CHAPTER 6:

MODERN ANALOGUES AND DEPOSITIONAL MODELS

6.1 Introduction

Sequence stratigraphic position plays an important role in peat formation and coal seam thickness, extent, and distribution. Peat-forming environments and depositional environments of surrounding and adjacent strata may also affect coal characteristics by simultaneously influencing coal continuity, thickness, geometry, distribution, and quality (Flores, 1993). This chapter will discuss relationships between coal properties and the depositional environments of peat and surrounding strata. Depositional interpretations of coal-bearing facies successions together with comparisons to modern depositional analogues is the basis for the creation of depositional models for Desmoinesian coals across the Bourbon arch. To enhance coalbed methane exploration and production strategies, Flores (1993) emphasized the importance of understanding the heterogeneities of properties such as coal thickness, extent, geometry, and distribution, as well as the properties of surrounding sediments and their depositional environments. Creating depositional models of significant coal-bearing intervals can improve understanding of Desmoinesian coals in eastern Kansas.

Depositional models are summaries of sedimentary environments or systems, which can be used for comparison to other environments or systems. Depositional models provide a guide for future observations, evaluate the validity of existing concepts, and can be used as a tool for prediction of geologic situations with incomplete data (Walker, 1976; Miall, 1999). Models can be created from experimentation, simulation, theory, and the simplification of multiple observations from both modern and ancient rocks (A.W. Walton, personal communication, 2003). The depositional models in this study are based on a combination of core description and facies interpretation, cross-section correlation and interpretation, regional coal isopach and structural contour mapping, sequence stratigraphic concepts, and comparison to published observations and interpretations of modern depositional analogues. The depositional models for the Desmoinesian coals in eastern Kansas are used more as an explanatory tool than for predictive purposes.

Previous depositional models of peat-forming environments were generally based on either depositional interpretations of surrounding sediments or peat facies (Flores, 1993). Most of the previous research on coal deposits mainly focused on the underlying siliciclastics rather than on the coal itself (McCabe, 1984). Historically, Pennsylvanian coals have been classified as “upper delta plain”, “back-barrier coastal”, or “floodplain” coals (McCabe and Shanley, 1992). Wanless et al. (1969) described Pennsylvanian coal beds as having formed in situ and contemporaneously with active sedimentation within deltas, in abandoned fluvial or distributary channels and cutoff meanders of active fluvial settings, in both back-barrier lagoons and non-barrier coastal marshes (Mulberry coal of Missouri and Kansas), from “abrupt marine regression” (Lexington and Mulky coals of Missouri, Iowa, and Kansas), and from the infilling of pre-Pennsylvanian topography (Croweburg coal of the mid-continent).

Mire type (e.g. raised, low-lying, or floating) has been suggested as the dominant control on coal quality, extent, thickness, and geometry (McCabe, 1984, 1987, 1991; McCabe and Parrish, 1992; and McCabe and Shanley, 1992). Low ash coals originate from raised, or domed, mires and higher ash coals originate from low-lying or floating mires. Because peat forms at slower rates relative to episodic flooding and other depositional events from active sedimentary environments, only peats either far removed or self-excluded from active sedimentary deposition are able to form low ash coals. Thicker, lower ash peats form coals that are removed or excluded from sediment influx through 1) protection by the topographically positive nature of the raised mire allowing the mire's water table to exceed local base level; 2) water chemistry that results in clay flocculation and deposition at the peatland margins; and 3) sediment starvation by organic filtering or increased base level (McCabe, 1984). The potential for thick, low ash peat development is dependent on the amount of time that sediment supply is suppressed and the extent of the area affected by such sediment starvation (Aitken, 1994). Many well-known modern peat-forming depositional environments such as delta plains and fluvial floodbasins are not good coal-forming environments, but would result in very high-ash coals or carbonaceous shales (McCabe, 1984).

Underlying sediments are thought to play only a minor role in peat formation (McCabe, 1984, 1987, 1991; McCabe and Parrish, 1992; and McCabe and Shanley, 1992). This is due to the significant depositional hiatus occurring between the underlying paleosol or rooted horizon and the coal seam (McCabe, 1984). Underlying sediments may, however, provide a framework for peat deposition where localized topography and accommodation influence peat thickness, extent, distribution, and initial peat facies. As opposed to models postulated by Wanless et al. (1969) and Flores (1993), economically significant low-ash peat may not be contemporaneously related to underlying deposits (McCabe, 1984). Observations of the underclay facies in eastern Kansas support a significant hiatus between sediment deposition and peat accumulation. Pedogenic features indicate a moderately drained, exposed soil with a moderate-depth subsurface water table subject to seasonal rainfall and resulting shrink-swell cycles (e.g. clay illuviation and horizonation, slickensides, various stages of ped-structure development, rhizoconcretions, calcite nodules, and vertically oriented carbonaceous root traces). However, features indicative of more waterlogged soils have been observed within the underclay facies. These features include shallow laterally spreading carbonaceous root traces indicative of a near-surface water table; and gleyed appearance and drab-haloed root traces resulting from reduction.

A general depositional timeline is proposed for coal-bearing strata in eastern Kansas. Sediment was first subaerially exposed on the landward side of a prograding coastline. The water table may have lowered slightly during this regression allowing for paleosol development during the depositional hiatus. Plants may have colonized the newly exposed surface. Upon subsequent transgression, base level and the local water table rose. Moderately drained paleosols became more waterlogged and poorly drained, sometimes resulting in pedogenic overprinting of waterlogged soil features on more moderately drained features (e.g. Franklin County core interval 851’ to 853’; Appendix A). As transgression progressed, mire development initiated coincident with the water table rising above the paleosol surface. Transgression may have been coupled with warmer climate and increased precipitation (from seasonal to constantly wet; Cecil, 1990; Suchy and West, 2001). The flat ramp setting of the eastern Kansas enhanced extensive mire development. For example, the Croweburg coal is correlative from central Oklahoma to eastern Pennsylvania and from western Iowa to central West Virginia and may have been the most extensive peat swamp in geologic history (Wanless et al., 1969). Eastern Kansas coals are interpreted to form during initial transgression within a parasequence rather than following coastal progradation. The typical abrupt transition of eastern Kansas coal facies into transgressive lag or deeper water marine facies without intervening marginal marine or non-marine facies is characteristic of transgressive coals (Diessel, 1998).

Coal seam characteristics (e.g. depositional orientation, average thickness, seam geometry, and aerial extent) are suggestive of peat-forming environments and can be used as a tool for interpretation and prediction (Flores, 1993). Seam geometry and properties of eastern Kansas coals, mire type, and depositional interpretations of underlying sediments are used to construct depositional models. Coals in the Desmoinesian section of the Bourbon arch region were influenced by 1) pre-Pennsylvanian topography, 2) position within the tidal coastal plain or estuarine incised valley, and 3) relative abruptness of marine regressions. In general, coal seam properties (depositional orientation, average thickness, lateral extent and continuity, and geometry) can be related to depositional environments underlying individual coal units (Table 6.1).

Table 6.1 Coal seam characteristics (from Table 3.1) and interpretations.

COAL	Seam Orient.	Dep. Orient.	Geometry	Depositional Setting or Control
Mulberry	NW-SE	ND	Lenticular; Pod-like	Marine Regression
Lexington	NW-SE	ND	Lenticular; Pod-like	Marine Regress.; Coastal Plain
Summit	NW-SE	ND	Circular and pod-like	Marine Regression
Mulky	NW-SE	ND	Circular and pod-like	Marine Regression
Bevier	NE-SW	Dip	Lenticular; Elongate	Coastal Plain
Croweburg	NE-SW	Dip	Elongate; Lenticular	Coastal Plain
Mineral	NW-SE	Strike	Lenticular	Coastal Plain
Scammon	NE-SW	Dip	Elongate	Estuarine
Tebo	NW-SE	Strike	Lenticular	Coastal Plain
Weir-Pittsburg	NE-SW	Dip	Lenticular	Coastal Plain
Dry Wood	NE-SW	Strike	Lenticular	Coastal Plain
Rowe	NW-SE	Strike	Lenticular	Coastal Plain
Neutral	NW-SE	Strike	Lenticular	Coastal Plain
Riverton	NW-SE	ND	Lenticular; Elongate	Pre-Penn. Topo.; Estuarine

ND=Not Discernible

Table 6.1 (continued)

COAL	Avg. thick. (ft.)	Extent (mi^2)	Continuity (mi^2)	% of extent	Area > than avg. thick. (mi^2)	% of extent	# data pts.
Mulberry	0.9	3617	2046	56.6	2298	63.5	805
Lexington	0.4	1151	232	20.1	969	84.2	817
Summit	0.8	4071	1511	37.1	2333	57.3	846
Mulky	1.0	4133	2334	56.5	2334	56.5	845
Bevier	1.5	4246	3987	93.9	2418	57.0	647
Croweburg	1.0	4067	2146	52.8	2146	52.8	602
Mineral	1.0	4064	2166	53.5	2166	53.3	554
Scammon	0.8	3780	1307	34.6	2060	54.5	541
Tebo	0.8	3841	1526	39.7	2407	62.7	488
Weir-Pittsburg	0.8	3327	1201	36.1	1719	51.7	488
Dry Wood	0.4	1925	310	16.1	1526	79.3	282
Rowe	0.6	3128	747	23.9	2247	71.8	283
Neutral	0.7	3429	1236	36.0	2221	64.8	282
Riverton	1.2	3578	2461	68.8	2098	58.6	241

6.2 Depositional Models and Modern Analogues

6.2.1 Pre-Pennsylvanian Topography

Lange (2003) interpreted the Riverton coal as forming in close association with the underlying karsted Mississippian Limestone terrain (Fig. 6.01). This model suggests that Pennsylvanian sedimentation initialized in low-lying erosional valleys where ponds, lakes, and marshes developed. The Riverton coal initially developed as low-lying mires in paleotopographic lows, but may have locally developed into raised mires supported by its own water table as base level increased due to transgression (McCabe, 1984; Lange, 2003). Lange (2003) based this interpretation on the lenticular geometry, localized orientation parallel to either depositional strike or dip, thickening (up to 4.5 ft. [1.4 m]) over Mississippian structural lows, and slight thinning of the Riverton coal isopach over structural highs in southeastern Kansas. The formation of raised mires during the time of Riverton deposition is supported by the hypothesis of Cecil (1990), which dates the transition from raised mire to planar mire formation around the early- to middle-Desmoinesian.

The Riverton coal appears to form on both localized structural highs and lows of the Mississippian Limestone terrain in the Bourbon arch study area, ultimately pinching out to the northeast onto a regional paleotopographic high. Coal seam geometry is lenticular to elongate, with indeterminate orientation. Thickness is up to 3.7 ft (1.1 m; Fig. 3.06; Fig. 3.09). The Riverton is extensive over much of the study area (3578 square miles [9267 km^2]) and is continuous over 2461 square miles (6374

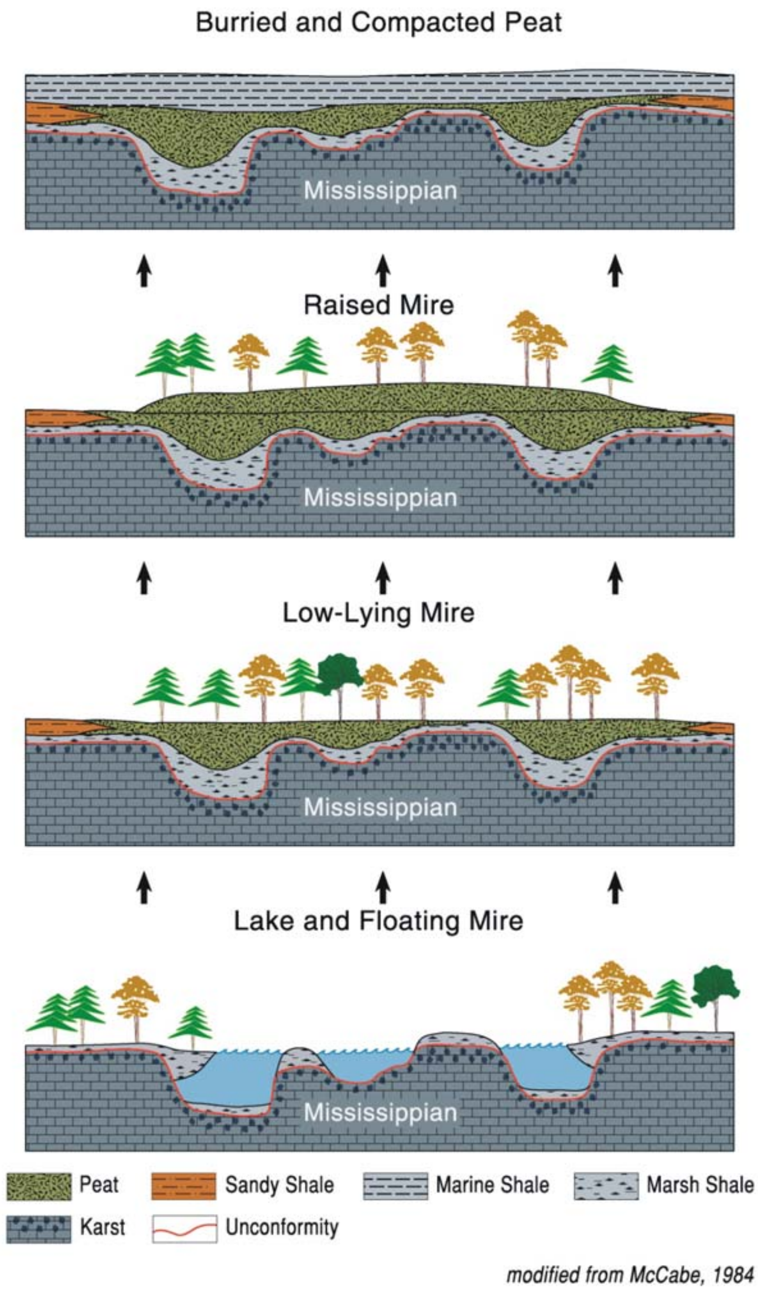

Figure 6.01 Depositional model for peat accumulation influenced by pre-Pennsylvanian topography (Riverton coal of the southern portion of the study area). During initial stages of transgression, lakes and marshes formed in karst lowlands and were followed by low-lying mires. Upon further transgression, raised mires may have formed, given the right conditions. Mire formation is thickest in karsted lows and thin on karst highs (from Lange, 2003; modified from McCabe, 1984).

km^2) or 68.8% of its extent (Table 6.1). Despite the slight differences in depositional trends between the Cherokee basin and Bourbon arch, the depositional model of the Riverton coal proposed by Lange (2003) appears to be valid for the southern portion of the current study area (Fig. 6.01). However, Riverton coal ash contents ranging from 11.7 to 19.7 % and averaging 15.2 % reduces the probability of raised mire development within the current study area. Higher ash content (ranging from 10.5 to 34.4 %; averaging 19.3 %) in the Cherokee basin indicates an even less protected environment of deposition (Fig. 3.04). Published ash contents are 6.5 % or less for raised mires (McCabe, 1984; McCabe and Shanley, 1992). Sulfur contents for the Riverton in the Bourbon arch are not available, but high sulfur contents (2.8% to 10.7%) in the Cherokee basin indicates a marine influence during or immediately following deposition (Fig. 3.06; Lange, 2003).

In the northern portion of the study area, Atokan(?) strata underlie the Riverton coal, decreasing the influence of pre-Pennsylvanian topography northward into the Forest City basin. Although the coal was not observed in core, facies underlying the Riverton coal (or the overlying Warner Sandstone) include offshore transition, restricted estuarine basin, lower and upper tidal flats and channels, and paleosol (Fig. 3.08; Appendix A). Based on facies evidence, a possible estuarine model may explain the depositional pattern of the Riverton coal in the northern Bourbon arch and southern Forest City basin.

6.2.2 Coastal Plain

Most significant coals in the Bourbon arch are associated with a coastal plain setting (Fig. 6.02). Coastal plain peats form behind both barred and non-barred shorelines, along and over lagoons, over filled estuaries, and over interfluvial lowlands (Flores, 1993). As observed in both cores, coastal plain-associated coals of the Bourbon arch typically overlie tide-influenced siliciclastic deposits (Appendix A; Johnson, 2004).

Comparison to modern depositional systems in western Indonesia was used to create a generalized depositional model for coastal plain coals across the Bourbon arch (Fig. 6.02). A complete stratigraphic succession of coastal plain coal-bearing strata in the Bourbon arch is black shale (deep marine), gray shale (offshore transition or restricted tidal estuary), heterolithic siltstone (tidal flats or lower subtidal coastline), heterolithic sandstone (upper tidal flat, tidal channel, or shoreline), underclay (paleosol), and coal (mire). Due to erosion, non-deposition, or relative sea-level fall, the succession is often incomplete and any facies may directly underlie the underclay and coal facies. Very similar facies successions are found in both the central Sumatra basin (Cecil et al., 1993), and the compound delta of the Klang and Langat rivers of the Malay Peninsula (Coleman et al., 1970). Both modern analogues are very similar sedimentologically, but depositional interpretations differ.

A tide-influenced compound delta is currently prograding into the Strait of Malacca, with sediment originating inland through tidal distributary channels and longshore tidal drift (Coleman et al., 1970). Extensive tidal flats are found directly

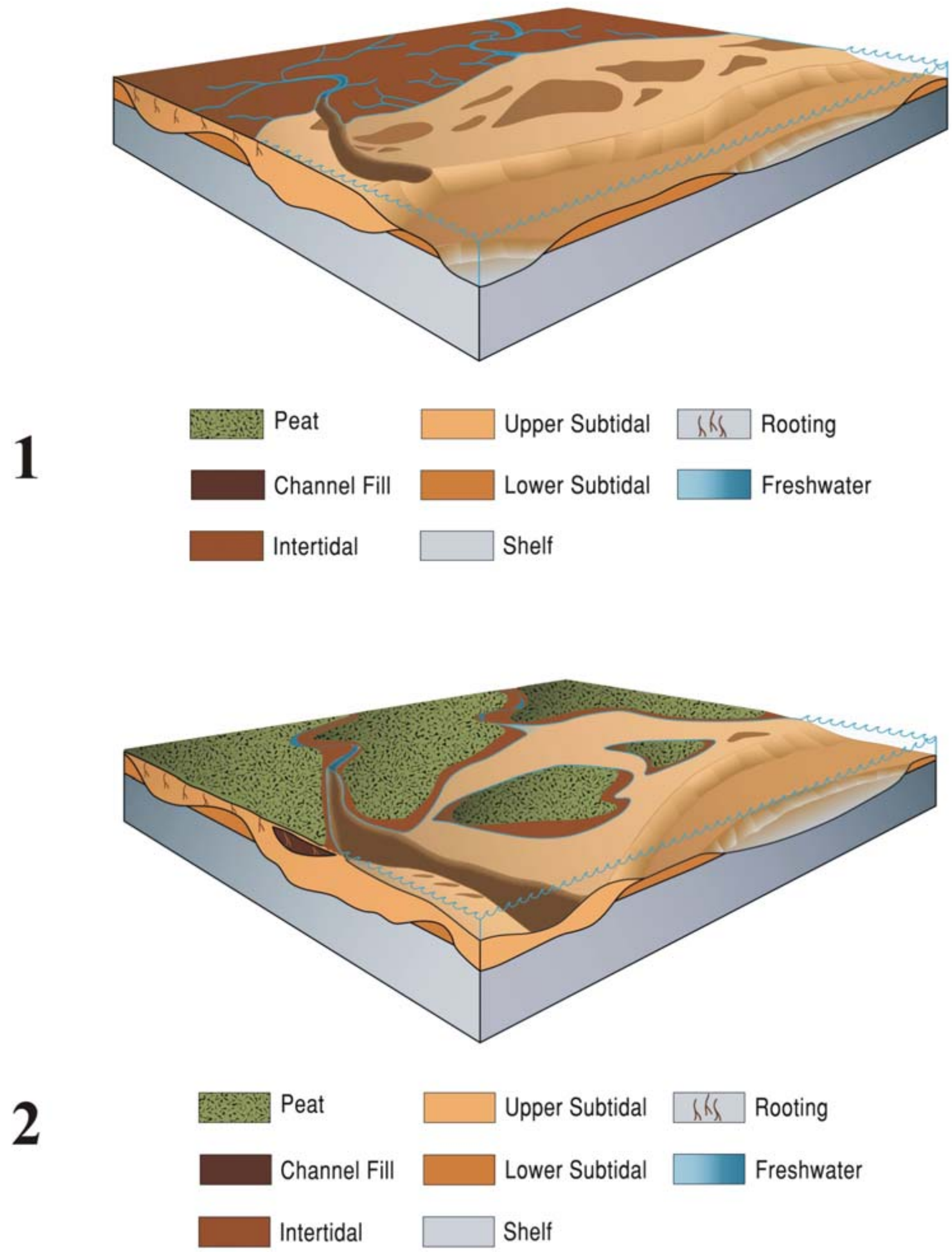

Figure 6.02 Two-phase depositional model for peat development in coastal plain settings, based on modern observations of Cecil et al., (1993). The tide-influenced coast progrades into the basin, resulting in subaerial exposure and pedogenic processes on the trailing coastal plain (1). Subsequent transgression and base level rise results in channel infilling, tidal flat amalgamation, and mire development in areas protected from siliciclastic influx (2).

offshore of the tidal channels. Large expanses of mangrove swamps and low-lying and raised mires occur between small streams and tidal channels. The mires are interpreted as forming contemporaneously with the prograding tidal delta (Coleman et al., 1970). Across the Strait of Malacca is the central Sumatra basin and the Island of Sumatra, where a very similar depositional system exists (Cecil et al., 1993). The tidally influenced coastline in this region is characterized by net erosion or non-deposition rather than progradation (Cecil et al., 1993). Progradation of the tidal coastline is interpreted to have occurred during a lower sea-level stand several thousand years prior to formation of the peat mires, which are a consequence of present-day marine transgression and coastal inundation (Cecil et al., 1993). Thick, laterally extensive, low-lying and raised mires are developing between tidal channels on the coastal plain in both modern analogues. Peats in the region have elongate to lenticular geometries oriented generally parallel with the coastline, and relatively low ash and sulfur contents. Due to the role that mire relief plays, low-lying mires have higher ash and sulfur contents than their domed counterparts. Low-lying mires are more prone to tidal effects than are raised mires, and thus form within comparably more brackish waters than do raised mires (Coleman et al., 1970; McCabe, 1991; Cecil et al., 1993; Flores, 1993).

The coal characteristics and underlying deposits of coastal plain coals in the Bourbon arch resemble characteristics described on the Island of Malacca (Cecil et al., 1993). Coals developed within the coastal plain setting include the Neutral, Rowe, Dry Wood, Weir-Pittsburg, Tebo, Mineral, Croweburg, and Bevier.

Generally, these coals have lenticular geometries oriented parallel to depositional strike. Coastal plain coals of the Bourbon arch typically have higher lateral extents and continuities than coals of other interpreted depositional settings (Table 6.1). Coal quality values are summarized in Table 6.2.

Table 6.2 Coal characteristics of coastal plain-associated coals.

	Thickness (feet)		Ash (%)		Sulfur (%)	
	Max.	Max. Avg.	Range	Avg. Range	Range	Avg. Range
Bourbon arch	3.8	1.5	6.6 - 73.0	15.3 - 32.7	1.9 – 8.7	2.0 - 5.9
Cherokee basin	6.0	1.5	4.9 - 80.7	15.4 - 35.4	1.4 – 9.8	1.4 – 6.3

(Cherokee basin values updated and modified from Lange, 2003)

Ash contents indicate deposition in settings both proximal to—and protected from—active siliciclastic sedimentation. Locations with low ash contents and greater seam thickness may reflect raised mire development. Sulfur contents reflect moderate to heavy marine influence stemming from deposition in marginal marine- to marine settings, or from rapid marine transgression over the coals.

6.2.3 Estuarine

The Scammon coal (and possibly the Riverton coal of the northern Bourbon arch) and numerous unnamed and localized coals (e.g. ‘Aw’ and various Bluejacket coals; Harris, 1984; Staton, 1987; Huffman, 1991) were likely deposited in the transgressive estuarine fills of incised valleys. An incised valley is defined as a “fluvially-eroded, elongate topographic low that is typically larger than a single channel-form, and is characterized by an abrupt seaward shift of depositional facies across a regionally mappable sequence boundary at its base” (Zaitlin et al., 1994).

Lange (2003) proposed a depositional model that adequately explains the process of valley incision, transgression and resulting valley fill, and peat formation related to incised valley complexes (Fig. 6.03). During marine transgression, restricted estuarine sediments fill incised valleys that were created during previous lowering of base level (relative sea level; Zaitlin et al., 1994). Facies of incised valleys include erosive-based fluvial sandstones, finer-grained estuarine central basin deposits, and estuarine sandstones (tidally-influenced flats and channels). Peat mires may form above paleosols at the top of this sequence in the upper estuary (Zaitlin et al., 1994). Estuarine valley peats result in thin, dendritic-shaped coal geometries with limited lateral extent and orientation with depositional dip (Wanless, et al., 1969; Lange, 2003). Ash contents of estuarine coals are moderate to high (13.6% to 32.7%; Fig. 3.04) due to the proximity of peat deposits to estuarine channel processes (tides and fluvial activity). As transgression oversteps the limits of the incised valley, mires may develop on previously subaerially exposed coastal plain. The dendritic coal isopachs are characteristic of the underlying estuarine depositional system.

6.2.4 Marine Regression

In eastern Kansas, several coals of the Cherokee and Marmaton groups were observed directly overlying marine limestones. Wanless et al. (1969) interpreted the Mulky and Lexington coals of the mid-continent as forming from "abrupt marine regression", where sea level dropped suddenly allowing for possible subaerial exposure, and then peat formation during subsequent transgression. Lange (2003) also associated the Mulky, as well as the stratigraphically higher Summit coal, with

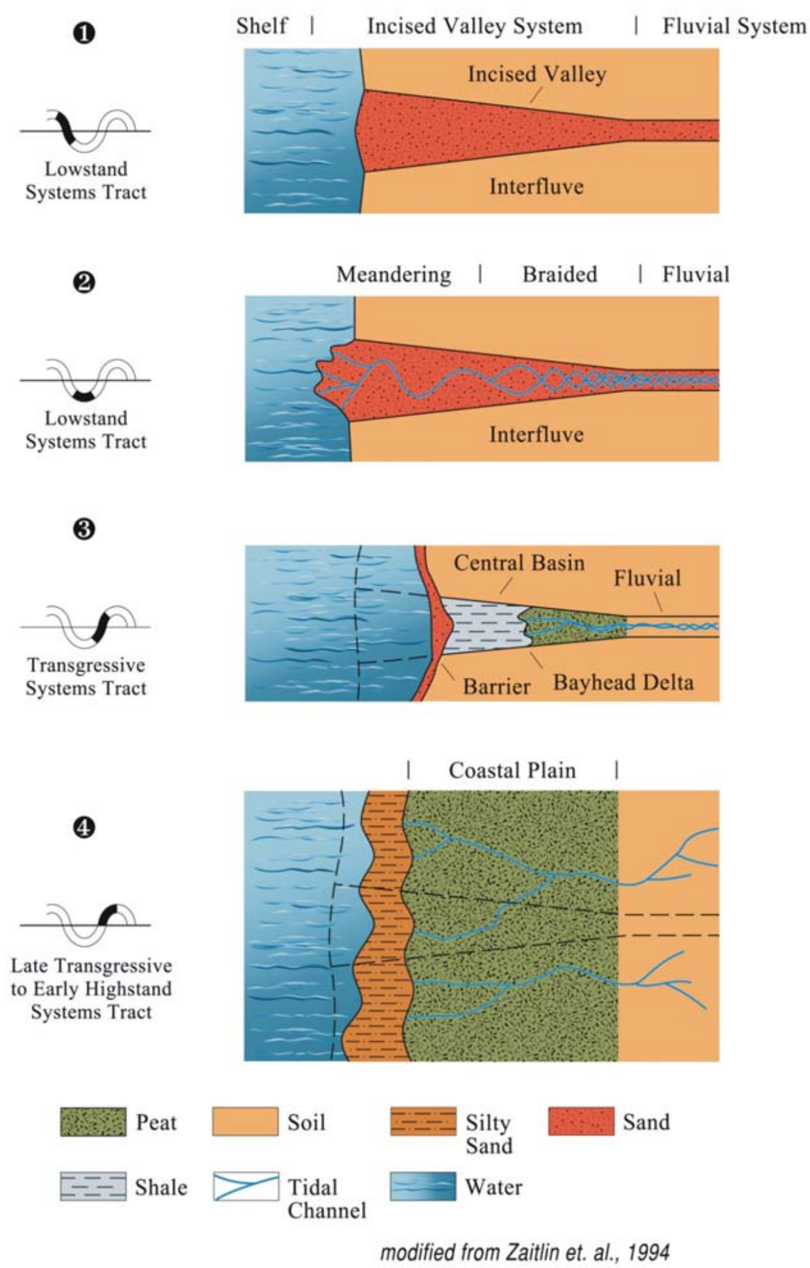

Figure 6.03 Estuarine depositional model for peat accumulation (Scammon coal, numerous unnamed coals, and possibly the Riverton coal of the northern portion of the study area). Following valley incision (1 and 2), the onset of transgression results in thin, isolated mires within the valley (3). Mires may become more developed and extensive as the valley is completely filled during later stages of transgression (4; from Lange, 2003; modified from Zaitlin et al., 1994).

this depositional control. In the Bourbon arch study area the Mulky, Summit, Lexington and Mulberry coals can be simultaneously explained by Lange's (2003) marine regression depositional model developed for the Cherokee basin. However, due to the more landward position of the Bourbon arch relative to the Cherokee basin during the Marmaton, minor modifications are proposed to the marine regression model for the Mulky coal. No modern analogues were found to adequately help explain depositional processes in the marine regression model.

<u>Summit Coal</u>

The marine regression model of the Cherokee basin postulates that the Mulky and Summit coals, which overlie the Breezy Hill and Blackjack Creek limestones, respectively, formed on small-scale localized topographic limestone highs during maximum regression or the ensuing transgression (Fig. 6.04; Lange, 2003). Supportive observations include highly variable thicknesses and lateral continuity; circular, pod-like seam geometry that thickens over structural highs of the underlying limestone; minor paleosol or caliche development capping each limestone prior to peat formation; and high ash (36.5% to 88%) and sulfur (>11%) contents and carbonaceous nature resulting from such close association with marine processes (Lange, 2003).

This interpretive model is valid for the Summit coal of the Bourbon arch study area. The Summit coal in the Bourbon arch region similarly has a circular, pod-like seam geometry that thickens over the topographic highs of the underlying Blackjack Creek Limestone; is laterally discontinuous (<1511 square miles [<3913 km^2]); and

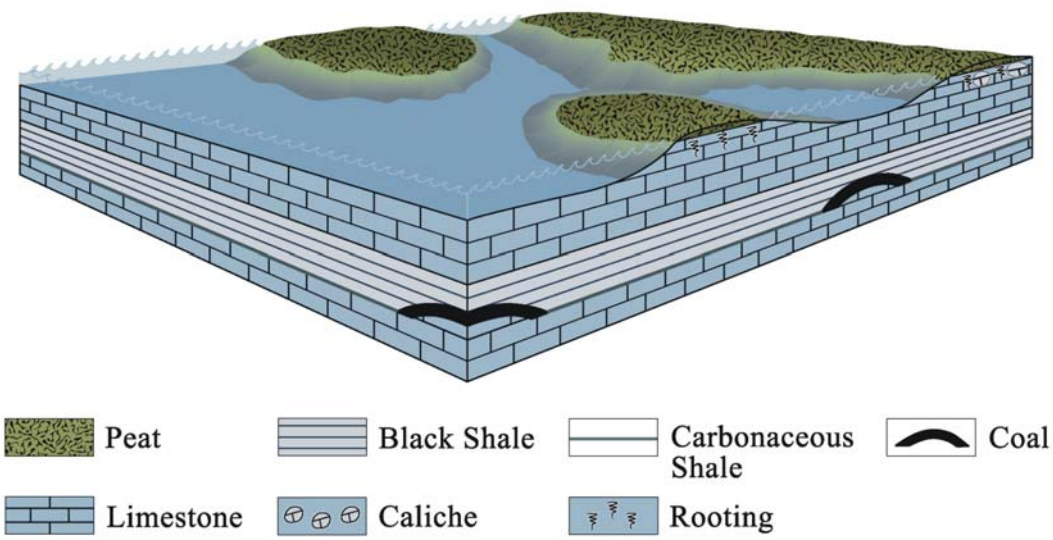

Figure 6.04 Lange's (2003) marine regression depositional model for peat development above marine regressive carbonates. The model is applicable for the Mulky and Summit coals in the Cherokee basin, but only for the Summit coal in the Bourbon arch study area. The model postulates that marine regression resulted in exposed or topographically high areas of limestone. These became favorable areas for peat formation during the lowstand or ensuing transgression.

has high ash content due to proximity to marine processes (74.1%; Fig. 3.04; Fig. 3.25; Table 6.1). Another notable trend observed in mapping is that the Summit coal thickens over and follows thicker isopach contours of the underlying Blackjack Creek Limestone, resulting in a more laterally-continuous, crescent-shaped coal seam trend through Franklin, northern Anderson and Linn, and Johnson counties (Fig. 3.25).

Mulky Coal

The marine regression model is valid for Mulky coal of the very southern portion of the study area where the Breezy Hill Limestone is developed. As observed in core and well log, the Breezy Hill is absent over nearly the entire study area. In its place is a thick, sandy, sometimes-calcareous paleosol horizon. The upper surface of the paleosol is interpreted as a sequence boundary and major exposure surface (Chapter 5). The paleosol underlying the Mulky coal or Excello shale is moderately developed and contains of a thick profile of pedogenic features such as carbonaceous rooting, abundant calcareous and siderite-lined rhizoconcretions, blocky ped structures (some columnar), and a deep horizon of pedogenic slickensides and clay cutans resulting from soil shrinking and swelling, and clay eluviation, respectively (Fig. 3.23; Appendix A; Johnson, 2004).

The Mulky coal overlies this paleosol surface on the Bourbon arch. The coal varies from discontinuous, circular and pod-like in the south to more continuous and irregular in the north, averaging <2334 square miles [6045 km^2] between the two areas (Table 6.1). The coal still tends to form on localized highs in the south and more regional highs in the north. Ash and sulfur contents are high (15.4 to 38.8% and

4.5%, respectively; Fig. 3.04), suggesting proximity to active marine depositional processes. Based on these observations and coal isopach mapping, the marine regression model is extended to include more landward environments with paleosol development for the Mulky coal in the Bourbon arch region (Fig. 6.05).

Lexington Coal

The Lexington coal occurs directly above a mixed siliciclastic-carbonate succession. Neither the coastal plain or abrupt marine regression models adequately explain the controls on the Lexington coal formation alone. The Lexington appears to be highly influence by the topography of the underlying Higginsville Limestone, and so is grouped with other coals of the marine regression models.

The Lexington coal tends to be thicker on localized highs and thinner in lows of the underlying Ft. Scott Limestone in the northeast portion of the study area (Fig. 3.27). The coal has a pod-like to lenticular geometry and is moderately continuous (232 square miles [601 km^2]) given the coal's minor extent (1151 square miles [2981 km^2]; Table 6.1). Ash contents (9.6 % to 65.7 %; average 35.9 %; Fig. 3.04) suggest widely varying association with active deposition and a low-lying planar mire. Sulfur content (3.4 %) suggests marginal marine influence. The Lexington coal is interpreted to form in a tidal coastal plain depositional setting that was highly affected by abrupt marine regression of the pre-existing Ft. Scott Limestone topography (Fig. 6.06).

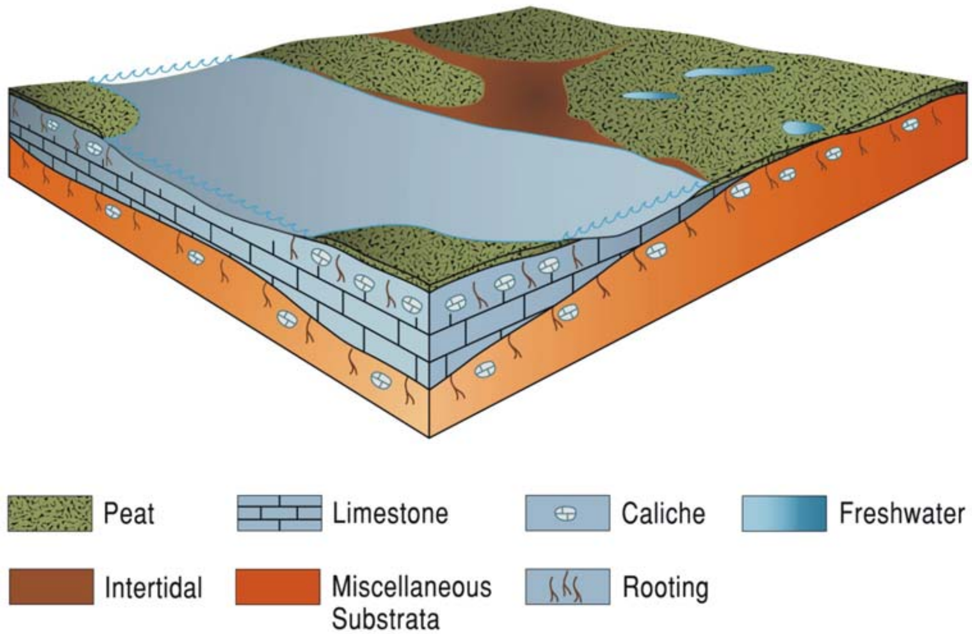

Figure 6.05 Modified marine regression depositional model for the Mulky coal in the Bourbon arch. The Mulky coal is developed directly over a thick, sandy paleosol horizon, rather than over the Breezy Hill Limestone as in the Cherokee basin due to the northward pinchout of the limestone. Paleotopographic highs were favorable sights of significant peat accumulation during marine transgression.

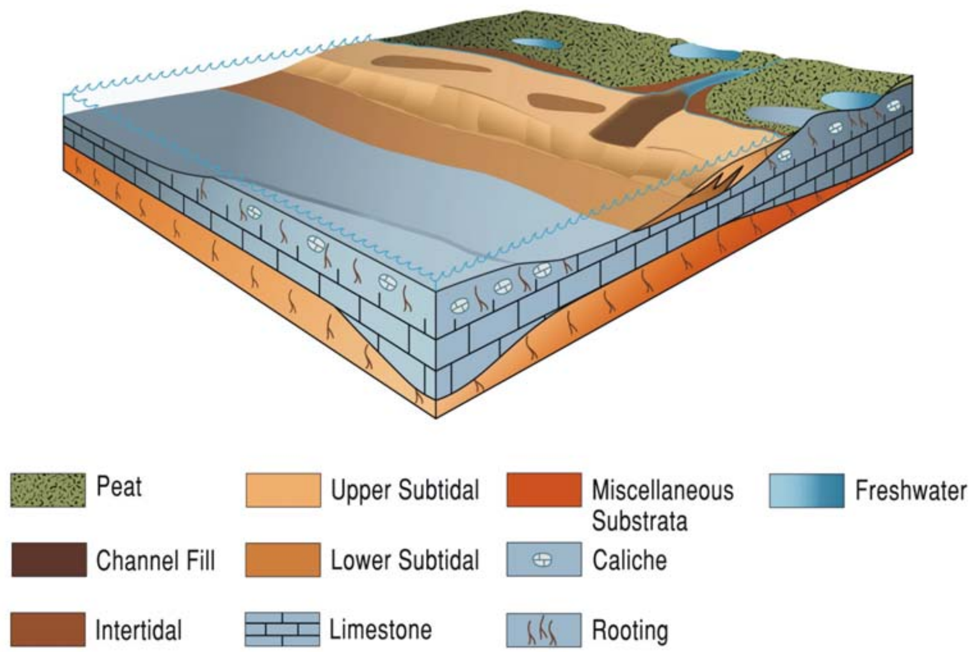

Figure 6.06 Modified marine regression model for the Lexington coal. The Lexington was similarly influenced by paleotopographic highs of the underlying Ft. Scott Formation with greater peat accumulation occurring on relatively high paleotopography. However, the Lexington overlies tidally influenced sandstone facies, which are the result of transgressive coastline deposition immediately following marine regression and subaerial exposure.

Mulberry Coal

Although Wanless et al. (1969) interpreted the Mulberry coal as forming in a coastal plain setting, more detailed observations in the Bourbon arch suggest that the marine regression model more accurately explains the coal's characteristics. The Mulberry coal, as observed in both core and well log, directly overlies the Pawnee Limestone, a laterally continuous limestone that formed a near-planar upper surface prior to peat formation. A small paleosol profile occurs between the weathered upper surface of the Pawnee Limestone and the Mulberry coal (Fig. 3.28). The Mulberry coal has a lenticular to pod-like seam geometry and thickens on structural highs of the Pawnee Limestone (Fig. 3.29). The Mulberry is extensive (2400 square miles [6200 km^2]) and fairly continuous (150 square miles [400 km^2]) over much of the northern half of the study area (Table 6.1). Ash (14.1 to 22.1 %) and sulfur (2.4 %) contents are moderate suggesting less interaction with marine processes relative to the Mulky or Summit coals (Fig. 3.04; 3.05). The Mulberry coal most likely formed as a planar, low-lying mire, as opposed to a raised mire (Fig. 6.07; McCabe, 1984; Cecil et al., 1993).

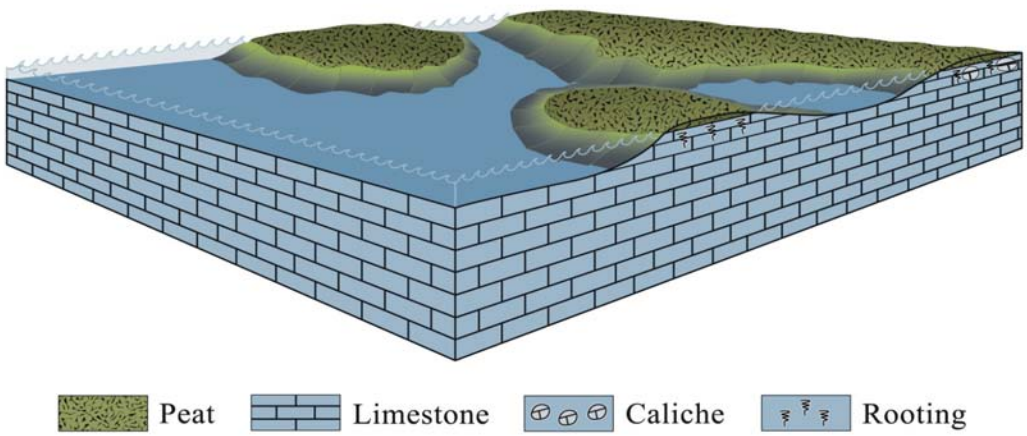

Figure 6.07 Marine regression depositional model for peat development above marine regressive carbonates modified and applied to the Mulberry coal in the Bourbon arch. Marine regression resulted in exposed, topographically high areas of Pawnee Limestone. These raised areas became favorable for peat formation during the lowstand or ensuing transgression (modified from Lange, 2003).

6.3 Discussion

6.3.1 Depositional Controls on Peat Formation

Based on core description and facies interpretations of underlying strata, and isopach mapping of coals, depositional environments of coal-bearing strata do not exhibit a direct relationship to coal seam extent, continuity, or average thickness (Figs. 6.08 and 6.09). Coal seam characteristics (extent, continuity, and average thickness) are related to sequence stratigraphic position and the related variations of accommodation necessary for peat development (Chapter 5). Underlying strata provide a framework for peat formation, and depositional environments of coal-bearing strata influence coal quality. No direct correlation exists between ash content and specific depositional environments. However, coals associated with marine regression tend to have higher ash contents than other coal-associated environments (Fig. 6.10). This relationship is due to marine-regression peats forming proximal to active marine processes, and close spatial relationships of peat and organic-rich shales. Other depositional models form peats removed and protected from active sedimentation processes (e.g. estuarine, coastal plain, or coals influenced by pre-Pennsylvanian topography).

6.3.2 Depositional Environments and Coalbed Gas Content

No definitive relationship exists between depositional environments of coal-bearing strata and gas content (Fig. 6.11). Crossplots of average gas content (scf/ton; a.r.) versus average coal thickness (Fig. 6.12; Cherokee basins and Bourbon arch coals), extent (Fig. 6.13; Bourbon arch only), and continuity (Fig. 6.14; Bourbon arch

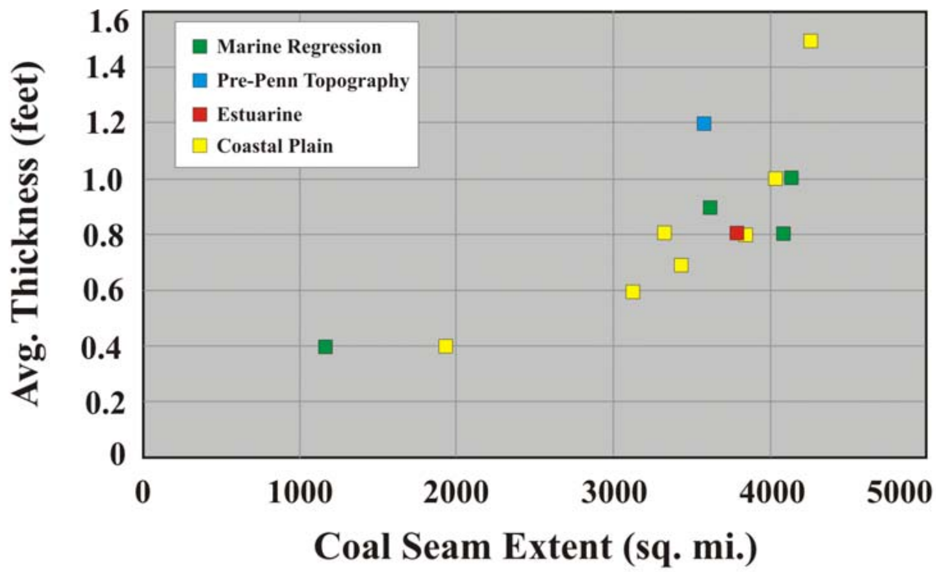

Figure 6.08 Crossplot of coal seam extent (square miles) versus average thickness (feet) for Bourbon arch coals based on depositional environment (Table 6.1; modified from Fig. 5.04). Although coal seam extent and average thickness are directly related, no apparent relationship exists between these properties and depositional environment.

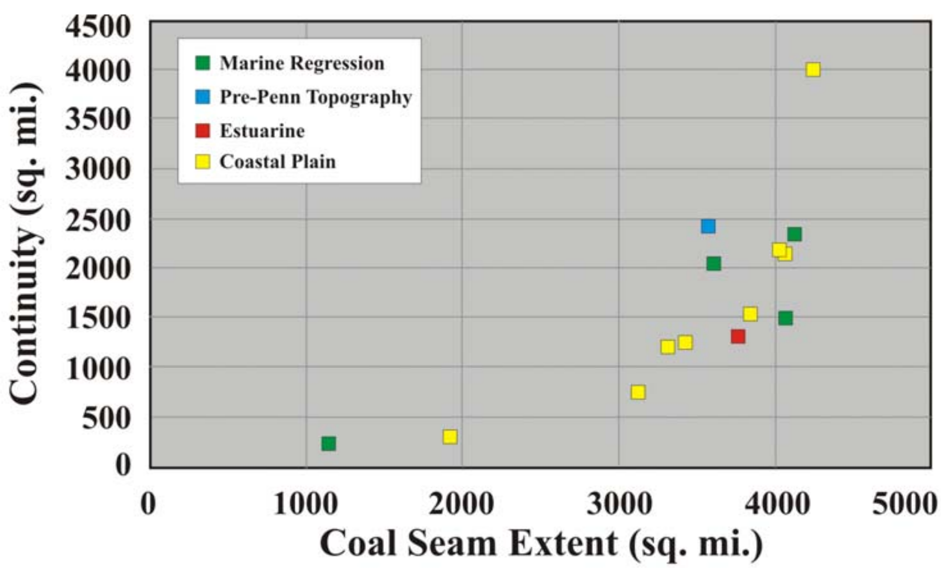

Figure 6.09 Crossplot of coal seam extent (square miles) versus coal seam continuity (square miles) for Bourbon arch coals based on depositional environment (Table 6.1; modified from Fig. 5.05). Although coal seam extent and continuity are directly related, no apparent relationship exists between these properties and depositional environment.

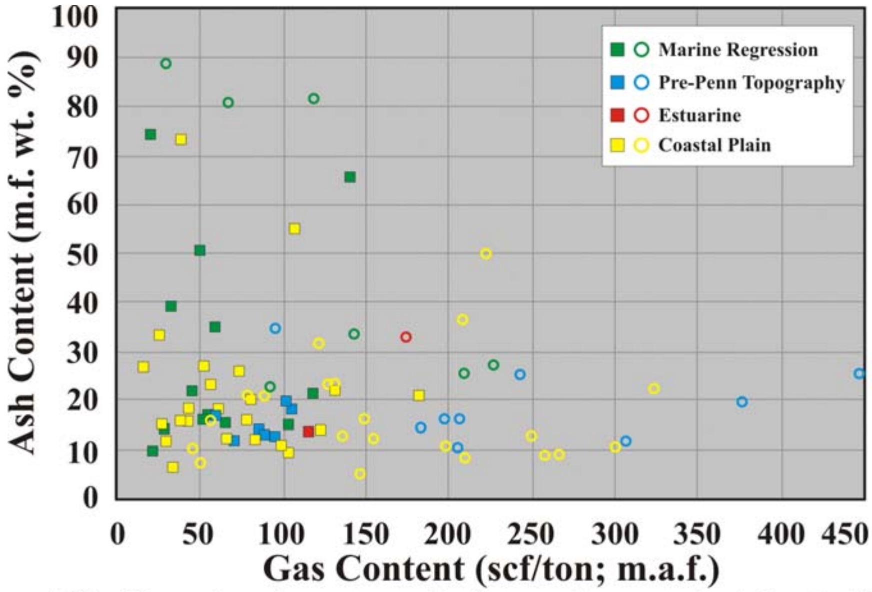

Figure 6.10 Cross-plot of gas content (scf/ton; moisture- and ash-free basis) versus ash content (wt. %; moisture-free basis) for individual coals in the Bourbon arch (color-filled shapes) and Cherokee basin (outlined shapes) based on depositional environment (modified from Fig. 5.06). Coals associated with coastal plain and pre-Pennsylvanian topography-influenced environments tend to have lower ash and higher gas contents than coals associated with marine regression, which tend to have higher ash and lower gas contents.

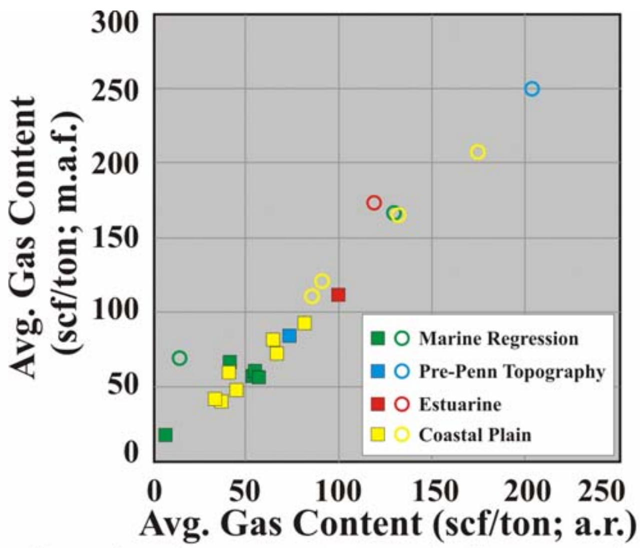

Figure 6.11 Crossplot of average gas content (scf/ton, as received) versus average gas content (scf/ton; moisture- and ash-free) for coals in the Bourbon arch (squares) and Cherokee basin (open circles) based on depositional environment (modified from Fig. 5.07). No distinct correlation exists between depositional environment and gas content, although marine regression-associated coals tend to have lower gas contents than coals associated with other environments.

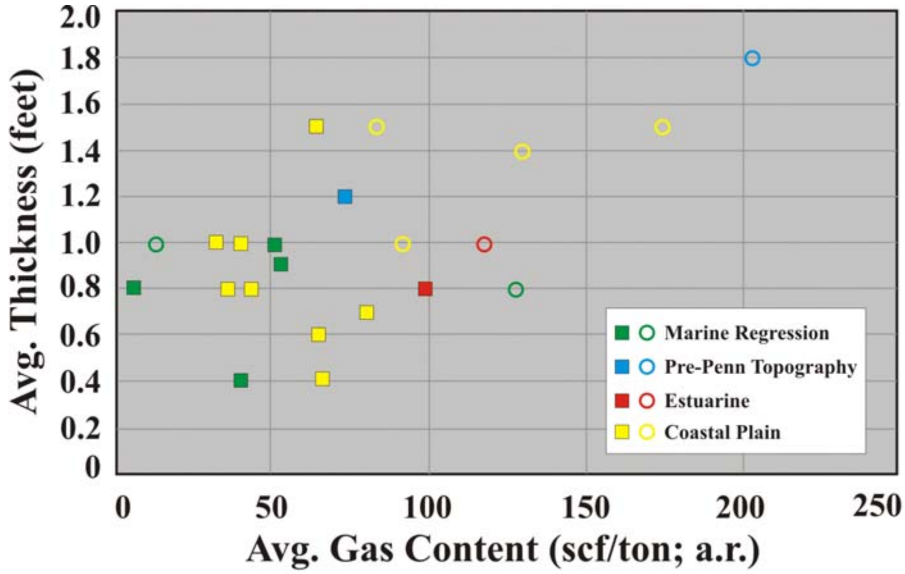

Figure 6.12 Crossplot of average gas content (scf/ton, as received) versus average thickness (feet) for coals in the Bourbon arch (squares) and Cherokee basin (open circles) based on depositional environment (modified from Fig. 5.08). Average gas content increases with average coal seam thickness, however no relationship exists between depositonal environment and gas content in eastern Kansas.

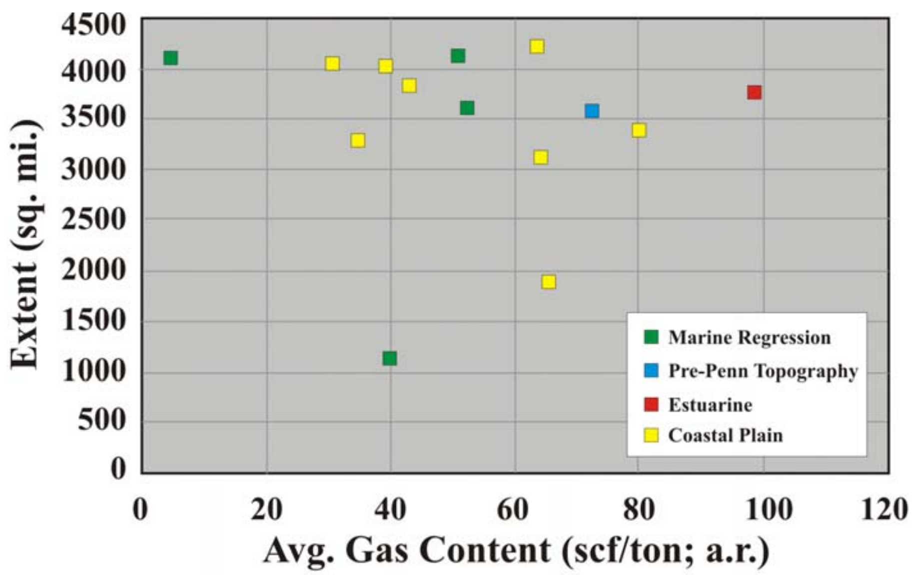

Figure 6.13 Cross-plot of average gas content (scf/ton, as received) versus coal seam extent (square miles) for coals in the Bourbon arch based on depositional environment (modified from Fig. 5.09). No apparent relationship exist between depositional environment, gas content, and coal seam extent.

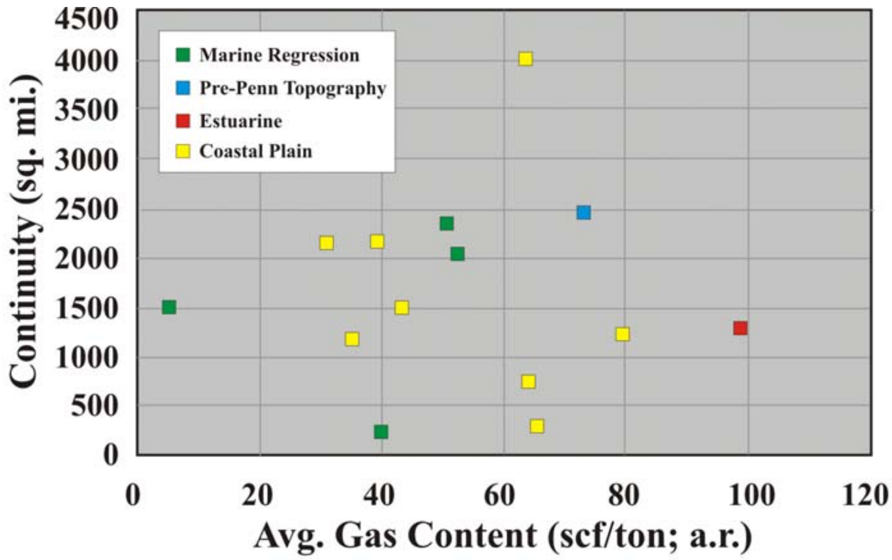

Figure 6.14 Crossplot of average gas content (scf/ton, as received) versus coal seam continuity (square miles) for coals in the Bourbon arch based on depositional environment (modified from Fig. 5.10). No apparent relationship exists between gas content, coal seam continuity, and depositional environment.

only) show no conclusive relationship between depositional environments and average gas content of each seam. However, plotting gas content (scf/ton; a.r.) against depth (feet; Fig. 6.15) and ash content (moisture-free wt. %; Fig. 6.10) suggests that coals associated with marine regression have relatively lower gas contents compared to estuarine and coastal plain coals. In general, coastal-plain coals and coals influenced by pre-Pennsylvanian topography have the highest gas contents of all depositional environments.

Examination of Figure 6.15 reveals that depositional environments are biased towards relative position within the Desmoinesian Stage. Pre-Pennsylvanian topography coals, with relatively higher gas content, are early Cherokee Group and tend to be found in deeper parts of eastern Kansas. Coastal plain and estuarine-

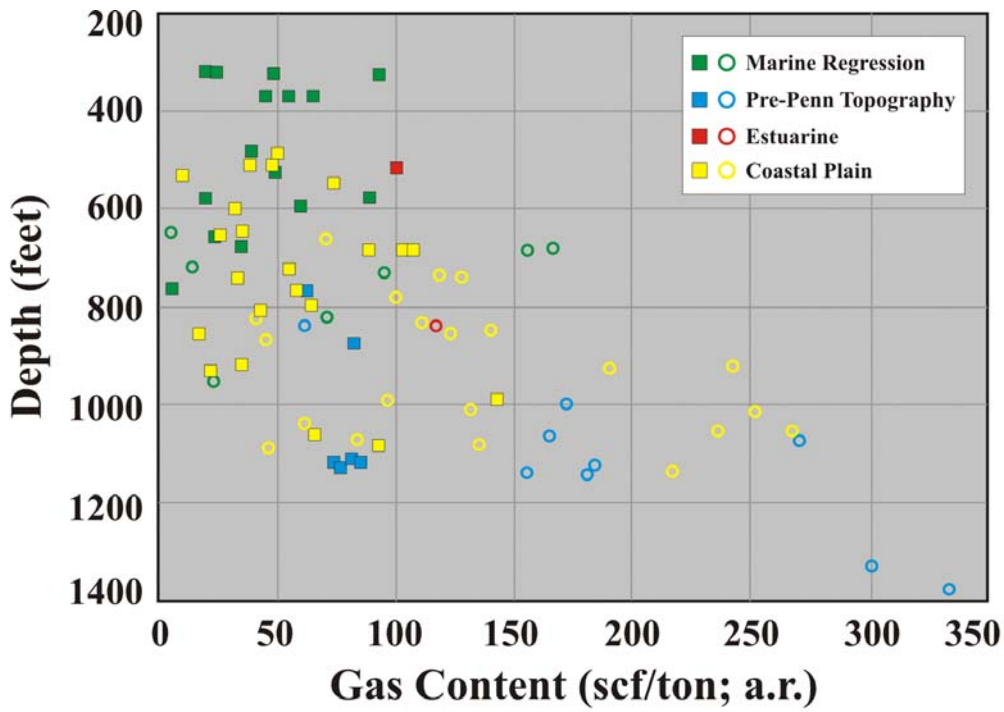

Figure 6.15 Cross-plot of gas content (scf/ton; as received) versus depth in feet for individual coals in the Bourbon arch (color-filled shapes) and Cherokee basin (outlined shapes) based on depositional environment (modified from Fig. 4.13). Coals associated with coastal plain and pre-Pennsylvanian topography-influenced environments tend to be deeper and have higher gas contents relative to coals associated with marine regression, which tend to be shallower and have lower gas contents.

associated coals, with relatively intermediate gas contents, are found in mid-Cherokee strata at intermediate depths. Marine regression coals, with relatively low gas contents, are found in the upper Cherokee and lower Marmaton at relatively shallow depths in eastern Kansas. The correlation between depositional environment and relative gas content is strongly influenced by coal seam depth.