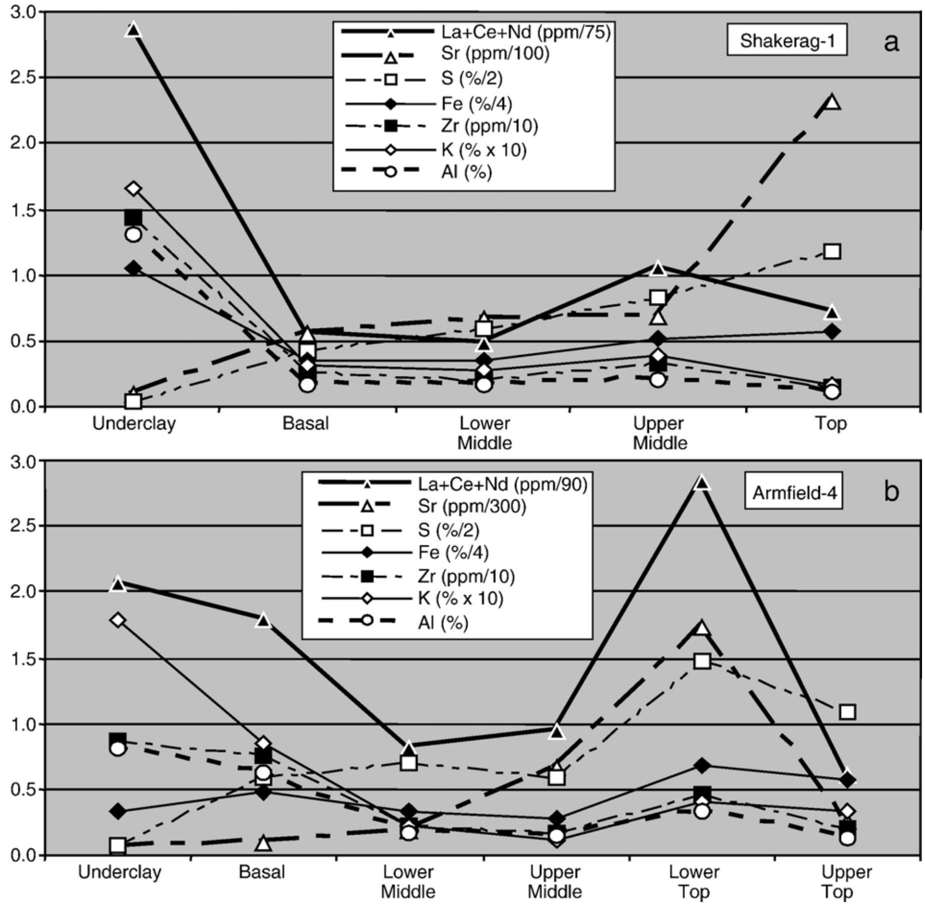

Fig. 11. Incremental variations (wt.% or ppm, as shown) in selected trace elements (La+Ce+Nd, Sr, total S, Fe, Zr, K, and Al) from seam underclay upwards to top coal bench for bench-column samples from (A) Shakerag-1 and (B) Armfield-4.

species in all Bon Air sites except Armfield. Up to 3 ft (1 m) in diameter and 130 ft (40 m) tall in clastic-rich habitats, they were probably smaller in coal-producing mires, with basal diameters of lepidodendrid trunk segments preserved in coal balls only 6–14 in. (15–35 cm) in size (Phillips, 1979; DiMichele and Phillips, 1985, 1994). As evidenced by their large root lacunae (air chambers), their thick and chemically resistant bark, and the floating aquacarp each used reproductively for spore dispersal, both required standing water, or oversaturated peat, typical of flooded parts of mires. *Lepidodendron,* common in moderate-ash coals with few small ferns and with maxima in coal seam benches having clastic partings or abundant mineral debris, seems to have preferred flooded mire areas with regular nutrient influx (Eble, 1990). Evidence is limited for *Lepidophloios harcourtii*, but *L. hallii* occurs in coals with slightly lower ash and even fewer ground-cover plants than *Lepidodendron* (DiMichele and Phillips, 1994), suggesting that *L. hallii* (and *L. harcourtii* ?) preferred flooded, mire-central habitats even more distal from nutrient-rich contemporaneous channels than those preferred by *Lepidodendron*.

Densosporites-producers like *Omphalophloios* were the dominant plants in all stages of the Armfield mire, and were relatively abundant in latter phases of the Shakerag mire. *Densosporites* has been suggested as an indicator of mire doming (e.g., Smith, 1962) or marine influx (e.g., Habib, 1966; Habib and Groth, 1967). However, its occurrence in a wide range of habitats in Appalachian coals, including mineral-rich and mineral-poor ones, and its nearly ubiquitous association with high inertinite and elevated collodetrinite contents, suggest that *Densosporites*-producers like *Omphalophloios* did not dominate ever-wet mires, but instead thrived in mires under edaphic stress (particularly water table lowering or subaerial exposure, as well as nutrient deficiency, clastic influx, or pH, salinity, or climatic changes (Smith, 1962; Butterworth, 1966; Habib and Groth, 1967; Eble and Grady, 1990; Pierce et al., 1991; Eble and Hower, 1995).

Paralycopidites palynoflora are most abundant in Shakerag benches and are conspicuous in the uppermost and basal Armfield benches. Often associated with plants typical of peat-to-clastic transition habitats (e.g. medullosan pteridosperms) (DiMichele and Phillips, 1988, 1994), spores of this reproductively-prolific tree were not adapted to dispersal in consistently flooded areas (DiMichele, 1980) and are more common in coal seat-rocks, interbedded shales, or other clastic lithologies than in coal per se. In coals, *Paralycopidites*-rich assemblages typically occur with mineral partings, elevated inertinite levels, high ash yields, and/or poorly preserved or heavily degraded peat (DiMichele and Phillips, 1994), suggesting peat substrates subject to subaerial exposure and oxidation, but periodically flooded by clastic-rich streams. Such conditions occur in overbank areas between channel levees and mire interiors (DiMichele and Phillips, 1994), but they can also occur in a domed mire gradually subsiding to planarity and eventual peat burial (Eble and Hower, 1995). Relatively common *Paralycopidites* taxa in all Shakerag benches, together with a quartz-rich underclay and upper seam truncation by channel sandstone, support channel-proximity of the Shakerag mire. In addition, just below the Shakerag seam top, bench features imply even more channel influence: sharply increased *Paralycopodites* genera, increased ash and inertinite (Fig. 5), decreases in the marine element Br, and increasing concentrations of Al, Ba, Ce, Cu, Cr, Fe, Hg, K, La, Mn, Nd, Ni, S, Sr, Sm, Th, V, Y, and Zr (Tables 7 and 8), all of which except sulfur collectively suggest fluvial influx (Wedepohl, 1978; Harris et al., 1981; Diessel, 1992; Rimmer, 1991; Hickmott and Baldridge, 1995). A mire change in the bench just below the top is also recorded at Armfield (Fig. 6): sharply increased ash, inertinite, Al, K, Ba, Cr, V, Ni, Mn, Fe, S, Sm, Sr, La, Ce, Nd, Th, Y, and Zr (as at Shakerag), lower Br, and increased P and U (Tables 7 and 8). While this bench per se has no *Paralycopodites* genera, elevated levels of such genera do occur immediately thereafter, in the ash-and-sulfur-rich top bench, as well as in Armfield's ash-rich basal bench. The data suggest that for all seams, abundances in *Paralycopodites* taxa reflect periods of clastic influx into the Bon Air mires.

5.3. Upward sulfur enrichment

The steady (Shakerag) to irregular (Armfield) upward increases in sulfur and chalcophile elements (e.g., Hg) that Bon Air benches display (Tables 7 and 8) are phenomena known in other coals (e.g., the Stockton coal, Eble and Grady, 1993; Hower et al., 1996; the Manchester coal, Sakulpitakphon et al., 2004; the Dean coal, Mardon and Hower, 2004). Marine influxes into paleomires can clearly increase sulfur in coal (Williams and Keith, 1963), but coals and peats without clear marine influence (Cecil et al., 1979; Renton et al., 1979; Renton and Bird, 1991; Phillips and Bustin, 1996) document that sulfur emplacement in peat is also affected by mire pH and/or water table levels, which control decomposition of the peat. In general, sulfur in coal reflects the availability of sulfide (S^{2-}) generated by bacterial reduction of peat water sulfate (Williams and Keith, 1963; Ward, 2002). High humification and greater sulfur emplacement are typical of more neutral peats (pH 4–8), which favor bacterial activity and associated sulfate reduction (Cecil et al., 1979; Schopf, 1952), while ever-wet acid peats (pH < 4–4.5) can suppress bacteria and sulfate reduction (Renton and Bird, 1991).

However, work on modern peats in Panama (Phillips and Bustin, 1996) shows that bacterial activity, humification, and total sulfur can be high in both neutral and acid peats (even at pH < 3) if plant growth is largely subaerial (as in forest swamps, especially raised ones) or if base level drops, both of which foster biomass loss and lower biomass/sulfate ratios. Nonetheless, even raised forest swamps produce low-sulfur peats if groundwater cannot recharge mire sulfate, and large modern domed mires are compacted, anaerobic, and low in hydrologic conductivity below their surface layer (Moore, 1995), making recharge difficult. These studies suggest that while doming of large forest-swamp mires should produce thick, well-compacted peats with poor sulfate recharge and low total sulfur, gradual doming of small, short-lived forest swamps, such as those of the Bon Air, might produce thin, less-compacted, well-recharged peats marked by upward *increases* in biomass degradation, sulfate reduction, and total sulfur.

5.4. Domed versus planar mires

In the past two decades, the significance of mire doming in coal-forming processes has become more apparent (Greb et al., 2002a). Domed (raised) mires and planar (low-lying) mires are the two basic types of forest mires responsible for thick Carboniferous peats that produced mineable coal (Moore, 1989, 1995; Greb et al., 2002a). Most Lower to mid-Middle Pennsylvanian coals (e.g., the Eastern Kentucky Coal Field) probably formed from domed peats (Esterle and Ferm, 1986; Eble and Grady, 1990, 1993; Greb et al., 2002b) as a result of a latest Mississippian to earliest Pennsylvanian tropical climate change from dry-seasonal tropical to ever-wet tropical. The Bon Air coal is of this age. By contrast, most upper-Middle to Upper Pennsylvanian coals (e.g., the Western Kentucky Coal Field) probably resulted from planar peats (Calder et al., 1996; Greb et al., 2002b) as a result of a late Middle Pennsylvanian tropical climate change back to dry-seasonal (Cecil et al., 1985). Modern planar mires (e.g., the Venezuelan Orinoco delta, or the United States Mississippi-delta, Okefenokee, Snuggedy, and Everglades mires) typically occur near the water table and are largely rheotrophic (flow-fed by groundwater or surface flow). Modern domed mires (e.g., temperate Atlantic/Pacific coastal peats and tropical forest peats of Indonesia/Malaysia) are ombrotrophic (rain-fed) and lie above the land surface (Gore, 1983; Cameron et al., 1989; Moore, 1989; Greb et al., 2002a). Most modern mires are initially planar, but become domed if moisture is sufficient to raise or perch the water table (Anderson, 1961, 1964; Romanov, 1968).

Anderson (1961, 1964, 1983) noted species changes, decreasing tree size and nutrients, and increasing peat oxidation from margins to centers of modern domed mires of Indonesia and Malaysia. Later, these modern analogs were used with UK coal data (Smith, 1957, 1962) to infer domed origins for many low-ash, low-sulfur coals (e.g., McCabe, 1984; Cecil et al., 1985). Doming also alters clay minerals in the peat: illite-rich initial assemblages are progressively leached to more kaolinitic ones (Eble and Grady, 1993) as water table fluctuations promote peat degradation, organic acids, and low pH (Cecil et al., 1985). Authigenic kaolinite precipitates as mobile silica in the mire (Ward, 2002) reacts with Al mobilized from existing clays, feldspars, or volcanic glass (Loughnan, 1969). Mire doming also limits influx of clastic debris, generally quartz- or illite-rich and kaolinite-poor, (McCabe, 1984), as has been observed in many Sydney and Bowen Basins coals (Australia) (Ward, 1989, 2002; Ward and Christie, 1994), where clays in planar-origin basal benches are illite-dominant with minor poorly ordered (detrital) kaolinite, while those in middle to upper (domed) benches are dominated by well-ordered (authigenic) kaolinite.

5.4.1. Idealized cycles in domed paleomires

From basal to upper benches, coals of domed origin often show a vertical cycle of palynologic, petrographic, geochemical, and mineralogic features–a cycle of "compositional groups"–that suggest that most domed paleomires began as planar mires, evolved to domed conditions as vegetation flourished, and, in many cases, returned to planar conditions (through base level rise or mire subsidence) prior to burial (Eble and Grady, 1993; Eble et al., 1994; Greb et al., 2002a). In idealized cycles, rheotrophic assemblages of the pioneering (lowermost) bench give way to main-rheotrophic-phase assemblages of lower benches, to ombrotrophic mid-seam assemblages, and eventually to rheotrophic upper-bench assemblages. The pioneering phase develops as base-level rise forces pre-peat water to pond in low-lying areas (Greb et al., 1999), often on clay-rich substrates that will lithify into shaley seatrock. Ash yields of this pioneering phase are quite high (>10%), but vitrinite, inertinite, and sulfur are all variable as vegetative cover and fluctuating but generally rising water table levels establish themselves. Species adapted to clastic-rich, variably wet conditions (e.g., seed ferns, calamites, and *Paralycopodites*) are often abundant.

Main-rheotrophic-phase (lower) benches will display a dominance of large, ever-wet arboreous lycopsids, abundant detrital and plant-derived mineral matter (ash), abundant well-preserved and unoxidized woody debris (vitrinite, especially collotelinite), variable inertinite, and often illite-rich and kaolinite-poor clay assemblages indicative of clastic influx, rapid burial, and/or near-neutral pH peat waters. From these benches to middle-seam benches, features become more typical of ombrotropism: mixed palynoflora with generally less abundant large lycopsids and generally more abundant "herbaceous" species (ferns and *Omphalophloios*-like lycopods), lower total vitrinite, collotelinite, ash yield, and illite, and higher collodetrinite, inertinite, and kaolinite. From seam middle to seam top, an idealized cycle would show an opposite trend, back to planarity and rheotrophism: a general increase in large lycopods, total vitrinite, collotelinite, ash, and illite, and a general decrease in "herbaceous" species, collodetrinite, inertinite and kaolinite. Uppermost benches in some cases may be sharply overlain by siliciclastics (as at Shakerag in our study), indicating dome collapse and/or rapid clastic influx, but the seam top often represents simply an end of peat accumulation, brought on by fire or drought degradation of the peat surface, incursion of salt water into the mire, rising base level due to compactional or tectonic mire subsidence, or unusual events such as large floods or pyroclastic deposition (Greb et al., 2002a). In cases of gradual inundation (drowning) by rising base level, upper bench coal may grade upwards, with increasing clastic partings, into carbonaceous or coaly shale (DiMichele et al., 1996; Greb et al., 2002a), as is true at the Armfield site of our study.

The planar mire of the pioneering and lower benches would thus evolve through doming to be less supportive of large arboreous lycopsids requiring persistent standing water, more supportive of subaerially tolerant species like *Omphalophloios*, more saturated with kaolinite-producing acidic pore waters (due both to less-frequent mire flushing by near-neutral fluvial waters and poorer hydrologic conductivity in the mire's well-compacted lower layer; Moore, 1995), and more susceptible in general to subaerial oxidation and bacterial decay, especially in the loosely compacted, periodically aerobic, hydrologically conductive surface layers (Moore, 1995). The decay processes would be marked by loss of plant biomass, greater accumulation of degraded or gellified plant debris (collodetrinite), lesser accumulation of large well-preserved plant debris fragments (collotelinite), and greater accumulation of oxidized to charcoalized plant debris (inertinite) produced by subaerial exposure, drought, and/or fire. In its waning stage, the mire would become more planar, more flooded, less subaerial, less oxidizing, and less acidic, and an opposite trend of components would develop, with increasing overall preservation of plant debris in the peat.

Single parameters cannot be used as diagnostic of a paleomire type (Greb et al., 2002a). For example, *Densosporites*-producers flourished in such wide-ranging Appalachian coal swamp conditions (Eble and Hower, 1995), from ever-wet to subaerial conditions, that abundant densospores alone do not indicate domed, ombrotrophic mires (Greb et al., 2002a). Similarly, while all modern domed mires have low ash (typically <5%) (Neuzil et al., 1993), modern planar mires may also have low ash yields where mineral matter deposition in the mire is inhibited by vegetative baffling (White, 1913; Kravits and Crelling, 1981), infrequent clastic influx (McCabe, 1984), distal location of clastic sources relative to the mire (McCabe, 1984), or sufficient pH differences between mire and fluvial waters that clays flocculate and settle at the mire/channel boundary (Staub and Cohen, 1978). Mineral matter can also be post-depositionally added to, or leached from, a peat or its coal during burial and diagenesis regardless of mire origin (Williams and Keith, 1963; Gluskoter and Simon, 1968; Spears, 1987). In addition, while inertinite clearly forms from oxidative degradation of woody debris, this occurs not only in subaerial parts of domed peats, but also in planar mires if they experience periodic droughts (DiMichele and Phillips, 1994), influx of well-oxygenated extra-mire waters (Calder, 1993; Calder et al., 1996), or crown fires (Scott and Jones, 1994). In general, the origins of the various inertinite macerals have generated more controversy than any other maceral group (Scott, 2002). Finally, studies of both present-day mires (Anderson, 1964; Gore, 1983) and coals (Littke, 1987; Pierce et al., 1991; Greb et al., 1999) indicate that modern "domed" mires not only begin as planar, rheotrophic mires, but often have rheotrophic margins at any one time, making "domed" versus "planar" labelling an oversimplification.

5.4.2. Doming of the Armfield paleomire

Based on thin, incremental coal-bench samples (6–12 in., 15–30 cm) shown to record intra-bed or intra-seam variations in coals (Greb et al., 2002a; Scott, 2002), the Bon Air seam at Armfield appears to show a complete "compositional cycle" from planar mire to domed to planar again (Fig. 6). Its basal bench (1.5 in., 3.8 cm) is a pioneering bench with extremely high ash (38.0%), moderately low sulfur (1.19%), a low ratio of kaolinite to illite/smectite, moderately high quartz, high total vitrinite, a high collotelinite/collodetrinite ratio, low liptinite, moderately high inertinite, very abundant *Densosporites* palynomorphs, moderately abundant *Lepidophloios* and *Lepidodendron* palynoflora, minor but conspicous genera of species typical of subaerial channel levees or levee/mire transitions (*Paralycopodites,* calamites, and small ferns), depleted levels of Br, and elevated levels of Al, Rb, Sr, Cr, Sc, Th, V, Y, Zr, La, Ce, Nd, Sm, Eu, Tb, Yb, and Lu. The low Br, relatively low sulfur, and elevated levels of fluvial trace elements do not fit a model of marine influx to account for the high ash yield. Rather, these data and the low-sulfur, shale-only, fluvial trace element-enriched stratigraphy above and below the coal suggest that Armfield's mire began as a floodplain depression, perhaps an oxbow lake, spatially distal from channel sand and silt, yet low enough in the floodplain to regularly receive overbank clays and promote burial preservation of biomass, high-ash peat, clay partings, and high vitrinite and collotelinite contents. Periodic drying and subaerial oxidation between flooding events promoted fern growth and elevated inertinite levels. From basal bench to upper middle benches, changes in the Armfield seam suggest doming of a small paleomire whose peat was not highly-compacted: increases in kaolinite, total sulfur, *Omphalophloios* genera, and liptinite (less susceptible than vitrinite to subaerial degradation and prolifically produced by *Omphalophloios*); decreases in total vitrinite, collotelinite/collodetrinite ratios, ash, and clastic-associated species (calamites and *Paralycopodites*); an initial drop and then gradual rise in inertinite; and continued minor small ferns.

Armfield's lower-top bench shows evidence of a waning mire stage marked by subsidence and periodic influx of quartz-rich overbank detritus: increased palynoflora of all arboreous lycopsids (especially those of *Lepidodendron*, which particularly favored higher nutrient influx), appearance of *Sigillaria* (which occupied clastic-rich and channel-marginal areas peripheral to mires) (DiMichele and Phillips, 1994), very low kaolinite but very high quartz proportions, and increased total vitrinite and collotelinite/collodetrinite ratios. Nonetheless, the mire appears to have been severely affected during this interval by oxidative degradation, microbial decomposition, and/or peat fire, producing very high inertinite contents and reducing plant biomass sufficiently that net ash and sulfur contents increased still more. By the time the uppermost bench was deposited, the Armfield mire probably had subsided to planarity, evidenced by lower inertinite, liptinite, and kaolinite, relatively lower but still high sulfur, moderately high ash, higher contents of total vitrinite, collotelinite, and quartz, and re-emergence of, or increases in, calamites and *Paralycopodites*. Armfield's paleomire was eventually buried by overbank clays (coaly caprock shale) with the same trace element signature as the mire's initial seatrock clays (Tables 7 and 8).

5.4.3. Doming of the Shakerag paleomire

Although sandstone truncation of the seam top at Shakerag shows that at least some of its peat was eroded, benches at Shakerag (Fig. 5) upwardly record a planar-to-domed mire evolution similar to that in basal to middle Armfield benches (Fig. 6). Basal bench features at Shakerag (high total vitrinite, a high collotelinite/collodetrinite ratio, relatively high ash, moderately high quartz/kaolinite ratios, conspicuous ferns of all types, abundant genera of *Lepidophloios* and especially *Lepidodendron*, moderate *Paralycopodites* and *Densosporites* genera, moderate inertinite, very low sulfur and liptinite, and stratigraphic position within complexly flaser-bedded sandstone/siltstone/shale) are consistent with a planar mire proximal to contemporaneous fluvial channels. Arboreous, often-flooded lycopsid communities, supported by frequent detrital influx, would have dominated much of the time, but periodic drying would have supported occasional flourishes of subaerially tolerant species observed in this bench, including *Omphalophaloios*, *Paralycopodites*, and ground-cover ferns.

Above this basal bench, Shakerag benches show a continual rise in sulfur, sharply increased *Paralycopodites* and *Omphalophloios* but less *Lepidodendron* palynoflora in the two top benches, a general decrease in total large lycopsids, a general increase in liptinite, a steady decrease in collotelinite/collodetrinite ratios and total vitrinite, and upward alternations (decreasing, increasing, then decreasing again) in quartz/kaolinite ratios, inertinite and ash. We interpret that from base to top, the Shakerag mire was gradually doming, but subjected at least once (the bench just below the top) to local clastic incursions and drought (or fire) to produce sharp increases in *Paralycopodites* palynomorphs, inertinite, liptinite, quartz/kaolinite ratios, and ash. Both the Armfield and Shakerag mires probably evolved from planar to domed during their early stages. Whether the Shakerag mire ever cycled back to planarity as at Armfield is unclear, given the unquantifiable amount of Shakerag peat scoured by overlying channel sands. Peat deposition at Shakerag may have completed a cycle that is now partially missing. Alternatively, high subsidence and sedimentation rates typical of channel-proximal habitats might have impeded any gradual return to planarity.

5.5. Coal facies models

While domed-mire models seem appropriate for the description of the Bon Air coals, with better spatial control of coal quality and botanical features, coal facies models would have been an additional approach. As with the domed-mire models, such studies are not without complications and the extrapolation of descriptive petrographic-botanical-geochemical parameters into models of coal facies should be approached with caution, as discussed by Wust et al. (2001) and Moore and Shearer (2003), among others. Coal facies models have been extrapolated from Diessel's (1986) model, based on the Permian Sydney (New South Wales) Basin, to everything from Pennsylvanian coals to modern peats, with varying success. Recent applications of coal facies models include the studies of Gmur and Kwiecinska (2002), in which they applied the latest modifications of vitrinite nomenclature (ICCP, 1998) to studies of Pennsylvanian coals from the Upper Silesian Basin; studies of Pennsylvanian Asturian coals by Piedad-Sánchez et al. (2004); and the multidisciplinary studies of Bechtel et al. (2002, 2003, 2004) of Tertiary coals of Austria and Slovenia. Hower and Eble (2004) have summarized the individual parameter studies and multidisciplinary facies studies for coals of the eastern United States.

6. Summary

All Bon Air seams of our study were likely small, spatially distinct, forest swamp paleomires ($\leq$0.2–1.0 mile wide, 0.3–1.6 km) of Early Pennsylvanian age (Westphalian A, Langsettian). *Densosporites* palynoflora of *Omphalophloios*-like small lycopsids dominate the shale-hosted Armfield seam, while genera of large lycopsids (*Lepidodendron hickii* and *Lepidophloios harcourtii* and *hallii*) dominate where coals are hosted by siltstones, sandstones, and shales (Dotson, Rutledge, and Shakerag sites). All sites contain minor fern, calamites, *Sigillaria*, and *Paralycopodites* taxa, especially in seam bases or tops, with *Paralycopodites* genera ubiquitous in coal at Shakerag and locally > 10%.

Macerals vary significantly between sites. Collotelinite and total vitrinite are higher at Shakerag (up to 47% and 80%, respectively); Dotson and Rutledge seams contain more inertinite (36–37%) and less vitrinite (40–41%) than other sites, and Armfield's seam has high liptinite (25–28%) and vitrinite (56–62.5%). Moderately high ash (11.0–20.0%) and moderate sulfur (1.24% avg.) are typical, but individual samples or benches may contain up to 38% ash and 2.9% sulfur.

Armfield's mire was probably channel-distal, perhaps an oxbow lake or floodplain depression, which cycled from planar to domed to planar again prior to burial. Its lower- and uppermost benches suggest near-neutral pH, planar-mire conditions: abundant collotelinite, total vitrinite, ash, and fluvial trace elements; abundant palynoflora of small and large lycopsids, relatively abundant *Paralycopodites* genera, low kaolinite content, and variable sulfur. The middle benches, with lower ash, vitrinite, and collotelinite, less palynoflora of both large lycopsids and *Paralycopodites*, and more liptinite, kaolinite and *Densosporites* palynomorphs, suggest doming of the Armfield mire.

The seam at Shakerag shows similar upward trends as in the early Armfield stages (generally decreasing vitrinite, collotelinite, *Lepidodendron,* and total large lycopsids; and generally increasing liptinite, inertinite, sulfur, and *Densosporites*), which suggest that its mire also grew from planar to domed. However, the Shakerag mire, with its abundant *Paralycopodites*, quartz-and-illite-rich underclay, alternately quartz-rich and quartz-poor benches, and truncation by overlying channel sandstones, was apparently more channel-proximal than the Armfield mire and may not have returned to planarity. The Dotson and (especially) Rutledge mires, with more abundant inertinite and small fern taxa but less vitrinite, collotelinite, sulfur, and *Paralycopodites* palynoflora than other sites, appear to have been topographically higher, domed longer, or otherwise more prone to drought or fire than the other mires.

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