CHAPTER 5:

SEQUENCE STRATIGRAPHY

5.1 Introduction

Current sequence stratigraphic concepts may clarify the controls on distribution and extents, thickness, and quality of eastern Kansas coal seams. These stratigraphic parameters can influence coal gas content. Sequence stratigraphy is the study of sedimentation patterns and facies relationships within a chronostratigraphic framework of erosional or non-depositional surfaces, or their lateral correlative conformities (Van Wagoner et al., 1990; Posamentier and Allen, 1999). Sequence stratigraphy is used to analyze the ways that sedimentary basins fill, classify strata into a predictive depositional framework for correlation, describe the spatial and temporal relationships of a reservoir, and to correlate strata to global sea level records (Posamentier and Allen, 1999).

Sequences and Sequence Boundaries

The depositional sequence—defined as a succession of relatively conformable, genetically related strata bounded at the top and base by unconformable surfaces or their landward or basinward correlative conformities—is the fundamental unit of sequence stratigraphic analysis (Van Wagoner et al., 1990). Sequence boundaries are defined as unconformities, or landward or basinward correlative conformities, that are laterally continuous over at least the basin scale and separate older underlying sediments from younger overlying sediments by a significant depositional hiatus. Sequence boundaries may be recognized in well log, core, or outcrop by one or more of the following criteria:

1) Subaerial erosional truncation (channel incision), laterally equivalent subaerial exposure surfaces (developed paleosol profiles), and downdip submarine erosion;
2) Stratigraphic onlap onto a coast;
3) Change from prograding parasequence set stacking pattern to retrograding parasequence set stacking pattern;
4) Downward shift in coastal onlap;
5) Basinward shift in environments (landward facies directly overlying basinward facies with no intermediate environments in between; Van Wagoner et al., 1990).

Parasequences, Parasequence Stacking Patterns, and Systems Tracts

Whereas the depositional sequence (hereafter "sequence") is the fundamental unit of sequence stratigraphy, at a smaller scale, the parasequence is the fundamental unit of the sequence. Parasequences are genetically related stratigraphic successions bounded by flooding surfaces, or their correlative conformities. A parasequence boundary is equivalent to a flooding surface with overlying facies showing a deepening of depositional setting. Parasequence boundaries have correlative surfaces both on the coastal plain as an exposure surface, root horizon, or as localized erosion, and basinward as an upward succession of facies suggestive of deepening depositional setting. A flooding surface does not always imply inundation of a subaerially exposed surface. A flooding surface may occur over paleosol, offshore transition, open marine limestone, or any other depositional facies. At some point within the sequence, flooding surfaces reach a maximum landward position known as maximum transgression. The horizon of maximum transgression within a sequence is known as the maximum flooding surface (MFS; Van Wagoner et al., 1990).

Within a sequence, parasequences are classified into parasequences sets based on predictive stacking patterns. Parasequence stacking patterns are responsive to variations of sediment supply and accommodation. Parasequences can stack into landward-stepping retrogradational sets, aggradational sets, and basinward-stepping progradational parasequences sets—all belonging to various forms of systems tracts. The lowstand systems tract (LST) is bounded below by a sequence boundary and above by an initial flooding surface, and contains progradational or aggradational parasequence-stacking patterns. In the current study, fluvial deposits are considered to be part of the LST, and are overlain by the initial flooding surface. The transgressive systems tract (TST) is bounded below by the initial flooding surface and above by the maximum flooding surface, and contains retrogradationally stacked parasequences. Finally, the highstand systems tract (HST) is bounded below by the maximum flooding surface and above by a sequence boundary, and consists of aggrading or prograding parasequences stacking patterns (Van Wagoner, 1990; Posamentier and Allen, 1999). Systems tracts are arranged LST, TST, and HST through one depositional sequence.

5.2 Sequence Stratigraphy of Desmoinesian Strata

Previous sequence stratigraphic interpretations of Desmoinesian strata in eastern Kansas are rare. Walton (1996) was the first to apply sequence stratigraphic concepts to Cherokee Group strata, concluding that numerous sequences exist, occurring above paleosols and at basal contacts of incised channels. Lange (2003) incorporated a sequence stratigraphic interpretation of the Cherokee Group and overlying Ft. Scott Formation into a study of the coalbed methane resource potential in the Cherokee basin. Lange (2003) interpreted seven sequences within the studied interval in the Cherokee basin. There are nine sequences interpreted within the Bourbon arch (Fig. 5.01). One newly defined sequence is positioned beneath the McLouth Sandstone (Fig. 3.02), stratigraphically lower than the first encountered in the Cherokee basin (CG1; Lange, 2003). The other newly defined sequence is positioned above the Ft. Scott Formation (Fig. 3.02), stratigraphically higher than any strata Lange (2003) described. Two cross sections further illustrate the sequence stratigraphic interpretation on a regional scale (Figs. 5.02 and 5.03).

Previous investigations did not focus on sequences down to the parasequence level. Lange (2003) cited excellent well log coverage, but poor lithologic core control within the Cherokee basin as the main factor in the inability to correlate individual beds and parasequences. The sparse core and well log control also exist on the Bourbon arch. Select aspects of sequence stratigraphic interpretation—sequences, sequence boundaries, systems tracts, and where discernible parasequence set stacking

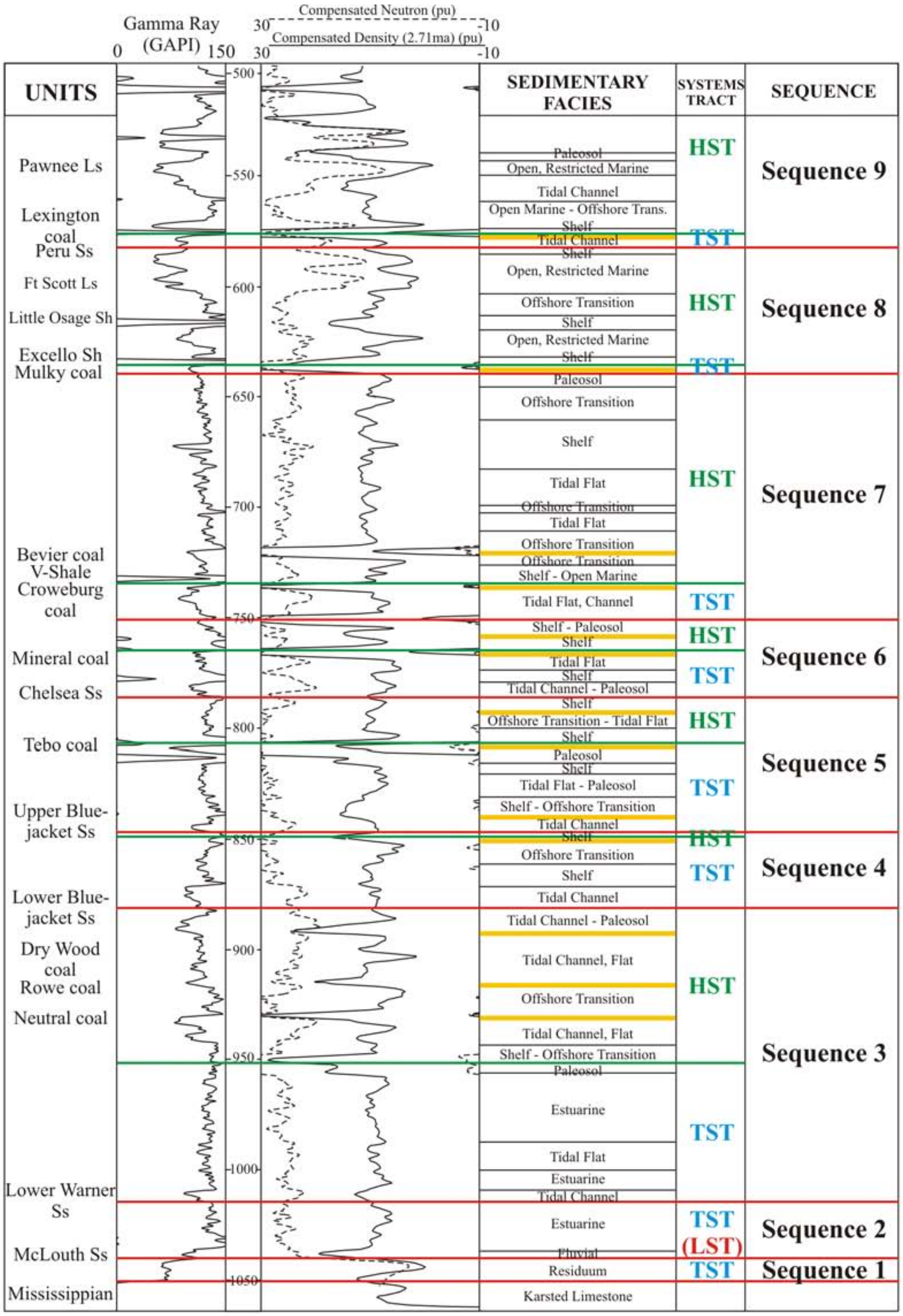

Figure 5.01 Sequence stratigraphic interpretation of the Rose Hill #1-6 core and well log in Miami County. Interpretation includes sequence boundaries (red lines), maximum flooding surfaces (green lines), generalized depositional facies (yellow line indicating paleosol and overlying mires), systems tracts, and sequences. See Chapter 3 for description of depositional facies successions and Johnson (2004) for core description.

patterns are incorporated. Parasequences and parasequence boundaries were noted in core, but were not correlated.

5.2.1 Sequence 1

Sequence 1 is confined to the Forest City basin in the far northern portion of the study area (Figs. 5.02 and 5.03). Due to earlier deposition in the Forest City basin, Sequence 1 has no corresponding sequence in the Cherokee basin (Lee, 1943; Anderson and Wells, 1968; Rascoe and Adler, 1983). The basal sequence boundary is defined as the top of the extensively karsted Mississippian Limestone. The Mississippian-Pennsylvanian unconformity was the result of widespread subaerial exposure and erosion (Fig. 5.01; Rascoe and Adler, 1983; Watney et al., 2001). As seen in core, Sequence 1 within the study area contains both basal Pennsylvanian conglomerate and paleosol facies. A flooding surface may be coincident with the basal sequence boundary, as well as above the paleosol facies (Fig. 3.08; Appendix A; Johnson, 2004). These subaerial facies are interpreted as LST or TST deposits, based on the onlapping nature of black shales, coals with moderate continuity, and sandstones within Sequence 1 north of the study area (Figs. 5.02, and 5.03; Newell et al., 2004). A MFS, indicated by a transition from retrograding to aggrading or prograding parasequence stacking patterns, was not recognized in core or in cross section.

The upper sequence boundary is interpreted as the basal contact of the McLouth Sandstone or the upper surface of a correlative interfluve paleosol (Fig. 5.01). Evidence supporting the upper sequence boundary interpretation includes an incised valley and onlap stratal geometries. Both geometries are correlative in cross section in the northern portion of the study area (Figs. 5.02 and 5.03). Sequence 1 pinches out by onlapping onto the Mississippian erosional surface to the south and east (Figs. 5.02 and 5.03).

5.2.2 Sequence 2

Sequence 2 is equivalent to Cherokee Group Sequence CG1 of Lange (2003) in southeastern Kansas. Sequence 2 is present across the entire study area (Figs. 5.02 and 5.03), except for localized areas on the Bourbon arch where the overlying Warner Sandstone has incised down onto the karsted Mississippian Limestone. In the northern portion of the study area, the basal sequence boundary is interpreted as the basal contact of the McLouth Sandstone (Fig. 5.01). Where the McLouth pinches out onto the northern flanks of the Bourbon arch (Huffman, 1991), the basal sequence boundary merges into the Mississippian-Pennsylvanian unconformity, which is the basal sequence boundary for the southern portion of the study area and into the Cherokee basin (Figs. 5.02 and 5.03; Lange, 2003).

Above the basal boundary, the sequence contains the McLouth Sandstone, observed in core as sharp-based tidal or fluvial channel sandstone, and paleosol facies (Fig. 3.02; Appendix A; Johnson, 2004). Where the McLouth Sandstone is present in Sequence 2, the initial flooding surface overlies tidal or fluvial channel sandstone facies. Where the McLouth Sandstone is absent, the flooding surface is coincident with the sequence boundary, and marginal marine or marine deposits overlie the sequence boundary. Flooding surfaces occur atop paleosols within the McClouth

Sandstone (Fig. 3.08; Appendix A; Johnson, 2004). As observed in well logs in both the Bourbon arch and Cherokee basin, several thin, discontinuous coal seams overly the McLouth and Mississippian Limestone (Figs. 5.02 and 5.03; Lange, 2003). As observed in both cores, parasequence stacking patterns above the McLouth Sandstone suggest a retrogradational parasequence set, and include offshore transition, estuarine central basin, tidal flat, tidal channel, and paleosol facies (Fig. 3.08; Appendix A; Johnson, 2004).

The Riverton coal of Sequence 2 is the first laterally continuous coal in the study area (Fig. 3.09). Facies overlying the Riverton coal were only observed in well logs. Previous investigation of the Cherokee basin described a black, phosphatic shelf shale facies overlying the Riverton coal (Lange, 2003). This shelf shale was interpreted as the maximum flooding surface and transition into the HST of CG1 (Sequence 2-equivalent). A similar black shale signature (i.e. the highest gamma-ray response of the sequence) is observed directly above the Riverton coal in cross sections through the study area (Figs. 5.02 and 5.03). Based on the correlative sequence in southeast Kansas and the retrograding parasequence stacking pattern observed in core, strata underlying the shale immediately above the Riverton coal are interpreted as parts of the TST and LST (Fig. 5.01; Appendix A; Johnson, 2004).

Highstand systems tract (HST) deposits of Sequence 2 were not observed in cores described across the Bourbon arch, but are interpreted in log cross sections (Figs. 5.02 and 5.03). Additional evidence supporting a HST interpretation for sediments overlying the shale immediately above the Riverton coal include thin, discontinuous coals that thin upward and away from the MFS observed in the Forest City basin (W.M. Brown, personal communication, 2004). The upper sequence boundary is interpreted as the basal contact of the lower Warner Sandstone or its interfluve expression (Fig. 5.01).

5.2.3 Sequence 3

Sequence 3 is continuous across the study area and into the adjacent Cherokee and Forest City basins (Figs. 5.02 and 5.03; Lange, 2003). The sequence contains the lower and upper Warner sandstones, several informally named coals (Dw, Cw, Bw, and Aw), the A-B shale, and the Neutral, Rowe, and Dry Wood coals (Figs. 3.02 and 5.01; Harris, 1984). The basal sequence boundary is regarded as the basal contact of the lower Warner Sandstone (Figs. 5.01 and 3.08; Appendix A; Johnson, 2004). Evidence supporting the location of the sequence boundary includes regional correlation of an incised valley geometry (lower Warner Sandstone) in well-log cross sections (Figs. 5.02, and 5.03). Where the lower Warner Sandstone is absent, a thick paleosol profile is an indicator of a sequence boundary (Lange et al., 2003). In the Rose Hill #1-6 core, the fluvial deposits of the lower Warner Sandstone erode through the Riverton coal into the TST of the underlying sequence (Johnson, 2004). In the Franklin County core, the basal sequence boundary is overlain by LST fluvial conglomerate and associated paleosol depositional facies (Fig. 3.08 and 5.01; Appendix A).

Transgressive systems tract (TST) facies were observed in both the Franklin County and Rose Hill #1-6 cores, and are correlated in well-log cross-section (Figs.

5.02 and 5.03). Estuarine central basin, tidal flat, tidal channel, and paleosol depositional facies were observed in the Rose Hill #1-6 core, while peat-mire and transgressive lag facies were found in the Franklin County core (Figs. 3.08, 5.01; Appendix A; Johnson, 2004). In the Rose Hill #1-6 core, parasequence stacking patterns of the Sequence 3 TST show a deepening upward progression and a retrogradational parasequence set (Johnson, 2004). The MFS of Sequence 3 is placed within the black A-B shelf shale. The A-B shale has the highest gamma-ray reading within the sequence and directly overlies the Aw coal (Fig. 5.01). The A-B shale was identified as the MFS in the Cherokee basin (Lange, 2003).

Above the MFS, parasequences observed in core suggest an aggradational or progradational stacking pattern, interpreted as the HST. Facies of the HST are very similar in both cores, and are correlative over the study area in well log cross sections (Fig. 5.02 and 5.03). The HST includes several coarsening upward successions of offshore transition, estuarine central basin, tidal flat, tidal channel, and paleosol facies. Typically, a flooding surface separates underlying paleosol facies from overlying mire environments (Neutral, Rowe, and Dry Wood coals; Fig. 3.10, Appendix A; Johnson, 2004). Coals in the HST of Sequence 3 become thinner, more discontinuous, and less regionally extensive upwards (Figs. 3.06, 3.11, 3.12, and 3.13; Table 3.1). The basal contact of the lower Bluejacket Sandstone or its interfluve expression is recognized as the upper sequence boundary of Sequence 3 (Fig. 5.01; Appendix A; Johnson, 2004). Erosion by lower Bluejacket incision results in the decreasing lateral extent and continuity of Sequence 3 HST coals as seen in isopach maps (Figs. 3.11, 3.12, and 3.13). The upward trend of decreasing coal thickness through the HST, however, may be attributed to decreasing upwards through the highstand systems tract (Fig. 3.06; Aitken, 1994).

Sequence 3 is comparable, but not equivalent, to CG2 *and* lower portions of CG3 of Lange (2003) in southeastern Kansas. Lange (2003) identified and correlated only the upper of the two Bluejacket sandstones due to difficulty in recognition of the lower Bluejacket. In the current study, both the upper and lower Bluejacket sandstones were recognized. Both sandstones have incised-valley geometry when correlated laterally and have basal contacts interpreted as sequence boundaries (Figs. 5.02 and 5.03). Lange (2003) did correlate upper and lower Warner sandstones across the Cherokee basin. The base of the lower Warner Sandstone was interpreted as the basal sequence boundary for CG2 and is consistent with the sequence boundary interpretation of Sequence 3 in the Bourbon arch. Also, the maximum flooding surface (A-B shale) is consistently correlated between the two study areas. However, the basal contact of the "incising" upper Warner Sandstone, although only recognized by Lange (2003) and Lange et al. (2003) as underlying the Neutral coal in log cross-section, was interpreted as the lower sequence boundary for the Sequence CG3 in the Cherokee basin. In the Cherokee basin, the interfluve expression at which the sequence boundary was placed in core may not be correlative to an incised valley or a major unconformity. Across the Bourbon arch, no interfluve expression (thick paleosol profile), channel incision, or any other evidence for a sequence boundary is observed for the same stratigraphic position in core or in cross section (Appendix A; Johnson, 2004).

5.2.4 Sequence 4

Sequence 4 is continuous across the study area and into adjacent Forest City and Cherokee basins (Figs. 5.02 and 5.03; Lange, 2003). Lange's (2003) Sequence CG3 is the approximate counterpart of Sequence 4. Sequence 4 contains the lower Bluejacket Sandstone, informal Dbj and Cbj coals, and the Seville Limestone of Kansas (Figs. 3.02 and 5.01; Harris, 1984). The basal sequence boundary is interpreted as the basal contact of the lower Bluejacket Sandstone (Fig. 5.01). Evidence for this interpretation includes observed basinward shifts in facies. In the Rose Hill #1-6 core, tidal channel and tidal flat facies sharply and unconformably overlie weathered black shelf shale facies (Johnson, 2004). Additional evidence for this lower sequence boundary is the incised valley geometry of the lower Bluejacket Sandstone found in cross section (Figs. 5.02 and 5.03). Fluvial channel conglomerate and cross-bedded sandstone facies in the Franklin County core are interpreted as LST deposits. These coarse-grained depositional facies are observed to fill a large portion of the incised Bluejacket channel in cross section. In the Franklin County core, the initial transgressive surface of Sequence 4 is located overlying LST facies (Appendix A).

Sequence 4 TST deposits overlie LST deposits and the initial flooding surface in the Franklin County core, and directly overlie the sequence boundary in the Rose Hill #1-6 core (Fig. 5.01; Appendix A; Johnson, 2004). Across the study area, similar relationships of the Sequence 4 TST deposits and underlying sequence boundary were observed, but are typically associated near the margins of the incised lower Bluejacket paleovalley (Fig. 5.02 and 5.03). Lower TST facies of Sequence 4 observed in both cores are similar, and generally include tidal channel and tidal flat facies, paleosol or transgressive lag overlain by a flooding surface, and in the Franklin County core, a peat-mire. Overlying the flooding surface is shelf shale and offshore transition facies grading upwards into tidal channel and tidal flat, paleosol and mire facies. Upwards in both cores, an additional flooding surface separates paleosols from overlying peat-mires. The upper Bluejacket Sandstone of the overlying sequence sharply overlies this unnamed coal in the Franklin County core (Appendix A; Johnson, 2004). In the Rose Hill core, weathered black shelf shale overlies the coal and flooding surface, which is in then sharply overlain by the upper Bluejacket. Based on retrogradational parasequence stacking patterns in the Rose Hill #1-6 core and regional cross sections, the Sequence 4 MFS is interpreted at the base of the shelf shale directly underlying the upper Bluejacket Sandstone (Figs. 5.02 and 5.03; Johnson, 2004).

Sequence 4 HST deposits, as observed in core and in cross section, are rarely preserved within the study area (Figs. 5.02 and 5.03). The upper sequence boundary of Sequence 4 (described below) is equivalent to the upper sequence boundary of CG3 in the Cherokee basin (Fig. 5.01; Lange, 2003).

5.2.5 Sequence 5

Sequence 5 is correlative across the entire study area and is equivalent to Lange's (2003) CG4 sequence (Figs. 5.02 and 5.03). Sequence 5 consists of the upper Bluejacket Sandstone; informally-named Bbj and Abj coals; Bjb shale; and the Weir-Pittsburg, Tebo, and Scammon 'B' coals (Figs. 3.02 and 5.01; Harris, 1984; Huffman, 1991). The basal sequence boundary is interpreted as the basal contact of the upper Bluejacket Sandstone, or its interfluve expression. Evidence supporting this interpretation includes incised channel geometry, thick paleosol profiles beneath the boundary observed in core, and retrograding parasequence stacking patterns above the boundary observed in both core and log cross sections (Figs. 5.01, 5.02 and 5.03; Appendix A; Johnson, 2004).

Lowstand systems tract (LST) deposits were not observed in core, so the initial flooding surface coincides with the basal sequence boundary of Sequence 5. Retrograding parasequences interpreted as part of the transgressive systems tract directly overlie the sequence boundary and flooding surface in core and cross section (Figs. 5.02 and 5.03; Appendix A; Johnson, 2004). These deposits include tidal channel and tidal flat facies grading upwards into paleosol and mire facies, which are overlain by transgressive lag (fossiliferous black shale) and shelf shale facies. A flooding surface separates the paleosol facies from the mire facies. Progressing up section, both cores exhibit a similar number of flooding surfaces. Above a third flooding surface, shelf shale facies grade into offshore transition, and ultimately paleosol facies. In both cores neither paleosol is interpreted to represent a major unconformity. In the Rose Hill #1-6 core a faint, weathered flooding surface is observed within the paleosol facies (816 ft. depth; Johnson, 2004). In the Franklin County core, a better-defined flooding surface is overlain by weathered black shelf shale, grading upwards into a more landward environment (Figs. 3.14 and 5.01; Appendix A). In both cores, the flooding surfaces mark the stratigraphic position of the absent Weir-Pittsburg coal.

Based on the retrograding parasequence stacking pattern observed beneath the Tebo and Weir-Pittsburg coals in both cores, a maximum flooding surface is placed within the black shale above the Tebo coal (Fig. 5.01; Appendix A; Johnson, 2004). The more landward extent of the Tebo coal isopach map relative to the underlying Weir-Pittsburg coal isopach also supports this MFS placement (Figs. 3.15 and 3.16). This differs from Lange's (2003) interpretation of the shale overlying the Weir-Pittsburg coal and underlying the Tebo coal containing the MFS of Sequence 5. Using gamma-ray responses as a basis for identifying the maximum transgressive shale is inconclusive; either shale may have a higher relative gamma-ray character.

Highstand systems tract (HST) deposits above the MFS include black shelf shale, grading upwards into offshore transition, estuarine central basin, tidal flat, and paleosol facies, flooding surface, and subsequent mire facies (Scammon 'B' [?] coal). In the Rose Hill core, weathered black shelf shale facies overlies the discontinuous Scammon 'B' (?) coal. The Chelsea Sandstone of the overlying sequence is sharply incised into the shelf shale. The basal contact of the Chelsea Sandstone is the upper sequence boundary of Sequence 5 (Figs. 3.17 and 5.01; Johnson, 2004). In the

Franklin County core, the Scammon 'B' coal is overlain by a thick, moderately developed paleosol profile, part of which penetrates through a thin mudstone-limestone interpreted as open marine. This succession in the Franklin County core is considered the interfluve expression of the sequence boundary between sequences 5 and 6 (Figs. 3.14 and 5.01; Appendix A).

5.2.6 Sequence 6

Sequence 6 is laterally extensive across the study area and is partially equivalent to Lange's (2003) CG5 sequence (Figs. 5.02 and 5.03). The sequence includes the Chelsea Sandstone and the Scammon, Mineral, and Fleming coals (Figs. 3.02; 5.01). The lower sequence boundary is interpreted at the base of the Chelsea Sandstone. In cross-section, incision of the Chelsea Sandstone extends as far as the Weir-Pittsburg coal (Figs. 5.02 and 5.03). Both an incised channel and an interfluve expression of the basal sequence boundary of Sequence 6 were observed in cores (Appendix A; Johnson, 2004). The Chelsea Sandstone in the Rose Hill #1-6 core shows strong incision (Fig. 3.17). The sequence boundary is a developed interfluve paleosol in the Franklin County core (Appendix A). The basal sequence boundary, as observed in both cores, is coincident with an initial flooding surface.

Across the Bourbon arch, Sequence 6 typically starts in the TST. LST fluvial deposits may exist locally, but were not recognized in core. Tidal channel, tidal flat, and paleosol facies directly overlie the basal sequence boundary of Sequence 6 in the Rose Hill #1-6 core. Another flooding surface overlies these facies at the location of the absent Scammon coal. Above the flooding surface, shelf shale, offshore transition, tidal flat, and paleosol facies form a coarsening upward succession to the Mineral coal (Figs. 3.17 and 5.01; Johnson, 2004). In the Franklin County core, shelf shale, offshore transition, paleosol, and mire facies (Mineral coal) overlie the sequence boundary, and the exact position of the missing Scammon coal is difficult to discern. Placement just above the sequence boundary is a possibility (Appendix A). The Mineral coal is a highly continuous and relatively thick coal found throughout the area and into adjacent basins (Figs. 3.06 and 3.19). The base of the Mineral coal is considered a flooding surface. The black shale overlying the Mineral coal has the highest gamma-ray response within the sequence, and is interpreted as the maximum flooding surface (Fig. 5.01).

Above the MFS, HST facies in the Rose Hill #1-6 core consist of shelf shale grading upwards into paleosol and coal facies (Fleming coal). The Fleming is a very discontinuous, relatively thin coal, that was not mapped across the Bourbon arch. The base of the Fleming coal is considered a flooding surface. Overlying the Fleming coal is another shelf shale facies grading upwards into a moderately developed soil horizon with signs of oxidization (red color). The upper surface of this paleosol profile is interpreted as the interfluve expression of the upper sequence boundary of Sequence 6 (Figs. 3.20 and 5.01; Johnson, 2004).

In the Franklin County core, shelf shale facies directly overlies the Mineral coal. The Fleming coal succession observed in the Rose Hill #1-6 core is absent in the Franklin County core. A surface of erosion that directly overlies the shelf shale facies is interpreted as the upper sequence boundary. The shelf shale contains minor evidence of pedogenic alteration below the sequence boundary (Appendix A).

Sequence 6 corresponds to Sequence CG5 in the Cherokee basin (Lange, 2003), except for the placement of the upper sequence boundary. In southeast Kansas, the upper sequence boundary was placed either between the Fleming coal and overlying paleosol facies, or at the base of an underlying unnamed sandstone. In the Cherokee basin, the upper sequence boundary is marked by a basinward shift in facies from offshore transition upward into estuarine facies (Lange, 2003; Lange et al., 2003). Consequently, the Fleming coal in the Cherokee basin interpretation is placed into the TST of the overlying sequence (CG6) and associated with the overlying V-shale. The Fleming coal in this study is placed within the HST of Sequence 6 and is associated with the Mineral coal. There are two ways to explain this miscorrelation between the two basins: 1) the sequence boundaries are correctly placed in both respects, and the Fleming coal is miscorrelated from basin to basin—the Fleming of the Bourbon arch being located below the sequence boundary and the Fleming coal of the Cherokee basin located directly above the boundary; or 2) a sequence boundary is misplaced in one basin. Evidence in the current study supports placement of the sequence boundary above the Fleming coal across the Bourbon arch.

5.2.7 Sequence 7

Sequence 7 is continuous across the Bourbon arch and into adjacent basins (Figs. 5.02 and 5.03; Lange, 2003). The sequence consists of the informally named “Cattleman” sandstone, the Croweburg coal, ‘V’-shale, Verdigris Limestone, Bevier coal, and the Squirrel Sandstone of the Lagonda sandstone interval (Fig. 3.02; Jewett, 1954). The sequence is partially equivalent to Lange's (2003) sequence CG6. In addition to an interfluve expression at the basal sequence boundary, the sequence boundary is expressed by the basal contact of the incised, informally named "Cattleman" sandstone (Figs. 5.02 and 5.03; Jewett, 1954).

Upward from the basal sequence boundary in the Rose Hill #1-6 core, facies of the TST include shelf shale, tidal estuarine, tidal channel, paleosol, and mire facies (Croweburg coal; Fig. 3.20; Johnson, 2004). Facies overlying the sequence boundary in the Franklin County core include strongly pedogenically-altered tidal flat facies grading upwards into a sandy paleosol and a mire facies (Croweburg coal; Appendix A). LST facies were not observed in core (Figs. 3.20 and 5.01; Johnson, 2004). The base of the Croweburg coal is interpreted as a flooding surface. The Croweburg is moderately developed across the Bourbon arch. Previous researchers have concluded that the Croweburg is the most extensive, laterally continuous coal in the Pennsylvanian—reaching as far as Illinois (Fig. 3.21; Wanless, 1969). The overlying phosphatic shelf shale (V-shale) has the highest gamma-ray response of all shales in Sequence 7, and is interpreted to contain the MFS (Figs. 5.01; 3.20). In both cores, an open marine mudstone-wackestone limestone directly overlies the V-shale, which in turn, is overlain by a pedogenically altered offshore transition facies and a paleosol. Overlying this paleosol is the Bevier coal. The boundary between the Bevier and underlying paleosol is considered a flooding surface (Fig 3.20; Appendix A; Johnson, 2004).

The Bevier coal is the first coal of the HST of Sequence 7. Across the Bourbon arch, the Bevier coal is the thickest, most continuous, laterally extensive Desmoinesian coal (Figs. 3.06 and 3.22; Table 3.1). Progressing up from the Bevier coal, the HST contains several progradational to aggradational, coarsening upward successions consisting of shelf shale, offshore transition, estuarine, tidal flat, and tidal channel facies (Rose Hill #1-6; Fig. 5.01; Johnson, 2004). In the Franklin County core, observed upward-coarsening HST successions show little tidal influence and consist of shelf shale, offshore transition, prodelta, delta front, and paleosol facies (Appendix A). These coarsening upward successions are known collectively as the Squirrel sandstones. The top of each coarsening upward succession is interpreted as a flooding surface. The Breezy Hill Limestone, which caps the Squirrel sandstone succession and is present in the Cherokee basin, transitions into a pedogenically altered, calcareous sandstone northward onto the Bourbon arch (Lange, 2003; Lange et al., 2003).

Across the Bourbon arch, coals were not observed capping upward-coarsening successions above the Bevier. However, several Sequence 7 HST coals occur in the Forest City and Cherokee basins (Lange, 2003; W.M. Brown, personal communication, 2004). Evidence supporting a HST and a progradational parasequence stacking pattern is found in the Cherokee basin, where Lange (2003) mapped the Bevier and Iron Post coals in detail. Comparing coal isopach maps of the two coals in the Cherokee basin shows a distinct basinward (SW) shift of coal distribution from the Bevier to the Iron Post—suggesting that the stratigraphically higher Iron Post coal prograded further into the basin than the underlying Bevier coal.

The upper sequence boundary of Sequence 7 does not correspond to the upper boundary of the equivalent sequence CG6 in the Cherokee basin (Lange, 2003). The upper sequence boundary in the Cherokee basin is interpreted as the basal contact of the Squirrel sandstone directly above the Bevier coal, or its interfluve paleosol expression. No evidence exists across the Bourbon arch that supports a regional uncomformity (sequence boundary) at this stratigraphic position. Paleosol or other indication of subaerial expression was not observed in core between the Bevier coal and the base of the Mulky coal (Appendix A; Johnson, 2004). The upper sequence boundary of Sequence 7 is interpreted to occur overlying a thick paleosol profile that caps the Squirrel sandstone successions, or at the basal contact of an incising sandstone unit directly beneath the Mulky coal (Figs. 3.23 and 5.01; Appendix A; Johnson, 2004).

5.2.8 Sequence 8

Sequence 8 is regionally extensive across the Bourbon arch and into the Forest City and Cherokee basins (Figs. 5.02 and 5.03; Lange, 2003). The sequence consists of the Mulky coal, the Excello Shale, Blackjack Creek Limestone, Summit coal, Little Osage Shale, and the Higginsville Limestone (Figs. 3.02 and 5.01). The basal sequence boundary in the Bourbon arch is interpreted as an unconformity at the base of an unnamed, incised sandstone or interfluve paleosol equivalent directly beneath the Mulky coal (Fig. 5.01; Appendix A; Johnson, 2004). The sequence boundary in the Cherokee basin appears to be less prominent, and may be the basinward correlative conformity. Evidence supporting this interpretation across the Bourbon arch includes: 1) the absence of the Breezy Hill Limestone underlying the Mulky coal, and replacement with more landward facies reflecting less accommodation; 2) incised valley geometry of the sandstone beneath the Mulky coal; 3) a thick, moderately-developed paleosol profile at the top of the sequence; and 4) the progradational parasequence stacking pattern characteristic of the HST of the underlying Sequence 7 (Figs. 3.23, 3.26, 5.02, and 5.03; Appendix A; Johnson, 2004).

Lowstand systems tract deposits of Sequence 8 were not recognized in the sequence, and TST deposits are minimal. As observed in the Rose Hill #1-6 core, Sequence 8 TST deposits are completely composed of either channel fill or mire facies (Mulky coal; Fig. 3.23; Johnson, 2004). TST deposits are absent in the Franklin County core (Appendix A). The overlying Excello shelf shale is interpreted as the MFS for Sequence 8 (MFS of Sequence CG7 of Lange, 2003). The presence of phosphate nodules indicates relatively deep-water depths (Heckel, 1977). The highest gamma-ray readings of any shale in the sequence support placement of the MFS in the Excello Shale (Figs. 3.23 and 5.01; Johnson, 2004).

In the Rose Hill #1-6 core above the Excello MFS, shoaling-upward deposits of the Sequence 8 HST include open marine mudstone-wackestone, and offshore transition gray shale, capped by a slightly weathered, restricted marine mudstone-wackestone facies grading upwards into a paleosol (Blackjack Creek Limestone and Little Osage Shale). A flooding surface is placed directly over the Blackjack Creek

Limestone based on evidence of weathering and exposure. Another flooding surface occurs above the paleosol, beneath the normal location of the Summit coal. Overlying this flooding surface is another shelf shale (Little Osage Shale; Figs. 3.23 and 5.01; Johnson, 2004). Above the second shelf shale facies of Sequence 8 in the Rose Hill #1-6 core, offshore transition gray shale facies and open marine mudstone-wackestone grade up into a similar but restricted marine facies, and paleosol. Above this weathered carbonate is a flooding surface, which is in turn overlain by a shoaling upwards succession of open marine, restricted marine, intertidal mudstone-wackestone, and paleosol facies (Higginsville Limestone; Johnson, 2004). Overlying the paleosol facies is another flooding surface. Although not observed in core and rarely seen in well logs in the southern portion of the Bourbon arch, a very localized coal may be present above the Higginsville Limestone and the overlying flooding surface. In the Rose Hill #1-6 core, however, the paleosol is overlain by shelf shale facies (Fig. 3.26; Johnson, 2004).

In the Franklin County core, Sequence 8 LST and TST deposits are absent, and HST deposits differ from those described in the Rose Hill #1-6 core. HST deposits are interpreted to directly overlie the basal sequence boundary and paleosol of the underlying sequence. Depositional facies interpreted from the core include a very thin, shallow marine wackestone; shallow open marine Chaetetid boundstone facies; fining-upward shoal water marine packstone-grainstone (Blackjack Creek Limestone [?]), open marine wackestone and packstone facies, and restricted marine wackestone facies (Higginsville Limestone) in a upward shoaling-deepening-shoaling succession. The Excello shelf shale (?), Mulky coal, Summit coal, and Little Osage shelf shale are absent (Appendix A). In the Franklin County core, the thinness and absence of strata within Sequence 8 is interpreted to result from localized erosion and non-deposition. Similar characteristics were observed in logs surrounding the Franklin County core location (eastern Franklin and western Miami counties) and is attributed to local structural uplift during deposition of Sequence 8 (Figs. 3.07; 3.24, 3.25; Chapter 3, Sections 3.2.10 and 3.2.11).

In the Rose Hill #1-6 core, the upper boundary of Sequence 8 is interpreted as the basal contact of the Peru Sandstone (Fig. 3.26; Johnson, 2004). The Englevale "Peru" Sandstone illustrates a basinward shift in facies—a tidal channel facies sharply overlying a shelf shale facies (Figs. 3.26, 5.01). In the Franklin County core, the upper boundary of Sequence 8 is placed just above the top of the Fort Scott Limestone Formation (Appendix A).

5.2.9 Sequence 9

Sequence 9 is continuous throughout the Bourbon arch and into adjacent basins (Figs. 5.02 and 5.03). The Englevale "Peru" Sandstone, Lexington coal, Anna Shale Member, Pawnee Limestone, Bandera Shale, Mulberry coal, as well as other overlying units comprise Sequence 9 (Fig. 3.02). The basal contact of the Peru sandstone is interpreted as the base of Sequence 9 (Fig. 5.01). As observed in the Rose Hill #1-6 core, estuarine tidal channel and tidal flat facies of the Peru sandstone sharply overlying shelf shale facies indicate a basinward shift in facies (Fig. 3.26; Johnson, 2004). The marginal marine nature of the Peru channel fill supports a flooding surface coincident with the sequence boundary (Fig. 5.01). The Peru sandstone grading upward into paleosol facies, and overlain by a flooding surface and Lexington coal, are placed into the TST (Figs. 3.26 and 5.01; Johnson, 2004). Above the Lexington coal is the laterally continuous and phosphatic Anna Shale with a gamma-ray response higher than any other black shelf shale facies in Sequence 9. The Anna Shale is interpreted as the MFS of the sequence (Fig. 5.01). In the Franklin County core, Sequence 9 TST deposits consist of shelf shale, tidal flat (?) or offshore transition facies, and more shelf shale (Anna Shale; Appendix A).

In both core, initial HST deposits observed above the Anna shelf shale are the open marine mudstone-wackestone-packstone facies of the Myric Station Limestone. A flooding surface overlies this facies as the open marine carbonates are overlain by black shelf shale. The HST deposits of Sequence 9 continue to shoal upwards into offshore transition facies, sharply overlain by tidal channel deposits. Above the tidal channel facies, the open marine mudstone-wackestone facies of the Laberdie Limestone indicates a deepening event. Facies within the Laberdie Limestone shoal upwards from open marine at the base, to restricted marine or intertidal near the top. A paleosol facies occurs above the Laberdie Limestone. The Mulberry coal should be located above this paleosol. In the Rose Hill #1-6 core, the Mulberry is missing and the flooding surface separates the paleosol from the overlying open marine facies of the Amoret Limestone of the Altamont Formation (Figs. 3.28 and 5.01; Appendix A; Johnson, 2004).

Although more strata are described above the Mulberry coal in core, the top of the Mulberry coal was the upper limit of depositional and sequence stratigraphic interpretation. Very few coals exist above the Mulberry.

5.3 Discussion

5.3.1 Depositional Succession

Interpreted sequences within the Bourbon arch reflect variations in relative sea level, which is dependant on tectonics, sediment supply, and eustasy. Sequence boundaries across the Bourbon arch record periods of relative sea level fall, resulting in lowstand channel incision and fluvial deposition, subaerial exposure of interfluve regions, sediment bypass, and subsequent deposition southward into the Arkoma basin. Upon initial transgression, sediment is increasingly trapped landward, causing incised valleys to fill with restricted estuarine deposits, while interfluves experience continued weathering and pedogenesis until finally inundated. Prograding pulses of sediment (parasequences) are deposited in a landward-stepping manner as part of the TST up to a point of maximum transgression, where sediment is eventually restricted to a landward maximum (MFS). Across the Bourbon arch the maximum flooding surfaces are characterized by very slow marine deposition and associated black shale facies. Above the MFS and into the highstand, basinward-stepping, shoaling-upward, progradational pulses of sediment (parasequences) were deposited. As the coastline prograded during the HST, each sediment pulse shoaled upward and became subaerially exposed. Near the end of the HST, sediment supply reached a maximum as the coastline progressively prograded basinward. At some point within the HST, a relative sea level fall resulted in channel incision and sequence boundary formation.

5.3.2 Stratigraphic Controls on Peat Formation

Based on the sequence stratigraphic framework (Fig. 5.01), statistical coal analysis (Fig. 3.06; Table 3.1), and coal isopach mapping, sequence stratigraphic position appears to be a significant factor on Desmoinesian coal thickness, extent, and distribution (Figs. 5.04 and 5.05). Thick peat formation is dependent on the rapidly increasing accommodation for continued peat accumulation. Relative sea level affects relative base level and the landward water table required for peat growth and accumulation. The thickest peat deposits form at the times of high accommodation and rising base level where mires were sustained and preserved (McCabe and Parrish, 1992; McCabe and Shanley, 1992).

Periods of high accommodation and rising relative base level occur from the late LST to the early TST, and from the late TST into the early HST (coinciding with the MFS, or transgressive maximum; Aitken, 1994; Diessel, 1998). One model of peat development through the depositional sequence states that upward from the basal sequence boundary, coals become thicker, higher quality (less ash), more continuous, and more widespread through the TST up to the maximum flooding surface (Aitken, 1994). Beyond the MFS and into the HST, coals become thinner, higher in ash content, more discontinuous, and less extensive. This model can be applied to Desmoinesian coals in eastern Kansas.

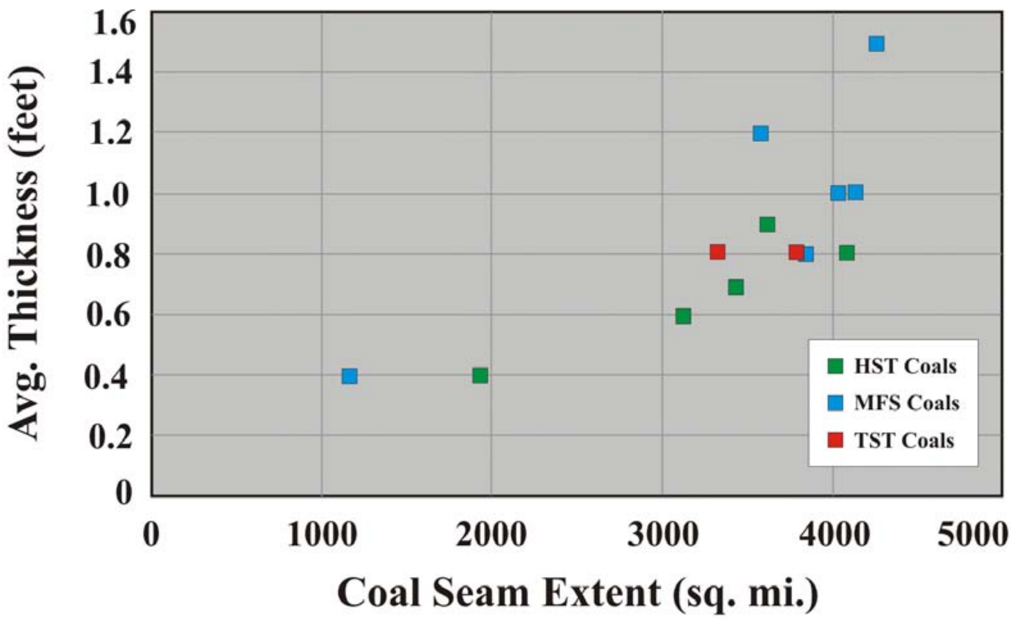

Figure 5.04 Crossplot of coal seam extent (square miles) versus average thickness (feet) for Bourbon arch coals based on sequence stratigraphic position (Table 3.1). Greater extent correlates to greater average thickness. The most extensive and thickest coals occur at or near the MFS.

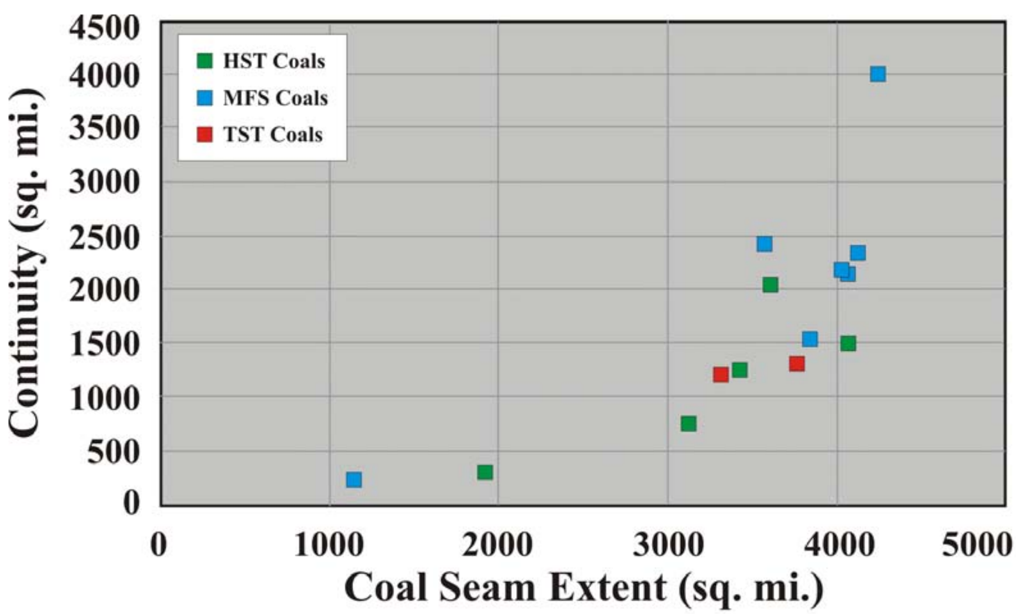

Figure 5.05 Crossplot of coal seam extent (square miles) versus coal seam continuity (square miles) for Bourbon arch coals based on sequence stratigraphic position (Table 3.1). Greater coal continuity correlates to more extensive coals. The most extensive and continuous coals occur at or near the MFS.

Coals adjacent to interpreted maximum flooding surfaces tend to be the thickest, most laterally extensive coals in the study area (Figs. 3.06; 5.04; and 5.05). Coals associated with transgressive maximum shales include the Riverton (Riverton shale), Tebo (Tebo shale), Mineral (Mineral shale), Croweburg and Bevier (V-shale), Mulky (Excello Shale), and the Lexington (Anna Shale). More discontinuous coals found farther away from the MFS include the Neutral, Rowe, Dry Wood, Weir-Pittsburg, Scammon, Summit, and Mulberry, as well as numerous discontinuous, often unnamed coals (Fig. 3.02). In addition to the decreasing accommodation through the HST, coal continuity in the HST is further hindered by the increased likelihood of channel incision and erosion coincident with the overlying sequence boundary. The Neutral, Rowe, and Dry Wood coals illustrate this point (Figs. 3.11, 3.12, and 3.13, respectively). In addition, coals positioned within the LST or early TST may be confined within incised valleys, resulting in less extensive regional distribution (Figs. 5.02; 5.03; 5.04; 5.05).

Whereas coal thickness can be related to stratigraphic position, coal ash content appears to be random (Figs. 3.04; 3.06; 5.06). Although Aitken (1994) postulated that coal quality increases (decrease in ash and sulfur content) through the TST, peak at the MFS, and decrease upwards through the HST, this was not observed from available data in eastern Kansas. There are two possible explanations for the absence of a relationship between coal quality and stratigraphic position. First, the available sample datasets are small and incomplete making statistical analysis difficult. Eleven data points was the maximum, while several coals are represented

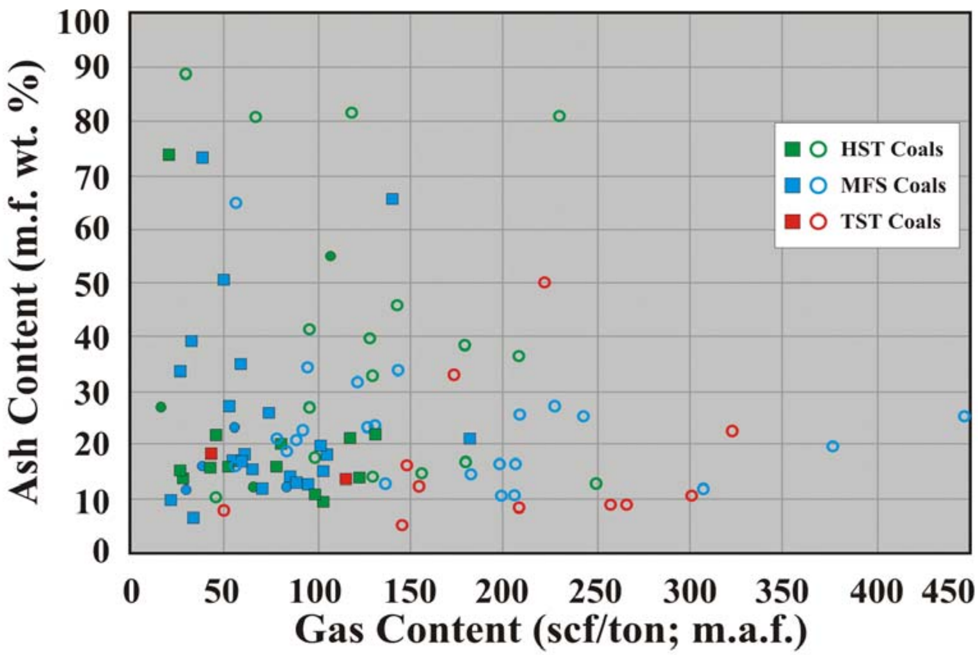

Figure 5.06 Cross-plot of gas content (scf/ton; moisture- and ash-free basis) versus ash content (wt. %; moisture-free basis) for individual coals in the Bourbon arch (color-filled shapes) and Cherokee basin (outlined shapes) based on sequence stratigraphic position. MFS and TST coals generally have higher gas contents than HST coals. Ash content is not related to sequence stratigraphic position.

by a single data point. Second, ash and sulfur contents may be more reflective of peat-forming environment and depositional environments of surrounding strata rather than sequence stratigraphic position (e.g., Summit coal; Fig. 3.04). Variations in sulfur values may reflect a coal's proximity to overlying marine shales rather than peat forming environment (McCabe, 1984).

5.3.3 Sequence Stratigraphy and Coalbed Gas Content

Sequence stratigraphic position influences coal seam characteristics, where MFS-associated coals tend to have greater coal extent, continuity, and average thickness. However, a relationship was not observed between MFS coals in eastern

Kansas and high average gas content (Fig. 5.07). Several gas-rich coals (e.g. Riverton, Mineral, Bevier, and Lexington) are associated with a MFS, and in general, MFS and TST coals have higher gas contents than HST coals on an individual coal basis (Fig. 5.06); but sequence stratigraphic position, by itself, does not govern average gas content. Plotting average gas content versus average coal thickness (Fig. 5.08; Cherokee basins and Bourbon arch coals) indicates a direct relationship. However, Figure 5.08 and crossplots of average gas content versus extent (Fig. 5.09; Bourbon arch only) and versus continuity (Fig. 5.10; Bourbon arch only) show no conclusive relationship between MFS-associated coals and average gas content. A crossplot of gas content (scf/ton; a.r.) against depth (feet) suggests that 1) Cherokee basin TST and MFS-associated coals generally have higher gas contents than Cherokee basin HST coals, while Bourbon arch TST, MFS, and HST-associated coals are highly variable relative to each other; 2) eastern Kansas MFS coals have the greatest range of gas content; and 3) several Cherokee basin MFS-associated coals have the highest gas content in eastern Kansas (Fig. 5.11). Factors such as depth and depositional environment may also play a role in higher coalbed gas content.

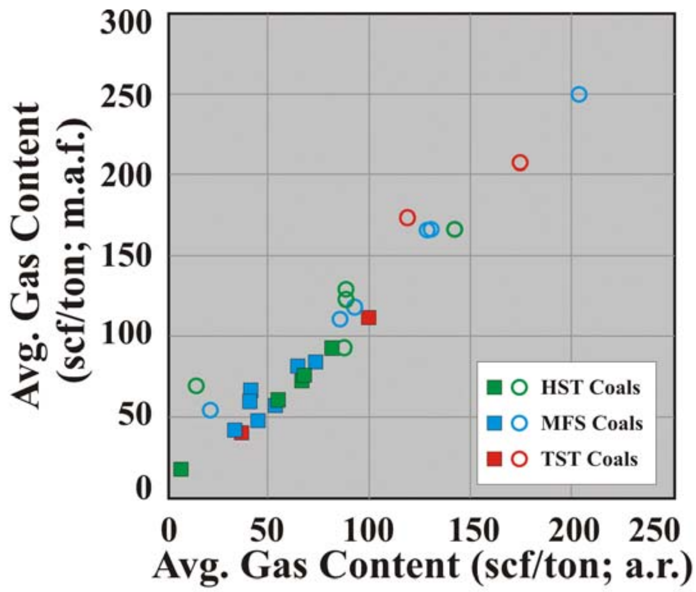

Figure 5.07 Crossplot of average gas content (scf/ton, as received) versus average gas content (scf/ton; moisture- and ash-free) for coals in the Bourbon arch (squares) and Cherokee basin (open circles) based on sequence stratigraphic position. No distinct correlation exists between sequence stratigraphic position and gas content.

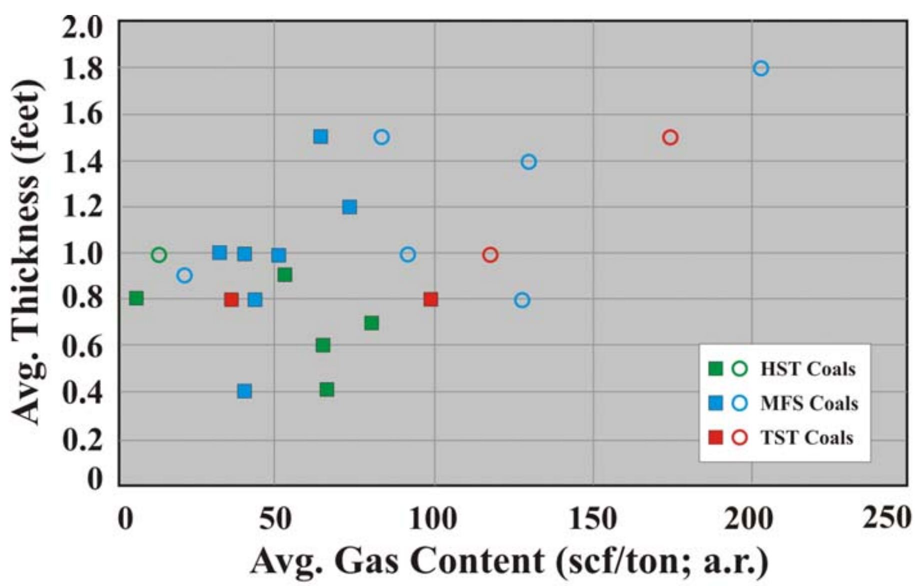

Figure 5.08 Crossplot of average gas content (scf/ton, as received) versus average thickness (feet) for coals in the Bourbon arch (squares) and Cherokee basin (open circles) based on sequence stratigraphic position. Average gas content increases with average coal seam thickness. MFS-associated coals tend to have greater thickness, but not necessarily greater gas content.

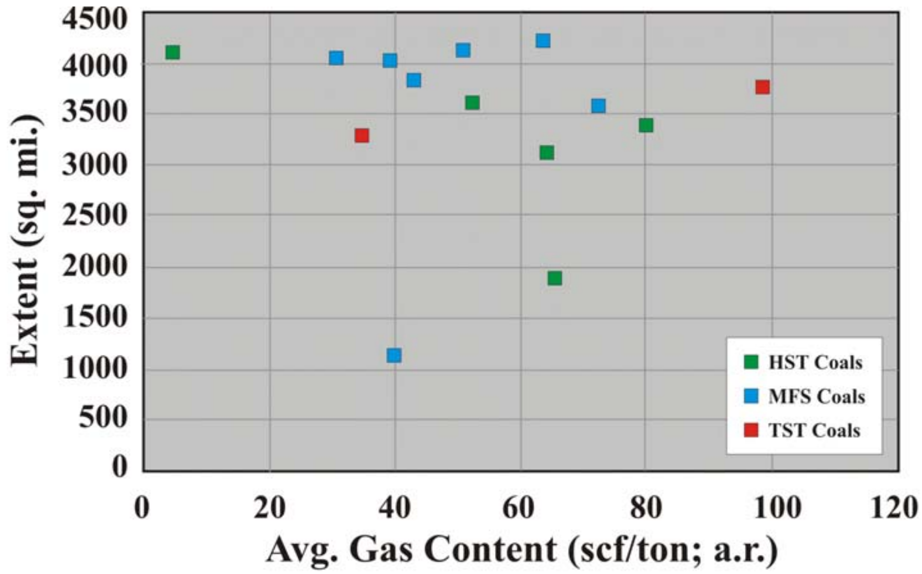

Figure 5.09 Cross-plot of average gas content (scf/ton, as received) versus coal seam extent (square miles) for coals in the Bourbon arch based on sequence stratigraphic position. Average gas content shows no apparent correlation with coal seam extent. MFS-associated coals do tend to have greater extent, but not necessarily greater gas content.

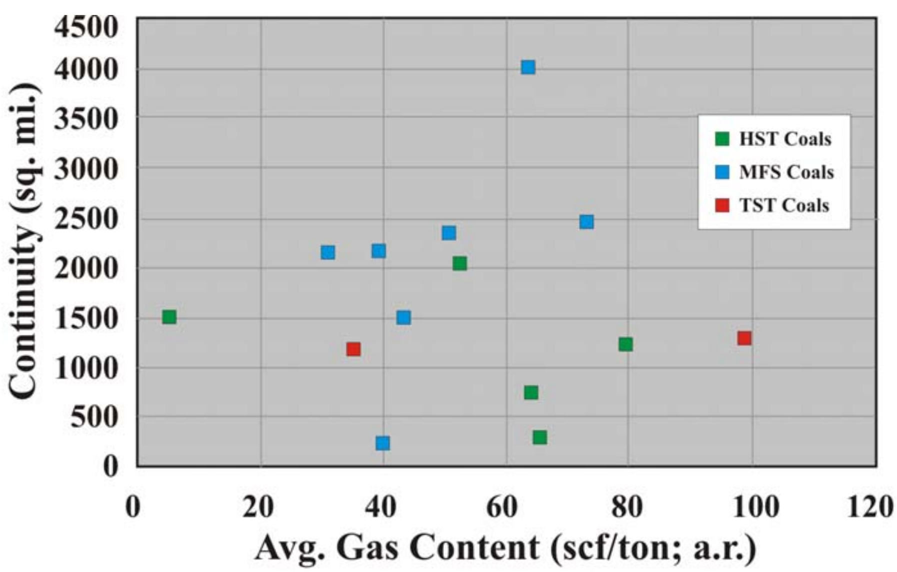

Figure 5.10 Crossplot of average gas content (scf/ton, as received) versus coal seam continuity (square miles) for coals in the Bourbon arch based on sequence stratigraphic position. Although MFS coals tend to be more continuous, no apparent correlation between gas content and coal seam continuity is evident.

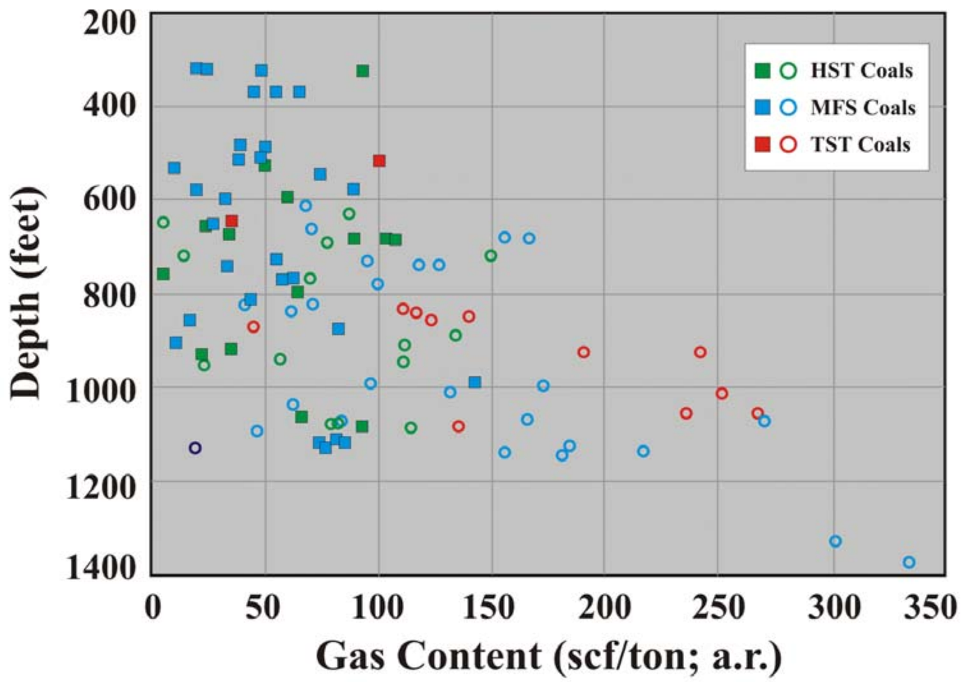

Figure 5.11 Cross-plot of gas content (scf/ton; as received) versus depth in feet for individual coals in the Bourbon arch (color-filled shapes) and Cherokee basin (outlined shapes) based on sequence stratigraphic position (modifed from Fig. 4.13). MFS and TST coals tend to have higher gas contents than HST coals in eastern Kansas. MFS coals also have the greatest range and highest values of gas content.