Chapter Five : Depositional Models

Depositional models are intended as teaching tools, mental concepts, and temporary fixed points in nature (Miall, 1999). The function and utility of a model aids in the distillation of many observations for ease of comparison, and serves as a framework and guide for future investigations (Walker, 1976). In the subsurface, models serve as predictive tools for reconstructing sparsely observed systems or for interpreting preliminary results.

5.1 Previous Models and Work

Previous studies of the development of Pennsylvanian coal beds in the mid-continent have shown that coal accumulation is influenced by several general environmental factors (eg. climate, sea level change, basin subsidence, sediment accumulation, and depositional environment). Depositional environment reflected in the type of mire in which peat developed is believed the most important control on distribution, thickness, and quality of coal (Wanless et al., 1969; McCabe and Shanley, 1992).

According to Wanless et al. (1969) distribution of Pennsylvanian coals are controlled by environmental patterns such as widespread deltas, unfilled channels, estuaries, coastal marshes, barred and non-barred coast lines, cut-off stream meanders, coastal plains exposed after regression, and pre-Pennsylvanian topographic irregularities. Flores (1993) suggested that when studying coals in the ancient, depositional orientation, average thickness, areal extent, and geometry of coal beds are reflective of the environment of deposition, and can be used as a predictive model. Conversely, McCabe and Shanley (1992) stressed equal or greater importance on the concept that the type of mire in which peat accumulated is reflected in the characteristics of coal beds. With the mire concept, low-ash coals are predicted to have formed from raised mires, while high ash coal formed in low-lying mires. Marine influenced mires will have higher sulfur contents while inland mires will tend to be protected from influence of marine water during coalification, and will have reduced sulfur contents (< 2.5 %).

Pennsylvanian coals are widely distributed throughout the mid-continent, and have been correlated for hundreds of miles (Wanless et al., 1969). Transition into or out of coal from other lithologies is relatively sharp. The abruptness in which coal accumulation is initiated and terminated has been attributed to climatic shifts, such as changes in humidity, precipitation and temperature (Wanless et al., 1969). During the Pennsylvanian, the mid-continent is believed to have been a vast level plain near sea level. This plain was subject to frequent extensive marine transgressions, when the sea covered most of the continental interior (Wanless, 1969). The occurrence of frequent marine transgressions likely played an important factor in development and demise of the numerous thin Cherokee Group coals.

Previous work also suggests that most Pennsylvanian coals accumulated in situ (Wanless, 1969). Support for this interpretation is from observed rooting into underlying rock such as underclay or seat earth, shale, sandstone or limestone (Staub and Cohen, 1970). The origin of underclay beneath many of the coals is a subject of debate, in relation to depositional or post depositional weathering, and classification as a soil (Wanless et al., 1969). In general, most Pennsylvanian underclays are accepted as, originally deposited outside the basin of peat accumulation, and as a soil under swampy conditions. The underclay is subsequently altered by leaching during peat accumulation, and not directly related to upland soil development (Wanless et al., 1969).

Many studies conducted in the last decade have been in relation to the understanding of coal deposits within a sequence stratigraphic framework due to the increased interest in the hydrocarbon potential of coals (Aitken, 1994; McCabe and Shanely, 1994; Boyd and Diessel, 1995; Bohacs and Suter, 1997; Diessel, 1998). A widely excepted view is that preservation of peat is dependent on near equal rates of increasing accommodation and peat production (McCabe and Shanely, 1994; Boyd and Diessel, 1995; Bohacs and Suter, 1997). Additionally, for mires, peat will not continue to accumulate with only an increase in accommodation and therefore an increasing water table is needed for sustained peat growth (Aitken, 1994; Bohacs and Suter, 1997). An increasing water table is strongly controlled by sea level rise and the precipitation/evaporation ratio (Aitken, 1994; Bohacs and Suter, 1997).

With an understanding of the delicate balance between peat production, accommodation and sea-level rise, coal seams can be predicted within a sequence stratigraphic framework. Base-level falls, typically occurring during early lowstand and late highstand systems tracts, lead to a loss in accommodation, incision, and valley formation, causing low peat preservation (Boyd and Diessel, 1995; Bohacs and Suter, 1997). When accommodation rates are significantly above peat production rates, mires will become stressed and inundated by clastics or stagnate water, due to base level rises typical of the mid-transgressive systems tract (Bohacs and Suter, 1997). During periods of aggradation, typical of late transgressive and early highstand systems tracts, peat-producing mires may block marine transgressions and stabilize coastlines for longer periods of time, leading to higher preservation of peat (Diessel, 1998; McCabe and Shanely, 1992).

Diessel (1998) has also applied sequence stratigraphy to amalgamated coal seams in Australia, where the coal is interpreted as forming over multiple sequences. Basinward marine splits in the coal seams are interpreted to represent prograding stacking patterns, and a marine split above a ravinement surface and angular unconformity is thought to be a sequence boundary (Diessel, 1998). In the case of the Cherokee basin coals, none of the coals observed appear to be amalgamated.

5.2 Modern Analogs

Comparison of modern peat forming environments to the inferred depositional environments in the Cherokee Group of the Cherokee basin aids in understanding the depositional controls on peatland growth and development in the ancient. Several works on modern environments such as that of the Orinoco Delta of South America (Andel, 1967), a Malaysian tropical delta (Coleman et al., 1970), and the Snuggedy swamp (Staub and Cohen, 1979) are analogs that have resemblance to environments during the Middle Pennsylvanian throughout southeastern Kansas.
The Orinoco Delta is situated off the coast of northeastern South America in Venezuela, Colombia and Brazil, and appears analogous to many of the coastal plain settings of the Cherokee basin. The Orinoco delta has built the entire coastal plain during a rapid coastal accretion that resulted in a wide zone of swamps and marshes with local chenier plains that merge into extensive tidal mud flats (Andel, 1967). Due to the low gradient, streams are not considered as significant transporters of sediment, and the coastal plain is subject to tidal flooding. Marine processes such as long shore drift supply clastic sediments to the coastal plain. The outer delta is described as a featureless marsh plain traversed by many swamp streams, estuaries, and distributary channels (Andel, 1967). Lithologies are similar to that of those described for Cherokee Group coastal plains and consist of sandy clays, mud flats, silty clays and peaty clays.

The Snuggedy swamp of South Carolina is analogous to coals associated with coastal plains and estuaries of the Cherokee basin. Peat development in these settings is described as thick extensive deposits underlain by a kaolonite rich underclay within a back-barrier estuarine depositional environment (Staub and Cohen, 1979). Similar to many of the coals in the Cherokee Group, coals in the Snuggedy swamp are formed above coarsening upward sands and shales described as lagoonal deposits, and thick well developed underclay's interpreted as soils. Peatlands are also dissected by crevasse and fire splays. In the ancient, the presence of fusinite within a coal bed is interpreted as the product of fire (Staub and Cohen, 1979). The presence of fusinite ranging from 0 up to more than 3.5 percent has been noted in many of the Cherokee Group coals of eastern Kansas (Bensley et al., 1990). Many of these peat fires can result in localized thin coals replaced by clastic "fire splay" deposits.

Peat accumulation in the Snuggedy swamp is controlled by sea level rise, rate of sediment influx and or basin subsidence, related to an increase in accommodation (Staub and Cohen, 1979). The preservation of peat in the Snuggedy swamp is related to rapid flooding. A similar condition of rapid transgression occurred with many of the Cherokee Group coals where deep marine deposits directly overly coal. The distribution and thickness of Snuggedy swamp peat is also a function of topographic relief, fresh water versus brackish water, and relation to barrier islands. According to Staub and Cohen (1979) the thickest and most continuous peat forms in fresh water, near barrier islands and in areas with a slightly higher topography. Areas near tidal channels are also higher in sulfur content due to marine influence.

A Malaysian compound delta of the Klang and Langat Rivers located off the west coast of the Malay Peninsula in southeast Asia is also analogous to many of the coastal environments formed during deposition of the Cherokee Group. This compound delta is described as a complex network of tidal passes that function as an open-ended estuary in which large mangroves and freshwater swamps form between channels (Coleman et al., 1970). Seaward, the delta transitions into irregular and extensive tidal mud flats that typically do not have any beach development. Much of the coastal mangrove swamps formed in the above settings are colonized on top of the muddy tidal flats at or just above the neap high water (Coleman et al., 1970). Tides and tidal current processes are considered as the primary control on the delta morphology. The widespread distribution of the Malay swamps parallels the shoreline and is rapidly prograding (Coleman et al., 1970). Cherokee coals such as the Weir-Pittsburg have similar distributions.

5.3 Depositional Models

Cherokee Group coals accumulated in a variety of depositional settings including, marshes, open and back barrier coastlines, estuaries, and fluvial flood basins. Pre-existing topography coupled with relative position within a systems tract, played a major role in the growth, distribution and quality of Pennsylvanian peatlands that eventually develop into coal. Interpretations of depositional environments and controls on peat development are primarily based on isopach map interpretations (Chapter Two), relation to underlying and overlying stratigraphy (Chapter Two) and proximate analysis (Chapter Three). A brief description of depositional orientation, average thickness and geometry of coal beds used for interpretations of depositional environments and controls on peat development are summarized in Table 5.1.

Coal Unit	Orientation	Average Thickness (ft)	Geometry	Depositional Setting or Control
Summit	Dip & Strike	1.0	Thin, circular	Topography
Mulky	Dip & Strike	0.75	Thin, circular	Topography
Iron Post	Dip	1.0	Thin, elongate	Fluvial Floodbasin
Bevier	Strike	1.5	Thin, lenticular	Coast Plain
Croweburg	Strike	1.0	Thin, lenticular	Coast Plain
Fleming	Dip	1.0	Thin, dendritic	Estuarine
Mineral	Strike	1.5	Thin, lenticular	Coast Plain
Scammon	Dip	1.0	Thin, dendritic	Estuarine
Tebo	Dip	0.9	Thin, elongate	Fluvial Floodbasin
Weir-Pitt.	Strike	1.5	Thin, lenticular	Coast Plain
Aw	Dip	1.7	Thin, elongate	Fluvial Floodbasin
Riverton	Dip & Strike	1.8	Thin, lenticular	Pre-Penn. Topography

Table 5.1 – Interpretations for Cherokee Group coal depositional settings and controls according to depositional orientation, average thickness, and geometry (approach is modified from Flores, 1993).

5.3.1 Abrupt Marine Regression

Several times through the Middle Pennsylvanian in southeast Kansas coal beds are found directly above fossiliferous marine limestones or shales with little or no underlying paleosol development. When present, the clay (paleosol) overlying the limestone may have either accumulated during the marine regression or be non-marine in origin. It would appear that these Cherokee Group coals formed after an abrupt regression on extensive low-lying plains (Wanless, 1969). Examples include the Mulky coal situated above the Breezy Hill Limestone of the Cherokee Group, and the Summit coal located above the Blackjack Creek Limestone of the Fort Scott. The limestone formed in a relatively shallow sea with a moderately smooth floor (Wanless, 1969). However, small-scale topographic highs on the sea floor provided areas that submerged earlier than the rest of the sea floor, creating a favorable surface for initiation of peat accumulation.

The Mulky and Summit coals tend to be highly variable in thickness and show thin, circular geometries as the coals thicken onto structural highs (Figures 2.32, 2.33). Variation in thickness appears related to subtle changes in topography. It appears that shallower areas emerge and peat swamps initiate prior to the peat swamps that formed in deeper areas (Figure 5.01). The initial formation of a peat hammock would form a freshwater lens due to the topography followed by enhancement of the lens through enhancement of topographic relief (Spackman et al., 1969). Proximate analysis indicates that the Mulky and Summit coals tend to be carbonaceous shale or high-ash coal rather than a pure coal. The Mulky and Summit coals have ash contents that range from 36.3 to 88.8 percent and sulfur contents that are greater than 11 percent. The close association with marine carbonate sediments and low relief can explain the high-ash, high-sulfur and carbonaceous nature of the coal (Figure 5.01). Continued peat growth in topographic lows subject to periodic invasion by admixed marine mud results in carbonaceous shale, or high-ash, and sulfur-rich coals. It appears that the better quality low-ash and thickest coal develops in mires on topographic highs more protected from the marine influence. The influence of topography and relative marine influence are themes throughout deposition of the Cherokee Group coals.

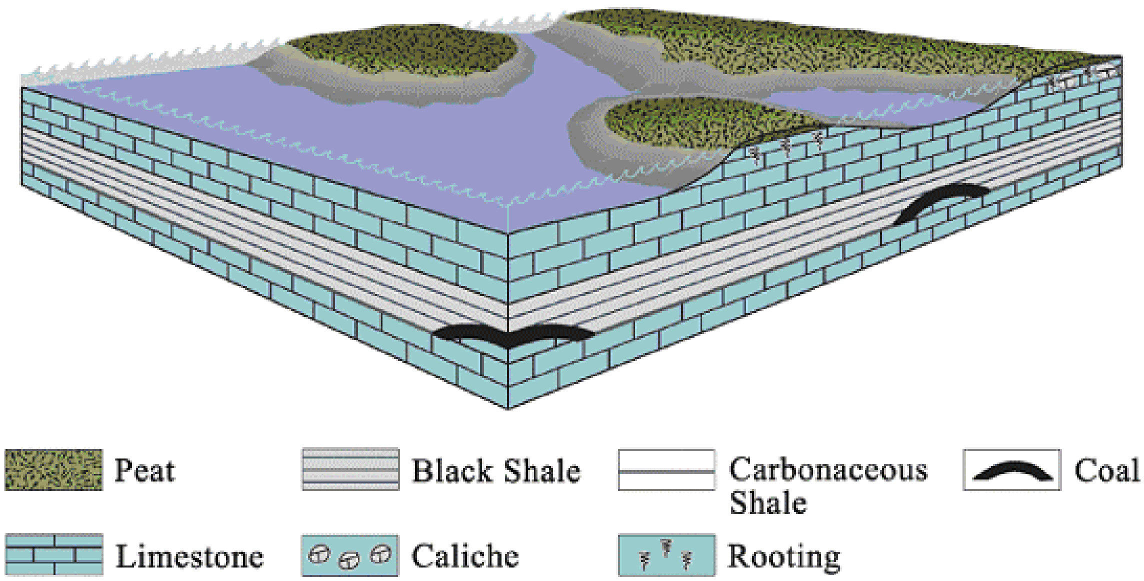

Figure 5.01 - Depositional model for peatland development above regressive marine carbonates. Variation in coal thickness may be due to subtle changes in topography, where shallower areas that submerge before deeper areas are conducive to peat development.

5.3.2 Fluvial Floodbasin

Distribution of peatlands associated with fluvial flood basins increase in thickness and abundance away from fluvial axes. Detritus decreases away from fluvial axes except when detritus is transported by crevasses splays and overbank processes (Flores, 1993; Figure 5.02). Coal beds formed from peatlands in the above setting are commonly interbedded with marine to marginal marine coarsening upward mudstones, siltstones and sandstones, fining-upward fluvial channel sandstones, coarsening-upward crevasse-splay mudstones, siltstones, and sandstones, and thin lacustrine deposits (McCabe, 1991; Flores, 1993). Geometry of coal beds in this setting vary from dendritic, elongate, lens, and lenticular along depositional dip (Flores, 1993). Coal adjacent to channels that are thin and or contain splits, suggests contemporaneous channel and peat development (McCabe, 1991).

Laterally extensive although discontinuous, thin, elongate, and dendritic coals such as the Iron Post, Tebo, and Aw coals are interpreted to have formed in an associated fluvial floodbasin setting. Many other local and informally known coals may have also formed in settings similar to that of the Iron Post, Tebo, and Aw. The ash content of coals in floodbasin sediments can be highly variably depending on the amount of detritus transported into the peatland. In the Cherokee basin, coals interpreted as deposited in floodbasin settings have between 11.4 and 64.7 percent ash. Presumably the range in ash content is also a reflection from the type of mire.

Raised and low-lying mires have been suggested as an explanation of differences between ash contents of coals (McCabe and Shanley, 1992). Sulfur contents are typically less than 4 percent due to the decreased marine influence.

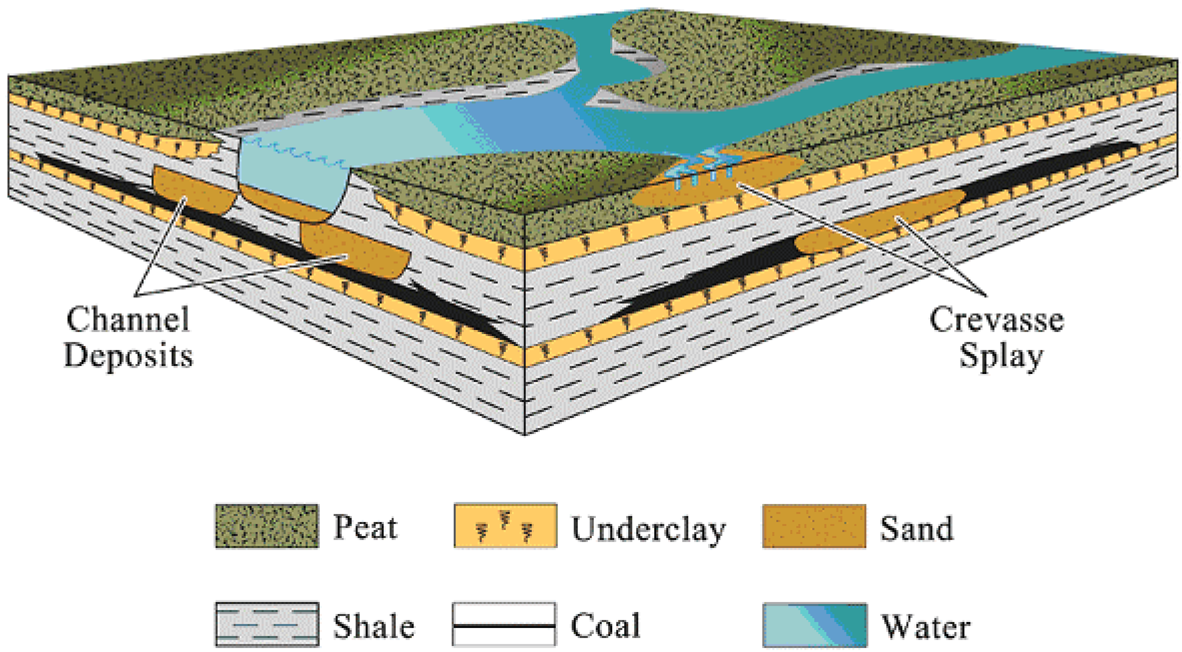

Figure 5.02 - Depositional model for peatland development associated with fluvial systems. Coals that develop from peatlands in fluvial systems tend to thicken away from channels and split toward channels. Areas of peatlands are removed by fire splays, crevasse splays or eroded by fluvial incision.

5.3.3 Estuarine

Several times throughout deposition of the Cherokee Group, relative sea level dropped, resulting in fluvial incision. Remnants of this process are indicated by several mappable, fluvially eroded, elongate topographic lows that are typically larger than any one single channel form. These features are known as incised valleys (Zaitlin et al., 1994). During sea level rise, incised valleys are filled with fluvial sands, estuarine sands, and shelf muds (Zaitlin et al., 1994; Figure 5.03). As for relation to peat accumulation, the inner incised valley where the bay head delta is formed is the most important. With a continued transgression, stream gradient and capacity decreases, and freshwater organic facies increase in abundance on less mature soils of the upper estuary (Zaitlin et al., 1994; Figure 5.03).

In the mid-continent several Middle Pennsylvanian coals have been interpreted as developing in estuaries prior to drowning (Wanless, 1969). Coals associated with estuarine environments are described as occupying linear troughs that range from less than 1.5 miles (2.4 km) up to more than 4 miles (6.4 km) in width and have thin dendritic geometries (Wanless, 1969 and; Flores 1993). Discontinuous, thin and dendritic coals, such as the Fleming coal, Scammon coal, and several informally known coals are interpreted to have formed in association with upper estuarine environments. The previously mentioned coals are also closely associated with lithofacies that are interpreted as bay head delta and central bay sediments (Chapter Two). The ash content of coals in estuarine strata is relatively high (30 percent +/-) due to the input of clastic material brought into the upper estuary by the fluvial system. Sulfur content of 6 percent is also relatively high due to the marine influence up into the estuarine system.

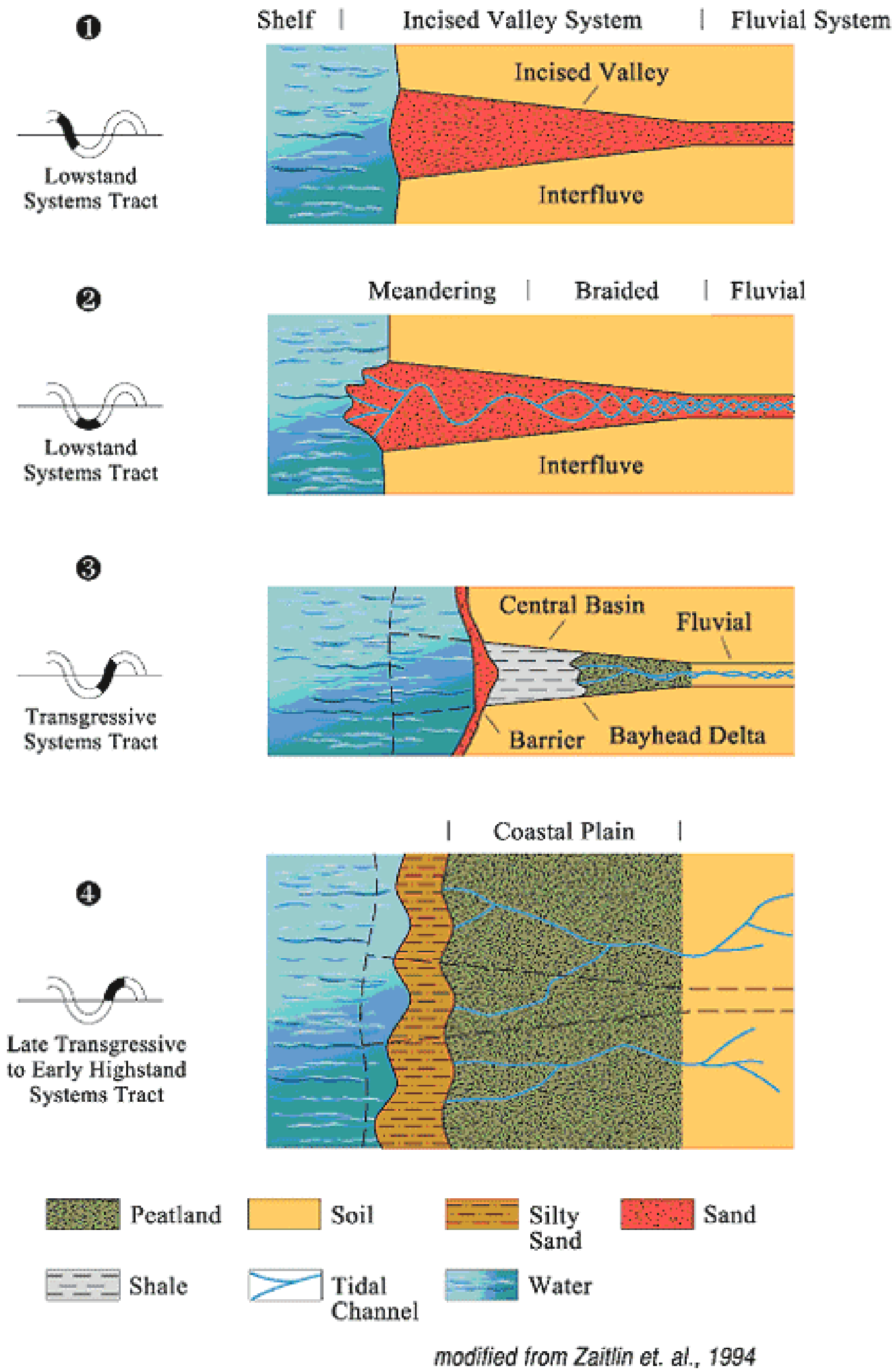

Figure 5.03 - Depositional model for peatland development in estuarine systems. Thin, locally developed coals are interpreted to have formed from peatlands constrained within estuarine valleys (3). After flooding of an estuarine valley, coastal plains and extensive peatlands will develop over top of the valley (4)

5.3.4 Coastal Plain

Peatlands in coastal plains develop above and behind open and back barrier shorelines, on estuaries, above infilled lagoons, and atop interfluves (Flores, 1993; Figures 5.03, 5.04). Back-barrier coals are generally laterally continuous and parallel to depositional strike (Wanless, 1969; Flores, 1993). Sustained growth and preservation of peat requires protection from marine influence. A gradual increase of base level will raise the water table aiding in the growth of mires. Continued transgression will lead to aggradation and eventually marine rocks bury the peatlands. In addition barred or stationary shorelines aid in the protection of peatlands from marine processes.

Coals such as the Bevier, Croweburg, Mineral, and Weir-Pittsburg have lenticular geometries oriented parallel to depositional strike and suggest peatland development on coastal plains. Average thickness of coastal plain coals is approximately 1.5 ft (0.5 m) with a normal distribution in thickness (Appendix 2). The scale of coastal coal development in the Cherokee basin is similar to peatland development described from coastal plains of the Malay Peninsula (Coleman et al., 1970). The ash content of coals interpreted, as coastal plain deposits is relatively low compared to other Cherokee basin coals. Cherokee Group coals associated with the coastal plain have ash contents between 19.5 and 32.7 percent. Sulfur contents are also relatively low, ranging from 1.9 to 3.6 percent, which suggests some protection from marine influence during coalification.

Topographic relief of the mire also plays a significant role in the development of peat. Low-lying peatlands are prone to tidal effects and form brackish mires, while fresh water peatlands form in elevated areas with high precipitation and migrate across the low-lying mires to form protected raised mires (Flores, 1993; McCabe, 1991; Figure 5.04). Tidal channels, estuaries, and short-headed streams, form drainage systems for peatlands peatlands on coastal plains (Coleman et al., 1970).

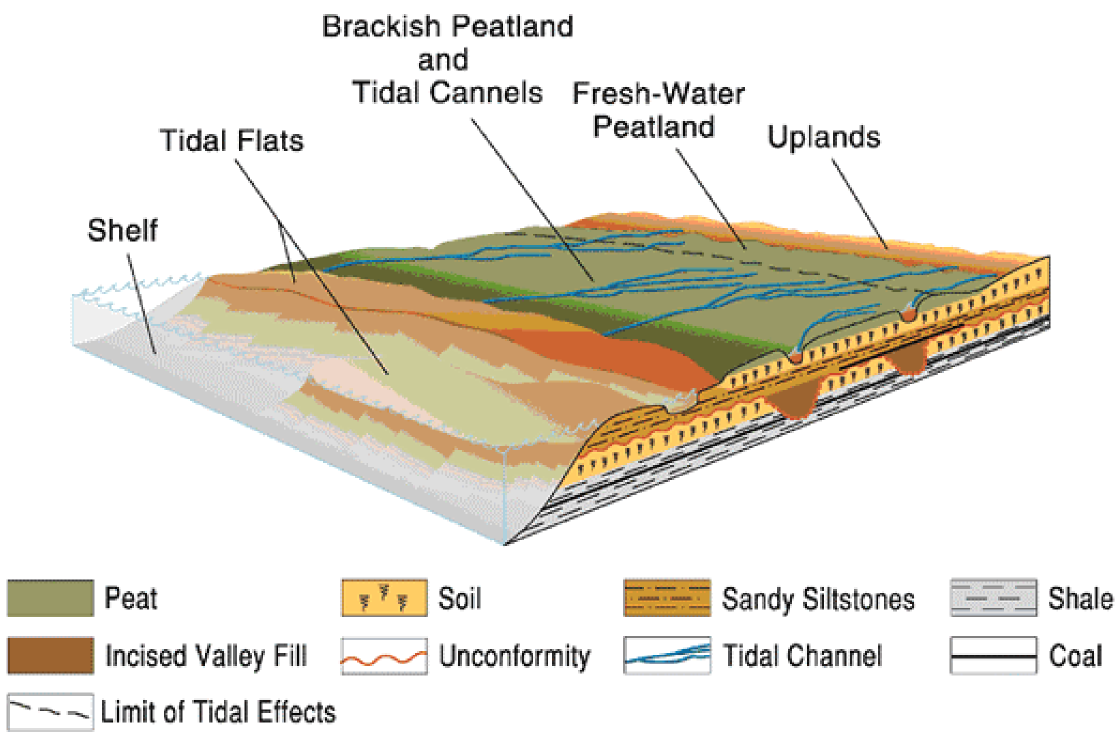

Figure 5.04 - Depositional model for peatland development associated with coastal plains. Low-lying peatlands are prone to tidal effects and from brackish mires, while fresh water peatlands form in elevated areas and migrate across the low-lying mires to form protected raised mires.

5.3.5 Pre-Pennsylvanian Topography

Topographic relief up to 300 feet (91.5 m) existed on the karsted limestone terrain in the central United States prior to deposition of Pennsylvanian sediments (Siever, 1951). As a result, initial Pennsylvanian sedimentation occurred in erosional valleys created by karstification. The karst topography on top of the Mississippian limestones provided many low-lying areas where lakes and marshes developed (Figure 5.05). During the initial Pennsylvanian transgression, low-lying mires formed across topographic lows as the water table rose. Raised mires developed above the low-lying mires (McCabe, 1991). Given sufficient precipitation raised mires can sustain their water table while building upward (McCabe, 1991; Figure 5.05). Margins of raised mires are typically steep and eventually pinch out into clastic sediments of marginal marine environments. The presence of marine deposits directly above the Riverton coal suggests that a transgression eventually drowned and buried the peatlands. Burial, compaction and coal formation can reduce coal thickness to less than 10 percent of original peat thickness and result in coals that appear to pinch out onto paleotopographic highs (Mukhopadhyay and Hatcher, 1993; Figure 5.05).

Coals such as the Riverton and informally known Riverton A-D coals will tend to thicken into Mississippian lows where peat developed from both raised and low-lying mires (Figure 5.05). Evidence of this relationship is indicated in the Riverton coal isopach map of Figure 2.16, and was observed at the outcrop scale of the Riverton coal in a sinkhole at the Sunflower lead-zinc mine in Cherokee County, Kansas (Figure 5.06). Ash contents of coals developed in this setting range from 7.3 to 35 percent, and sulfur contents are also highly variable and range from 2.8 to 10.7 percent. Variability in ash content is likely due to differences in peat development between raised and low-lying mires, and the relative influence of marine waters during coal formation. During coal formation, influx of marine water can result in a significant pyrite formation and relatively high sulfur content (> 5 %). Other early Cherokee Group coals (eg. Krebs Formation) have depositional patterns influenced by the topographic irregularities on top of the Mississippian limestones (Wanless, 1969).

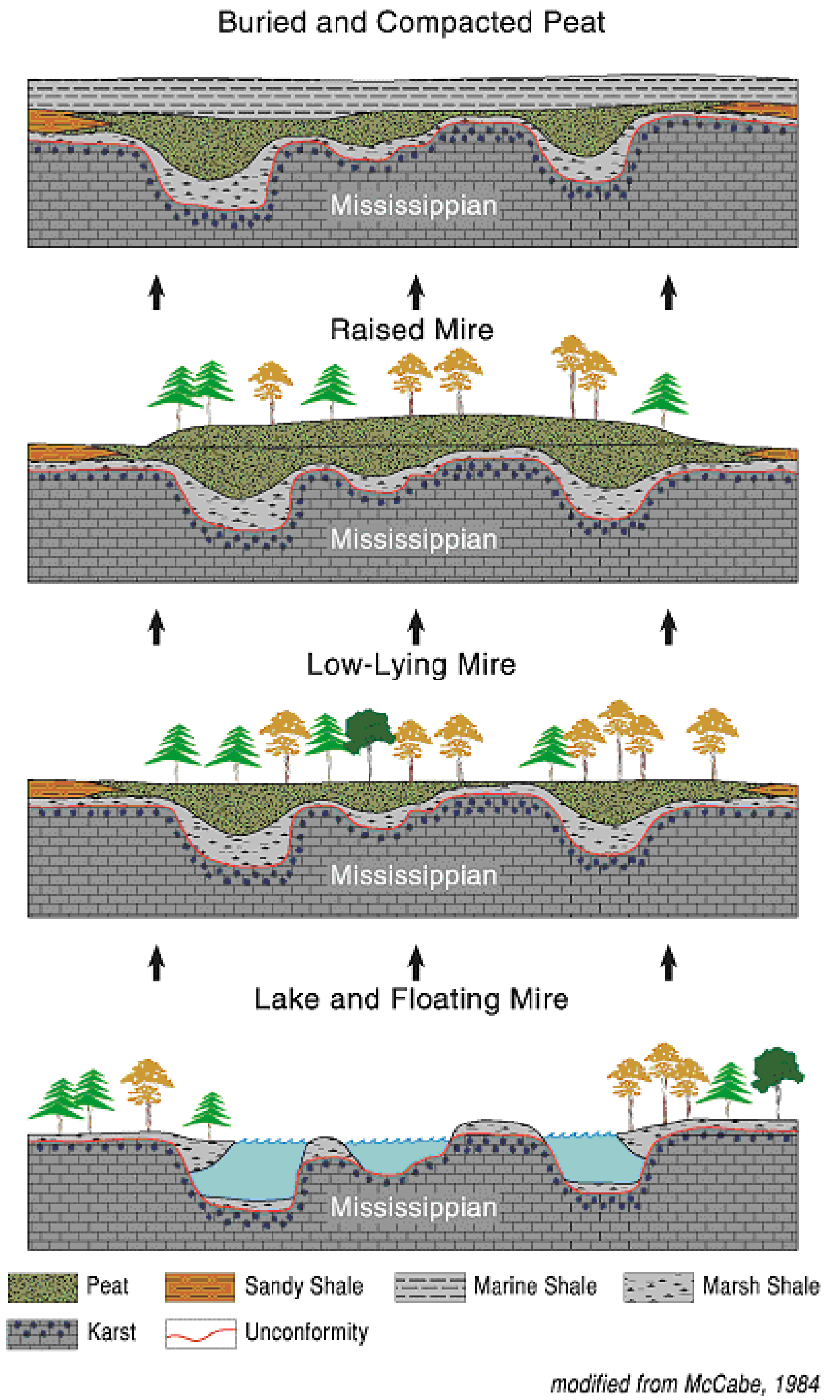

Figure 5.05 - Depositional model for peat development influenced by pre-Pennsylvanian topography. The karst topography on top of the Mississippian limestones provided many low-lying areas where lakes and marshes developed and subsequent peatlands. As a result, Riverton coals tend to thicken into Mississippian lows where peat developed from both raised and low-lying mires.

Figure 5.06 - Sink hole at Sunflower Pb-Zn mine in Cherokee County, Kansas: SW 10-T35S-R24E. Note the Riverton coal thickening into Mississippian lows.