ARCHITECTURAL MODELS FOR LOWER PENNSYLVANIAN STRATA IN DICKENSON/WISE COUNTY, SOUTHWEST VIRGINIA: A RESERVIOR CASE STUDY

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ABSTRACT

The lower Pennsylvanian, coal-bearing, siliciclastic strata in Dickenson/Wise counties of southwest Virginia were deposited in continental to marginal marine environments influenced by high-amplitude relative sea level fluctuations. Coal-bearing siliciclastics of the eastern facies belt are fluvio-deltaic in origin, with sediment derived from the erosion of low-grade metamorphic and Grenvillian-Avalonian terranes of the Alleghanian orogen to the southeast. Elongate NNE trending quartzarenite belts in the northwestern region of the basin are braided-fluvial deposits and were sourced by the cratonic Archean Superior Province to the north. This orthogonal relationship between the southeastern coal-bearing siliciclastics and the northwestern quartzarenites reflect a trunk-tributary drainage system operating during the lower Pennsylvanian in the central Appalachian basin.

Analysis of core, gamma ray and density logs, and six cross-sections within an approximately 20 km^2 study area reveals a hierarchy of bounding discontinuities and architectural elements. Discontinuities are both erosional (unconformable) and depositional (condensed) and are 3rd-order (~ 2.5 Ma) and 4th-order (~ 400 k.y.) in origin. Architectural elements are bound by 4th-order discontinuities and consist of upward-fining lowstand and transgressive incised valley fill, alluvial, and estuarine deposits, and upward-coarsening highstand deltaic deposits and represent 4th-order sequences. Lowstand and transgressive deposits are separated from the highstand deposits by marine flooding zones (condensed sections). 4th-order sequences are stacked into composite 3rd-order sequences. Sequence development can be attributed to 4th-order Milankovitch orbital eccentricity cycles superimposed on a lower-frequency eccentricity cycle.

Extensive coals occur in both transgressive and highstand systems tracts. Coals within the transgressive systems tract are associated with 4th-order flooding surfaces, while coals within the highstand systems tract occur within high-frequency deltaic autocycles. Therefore, coals formation in the central Appalachian basin can be attributed to be of both allocyclic (glacio-eustacy) and autocyclic (deltaic processes) mechanisms.

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1 **INTRODUCTION**

Renewed interest in the coal-bearing strata of the central Appalachian Basin has created an extensive dataset of use in characterizing stratigraphic relationships between lower Pennsylvanian strata. The lower Pennsylvanian strata of the central Appalachian Basin are defined by coal-bearing siliciclastics intercalated with thick, extensive quartzarenite sandbodies. The mixed siliciclastics and coal define the southeastern margin of the central Appalachian Basin and comprise a southeasterly-thickening wedge. The quartzarenite strata are NE-SW trending sandbodies located along the northwestern margin of the basin.

Several different depositional models have been assigned to these lower Pennsylvanian strata. The coal-bearing siliciclastics have been assigned to a fluvio-deltaic environment (Donaldson, 1974; Englund, 1974; Ferm, 1974; Donaldson et al., 1985; Englund et al., 1986; Englund and Thomas, 1990; Allen, 1993). The quartzarenite bodies have been attributed to both marine (Ferm and Cavaroc, 1969; Ferm, 1974; Horne et al., 1974; Miller, 1974; Englund, 1979; Englund et al., 1986; Englund and Thomas, 1990) and fluvial (Rice, 1984; 1985; Rice and Schwietering, 1988; Wizevich, 1992; Archer and Greb, 1995; Greb and Chesnut, 1996; Korus, 2002; Bodek, 2006; Korus et al., 2008) environments.

The lateral transition from quartzarenites into coal-bearing siliciclastics to the southeast is poorly understood. Some workers have argued that the transition is gradational (Englund and Delaney, 1966; Englund, 1974; Miller, 1974) while others have stated the quartzarenites “wedge-out” into the coal-bearing siliciclastics (Englund, 1974; Englund, 1979; Chesnut, 1994; Greb et al., 2004; Bodek, 2006).

1.1 Objectives

The primary objective of this study is to develop a high-resolution sequence stratigraphic framework for lower Pennsylvanian strata in the central Appalachian Basin in order to clarify stratigraphic relationships between the quartzarenite and mixed siliciclastic and coal facies associations. Focus is placed on reconstructing three-dimensional architectural relationships for these associations in order to understand their paleogeographic relationships.

Renewed interest in these stratigraphic units has arisen from the economic value of the coal seams interbedded within siliciclastic units and their increasing importance as a reservoir for natural gas. Coal thickness and extent has been attributed to position within a sequence (Bohacs and Suter, 1997; Gibling et al., 2004; Bodek, 2006), with the thickest and most extensive coals developed in aggradational to slightly retrogradational stacking patterns associated with transgressive systems tracts. Thus, a secondary objective of this study is to relate the thickness, extent and quality of coal seams to their relative position within sequences.

2 **GEOLOGIC HISTORY**

2.1 *Regional tectonics*

The Appalachian Basin is a product of the combined effects of the Taconic, Acadian, and Alleghanian orogenies (Quinlan and Beaumont, 1984). These collisions created a northeast-southwest trending foreland basin that extends approximately 1,075 miles from New York to Alabama (Ryder, 1995). Its width ranges from 20 to 310 miles and spans ten US states.

The central Appalachian Basin (Fig. 1A) covers much of West Virginia, Virginia, eastern Kentucky and northeastern Tennessee. The southeastern margin of the central Appalachian basin is marked by the fold-and-thrust belt, whereas the northwestern

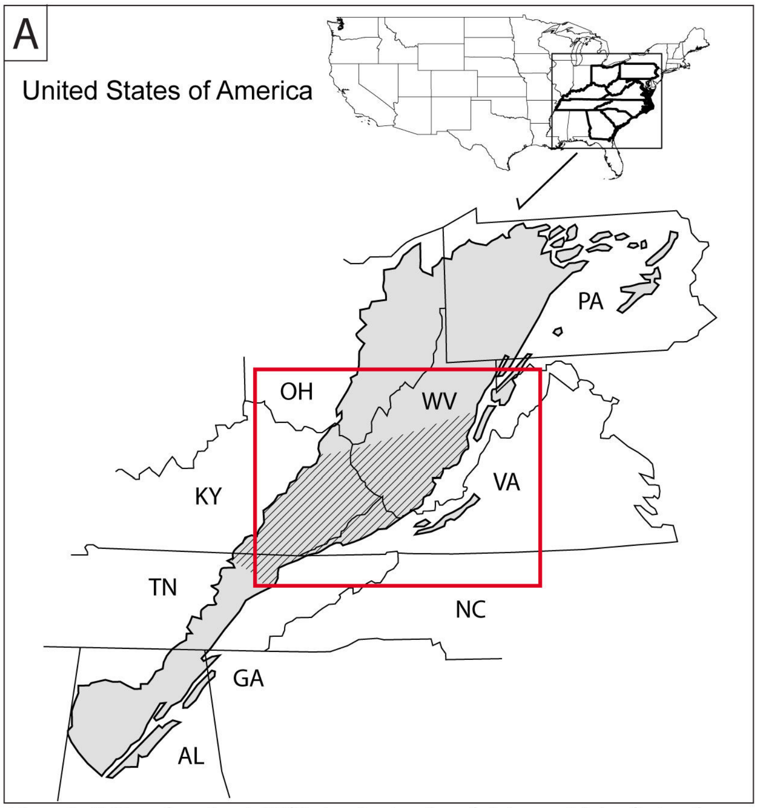


Figure 1: A) Map of continental USA showing location of states containing Carboniferous strata. Enlarged region shows the areal extent of Carboniferous strata (shaded region) in the Appalachian basin. The central Appalachian basin (hatched region) extends through southern West Virginia, eastern Kentucky, southeastern Virginia, and central Tennessee. The boxed in region contains the area shown in figures 1B and 1C. (Based in part from Cecil et al., 1985; Chesnut, 1994; Greb and Chesnut, 1996; Korus, 2002; Greb et al., 2004: Greb and Martino, 2005: Bodek, 2006)

margin is defined by the Cincinnati Arch (Fig. 1B; Greb and Martino, 2005; Bodek, 2006). To the north, the central Appalachian basin extends as far as the Kentucky River Fault System, the Irvine-Paint Creek Fault System, and a structural hingeline positioned in central West Virginia (Greb and Martino, 2005). Rice and Schwietering (1988)

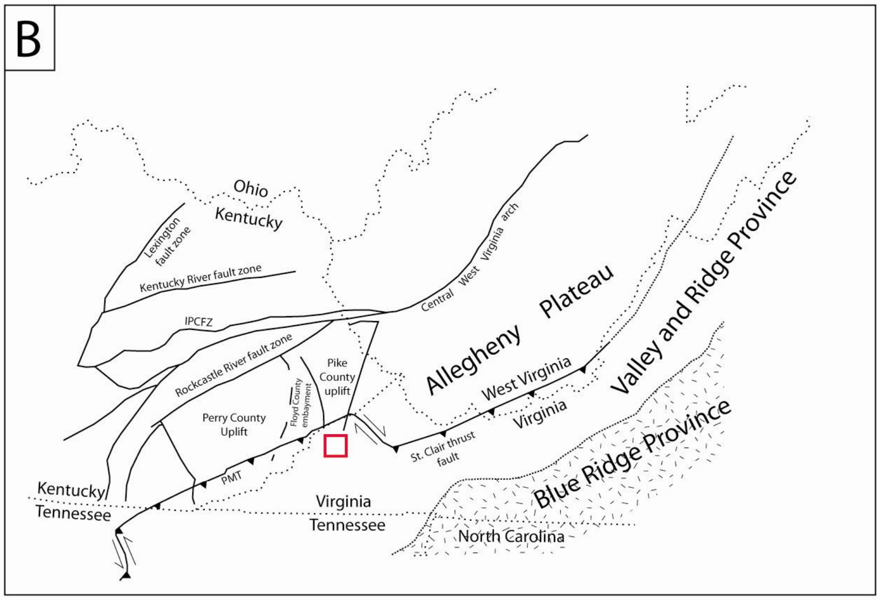


Figure 1: B) Map of important structures within the central Appalachian basin. Northwest of the study area is the Pine Mountain Thrust (PMT), Rockcastle River Fault Zone, Irvine-Paint Creek Fault Zone (IPCFZ), Kentucky River Fault Zone and the Lexington Fault Zone. The Perry County, Floyd County and Pike County Uplifts are a product of the Rockcastle River fault and Pine Mountain Thrust and are located in eastern Kentucky. The IPCFZ extends into West Virginia where it intersects the Central West Virginia Arch (CWA). Three provinces are displayed; the Alleghany Plateau which is bound by the CWA to the north and the St. Clair thrust fault to the south, the Valley and Ridge which is bound to the north by the St. Clair thrust fault and to the south by the uplifted Blue Ridge Province (hatched region). The study area (red box) is bound to the northwest by the PMT and is contained within the Valley and Ridge Province.
(Based in part from Ryder et al., 2008)

proposed the largest factor on accommodation in the basin was thrust loading induced subsidence in a central Appalachian basinal depocenter during the early Pennsylvanian Alleghanian orogeny, which created a southeasterward thickening wedge of sediment (Fig. 1C). Both terrestrial and marginal-marine sediments were deposited in up to 9,500 feet of accommodation throughout the early Pennsylvanian to Permian (Ettensohn, 2004)

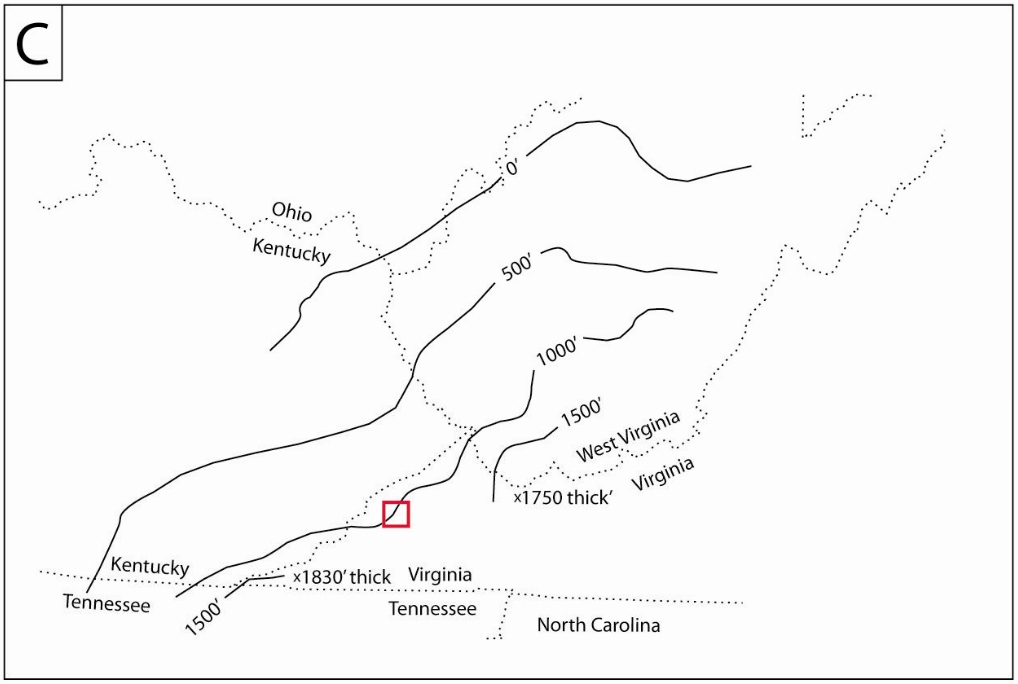


Figure 1: C) Isopach map of Lower Pennsylvanian strata (in feet). Preserved Lower Pennsylvanian strata thicken towards the southeast. The study area (red box) is within the 1000' contour line. (Based in part from Arkle, 1974; Ryder et al., 2008)

2.2 *"Layer-cake" stratigraphy*

Stratigraphic models of Carboniferous strata in the central Appalachian Basin began with the traditional assignment of tabular or "layer cake" bodies to distinctive lithologic units. This layer cake model depicted individual sediment bodies as laterally continuous and stacked to represent unique stratigraphic time intervals (i.e., layers of cake). More recently, it has been recognized that Carboniferous units are not as widespread and tabular as originally thought. Miller (1974) realized that units were truncated by, intertongued with, or graded laterally into either underlying or overlying strata. As a result of these newly discovered relationships, a more accurate and reliable stratigraphic framework was necessary.

2.3 *Stratigraphic relationships*

Based on studies of roadcuts and abundant well logs, it was realized that lower and middle Pennsylvanian strata are arranged in two interfingering facies belts; a southeastern facies belt comprised of mixed siliciclastic, coal-bearing strata and a northwestern facies belt consisting predominantly of quartzarenities (Fig. 2; Englund, 1974).

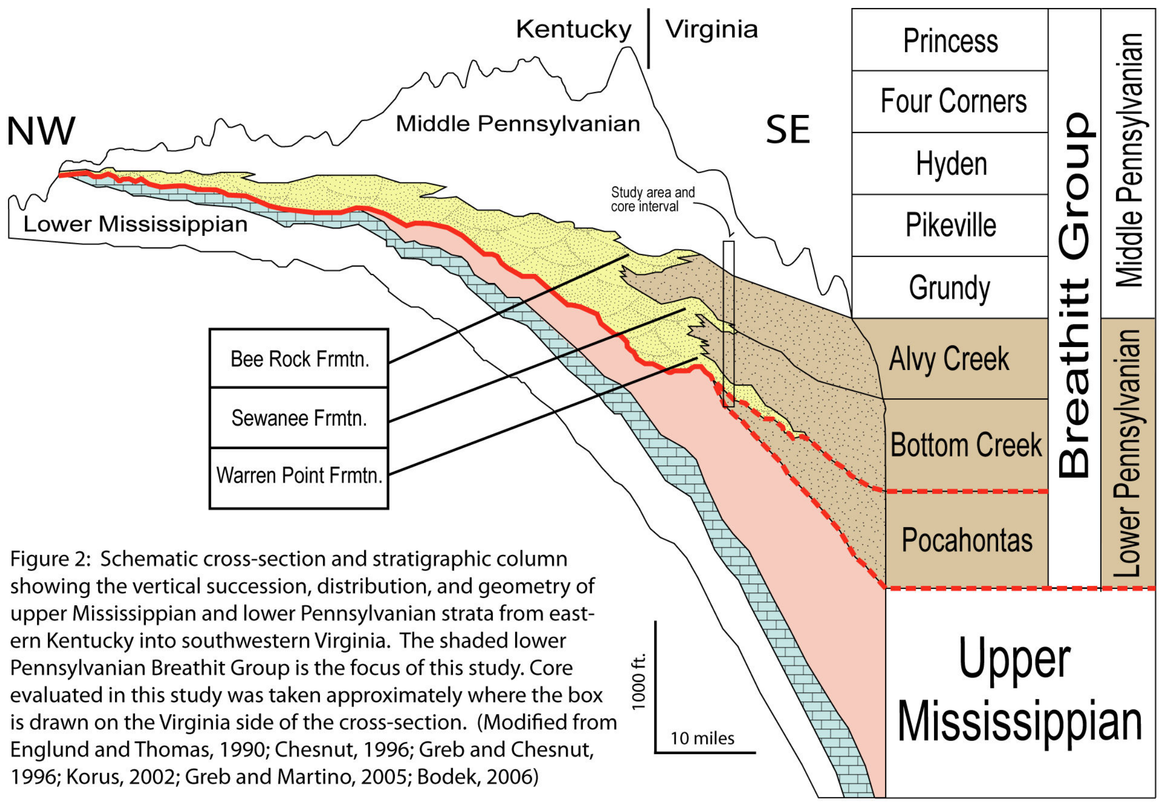


Figure 2: Schematic cross-section and stratigraphic column showing the vertical succession, distribution, and geometry of upper Mississippian and lower Pennsylvanian strata from eastern Kentucky into southwestern Virginia. The shaded lower Pennsylvanian Breathitt Group is the focus of this study. Core evaluated in this study was taken approximately where the box is drawn on the Virginia side of the cross-section. (Modified from Englund and Thomas, 1990; Chesnut, 1996; Greb and Chesnut, 1996; Korus, 2002; Greb and Martino, 2005; Bodek, 2006)

The coal-bearing siliciclastic strata comprising the lower and middle Pennsylvanian Breathitt Group consist mainly of sublithic, northwest-trending sandstone bodies with lesser amounts of siltstone, shale, underclay, and coal (Englund et al., 1986). The sublithic sandstones show northwesterly to westerly paleoflow directions and contain immature, low-grade metamorphic sediment derived from the Alleghanian orogen to the southeast (Rice, 1985; Rice and Schwietering, 1988). Previous workers have determined a maximum thickness for this facies belt of approximately 2,400 feet along the southeastern margin of the central Appalachian basin, from where it thins to the northwest (Miller, 1974; Englund, 1979; Englund et al., 1986; Englund and Thomas, 1990; Chesnut, 1994; Nolde, 1994a; Korus, 2002).

Quartzarenites sandstone bodies of the Breathitt Group define the northwestern facies belt and occur near the border of eastern Kentucky and southwestern Virginia. These sandstone bodies are oriented northeast-southwest. Individual quartzarenite units are approximately 37–50 miles wide (Greb et al., 2004), up to 500 feet thick and typically are made up of thinner (70–100 feet thick) individual quartzarenite beds (Chesnut, 1994, 1996). Wizevich (1992) documented southwesterly paleoflow within the quartzarenite belt. These quartz sandstone belts amalgamate cratonward (Wizevich, 1992; Greb and Chesnut, 1996; Greb et al., 2004; Bodek, 2006) and have an *en echelon* appearance in cross-section. Towards the southeast, the quartzarenite bodies bifurcate, pinch-out, and grade laterally into the coal-bearing siliciclastic belt (Fig. 2). Rice and Schwietering (1988) found the quartzarenites to be "confined" between their coal-bearing counterparts to the southeast and the uplifted upper Mississippian units to the northwest along the Cincinnati arch.

2.4 *Lower Pennsylvanian global correlations*

The Carboniferous Period, consisting of both the Mississippian and Pennsylvanian subsystems, was subdivided by the Eight International Congress on Carboniferous Stratigraphy and Geology in 1975 to aid in global correlations between established Russian stages and North American stratotypes (Davydov et al., 2004). Both the Mississippian and Pennsylvanian subsystems were subdivided into early, middle, and upper periods. For the purposes of this study, the early and middle Pennsylvanian subdivisions correspond to the international Bashkirian and Moscovian stages, respectively (Fig. 3; Davydov et al., 2004).

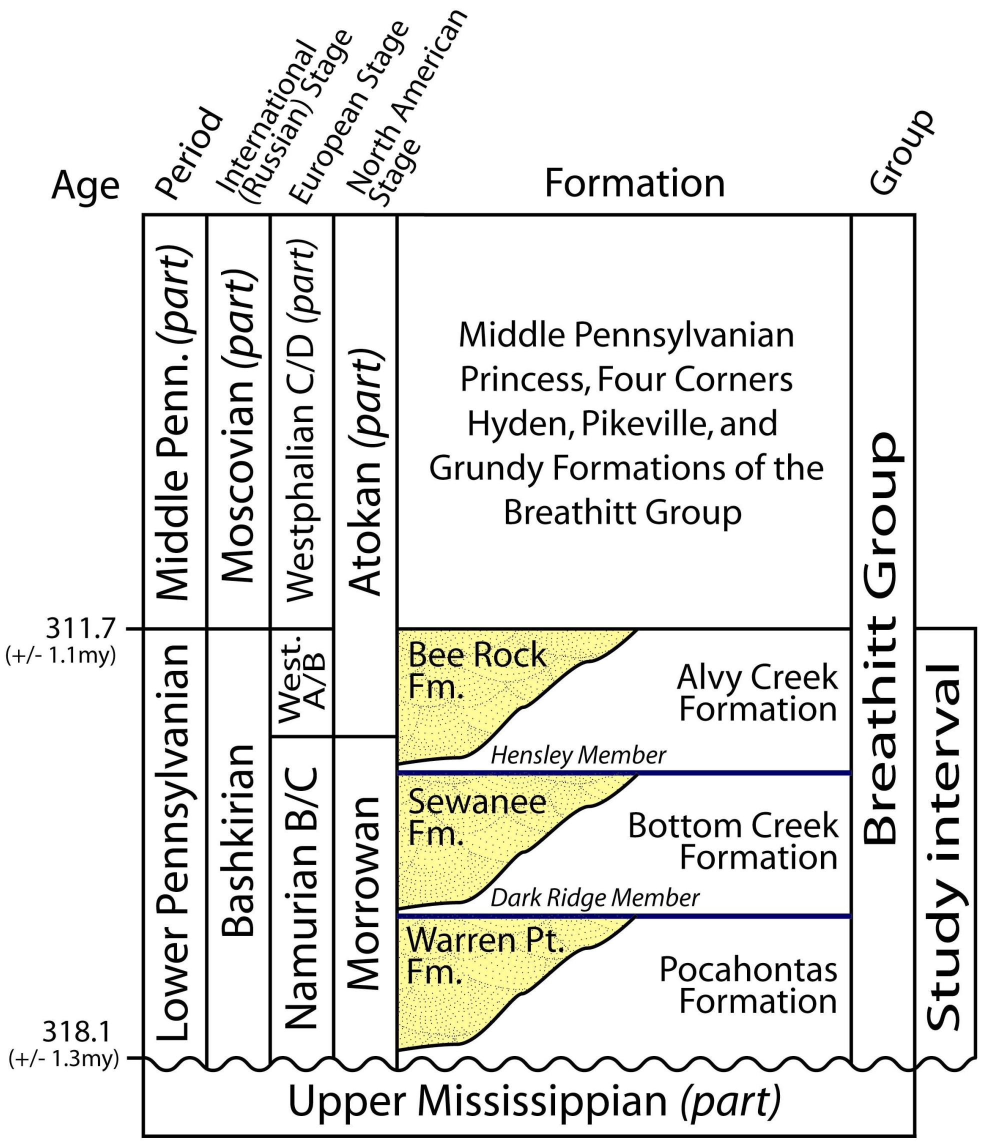


Figure 3: Stratigraphic relationship of lower and middle Pennsylvanian strata in the central Appalachian basin including period and global stage boundaries. Note age estimates for the upper and lower boundaries of the early Pennsylvanian period (*Davydov et al., 2004*). *(Modified from Chesnut, 1994; Bodek, 2006)*

When correlated with European stages, the base of the Pennsylvanian is equivalent to the base of the Namarian B Stage (Fig. 3). The early – middle Pennsylvanian boundary is marked by the boundary between the Westphalian B and C stages (Fig. 3). The base the North American Morrowan Stage is placed at the systemic Mississippian-Pennsylvanian unconformity (Groves et al., 1999). The base of the North American Atokan Stage is placed at the boundary between the European Numarian C – Westphalian A Stages (Fig. 3). Therefore, using North American Stages, the boundary between the early – middle Pennsylvanian is Lower Atokan in age (Groves et al., 1999; Davydov et al., 2004).

Davydov et al. (2004) was able to extrapolate specific date ranges for stage boundaries using radiometric dating and a regression line. Figure 3 shows the estimated ages along with their appropriate error bars. The base of the early Pennsylvanian is estimated at 318.1 ± 1.3 m.y., whereas the early – middle Pennsyvanian boundary is estimated at 311.7 ± 1.1 m.y. (Fig. 3). This gives a duration for the early Pennsylvanian of 4 – 8.8 m.y. with a mean of 6.4 m.y. (Davydov et al., 2004). This agrees with the determined duration for the early Pennsylvannian constrained by Bodek (2006).

2.5 *Paleoenvironmental models*

Based on established temporal and spatial constraints for stratal units in the central Appalachian Basin, depositional models were developed to incorporate the lateral facies relationships observed in the northeast-trending Breathitt quartzarenites and their southeastward coal-bearing siliciclastic counterparts. Three unique paleoenvironmental models have been proposed, but they all have the same dilemma: the uncertainty in the stratigraphic position or existence of the mid-Carboniferous unconformity.

2.5.1 Marine depositional model

The marine model infers a conformable upper Mississippian – lower Pennsylvanian relationship in the central Appalachian Basin (Ferm and Cavaroc, 1969; Ferm, 1974; Horne et al., 1974). Upper Mississippian carbonates were interpreted as deep-water offshore buildups and the upper Mississippian siliciclastics were interpreted as lagoonal mudstones. The coal-bearing siliciclastics were interpreted as fluvio-deltaic deposits along the southeastern margin of a cratonic sea whereas the quartzarenites were inferred to represent well-worked shoreline deposits of barrier-bar origin to the northwest of the delta plain (Horne et al., 1974). In this model, the Mississippian and Pennsylvanian system boundary was placed at the contact between upper Mississippian marine units and the lower Pennsylvanian barrier-bar quartzarenites.

The barrier-bar depositional model for the Pennsylvanian quartzarenites implied that sediment derived from the Alleghanian orogen to the southeast was reworked by a southwesterly directed longshore drift or ebb-dominated tidal flow along the shoreline of an epicontinental sea (Englund, 1974; Ferm, 1974; Horne et al., 1974; Miller, 1974; Hobday and Horne, 1977; Englund et al., 1986). Throughout the early Pennsylvanian, deposition of barrier-bar quartzarenites occurred during periodic still-stands of such duration that shorelines were stabilized (Englund et al. 1986).

The marine depositional model (Englund, 1974; Ferm, 1974; Horne et al., 1974; Miller, 1974; Hobday and Horne, 1977; Englund et al., 1986) provided a rational explanation for quartzarenites bodies aligned at right angles to the coal-bearing siliciclastics. Subsequently many workers have presented various forms of sedimentological evidence in favor of a fluvial origin for the quartzarenites (Bement, 1976; Rice, 1984; Rice and Schwietering, 1988; Wizevich, 1992).

2.5.2 Fluvial depositional model

Evidence contradicting a marine origin for the quartzarenites of the western facies belt and favoring a fluvial depositional environment was presented by a number of workers and included channelized scour and upward-fining channel sequences, unidirectional southwesterly paleocurrent directions, large basal bedforms, quartz-pebble conglomeritic lags, rarity of marine fossils, *in-situ* tree roots, and abundant plant fossils (Miller, 1974; Bement, 1976; Rice, 1984; Rice and Schwietering, 1988; Chesnut, 1988, Wizevich, 1992). Rice (1985) proposed that braided river systems carried sediment from the Canadian Shield to the Appalachian Basin during the late Mississippian. He inferred that rivers flowed southwards on the cratonward side of the Cincinnati arch through the Sharon-Brownsville paleovalley until the end of the Mississippian when Alleghanian orogenesis took place (Rice and Schwietering, 1988). During orogenesis, downwarping of the Appalachian basin associated with uplift of the Cincinnati arch (Quinlan and Beaumont, 1984) caused capture of these river systems and diverted their flow into the subsiding Pennsylvanian depocenter via the Sharon-Brownsville-Middlesboro paleovalley (Rice and Schwietering, 1988). Deposition of quartz-rich sediment along the western margin of the Appalachian Basin (western facies belt) continued until the middle

Pennsylvanian when the braided rivers were alluviated and abandoned (Rice and Schwietering, 1988).

The fluvial depositional model proposes two source areas which fed lithologically different sediment types into the central Appalachian Basin. The model suggests that clean quartz sand and gravel were carried into the basin from the Canadian Shield to the north, whereas immature feldspathic and lithic sandstones of the eastern facies belt were derived from the low-grade metamorphics of the Alleghanian orogen to the southeast (Greb and Chesnut, 1996).

2.5.3 Trunk-tributary depositional model

A trunk-tributary model has been proposed to accommodate the coeval facies of the eastern and western belts. The model explains the interplay of two separate fluvial systems draining different terrains and aids in understanding extrabasinal processes that dictated stratal architecture. During periods of sea level lowstand, westerly flowing (tributary) rivers drained the southeastern Appalachian fold-and-thrust belt (Rice and Schwietering, 1988) whereas large, bedload-dominated braided (trunk) rivers carried quartzose sediment from the Canadian Shield (Archer and Greb, 1995; Greb and Chesnut, 1996; Korus, 2002; Bodek, 2006). As sea level began to rise, transgression of this dual fluvial system persisted, drowning both the trunk and tributary incised valleys, forming estuaries (Greb and Martino, 2005). Drowning was followed by progradation of bay-head deltas into the estuaries to generate upward-coarsening parasequences. Coal beds associated with the parasequences developed in response to periodic abandonment of individual delta lobe switching as a result of load induced subsidence. Following bayhead delta formation, sea level fell resulting in incision, and another cycle of eustatic sea level change began. The trunk- and tributary sandstone bodies of this system are interpreted as incised valley fill successions (IVF) (Aitken and Flint, 1995; Greb et al., 2004; Greb and Martino, 2005; Bodek, 2006; Korus et al., 2008).

2.6 *Evidence for a systemic unconformity*

Ongoing stratigraphic work in the Appalachian Basin (Englund, 1979; Chesnut, 1991, 1994; Aitken and Flint, 1994; Beuthin, 1997; Bodek, 2006) has confirmed the presence of an unconformity dividing the Lower and Upper Carboniferous (between the Mississippian and Pennsylvanian systems). Unequivocal evidence for the existence of the unconformity was provided by Rice and Schwietering (1988) in the form of paleokarst features and incised paleochannels throughout the region at the Missisissippian-Pennsylvanian boundary. Other evidence to support a systemic unconformity is stratal onlap towards the northwest. Early Pennsylvanian strata display northwesterly onlap onto a southeasterly dipping Mississippian hiatal surface (Bodek, 2006).

Determining the approximate age and extent of the mid-Carboniferous unconformity was the focus of further research (Englund, 1979; Chesnut, 1991). A widespread unconformity at the base of the quartz rich Warren Point Formation was observed to progressively truncate older Mississippian strata northwestward into the basin along the uplifted Cincinnati arch. In southwestern Virginia near the Kentucky border, Englund (1979) noted near-complete removal of the upper Mississippian Bluestone Formation where the Warren Point disconformably rests on the basal Pride

Shale member of the Bluestone Formation. In eastern Kentucky, the unconformity truncates progressively older Mississippian units until it overlies early Mississippian carbonate strata. In the deeper southeastern portion of the basin, the unconformity is located above the early Pennsylvanian Pocahontas Formation, requiring the unconformity to be early Pennsylvanian in age (Chesnut, 1991). Englund (1979) noted a conformable contact between the early Pennsylvanian Pocahontas Formation and the late Mississippian Bluestone Formation in West Virginia where the basin is deepest. There the two formations intertongue with one another.

2.7 *Sequence stratigraphy of coal-bearing rocks*

Sequence stratigraphy is a dynamic tool in predicting the occurrence and geometry of sedimentary strata (Shanley and McCabe, 1994). Van Wagoner et al. (1988) define sequence stratigraphy as "The study of rock relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition, or their correlative conformities". Recognition of such bounding surfaces within continental strata has proved difficult; therefore, correlations have been made where fluvial strata and coeval marine strata are in close proximity (Shanley and McCabe, 1994).

Popularization of sequence-stratigraphic concepts for marine strata over the past two decades has given rise to interpretation of terrestrial coal-bearing strata within a sequence-stratigraphic framework. Application of sequence-stratigraphic concepts to coal-bearing strata has been enhanced by the fact that near marine, coastal plain, environments are required for coal formation (Aitken and Flint, 1994; Greb and Chesnut, 1996; Bohacs and Suter, 1997; Gibling et al., 2004). Bohacs and Suter (1997) developed a model relating relative sea level and peat production rate to coal thickness and lateral continuity. This model displays thin and discontinuous coals occurring during periods of relative sea level fall and when relative sea level reaches its peak. This is due to incision and erosion during sea level fall and the drowning of the mire by clastics when relative sea level has risen to it's peak (Bohacs and Suter, 1997). Thick isolated and thick, laterally continuous coals occur at or near the inflection point in the relative sea level curve. Using this model, it is possible to relate coal thickness and extent to position within a sea level cycle. It has been noted in many foreland basins that thick extensive coals are located within the late transgressive systems tract where stacking patterns are slighty retrogradational to aggradational (Cross, 1988; Bohacs and Suter, 1997; Gibling et al., 2004; Bodek, 2006).

2.7.1 <u>Pennsylvanian sequence stratigraphy</u>

It has long been recognized that the coal-bearing strata of the Pennsylvanian appear in cyclic packages, termed "cyclothems" (Wanless and Shepard; 1936). Workers have used the term cyclothem to characterize packages of rock in either a depositional (Aitken and Flint, 1994; Heckel et al., 1998) or genetic context (Galloway, 1989; Chesnut, 1994).

The genetic classification assigns packages of rocks from one major coal seam to the next – referred to as a "coal-clastic" cycle. Chesnut (1994) starts the package at the top of a major coal seam which is overlain by an upward-coarsening succession of mudstone, mixed mudstone/sandstone, and sandstone followed by a widespread disconformity. An upward-fining succession, capped by another major coal seam, is placed atop the disconformity – ending the genetic cyclothem. When describing a cyclothem in a depositional context, workers begin the sequence with the widespread disconformity (Aitken and Flint, 1994; Hampson et al., 1997; Heckel et al., 1998). This disconformity is typically marked by an erosionally based, valley or channel-fill sandstone or interfluve paleosol (Chesnut, 1994). Using the depositional classification, cyclothems are now considered to be bounded by sequence boundaries.

Despite the seeming appropriateness of depositional classification, Chesnut (1994) used the coal-clastic approach to subdivide the Breathitt Group into eight formations of approximate equal thickness and duration. Seven widespread marine zones identified by previous Appalachian basin mapping efforts were used as marker beds. Chesnut (1994) suggested that these marine zones represent maximum flooding surfaces marking the peak of major transgressive cycles during the deposition of the Breathitt Group. The duration of these transgressive cycles was determined to be approximately 2.5 m.y. (Chesnut, 1994). Within each major transgressive cycle, Chesnut (1994) identified either five or six coal-clastic cycles. Based on a 2.5 m.y. duration for each transgressive cycle, coal-clastic cycles were estimated to approximate 400 k.y. in duration (Greb et al., 2004). The major transgressive cycles were related to post-tectonic marine incursions followed by foreland basin subsidence after the Alleghanian orogeny (Quinlan and Beaumont, 1984; Chesnut, 1994). Long-term Milankovitch orbital eccentricity cycles (Read, 1995) have been inferred as the driving mechanism for the 400 k.y. duration coal-clastic cycles (Chesnut, 1994).

Within the lower and middle Pennsylvanian of the central Appalachian basin, two hierarchical depositional sequences have been identified (Aitken and Flint, 1994; Korus, 2002; Bodek, 2006; Korus et al., 2008). In the early Pennsylvanian strata, Bodek (2006) identified both major and minor sequence boundaries. Major sequence boundaries were those unconformities lying stratigraphically beneath 3rd-order maximum flooding surfaces, while minor sequence boundaries were unconformities positioned stratigraphically beneath minor flooding zones. Bodek (2006) identified a total of 18 minor sequence boundaries within the lower Pennsylvanian of the central Appalachian basin. Taking the estimated 7.5 m.y. duration for the early Pennsylvanian (Chesnut, 1994; Davydov et al., 2004), minor sequence boundaries were estimated to have developed every 400 k.y. (Bodek, 2006). Minor sequences developed between these boundaries and correspond to 4th-order orbital eccentricity cycles (Plint et al., 1992; Read, 1995), whereas 3rd-order composite sequences are comprised of stacked 4th-order sequences. Aitken and Flint (1994) identify 4th-order lowstand, transgressive, and highstand sequence sets based on amount of incision, stacking patterns of basal valley-fill sandstones, and amount of fine-grained facies within a sequence.

Both tectonic and eustatic mechanisms are inferred to produce 3rd-order composite sequences. Such 3rd-order sequences maybe be due to orbital eccentricity with a ~2.5 m.y. periodicity (Matthews and Frohlich, 2002). Bodek (2006) suggested that 3rd-order composite sequences represent these lower-frequency orbital eccentricity cycle as opposed to being tectonically induced.

3 METHODOLOGY

This study focuses on a coal-bed methane reservoir (Nora Field) located on the border of Wise and Dickenson counties in southwestern Virginia (Fig. 4). Nora Field is situated in an ideal location for investigating the stratigraphic relationships between quartzarenites and coal-bearing strata of the Breathitt Group as well as detailed coal seam mapping. Wise and Dickenson counties rest directly atop the southeastern margin of the central Appalachian Basin which has been a recent target for both conventional gas and coal-bed methane production for the last 50 years. Nora field has specifically been the target for coal-bed methane production and has over 250 wells recently drilled, with data in digital format, the majority of which were used in this study.

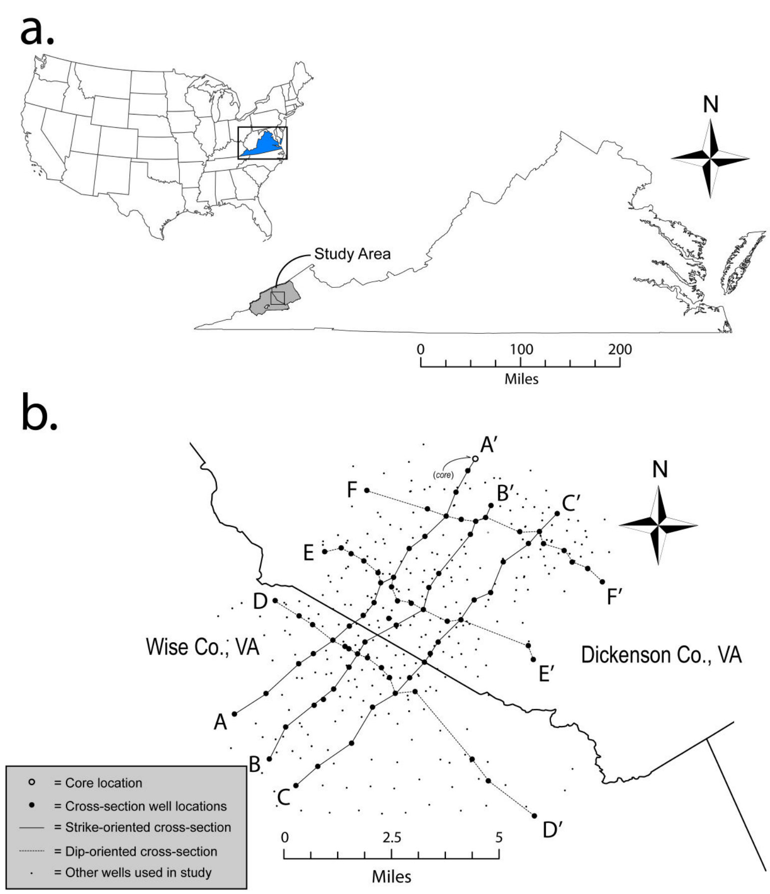


Figure 4: Locality Map. a) Maps showing the location of Virginia and the locations of both Dickenson and Wise Counties, Virginia. b) Map of the Dickenson/Wise County border, indicating the spatial location of well data points to construct strike-oriented cross-sections (A-A′, B-B′, and C-C′) and dip-oriented cross-sections (D-D′, E-E′, and F-F′).

3.1 *Continuous core description*

Complementing the wireline well log data used in this study is a 2,300 ft deep continuous CBM core that spans most of the Lower Pennsylvanian. This CBM core also has its accompanying gamma ray and density wireline well log data. Hereafter, this CBM core will be referred to as the “core”. The core was used to identify and record lithologic descriptions including mineralogy, grain-size, organic material, physical structures, and biogenic structures. These descriptions were aligned with the corresponding gamma ray signature (Appendix 1) and incorporated as the “cored well” in a strike-oriented cross-section (Fig. 4b). The core is instrumental in successfully identifying different facies successions in wireline logs. The core allows affirmation of gamma ray signatures for regional flooding surfaces, sharp-based sequence boundaries, and upward-coarsening and upward-fining successions which can then be translated from well to well forming a cross-section.

3.2 *Construction of cross-sections*

This study includes six cross-sections constructed in transects along and across the border of Dickenson and Wise Counties, Virginia. A total of 77 digital wells containing gamma ray and density log curves was used to construct the cross-sections, with each cross-section containing between 13 and 16 wells. Using Halliburton’s GeoGraphix XSection software, three cross-sections were oriented along structural strike of the basin (A-A’, B-B’, C-C’; Fig. 4b), whereas three cross-sections were oriented along structural dip of the basin (D-D’, E-E’, F-F’; Fig. 4b). Each cross-section was oriented such that they had common intersecting well points. The cross-sections were all hung on a common datum. In this study, the maximum marine flooding unit (Hensley Shale Member; Fig. 3) was used as the datum due to its regional extent within the early Pennsylvanian (Greb and Chesnut, 1992).

There are several drawbacks as well as benefits to studying a coal bed methane field. Nora field has largely been the target of CBM drilling over the past 20 years. Due to the relatively shallow nature of CBM wells, they do not always record the full extent of the lower Pennsylvanian section. Thus, deeper conventional wells, where available, were used to identify the contact dividing the Mississippian and Pennsylvanian systems. This is why only 18 conventional wells were used to construct the cross-sections (compared to ~ 60 CBM wells). While CBM wells are shallower, they are useful for accurate identification of coal seams and coal seam splits. CBM wells record density through the entire depth of the well, while conventional wells generally only record gamma ray at our depths of interest. So while there may be issues constraining the lower Pennsylvanian stratigraphy, this study has a strong handle on the extent of coal seams.

4 **DESCRIPTIONS**

4.1 *Facies and subsurface gamma ray responses*

Facies are described based on mineralogy, grain-size, organic material, sedimentary structures and biogenic structures from the continuous core in the study area. Facies descriptions are related to their corresponding gamma ray log to identify gamma ray response trends for both facies and vertical facies transitions (Fig. 5; 6). Figures 5 and 6 illustrate log and core descriptions for representative intervals of the core. Nine facies are identified within the core and can be subdivided into five distinct groups: conglomerates, sandstones, heterolithic strata, mudstone, black shale and coal.

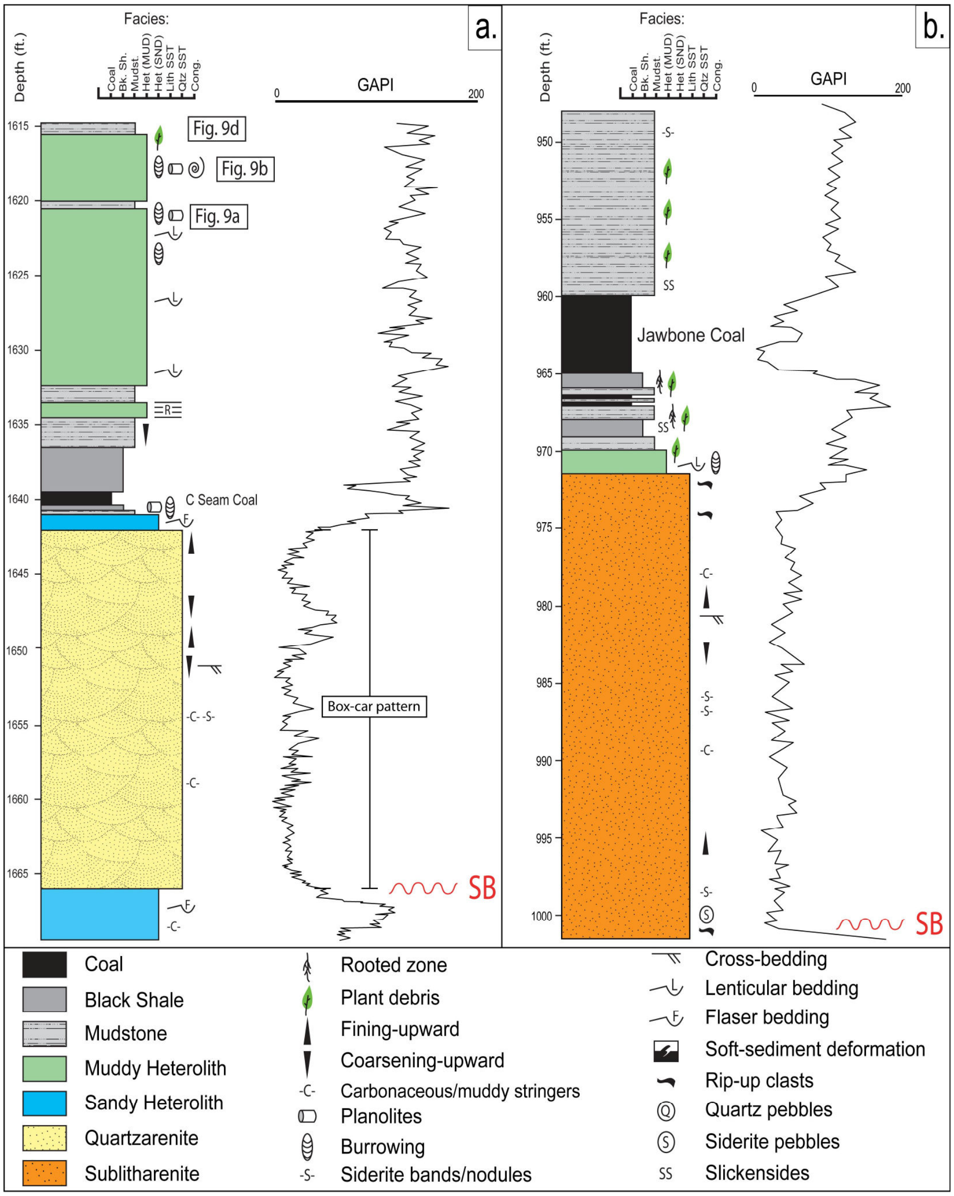


Figure 5: Representative log intervals from core descriptions including facies, sedimentary structures, and gamma ray curve. a) Quartzarenite-based log interval. This interval displays the vertical transition from sandstone to mudstone, developed as an upward-fining trend from quartzarenite through heterolithic facies, coal, and black shale. b) Sublitharenite-based log interval. This interval displays the vertical transition from sandstone to mudstone, developed as an upward-fining trend from sublitharenite through heterolithic facies, coal, and black shale.

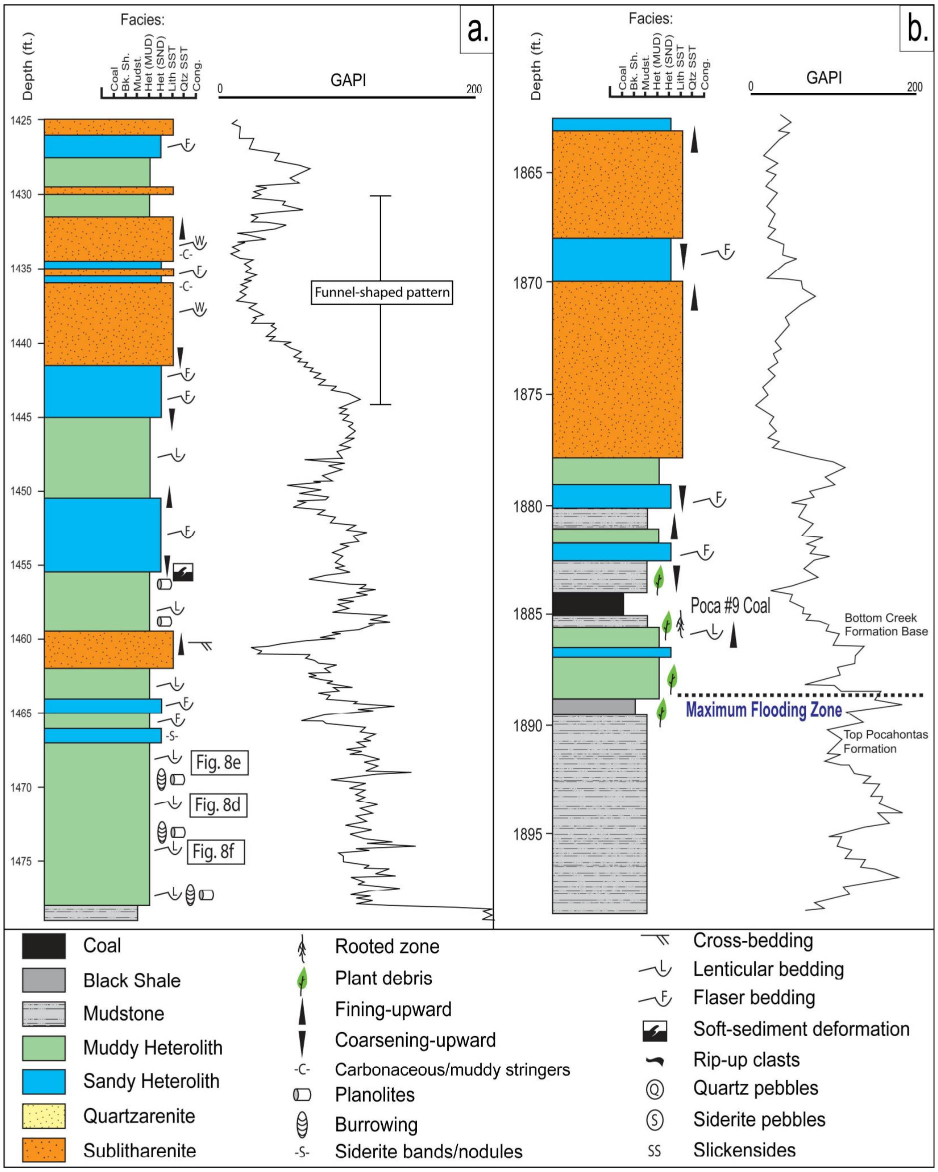


Figure 6: Representative log intervals from core descriptions including facies, sedimentary structures, and gamma ray curve. a) This interval displays the vertical transition from mudstone to sandstone, developed as an upward-coarsening trend from mudstone through muddy heterolithics, sandy heterolithics, and the sublitharenite cap. Note the thin upward-coarsening and upward-fining intervals within the overall upward-coarsening package. b) This interval displays the vertical transition from mudstone to sandstone, developed as an upward-coarsening trend from mudstone through black shale, coal, muddy heterolithics, sandy heterolithics, and the sublitharenite cap.

4.1.1 Conglomerate facies

Both quartz-pebble conglomerates and siderite-pebble conglomerates are observed in the core. Conglomeritic units make up a very minor percentage of the facies observed in core.

4.1.1.1 **Quartz-pebble conglomerate**

Quartz-pebble conglomerates are light-gray and occur in thin (1-4 ft), sharp-based beds. Vein quartz is the dominant pebble lithology (Fig. 7a). Quartz-pebble conglomerates are framework-supported within a quartzose, medium-grained sand to granule matrix. Pebbles range from 0.25 – 0.5 inches in diameter, are sub-rounded to rounded and are typically elongate. Rare heavy minerals within the matrix define distinctive horizons. Sedimentary and biogenic structures are generally lacking, making the facies massive. While quartz-pebble conglomerates are sharp-based, they generally grade into overlying lithologies. These conglomerates are typically found underlying quartzarenite units. Due to the relatively thin nature of these conglomerate beds, identifying a distinct gamma ray motif is difficult. Where the units are thicker (3-4 ft) these conglomerates display distinctive low gamma values similar to the overlying strata.

4.1.1.2 **Siderite-pebble conglomerate**

Siderite-pebble conglomerates are sharp-based and occur as thin (~1 ft) beds at the base of sublitharenite units. Pebbles are light-brown to brown-orange in color and occur within a medium-gray sublitharenite matrix (Fig. 7b). Siderite pebbles are sub-angular to sub-rounded and 0.25 – 0.5 inches in diameter and often elongate. Siderite-pebble conglomerates are structureless and massive and never thick enough to display a distinctive gamma ray response. In general, gamma ray values for siderite-pebble conglomerates are identical to that of bounding lithologies.

4.1.2 <u>Sandstone facies</u>

Sandstone bodies comprise a significant percentage of the overall facies displayed throughout the core. Two distinct standstone facies are identified in core. They are very clean quartzarenite units and sublitharenite units with smaller percentages of quartz.

4.1.2.1 **Quartzarenite**

The lower Pennsylvanian quartz-rich sandstones in core are diagnostic of the regionally mapped Warren Point, Sewanee and Bee Rock formations. Petrographic studies of the correlative Upper Raleigh Sandstone Member of the New River Formation in southern West Virginia allow for comparison with the Sewanee formation in the study area (Reed, 2003; Reed et. al., 2005). Based on the Dott (1964) sandstone classification, the Upper Raleigh Sandstone Member is a quartzarenite consisting of 96% quartz, 3% lithics, and 1% feldspar (average of 21 samples). The 96% quartz consists almost entirely (>95%) of monocrystalline quartz (Reed et al., 2005).

Quarzarenites are white to light-gray in color (Fig. 7c) and occur as relatively thick (25 – 85 ft) intervals that are typically cross-bedded in core and contain quartz pebble horizons throughout. Quartzarenites have distinctive sharp basal contacts and typically contain abundant carbonaceous stringers and mudstone/coal rip-up clasts for several feet directly above the basal contact (Fig. 7d). Quartzarenites are characterized by a distinctively low gamma ray “drop”, producing a well-defined sharp based “box-car” appearance (Fig. 5a; Walker, 1992). Quartzarenites in core generally display a decrease in mineralogical immaturity upwards. This is referred to as “dirtying” or “muddying” upward and is characterized by a gradual increase in gamma ray values (Fig.

5). This gamma ray response is also considered to represent an upward-fining succession. In the upper segments of these quartzarenites, interbedding of quartzarenites with heterolithic and mudstone facies is not uncommon.

4.1.2.2 **Sublitharenite**

The lower Pennsylvanian Breathitt Group is comprised of the Pocahontas, Bottom Creek, and Alvy Creek formations. These formations contain an abundance of lithic sandstone bodies along with other coal-bearing units. Petrographic studies of laterally equivalent sand bodies in Buchanan County, Virginia allow for a framework grain composition comparison with the lithic sandstone bodies of the study area in both Dickenson and Wise Counties, Virginia (Reed, 2003; Reed et al., 2005). The study focused on the Council Sandstone which rests stratigraphically below the Jawbone Coal and the second sublitharenite may represent the McClure Sandstone which is typically stratigraphically above the Aily Coal. Using the Dott (1964) sandstone classification, the two lithic sandstones sampled are sublitharenites consisting of 77% quartz, 15% lithics, and 8% feldspar (average of 13 samples) (Reed et al., 2005). Monocrystalline quartz dominates the 77% quartz while metamorphic clasts dominate the lithic fraction of the sublitharenites.

Sublitharenites are light to medium gray and typically occur as thick (25 – 70 ft) intervals of fine- to coarse-grained sandstone (Fig. 7e) which display cross-bedding in core (Fig. 7f). Similar to quartzarenite beds, sublitharenites are generally sharp-based (Fig. 8a) and contain carbonaceous stringers and mudstone/coal rip-up clasts for several feet directly above the basal contact. Sublitharenite units typically contain siderite pebble lags. Sharp-based sublitharenite intervals are up to 70 ft thick while thinner intervals are up to 20 ft thick. Thinner intervals display gradational upper and lower contacts and are isolated between finer-grained facies. Thicker sublitharenite facies display a moderately low gamma ray response with a sharp base, while the thinner sublitharenite beds display a gradational upper and lower gamma ray contact (Fig. 6). Sublitharenites, like quartzarenites, display a "dirtying" upward trend.

4.1.3 <u>Heterolithic facies</u>

The term heterolithic is used to describe strata consisting of interlaminated sandstone, siltstone, and mudstone (Walker, 1992). Both "sandy" and "muddy" heterolithic facies are described in core. Sandy heterolithic strata are comprised of greater than 50% sandstone with lesser amounts of mud, while muddy heterolithic strata contain greater than 50% mudstone with lesser amounts of sand. Heterolithic facies are contained within intervals of mudstone, black shale and coal, and are interbedded within the upper parts of quartzarenite and sublitharenite bodies (Fig. 5; 6).

4.1.3.1 **Sandy Heterolithic**

Sandy heterolithic facies are characterized by light- to medium-gray fine-grained sandstone intervals with dark-gray, mudstone drapes. Sandy heterolithic facies commonly display flaser (Fig. 8b) and wavy bedding. Rhythmic bedding is observed occasionally in thin beds of sandy heterolithics (Fig. 8c). Planolites and plant debris are occasionally present in the sandy heterolithic facies. Gamma ray response to sandy heterolithic facies is moderate due to a larger sand to mud ratio.

4.1.3.2 **Muddy Heterolithic**

Muddy heterolithic facies are characterized by dark- to very dark-gray mudstone intervals with lesser amounts of light- to medium-gray, fine-grained sandstone. Muddy heterolithic facies commonly display lenticular to wavy bedding (Fig. 8d). Rhythmic bedding is observed occasionally in thin beds of muddy heterolithics, as seen in the sandy heterolithic facies. Abundant burrowing with planolites (Fig. 8e, f; Fig. 9a), bioturbation (Fig. 9b), and plant debris, is locally present in muddy heterolithic facies in core. Gamma ray response to muddy heterolithic facies is moderate to moderately-high due to a larger mud to sand ratio.

4.1.4 Mudstone facies

Mudstones are dark-gray to very dark-gray and typically occur as moderately thick (1-25 ft) intervals of laminated, very fine-grained sediment, commonly intercalated with the aforementioned heterolithic facies. They typically contain scarce to abundant plant debris, soft sediment deformation (Fig. 9c), siderite nodules or horizons, and occasional thin carbonaceous stringers. The mudstones are commonly associated with coals and, where this occurs, abundant slickensides are present. They are characterized by a uniformly high gamma ray response due to the high percentage of mud (Fig. 5; 6).

4.1.5 Black shale facies

Carbonaceous "black" shale is dark-gray to black in color and typically contains abundant plant debris along with very thin (< 5cm) coal stringers (Fig. 9d). Black shale is a few inches to nearly 2 ft thick in core and is typically closely associated with coal beds. Black shale is often rooted when overlain by a coal. Where black shale is rooted, it is termed a "seat earth" in this study. Seat earth is characterized by intense vertical and horizontal rooting, such that core samples crumble to the touch. Black shale is often too thin to record an accurate gamma ray response. Where black shale is very thin, it displays a gamma ray response similar to bounding facies. Otherwise, black shale will display an extremely high gamma ray response or "kick which are useful for correlating wells.

4.1.6 Coal facies

Southwest Virginia coal is ranked as high-volatile bituminous. According to EIA (1994), sulfur content of southwest Virginia lower and middle Pennsylvanian coals averages 1.1% sulfur with typically less than 10% ash. Comparing these data to other localities, lower Pennsylvanian coals of southwestern Virginia are amongst the highest quality coals in the Appalachians (Milici and Campbell, 1997).

The lower and middle Pennsylvanian coals of the Central Appalachian Basin are estimated to contain 3.07 Tft^3 of recoverable coal bed methane gas (Rice, 1995). The seams targeted for desorbed methane in the lower Pennsylvanian are the Pocahontas #3, Pocahontas #4, Lower Horsepen, War Creek, Beckly, Lower Seaboard, Raven, and Jawbone (Ruppert and Rice, 2000). The core logged in this study was drilled in order to determine desorbed methane content of the economic coals within a specific coal bed methane field (NORA field) in Wise and Dickenson Counties. Therefore, any coals of sufficient thickness and depth (~3 ft. thick and below 500 ft depth) were removed from the complete core for analysis.

Coal thickness was determined by amount of removed core accompanied with the bulk density log. It is common practice in industry to calculate coal thickness by measuring the portion of the bulk density curve which falls below 1 g/cm^2 threshold. This will be referred to as the "bulk density technique". Combining the bulk density technique with removed core intervals, an accurate coal thickness estimate was possible for removed coal beds. Coal beds in the core ranged in thickness from 0.5 ft to 5 ft and are located within fine-grained facies or directly beneath sharp-based sandstone bodies. Where coals are overlain by sharp-based quartzarenite or sublitharenite bodies, coal rip-up clasts are often present within the basal few feet of the overlying sandstone body. Coal beds and black shale are often interbedded with mudstone and heterolithic facies. Underlying mudstone and black shale are often seat earths and display slickenside features and abundant plant debris. Overlying mudstone and black shale always lack roots and rarely contain plant debris.

Gamma ray responses for coal beds are similar to bounding lithologies where the beds are of insufficient thickness to record a gamma ray value (<1 ft). Where coal beds are thicker, they are characterized by a very low "drop" in the gamma ray value. Often this is not enough to calculate coal thickness and can be mistaken for a quartzarenite sandstone body where no bulk density log is available. Coals in this study are best characterized by their density log signature. Generally speaking, a coal seam can be identified at the point when the density log curve spikes below 1 g/cm^2.

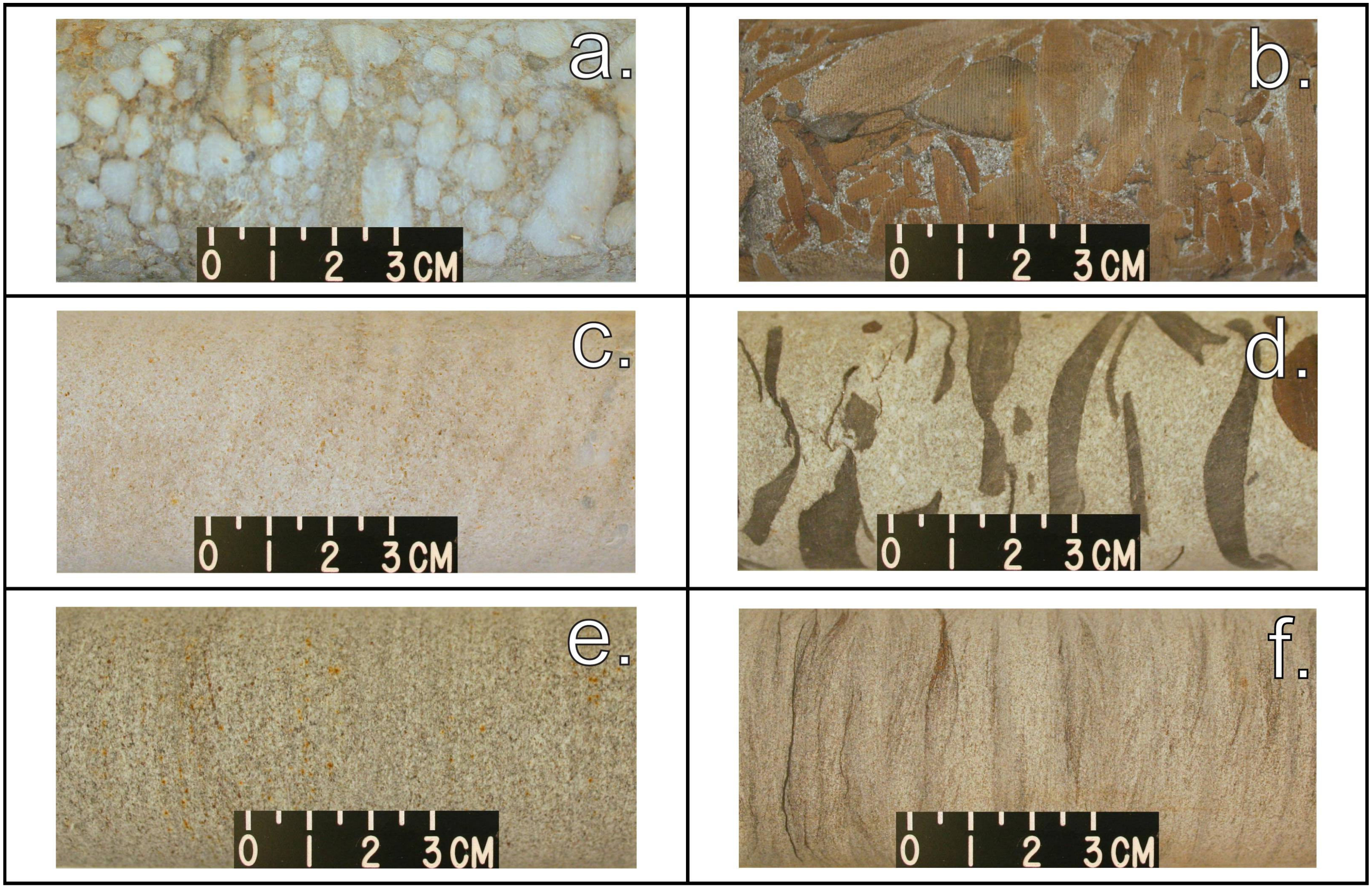


Figure 7: Core photographs of : a) Quartz-pebble conglomerate. b) Siderite-pebble conglomerate in a sublitharenite matrix. c) Quartzarenite. d) Quartzarenite containing rip-up clasts from underlying shale/mudstone. e) Sublitharenite. f) Cross-bedding in a sublitharenite. The left side of each frame is the “up” direction.

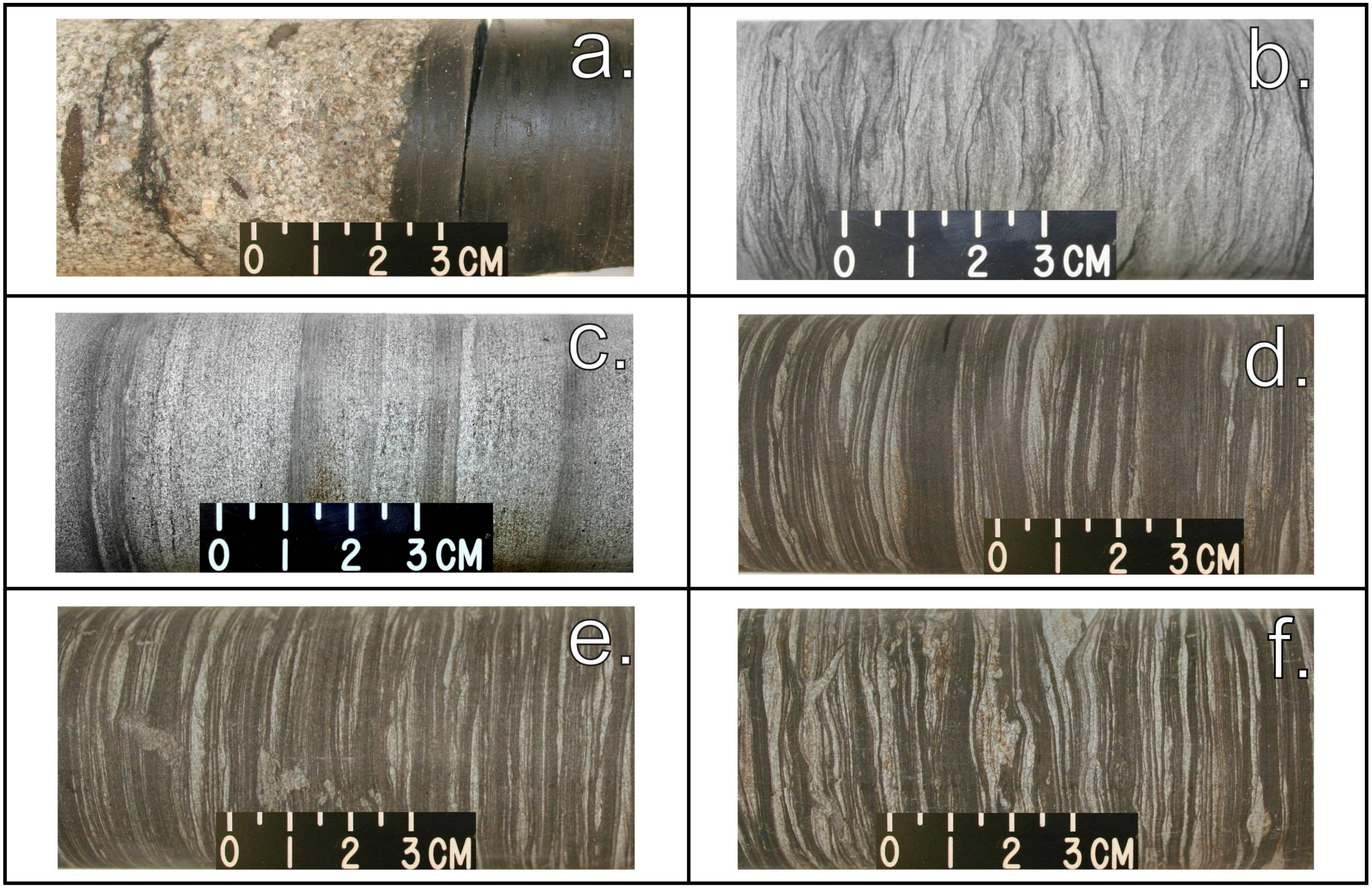


Figure 8: Core photographs of : a) Sharp contact between a sublitharenite and the underlying black shale. b) Flaser-bedded sandy heterolithic facies. c) Rythmically-bedded sandy heterolithic facies. d) Lenticular-bedded muddy heterolithic facies. e) Lenitcular-bedded muddy heterolith with abundant burrowing. f) Planolites, burrowing and bioturbation within a lenticular-bedded muddy heterolithic facies. The left side of each frame is the “up” direction.

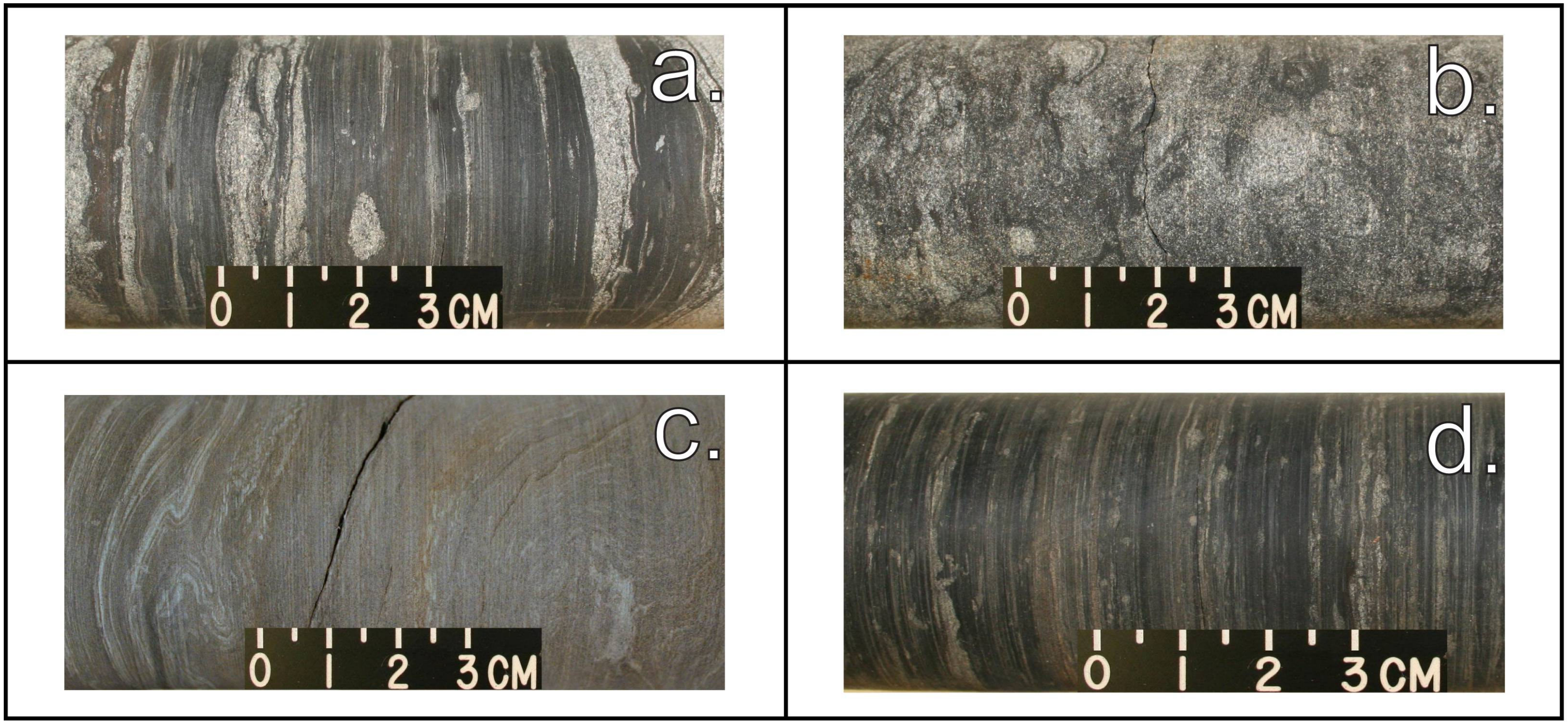


Figure 9: Core photographs of : a) Planolites within both black shale and muddy heterolithic facies. b) Intense burrowing and bioturbation. Note all bedding plane features have been destroyed. c) Soft sediment deformation in the form of ball and pillow structures within a laminated mudstone. d) Laminated black shale containing minor amounts of sand at the base. The left side of each frame is the “up” direction.

4.2 *Vertical facies transitions*

Whereas each individual facies can be characterized by a specific gamma ray signature, so too can vertical packages of facies. Gamma ray logs show abrupt "drops" and "kicks" in gamma ray values, as well as overall gamma ray value trends which increase or decrease. These gamma ray trends reflect vertical facies transitions in core and can be projected to adjacent subsurface well locations.

4.2.1 **Sandstone to mudstone transition**

Sandstone intervals in core display overall upward-fining trends; from conglomeratic facies at the base into medium- to fine-grained heterolithic facies at the top (Fig. 5a). These observations are displayed by a gradual upward increase in gamma ray values. Quartzarenite sandstones display much lower gamma ray values (Fig. 5a) than their sublitharenite counterpart (Fig. 5b), making for slight discrepancies between the two gamma ray log patterns. Quartzarenites display a much larger "drop" in the gamma ray value at the start the overall upward-finings trend. The vertical facies transition is commonly capped by a mudstone or black shale. In summary, the transition from sandstone to mudstone is characterized by sharp-based sandstone intervals that fine upward through sandy heteroliths, muddy heteroliths, mudstones and black shales. This trend is represented by a large rise in gamma ray values which steadily increase towards the top of the interval (Fig. 5). The gamma ray value trend makes a shape often referred to as "bell-shaped" (Walker, 1992).

4.2.2 **Mudstone to sandstone transition**

The mudstone to sandstone facies transition has an upward-coarsening trend in core and commonly begins with coal or black shale and is capped by sandstone or sandy heterolithic facies (Fig. 6a, b). The gamma ray pattern for this vertical facies transition is opposite that of an upward-fining facies trend and is referred to as "funnel-shaped" (Fig. 6a; Walker, 1992). Gamma ray values start high (representative of a mudstone or black shale) and decrease upwards, representing a change in facies from muddy heterolith to sandy heterolith to the eventual sandstone cap (Fig. 6a, b). Commonly, upward-coarsening facies transitions contain alternating thin upward-coarsening and upward-fining intervals (Fig. 6a, b). Similar to the overall upward-coarsening trend, thin upward-coarsening intervals grade from black shale or mudstone into heterolithic facies and/or sandstone facies of lesser thickness. Thin upward-fining intervals within the overall upward-coarsening trend display the transition from sandstone to heterolithics, mudstone, and black shale. Oftentimes, thin upward-fining intervals positioned within an overall upward-coarsening trend do not contain sandstone at their base; instead the interval begins with a sandy or muddy heterolithic facies (Fig. 6).

4.3 *Architectural elements*

Using the core to identify gamma ray signatures and patterns for individual facies and successions of facies has enabled correlation of such patterns (and lithologies) to adjacent wells in the study area. Six cross sections (Fig. 10a-f) have been constructed in this fashion in order to illustrate the architectural elements which make up the lower Pennsylvanian strata. According to Walker (1992), an architectural element is "a morphological subdivision of a particular depositional system characterized by a distinctive assemblage of facies, facies geometries, and depositional processes". The following section will describe the architectural elements within the study area while the succeeding section will interpret their depositional processes and environment.

4.3.1 **Sheet-like sandstone elements**

Sheet-like sandstone elements are defined by quartzarenite and less commonly sublitharenite sandstone bodies and are present throughout the entire study area. In cross-section, these sandstone bodies appear tabular and typically range in thickness from 30 – 140 ft (Fig. 10a-f). Tabular sandstone bodies are sharp-based and commonly overly fine-grained facies and/or coal. Quartz-pebble conglomerates define the base of sheet-like quartzarenite sandstone elements whereas siderite-pebble conglomerates define the base of sheet-like sublitharenite sandstone elements. Both quartzarenite and sublitharenite sandstone bodies contain abundant rip-up clasts overlying the conglomeratic facies. Sheet-like sandstone elements display an upward-fining grain-size trend and grade into the overlying heterolothic facies.

4.3.2 **Lenticular sandstone elements**

Lenticular sandstone elements are present throughout the entire study area, although in lesser amounts to the southeast, and are defined by both quartzarenite and sublitharenite sandstone bodies. In cross-sections, they appear as 15 – 150 ft sandstone lenses that occasionally pinch out laterally. Where lenticular sandstone elements pinch out laterally, they are replaced by an upward-coarsening facies succession and commonly a coal (Fig. 10a-f). Lenticular sandstone elements are sharp-based and generally overlie fine-grained facies. Similar to sheet-like sandstone elements, lenticular sandstone elements also grade upwards into heterolithic facies. Lenticular quartzarenite and sublitharenite sandstone bodies are defined by a basal conglomerate with coal and/or shale rip-up clasts. Basal sublitharenite conglomerates are typically characterized by siderite pebbles, while the basal quartzarenite conglomerates are characterized by vein-quartz pebbles or rip-up mudstone clasts.

4.3.3 **Upward-fining elements**

Upward-fining elements are defined by a steady increase in gamma ray values directly above both sheet and lenticular sandstone elements (Fig. 10a-f). This increase in gamma ray values represents the gradational change in facies from sandy and muddy heterolithic strata to mudstone and black shale, respectively. Upward-fining elements range from 10 – 70 ft thick. Upward-fining elements are commonly capped by coal, and the overall upward-fining succession is typically overlain by an upward-coarsening succession. In instances where lenticular sandstone elements are absent, an upward-fining succession may directly overlie an upward-coarsening succession (Fig. 10b).

4.3.4 **Mudstone-dominated elements**

Mudstone-dominated architectural elements are tabular in cross-section and typically overlie upward-fining elements (Fig. 10a-f). These elements range in thickness from 5 – 25 ft and consist of either all mudstone or alternating intervals of mudstone and muddy heterolithic facies. Mudstone-dominated elements typically overlie a coal and are capped by coarser-grained sandy heterolithic facies.

4.3.5 **Upward-coarsening elements**

Upward-coarsening architectural elements in cross-section consist of coal, overlain by black shale, mudstone, heterolithic facies, and thin sublitharenite sandstone bodies (Fig. 10a-f). Upward-coarsening successions typically overlie upward-fining successions and vary in thickness, ranging from 15 to over 200 feet. Minor variations in thickness are visible along both depositional strike and dip cross-sections. In dip-oriented cross-sections, upward-coarsening elements show an overall decrease in thickness towards the southeast (Fig. 10d-f). Upward-coarsening elements are comprised of broadly upward-coarsening facies successions, which contain thin intervals of coarsening- to upward-fining successions. Laterally extensive coals cap the minor upward-fining intervals within the upward-coarsening elements. Adjacent coarse-grained sublitharenite facies pinch out laterally into the thin facies successions (Fig. 10a-f), leaving discernable facies patterns within the broadly upward-coarsening successions. Upward-coarsening architectural elements are sharply truncated by overlying sheet or lenticular sandstone elements. Where upward-coarsening elements are completely absent, sheet and lenticular sandstone elements truncate underlying upward-fining elements (Fig. 10a).

4.4 *Bounding discontinuities*

Architectural elements identified in cross-sections (Fig. 10a-f) are bounded by regionally extensive discontinuities. These discontinuities are both erosional (unconformable) and depositional (condensed) (Walker, 1992). Both major and minor erosional discontinuities can be observed throughout both strike and dip oriented cross-sections (Fig. 10a-f). Both major and minor discontinuities have been identified in similar strata in the central Appalachian basin (Aitken and Flint, 1994; 1995; Korus, 2002; Korus et al., 2008).

Major discontinuities are characterized by relatively thin intervals of fine-grained facies beneath the erosional contact whereas minor discontinuities have significantly thicker intervals of fine-grained facies beneath the erosional contact. In many instances, all underlying fine-grained facies are removed beneath major discontinuities, such that sheet-like sandstone elements are amalgamated (Bodek, 2006). Major discontinuities occur at the base of sheet-like sandstone elements, such as the uppermost tongues of the Warren Point and Sewanee Formations (Fig. 10a-f).

Minor discontinuities commonly define the basal contact of lenticular sublitharenite sandstone bodies and occasionally lenticular quartzarenite sandstone bodies (Fig. 10a-f). Where lenticular sandstone elements pinch out laterally into upward-coarsening successions, the minor discontinuity is placed at the top of the upward-coarsening succession which generally corresponds to the base of a regionally extensive coal (Aitken and Flint, 1995).

Along with erosional discontinuities, both major and minor "marine zones" have been identified in cross-section (Fig. 10a-f). In the study area, two major marine zones have been identified and can be correlated with the basal two marine zones in the Breathitt Group (Chesnut, 1994). These major marine zones are the Hensley and Dark Ridge members and are at the base of the Alvy Creek and Bottom Creek formations, respectively (Figs. 3 and 10).

Major marine zones can be identified in cross-section based on their stratigraphic position. The Hensley Member overlies the uppermost tongue of the Sewanee Formation and the Dark Ridge Member overlies the uppermost tongue of the Warren Point Formation (Fig. 3 and 10c-f). Both major marine zones occur as thick (20 – 85 ft) intervals of coal, black shale, mudstone, and minor amounts of heterolithic strata containing abundant plant debris and Planolites (Appendix 1). The Pocahontas # 8, 9 and the X Seam coal beds are closely associated with the Dark Ridge Member while the Upper Seaboard and Upper Seaboard A coal beds are closely associated with the Hensley Member (Fig. 10a-f).

Minor marine zones have been identified in cross-section at the top of upward-fining elements which overlie minor discontinuities (lenticular sandstone elements). Throughout most of the study area, marine zones in minor sequences are thin fine-grained units, although some are thicker than those in major sequences. The thickest coal seams in the core (Pocahontas #1, Lower Horsepen, Beckley and Jawbone) are closey associated with minor marine zones.

5 **INTERPRETATIONS –** Architectural elements

5.1 *Sheet-like sandstone elements*

Sheet-like quartzarenite sandstone elements, defined by the uppermost tongues of both the Warren Point and Sewanee Formations of the Breathitt Group (Fig. 10a-f), have been interpreted as both marine (Ferm and Cavaroc, 1969; Ferm, 1974; Horne et al., 1974; Miller, 1974; Englund, 1979; Englund et al., 1986; Englund and Thomas, 1990) and fluvial origin (Rice, 1984; 1985; Rice and Schwietering, 1988; Wizevich, 1992; Archer and Greb, 1995; Greb and Chesnut, 1996; Korus, 2002; Bodek, 2006; Korus et al., 2008). The provenance of these sheet-like quartzarenites is debated. Workers advocating the marine depositional model propose that sediment was derived from low-grade metamorphics to the southeast and reworked in a nearshore environment to produce compositionally and texturally mature arenites. Those workers suggesting a fluvial depositional environment suggest that sheet-like quartzarenites were sourced from the northeast and deposited within bedload-dominated braided rivers.

Recent work has identified major quartzarenite bodies as northeast-southwest trending incised valley fill deposits (Rice and Schwietering, 1988; Beuthin, 1994; Archer and Greb, 1995; Bodek, 2006), which is consistent with a fluvial depositional model. Data from this study within Wise and Dickenson Counties, Virginia is consistent with that of Bodek (2006) and confirms the interpretation that sheet-like sandstone elements were deposited within broad, low-sinuosity, bed-load dominated braided rivers. These braided rivers flowed towards the southwest along the axis of the Alleghanian foreland basin, bounded to the west by the Cincinnati Arch (Rice and Schwietering, 1988).

Equivalent sandstones in Kentucky and Virginia may be due to down-dip accretion of individual bedforms, macroforms, and channel fill during high stages of flow (Bement, 1976; Wizevich, 1992). The coarse-grained conglomerates and rip-up clasts at the base of quartzarenite sandbodies are "lag deposits" (cf. Miall, 1985). Therefore, sheet-like quartzarenite sandstone architectural elements are interpreted as major incised valley fill deposits.

Sheet-like sublitharenite sandstone elements consist mainly of grains of quartz with lesser grains of mica schist (Reed, 2003; Reed et al., 2005), and were derived from the low-grade metamorphic terrain of the Alleghanian orogen to the southeast (Bodek, 2006). Sheet-like sublitharenites were deposited in bedload-dominated, low-sinuosity channels of a transverse drainage system (Korus, 2002). Many sublitharenite sandstone elements in figure 10 are displayed as tabular units due to the southeastern position of the cross-sections. These cross-sections lie closer the southeastern Alleghanian orogen than those of Bodek (2006), and thus are closer to the mouths of this tributary system. Sheet-like sublitharenite elements are interpreted as minor incised valley fill deposits.

5.2 *Lenticular sandstone elements*

Lenticular sandstone elements occur as both quartzarenites (Fig.10a- f) and sublitharenites (Fig.10a-f). Lenticular sublitharenite sandbodies consist mainly of quartz with lesser amounts of mica schist grains (Reed, 2003; Reed et al., 2005). The mica schist constituent of sublitharenite sandbodies indicates a metamorphic provenance.

Lenticular sublitharenites were derived from the low-grade metamorphic terrain of the Alleghanian orogen to the southeast (Bodek, 2006). Korus (2002) suggests that these sandstones were deposited within bedload-dominated, low-sinuosity, northwest flowing channels of a transverse drainage system fed by the Alleghanian orogen to the southeast. Erosional boundaries at the base of both sublitharenite and quartzarenite sandbodies are indicative of merging transverse draining rivers (Fig. 10a- f; Korus, 2002). Lenticular sandstone elements are interpreted as minor incised valley fill deposits.

5.3 *Upward-fining elements*

Upward-fining architectural elements cap both quartzarenite and sublitharenite sandstone bodies. Sandstone bodies displaying an overall upward-fining trend are indicative of waning flow conditions which, in turn, can be attributed to a decrease in stream/river gradient associated with a base level rise (Posamentier et al., 1998). As base level continued to rise, incised valleys were flooded, forming estuaries. Such estuaries are tidally influenced and characterized by sandy and muddy heterolithic strata (Fig. 7b-d, f; Fig. 8) and rhythmically bedded sand and silt (Greb and Martino, 2005). Coal beds at the tops of upward-fining successions (Fig.10a-f) are thick and laterally extensive, indicative of widespread peat accumulation during the final stages of estuarine infill. Coal beds are not unique to upward-fining successions above incised valleys, but also occur within adjacent interfluve areas (Fig. 10a-f). This suggests that base level rose sufficiently enough to back-flood both incised valleys and interfluves (cf. Shanley and McCabe, 1994).

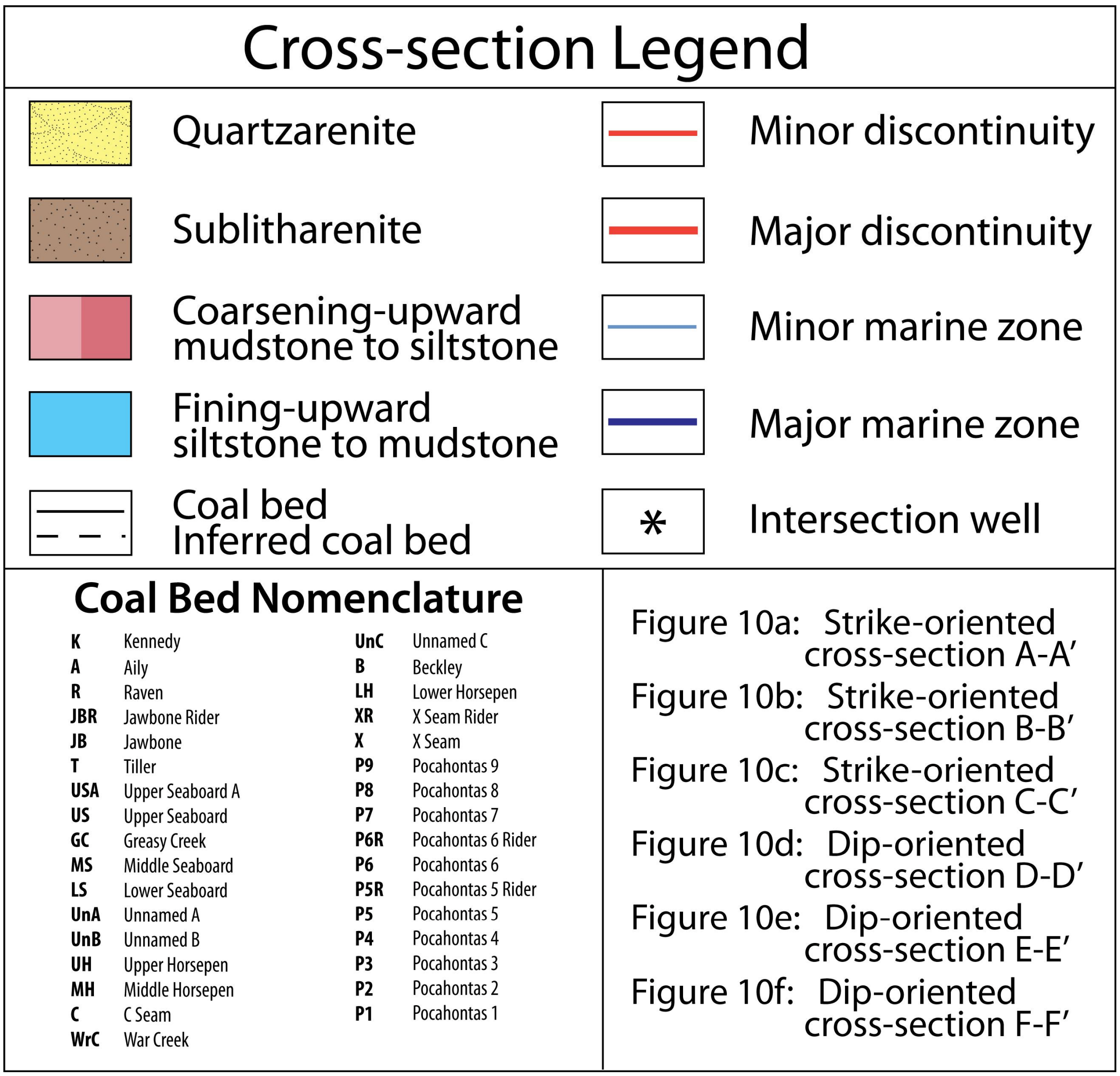
5.4 *Mudstone-dominated elements*

The mudstone and black shale-dominated elements directly overlying the upward-fining successions record continued base level rise and drowning of the peat mire by clastics (c.f. Shanley and McCabe, 1994; Gibling et al., 2004). Overall upward-fining architectural elements are often comprised of several mudstone-dominated elements.

This suggests periods of minor base level fluctuations and “peat mire drowning” events. After each minor drowning event, peat mires are given time to re-establish until the overall base level rise has reached a maximum.

5.5 *Upward-coarsening elements*

Upward-coarsening elements are interpreted as prograding bayhead delta deposits that accumulated during late stages of base level rise through early base level fall (Korus, 2002; Greb and Martino, 2005; Bodek, 2006). Overall upward-coarsening successions are comprised of repetitively stacked coarsening- to fining-upward intervals of strata. Similar stacked intervals have been attributed to channel avulsion, delta-lobe switching, and growth faulting (Bhattacharya and Walker, 1992). The laterally restricted sublitharenite sandstone bodies (Fig. 10a-f) that cap many upward-coarsening packages are analogous to distal-bar, mouth-bar, channel and/or beach deposits (Coleman and Wright, 1975; Bhattacharya and Walker, 1992; Reading and Collinson, 1996; O’Mara and Turner, 1999). The upward-fining intervals that are typically capped by coals represent overbank and crevasse-splay deposition followed by peat mire development on top of abandoned delta lobes (cf. Coleman, 1976). Peat mires are established on abandoned delta lobes due to localized transgressions driven by dewatering and compaction induced subsidence (Coleman, 1976; Bhattacharya and Walker, 1992). A modern example is the Mississippi River and the St. Bernard delta lobe. Localized transgression is currently occurring where delta lobe abandonment and subsidence has occurred (Bhattacharya and Walker, 1992; Demko and Gastaldo, 1996). Continued channel avulsion and delta lobe switching created the stacked pattern of upward-coarsening and upward-fining intervals within the overall upward-coarsening succession due to further subsidence and transgression (Bodek, 2006).



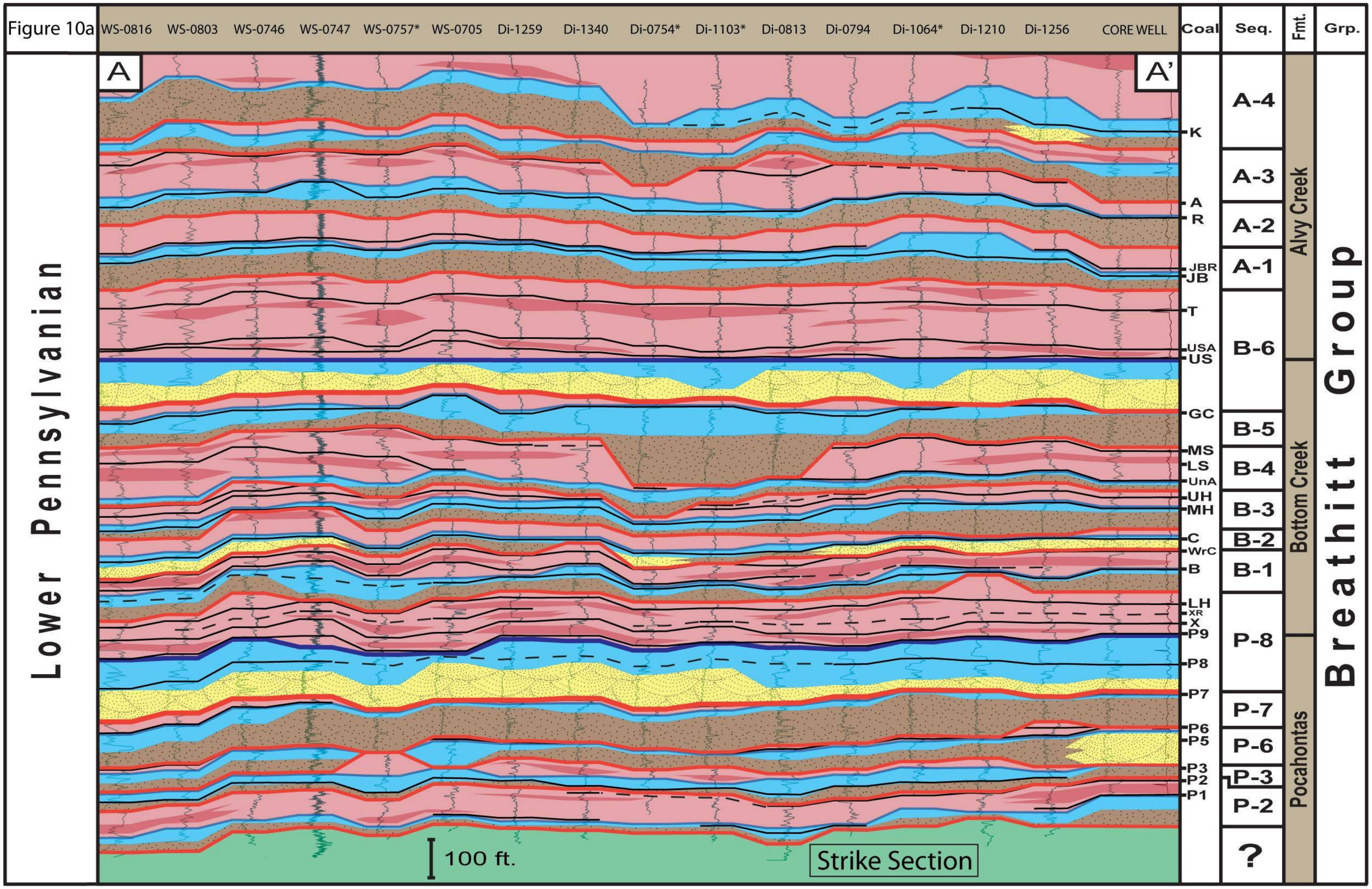


Figure 10a: Strike-oriented (SW-NE) cross-section A-A' incorporating the core well (for location see figure 4). Displayed are minor discontinuities (thin red lines), major discontinuities (thick red lines), minor marine zones (light blue lines) and major marine zones (dark blue lines). Sequences are bound by minor and major discontinuities. A complete sequence contains either quartzarenite (yellow) or sublitharenite (brown), followed by light blue fining-upward siltstone to mudstone and then red coarsening-upward mudstone to siltstone. This cross-section displays 15 sequences. Note extensive quartzarenite units at the base of major discontinuites and the major IVF within sequence B-5.

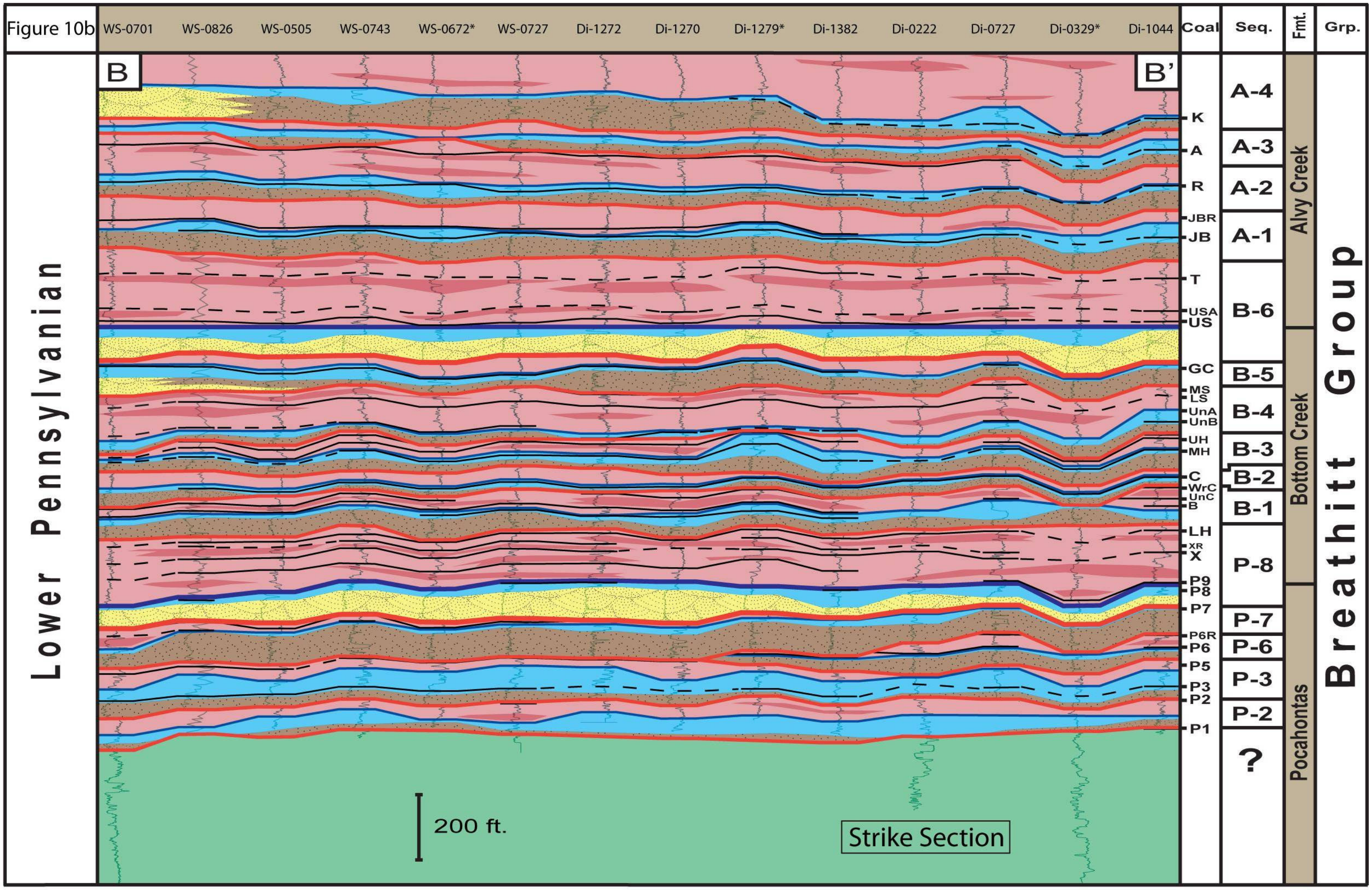


Figure 10b: Strike-oriented (SW-NE) cross-section B-B’ (for location see figure 4). Displayed are minor discontinuities (thin red lines), major discontinuities (thick red lines), minor marine zones (light blue lines) and major marine zones (dark blue lines). Sequences are bound by minor and major discontinuities. A complete sequence contains either quartzarenite (yellow) or sublitharenite (brown), followed by light blue fining-upward siltstone to mudstone and then red coarsening-upward mudstone to siltstone. This cross-section displays 15 sequences. Note extensive quartzarenite units at the base of major discontinuites.

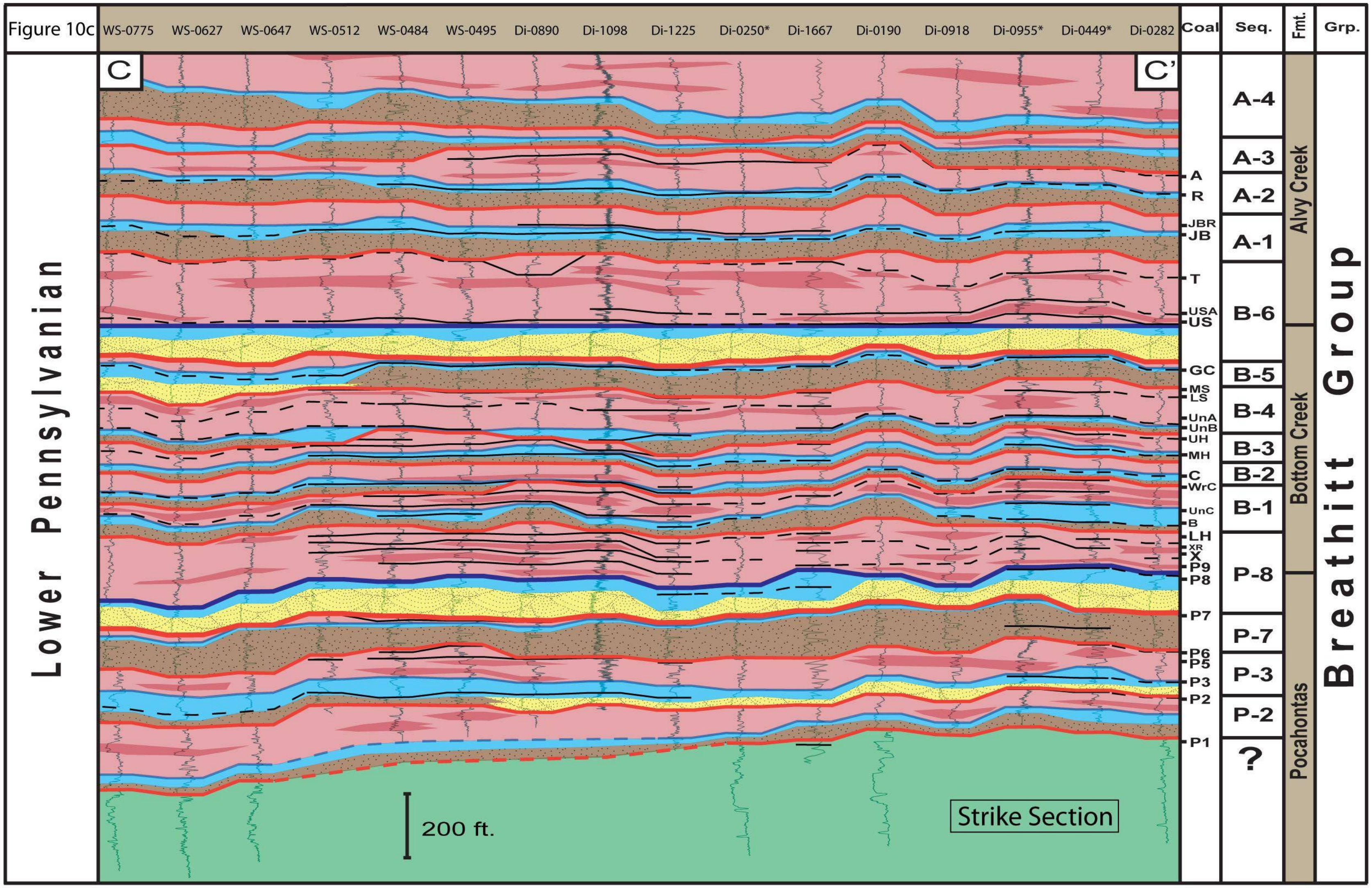


Figure 10c: Strike-oriented (SW-NE) cross-section C-C' (for location see figure 4). Displayed are minor discontinuities (thin red lines), major discontinuities (thick red lines), minor marine zones (light blue lines) and major marine zones (dark blue lines). Sequences are bound by minor and major discontinuities. A complete sequence contains either quartzarenite (yellow) or sublitharenite (brown), followed by light blue fining-upward siltstone to mudstone and then red coarsening-upward mudstone to siltstone. This cross-section displays 14 sequences. Note extensive quartzarenite units at the base of major discontinuites.

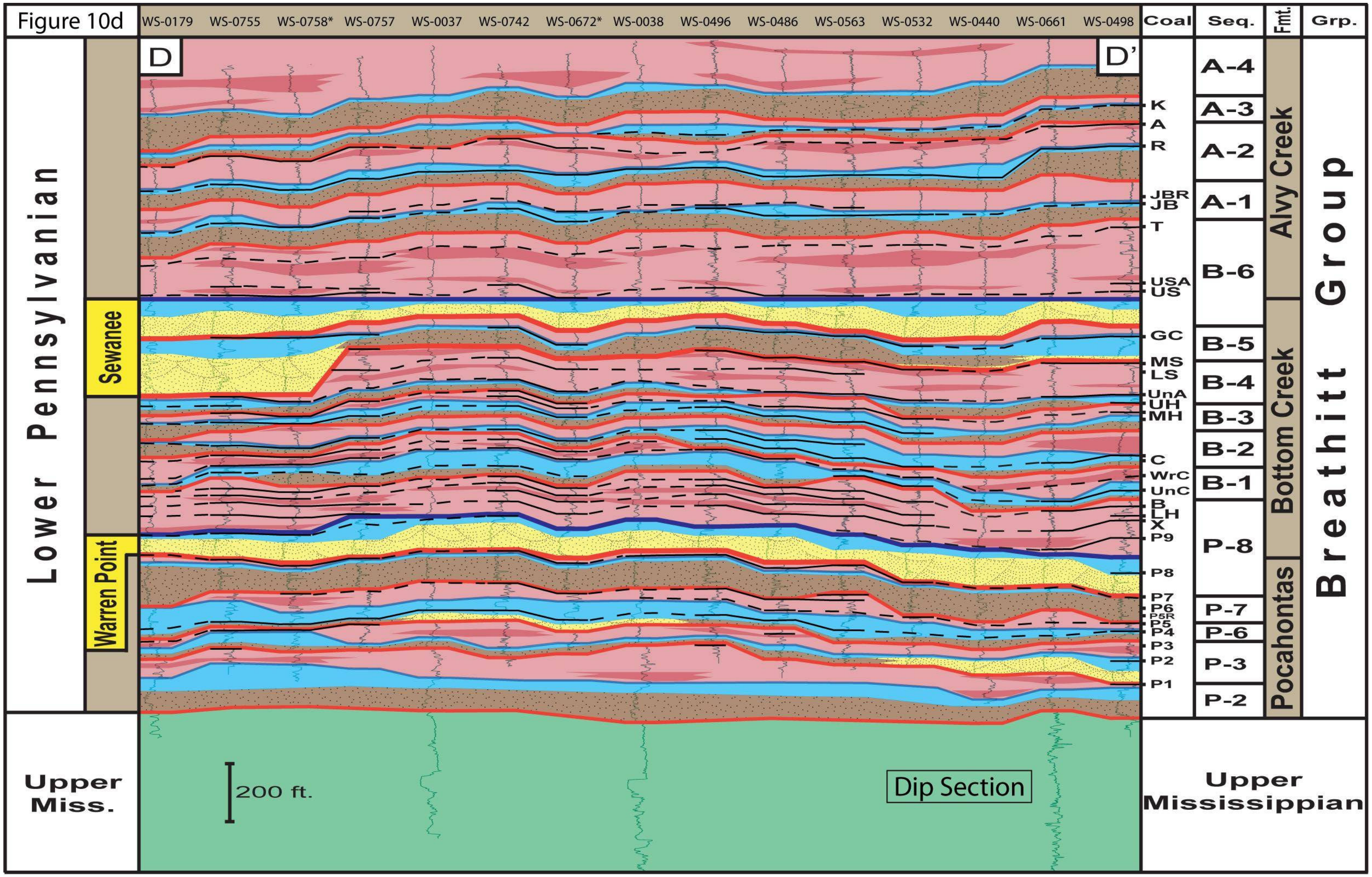


Figure 10d: Dip-oriented (NW-SE) cross-section D-D' (for location see figure 4). Displayed are minor discontinuities (thin red lines), major discontinuities (thick red lines), minor marine zones (light blue lines) and major marine zones (dark blue lines). Sequences are bound by minor and major discontinuities. A complete sequence contains either quartzarenite (yellow) or sublitharenite (brown), followed by light blue fining-upward siltstone to mudstone and then red coarsening-upward mudstone to siltstone. This cross-section displays 15 sequences. Note extensive quartzarenite units at the base of major discontinuites, representing the upper tongues of the Warren Point and Sewanee Formations.

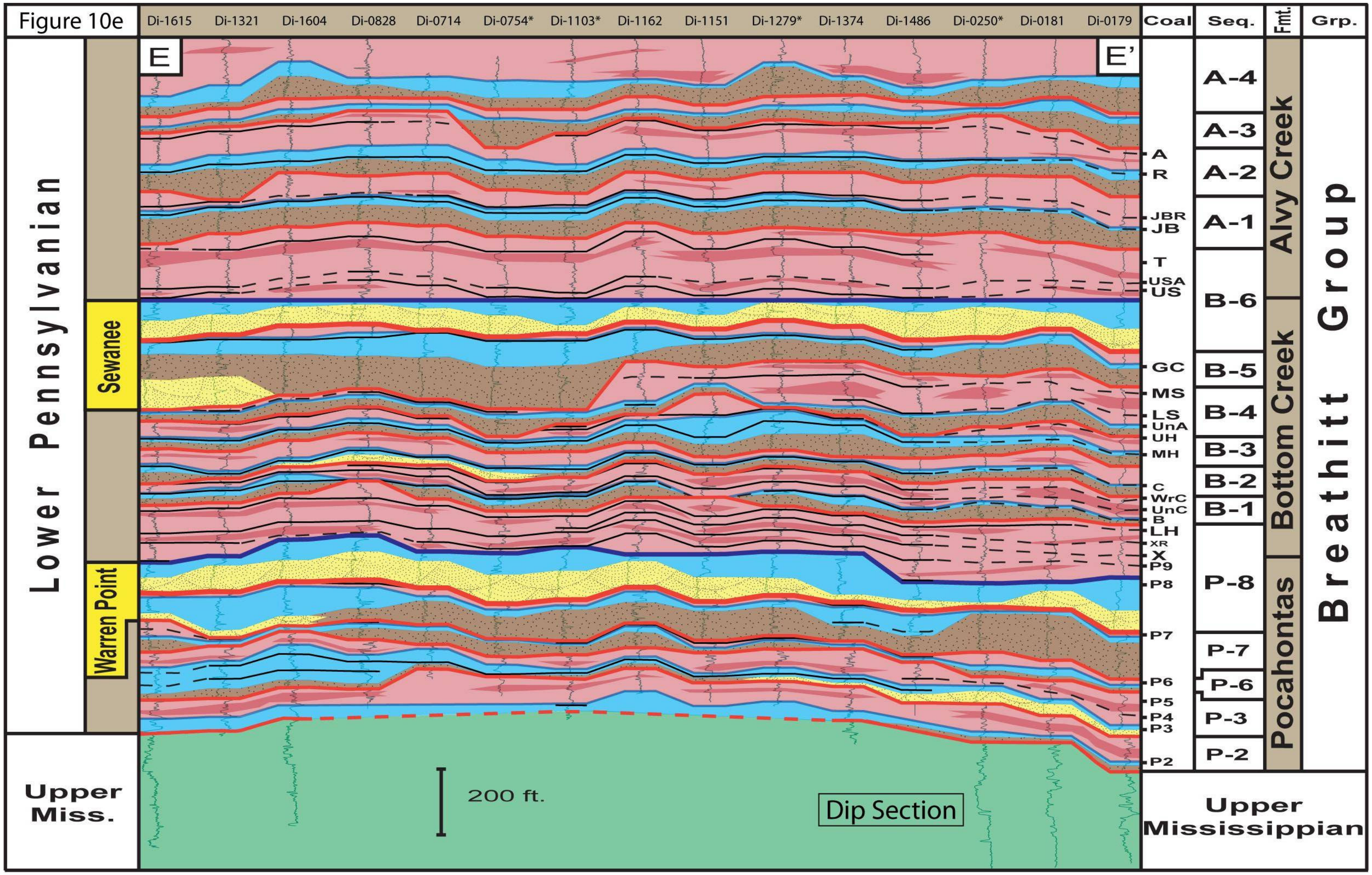


Figure 10e: Dip-oriented (NW-SE) cross-section E-E' (for location see figure 4). Displayed are minor discontinuities (thin red lines), major discontinuities (thick red lines), minor marine zones (light blue lines) and major marine zones (dark blue lines). Sequences are bound by minor and major discontinuities. A complete sequence contains either quartzarenite (yellow) or sublitharenite (brown), followed by light blue fining-upward siltstone to mudstone and then red coarsening-upward mudstone to siltstone. This cross-section displays 15 sequences. Note extensive quartzarenite units at the base of major discontinuites, representing the upper tongues of the Warren Point and Sewanee Formations.

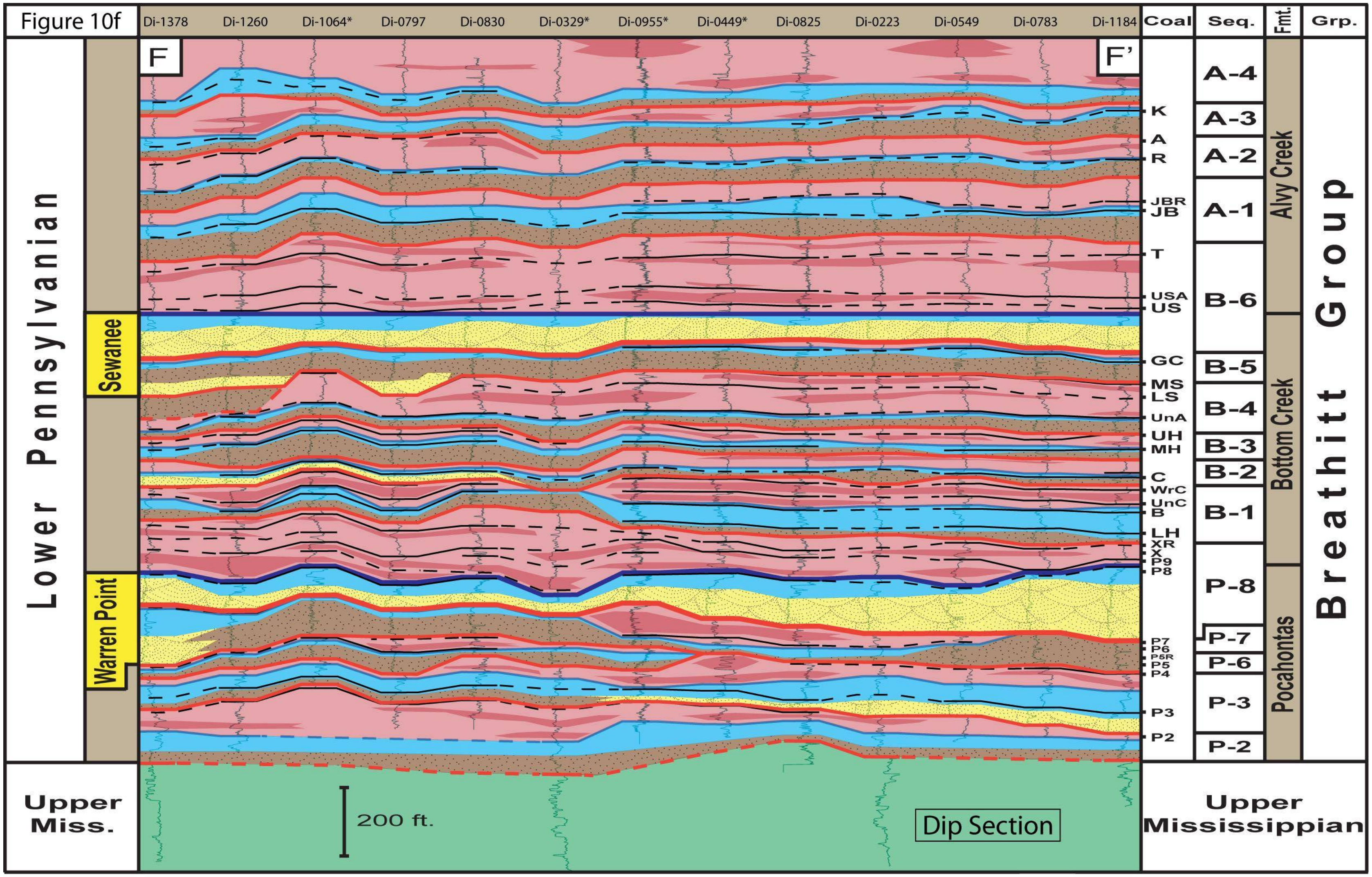


Figure 10f: Dip-oriented (NW-SE) cross-section F-F' (for location see figure 4). Displayed are minor discontinuities (thin red lines), major discontinuities (thick red lines), minor marine zones (light blue lines) and major marine zones (dark blue lines). Sequences are bound by minor and major discontinuities. A complete sequence contains either quartzarenite (yellow) or sublitharenite (brown), followed by light blue fining-upward siltstone to mudstone and then red coarsening-upward mudstone to siltstone. This cross-section displays 15 sequences. Note extensive quartza-renite units at the base of major discontinuites, representing the upper tongues of the Warren Point and Sewanee Formations.

5.6 *Trunk-tributary relationships*

The focus of many recent studies in the Appalachians has been toward explaining the lateral relationships between the quartzarenite and sublitharenite sandstone bodies (Korus, 2002; Greb et al. 2004; Bodek, 2006; Kvale and Archer, 2007). The studies performed by Korus (2002) and Greb et al. (2004) were regional in scale and lacked an appreciation of the fine-scale relationships between the facies. Similar to the study performed by Bodek (2006), this study incorporates a large dataset of high-density well spacing in order to view the fine-scale relationships between the individual sandstone bodies. This study is unique because it uses over 75 wells in 8 square miles (Fig. 4b) and spans the region where the transition from quartzarenite to sublitharenite sandstone bodies occurs (Bodek, 2006).

Bodek (2006) suggested that quartzarenite and sublitharenite sandbodies were deposited contemporaneously. This study agrees with that of Bodek (2006), showing that lenticular quartzarenite and sublitharenite sandbodies overlie common erosional discontinuities (Fig. 10a-f; Sequences: P-3, P-6, P-7, B-2, B-5, and A-4). Also, where these sandstones began to change composition from quartzarenite to sublitharenite, the gamma ray response indicates an intermediate "grading" composition or an interfingering relationship. Both of these observations support the notion that quartzarenites and sublitharenite sandstone bodies were deposited contemporaneously.

The quartzarenite and sublitharenite sandstone bodies were interpreted as incised valley fill (IVF) deposits of axial and transverse draining rivers, respectively (Korus, 2002; Bodek, 2006). With a drop in base level, the entire trunk-tributary drainage network down-cut, forming both trunk and tributary incised valleys (Fig. 11a). As base level began to rise, both incised valleys were infilled with a quartzose bedload in the trunk system and a sublithic bedload into the tributary incised valley. This study also illustrates that tributary IVF contains much finer grained facies than trunk IVF, which is in agreement with the conclusions of Kvale and Archer (2007) in correlative strata of the Illinois basin. The presence of peat mires positioned above trunk, tributary, and interfluve areas (Fig. 10a-f) suggests back-flooding was enough to drown both channel and interfluve areas as recognized by Shanley and McCabe (1994). With continued base level rise, deposition of brackish to marine mudstone took place across much of the study area (Fig. 11b; Greb and Martino, 2005). As the rate of base level rise began to slow and then steadily fall, deltaic deposits prograded over the fluvial, estuarine, coal-bearing, and brackish to marine facies (Fig. 11c). Deltaic deposits are broadly upward-coarsening

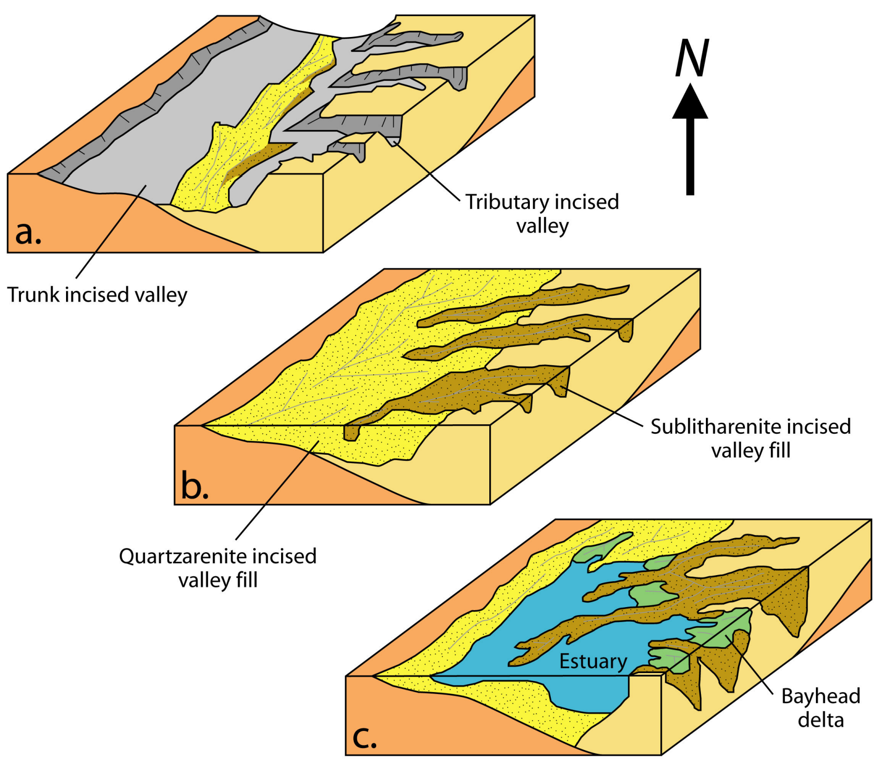


Figure 11: Paleogeographic reconstruction depicting: a) relative sea level fall and incision of axial (trunk) and transverse (tributary) valleys, b) relative sea level rise and contemporaneous back-filling of trunk and tributary incised valleys with quartzose and sublithic valley fill, respectively, and c) continued base level rise and back-flooding of trunk and tributary incised valleys, forming estuaries followed by progradation of deltaic facies into estuaries (modified from Korus, 2002; Bodek, 2006).

(Walker, 1992), whereas higher frequency upward-coarsening to upward-fining intervals record autogenic processes associated with delta lobe switching and eventual abandonment (O'Mara and Turner, 1999). Continued base level fall caused fluvial incision through deltaic deposits and rarely into the underlying IVF deposits.

5.7 *Overview of sequence stratigraphic concepts*

Sequence stratigraphy looks at "rock relationships within a chronologically significant framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition" (Van Wagoner et al., 1988; 1990). The basic unit of sequence stratigraphy, the "sequence", is a relatively conformable succession of unconformity-bound strata (Mitchum, 1977). There is a hierarchy of units comprising a sequence which represents progressively more time. Sequences are comprised of stacked parasequences (which in turn are comprised of lamina, laminasets, beds and bedsets) bound by flooding surfaces (Van Wagoner et al., 1988). This is referred to as a chronostratigraphic hierarchy of strata (Van Wagoner et al., 1990; Mitchum and Van Wagoner, 1991). Lower-order sequences arranged within higher-order sequences will often display a predictable facies stacking pattern, sediment body geometry, and position along depositional dip (Van Wagoner et al., 1988). The stacking pattern, sediment body geometry, and distribution of lower-order stratal units within a sequence set enable interpretation of depositional controls on the system. Controls on deposition within a sequence have been related to eustasy, subsidence and sediment supply (Van Wagoner et al., 1988). Individual facies may be predicted within a sequence stratigraphic framework through understanding controls on deposition and sequence architecture (Van Wagoner et al., 1988; Holz et al. 2002; Gibling et al., 2004).

Since changes in base level determine sediment body geometries, stacking patterns, and distribution of sequences, it is therefore necessary to identify factors which control base level. Base level represents the lower limit or subaerial erosion, or some surface related to sea level (Powell, 1875). Locally, sea-level can change as a result of eustacy and tectonism (Posamentier et al., 1988; Walker and James, 1992; Holz et al., 2002). This change in sea level is referred to as a relative sea level change and is defined by sea levels relative position to the shoreline. In some cases, the aforementioned local factors can magnify, dissipate, or even counteract the direction of global eustatic change (Plint et al., 1992). For example, a rise in relative sea level can take place during a period of global eustatic fall because local rates of subsidence exceed the rate at which global sea level is falling. It is the direction and magnitude of relative sea level change which controls sequence stacking patterns and their hierarchical nature. Sequence stacking patterns can therefore be related to both rates of relative sea level change and the specific direction of that change. Packages of unique stacking patterns are referred to as systems tracts (Posamentier et al., 1988; Van Wagoner et al. 1988; 1990). These systems tracts are referred to as the lowstand systems tract (LST), transgressive systems tract (TST), and highstand systems tract (HST) and occur as a response to a relative sea level fall, rise and peak, respectively (Van Wagoner et al., 1988, Posamentier et al., 1988; 1990).

Sea level can be linked directly to systems tracts and bounding discontinuities within sequences. Sequence boundaries, or bounding discontinuities, are created during the maximum rate of sea level fall. Two types of sequence boundaries have been recognized in the rock record (Van Wagoner et al., 1988). Type I sequence boundaries are formed when the rate of sea level fall is greater than the rate of basin subsidence at the depositional-shoreline break, creating a relative sea level fall at that position. Type I sequence boundaries are characterized by subaerial erosion and are associated with stream rejuvenation, a basinward shift in facies, a downward shift in coastal onlap, and onlap of overlying strata (Van Wagoner et al., 1988). Type II sequence boundaries are formed when the rate of sea level fall is less than the rate of basin subsidence at the depositional-shoreline break, creating no relative sea level fall at that position (Van Wagoner et al., 1988). Type II sequence boundaries are also characterized by subaerial erosion and a downward shift in coastal onlap, but they lack subaerial erosion due to stream rejuvenation and a basinward shift in facies (Van Wagoner et al., 1988).

The lowstand systems tract is found only associated with type I sequence boundaries (Van Wagoner et al., 1988, Posamentier et al., 1988; 1990) and is characterized by aggradational incised valley fill deposits that progressively onlap the sequence boundary in a landward direction (Shanley and McCabe, 1994). The top of the lowstand systems tract is represented by a transgressive surface that separates aggradationally stacked lowstand deposits from retrogradationally stacked transgressive deposits (Van Wagoner et al., 1988). The transgressive surface is commonly difficult to identify due to the lack of a vertical facies change (Walker and James, 1992; Reading and Collinson, 1996). The transgressive surface of erosion, or the initial flooding surface (typically marked by a lag deposit representing the transition from fluvial to estuarine sedimentation), is associated with a vertical change in facies and is easier to identify

(Allen and Posamentier, 1993; Zaitlin et al., 1994; Walker and James, 1992; Reading and Collinson, 1996).

As sea level continues to rise and backfilling occurs, incised valleys are infilled and then drowned to form estuaries (Fig. 11c; Boyd et al., 1992, Zaitlin et al., 1994). This marks the transition from lowstand systems tract to the transgressive systems tract. The upper bounding surface of the lowstand systems tract is defined by the maximum flooding surface (Van Wagoner et al., 1988). The maximum flooding surface is recognized as a highly radioactive black shale unit in marine strata (Galloway, 1989) whereas in alluvial strata, the maximum flooding surface is represented by the onset of marine processes (Shanley and McCabe, 1994). Greb and Martino (2005) suggest that tidal processes within fluvial landscapes may be considered the up-dip equivalent to marine condensed sections. Continued, gradual sea level rise initiates the highstand systems tract.

The highstand systems tract is characterized by a period of aggradation followed by the progradation of upward-coarsening deposits directly above the retrogradationally stacked transgressive deposits (Van Wagoner et al., 1988). The highstand systems tract consists of broadly upward-coarsening successions of prograding deltaic facies above transgressive systems tract deposits. The highstand systems tract ends as sea level drops to form another sequence boundary.

5.8 *Sequence stratigraphic interpretation of discontinuities*

A framework of major and minor discontinuities constructed across the study area (Fig. 10a-f) provides for a high resolution sequence stratigraphic evaluation of the lower

Pennyslvanian across the border of Wise and Dickenson Counties, Virginia. Using a genetic sequence stratigraphic framework based on maximum flooding surfaces (Galloway, 1989), Chesnut (1994) identified three major marine zones (major marine flooding surfaces) in the lower Pennsylvanian Breathitt Group. Chesnut (1994) attributed these major marine flooding surfaces to post-tectonic subsidence and incursion of marine waters. These three marine flooding surfaces divide the lower Pennsylvanian Breathitt Group into three formations of approximately 2.5 m.y. duration (Chesnut, 1994; Greb et al., 2004). These include the Pocahontas, Bottom Creek, and Alvy Creek formations capped by the Dark Ridge, Hensley, and Dave Branch shale members, respectively. The approximate 2.5 m.y. duration for each formation corresponds with a 3rd-order periodicity (Plint et al., 1992). Bodek (2006) suggests that using an average duration of 6.4 m.y. for the lower Pennsylvanian (Bashkirian Stage; Fig. 3; Davydov et al., 2004) that Chesnut (1994) age estimates are in agreement with those of Davydov et al. (2004). For purposes of this study, Bodek's (2006) age range estimates will be used for lower Pennsylvanian correlations.

The bases of sheet-like sandstone quartzarenite elements which are developed stratigraphically beneath the major 3rd-order marine flooding surfaces can be interpreted as 3rd-order sequence boundaries. Using the sequence stratigraphic approach of Vail et al. (1977), these widespread sharp-based and erosive sheet-like sandstone elements of the Warren Point (Fig. 10a, b, c; Sequence: P-8; Fig. 10d, e, f; Sequences: P-7 and P-8), Sewanee (Fig. 10a, b, c; Sequence: B-6; Fig. 10d, e, f; Sequences: B-5 and B-6), and Bee Rock formations can be interpreted as major incised valley fills. The base of each of these formations represents a 3rd-order sequence boundary while the major marine flooding surface directly overlying each unit represents the corresponding 3rd-order flooding surface.

Together with the major discontinuities, the stratigraphic succession also contains minor erosional discontinuities. These minor discontinuities are associated with the bases of lenticular sublitharenite sandstone elements that display a distinct upward transition in grain-size from coarse sandstone to fine-grained mudstone facies. The minor discontinuities reflect incision of the lenticular sublitharenite sandstone element into the underlying unit. These minor erosional discontinuities are also interpreted as sequence boundaries because the erosional discontinuity is regionally extensive (Aitken and Flint, 1994; Hampson et al., 1997). In the cross-sections (Fig. 10a-f), four to six minor sequences are present within each formation of the lower Pennsylvanian Breathitt Group, with the entire lower Pennyslvanian containing 15 such minor sequences. Using the estimated 7.5 m.y. duration for the lower Pennsylvanian by Chesnut (1994) and Davydov et al. (2004), the minor sequences are approximately 500 k.y. in duration. In Dickenson County, Virginia, Bodek (2006) found 18 total sequences within the correlative lower Pennsylvanian strata for which he estimated as 400 k.y. sequences using an estimated 7.5 m.y. duration for the lower Pennsylvanian (Chesnut, 1994; Davydov et al., 2004). The relative location of this study is farther southeastward, deeper into the Pocahontas Basin, than that of Bodek (2006). Therefore, as the wedge of sediment thickens towards the southeast, it is likely that wells incorporated into the accompanying cross-sections did not penetrate through the entire extent of lower Pennsylvanian strata. The lack of very early Pennsylvanian coals within the study area indicates that this is likely the case. Thus, for the purposes of this study, the findings of Bodek (2006) will be used to estimate the duration of minor sequences. Bodek (2006) attributed the 400 k.y. duration for each minor sequence to Milankovitch long-term global eccentricity cycles (Plint et al., 1992; Read, 1995). This suggests that minor sequences are 4th-order cycles bound by 4th-order sequence boundaries.

Similar to 3rd-order sequences containing major marine flooding zones directly stratigraphically above major discontinuities, 4th-order sequences have minor marine flooding zones which are developed stratigraphically above minor discontinuities (ex. Fig. 10a-f; Sequence: A-1). These are interpreted as 4th-order flooding surfaces and consist of intervals of mudstone, black shale and regionally extensive coal beds. While containing similar strata to 3rd-order marine zones, 4th-order marine zones are generally much thinner. Bodek (2006) also observed this thickness contrast between 3rd- and 4th-order marine zones.

Several fourth-order sequences comprise third-order sequences, to define composite 3rd-order sequences. The bases of 3rd-order sequences are shared with the base of the lowermost 4th-order sequence, defining a composite 3rd-order sequence boundary as well (Fig. 10a-f; base of Sequences: P-8 and B-6). Similar sequence hierarchy has been recognized by Chesnut (1994), Korus (2002), Korus et al. (2008), Greb et al. (2004) and Bodek (2006) in correlative strata. Both middle (Smith and Read, 2000) and upper Mississippian (Miller and Eriksson, 2000) strata of southern West Virginia display a similar sequence hierarchy. Fourth-order sequences within the middle Pennsylvanian of eastern Kentucky comprise lowstand, transgressive, and highstand sequence sets within the composite 3rd-order sequences (Aitken and Flint, 1994).

The lowstand systems tract is bounded by a type I sequence boundary at its base (Van Wagoner et al., 1988), defined by sharp, erosionally based incised valley fill deposits and their correlative interfluves (McCarthy and Plint, 1998). The lowstand systems tract in cross-section incorporates incised valley fill containing cross-bedded sandstones and conglomerates and an upward-fining succession up to the transgressive surface. The transgressive surface is defined where the first imprint of tidally influenced sedimentation occurs (Zaitlin et al., 1994; Reading and Collinson, 1996). Korus (2002) used paleocurrent reversal trends in lower Pennsylvanian alluvial strata from southern West Virginia as signs of the initial tidal influence. Greb and Martino (2005) mark the fluvial to estuarine transition as correlative to the down-dip marine zone, thus defining the transition from lowstand systems tract into the transgressive systems tract. In the core accompanying this study, alongside the core of Bodek (2006), this transition can be seen as a vertical change is facies from quartzarenite or sublitharenite to rhythmic, tidally influenced heterolithic strata (c.f. Peterson and Andsbjerg, 1996).

The transgressive systems tract (Fig. 10a-f), is present as an upward-fining transition of heterolithic facies, mudstone, black shale, and a laterally extensive coal bed. Rarely, the upward-fining transition is more broadly defined and contains multiple coal-capped upward-fining intervals. Coals within the transgressive systems tract are commonly overlain by black shale that marks the top of the transgressive systems tract. Thick black shale intervals overlying transgressive coal beds were formed in response to maximum flooding conditions that transgressed over accumulated peat deposits adjacent to estuaries (Zaitlin et al., 1994; Greb and Martino, 2005). Fourth-order maximum flooding surfaces are “minor marine zones” in cross-section (Fig. 10a-f). The 4th-order flooding surfaces mark the transition from upward-fining to broadly upward-coarsening successions. In a very few wells within each cross-section (Fig. 10a-f), the transgressive systems tract is incised by the overlying sequence boundary.

The highstand systems tract begins at the base of a laterally thick and persistent mudstone and continues to broadly coarsen upward. The highstand systems tract consists of multiple, high-frequency coal-capped, upward-fining intervals within the broadly upward-coarsening facies transition (Fig. 10a-f). These represent periods of continued transgression of the estuaries and deposition of bayhead deltas. Coals beds within the highstand systems tract are very thick (meters) and laterally persistant. This is in agreement with results of Bodek (2006). The highstand systems tract is terminated by the overlying sequence boundary. In cases where a sharp-based sheet-like or lenticular sandstone element is absent above the broadly upward-coarsening highstand systems tract, the sequence boundary is placed at the base of the regionally extensive coal capping the succession (Aitken and Flint, 1994; 1995).

5.9 *Preservation of highstand facies*

Highstand deltaic facies are incised by overlying coarse-grained quartzarenite and sublitharenite sandstone bodies of 3rd- and 4th-order sequences (Fig. 10a-f). Depending on the degree of incision, highstand deposits are preserved as thick intervals (>100 ft.) or relatively thin intervals (<50 ft.) The highstand facies are thin to completely removed beneath 3rd-order sequence boundaries, which are overlain by sheet-like quartzarenites (Fig. 10a; upper portion of sequence P-7). This reflects low accommodation during long term base level fall associated with 3rd-order sequence boundaries (Fig. 12). Highstand facies deposits are relatively thick (>100 ft) in the basal high-frequency 4th-order sequence in the lower part of the 3rd-order composite sequence (Fig. 10a-f; Sequence: P-8 and B-6). In return, the highstand facies deposits of the underlying sequences (Fig. 10a-f; Sequences: P-7 and B-5). High preservation of thick 4th-order HST in the lower part of the 3rd-order composite sequence results from high accommodation associated with longterm base level rise. Therefore, preservation of highstand facies deposits can be related to the sequence hierarchy which reflects accommodation.

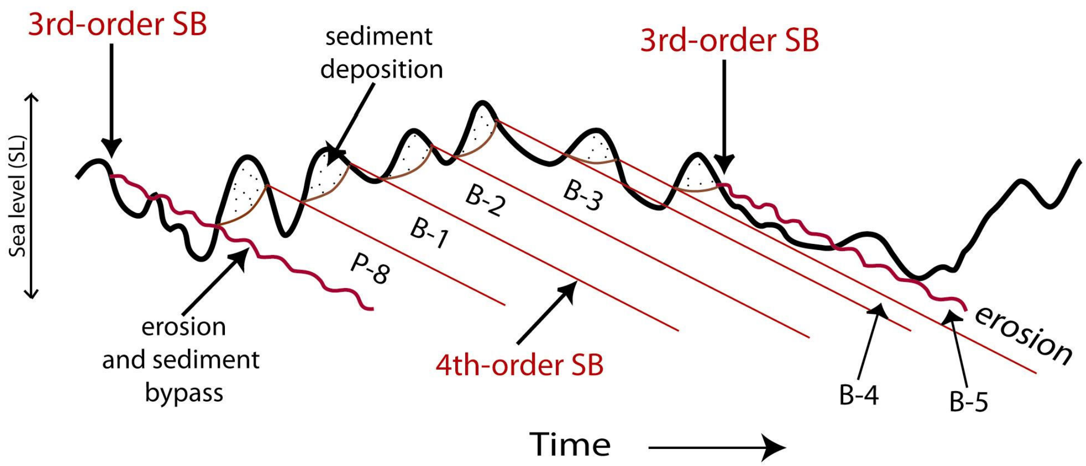


Figure 12: Schematic diagram showing the interaction between 3rd- and 4th-order sea level fluctuations for the Bottom Creek Formation of the Breathitt Group in south-western Virginia. Sequences P-8, B-1, B-2, B-3, B-4 and B-5 correspond to 4th-order sequences recognized in Figures 10a-f. 4th-order sequences associated with a 3rd-order sea level rise are thicker and more complete, whereas 4th-order sequences associated with a major 3rd-order sea level fall are thinner and less complete. 3rd-order sequence boundaries (SB) are created where the 3rd-order sea level curve has the steepest downward gradient.

6 **DISCUSSION**

This study, similar to Bodek (2006), uses both genetic (Galloway, 1989) and depositional sequence stratigraphic principles (Vail et al., 1977) to understand the lower Pennsylvanian strata of the Southwestern Virginia coalfields. In a genetic sense (Chesnut, 1994), Pennsylvanian strata are viewed as a hierarchy of marine zones (condensed sections) whereas in the Vail model (Aitken and Flint, 1994, 1995; Korus, 2002, Korus et al., 2008), the strata are characterized as a hierarchy of updip erosional disconformities at the base of fluvial sandstone bodies and correlative interfluves. In up-dip terrigenous settings, depositional sequence stratigraphy is used where evidence of marine deposition is lacking. But, since laterally extensive coal seams are found in close association with marine flooding surfaces (Bodek, 2006; Fig. 10a-f) it is important to take both a genetic and depositional sequence stratigraphic approach to develop a high-resolution sequence stratigraphic framework to determine the origin of economic coal seams.

Bohacs and Suter (1997) showed that peat production roughly equal to accommodation rate is conducive to the preservation of economically significant coal seams. Accommodation rate in nearshore environments can be attributed the combined effects of eustacy, tectonism, and sedimentation rates; also known as relative sea level change (Plint et al., 1992). Bohacs and Suter (1997) emphasize it is the *rate* of base level change which effects accommodation increases favorable for peat accumulation in paralic strata. However, peat production is largely a function of climate and vegetation (Bohacs and Suter, 1997), and relative sea level merely provides the space for this to accumulate.

As base level rapidly falls, accommodation space decreases, the ratio of peat production is greater than accommodation rate, and the mire therefore is exposed and reworked (Bohacs and Suter, 1997). As base level begins to rise, creating accommodation space which is matched by peat production to form coal seams that are thick and continuous. This relationship continues until just before base level reaches a maximum (maximum flooding surface) at which stage the rate of base level rise is much greater than peat production, creating thin and discontinuous coals due to drowning of the peat mire by clastics (Bohacs and Suter, 1997). Once maximum flooding conditions are met, the rate at which base level rises begins to gradually decrease. The same *rates* of base level change, both rising and falling, are seen prior to, and after maximum flooding (Bohacs and Suter, 1997), thus creating similar coal geometries and thicknesses as base level begins to fall again. Since coal thickness and geometry can be related to relative sea level change, coal seams can be placed within a sequence stratigraphic framework. Therefore, rates of accommodation increase needed in the formation and preservation of coal are located within aggradational to retrogradational stacked transgressive facies, and aggradational to progradational stacked highstand facies (Cross, 1988; Bohacs and Suter, 1997; Diessel et al., 2000; Holz et al., 2002).

Bodek (2006) found this connection between coal seam architecture and sediment body stacking patterns to be true within the lower Pennsylvanian strata of Dickenson County, southwestern Virginia. This study agrees with Bodek (2006), showing that laterally extensive coals occur within upward-fining transgressive facies as well as upward-coarsening highstand facies. The lowstand systems tract in the study area contains quartzarenite and sublitharenite incised-valley fill attributed to an axial and transverse drainage system, respectively (Korus, 2002; Bodek, 2006; Korus et al., 2008), alongside their corresponding interfluves (Van Wagoner et al., 1988, 1990; McCarthy and Plint, 1998). Coal is only present in the form of rip-up clasts at the base of lowstand systems tracts in the study area that reflect a drop in base level and erosion of underlying coal-bearing units.

The transgressive systems tract represents back-flooding of the IVF and the formation of estuaries to form the fluvial to estuarine transition (Zaitlin et al., 1994). In up-dip terrigenous environments, the transgressive surface at the base of the transition is difficult to identify. Several outcrop studies in the central Appalachian basin have identified paleocurrent reversals and ravinement deposits as indicators of the onset of the fluvial- to estuarine transition (Miller and Eriksson, 2000; Korus, 2002; Korus et al., 2008). Coal beds within the transgressive systems tract are positioned stratigraphically above the fine-grained estuarine facies and beneath the zone of maximum flooding. Coal beds within the transgressive systems tract of this study are the Pocahontas #1, Pocahontas #3, Pocahontas #4, Pocahontas #5, Pocahontas #8, Beckley, C Seam, Middle Horsepen, Unnamed B, Greasy Creek, Jawbone, Raven, and the Kennedy Coal (Fig. 10a-f). Transgressive coals are interpreted to form in close association with 4^{th}-order maximum flooding surfaces (Chesnut, 1994), thus can be attributed to allocyclic, Milankovitch orbital eccentricity driven eustatic sea level rise (Bodek, 2006).

Highstand coal beds in the study area occur as a package of multiple seams within the highstand systems tract and are not in close association with 4^{th}-order maximum flooding surfaces, making their origin more difficult to interpret. Highstand coals include the Pocahontas #2, Pocahontas #6, Pocahontas #7, Pocahontas #9, X Seam, X Seam

Rider, Lower Horsepen, Unnamed C, War Creek, Upper Horsepen, Lower Seaboard, Middle Seaboard, Upper Seaboard, Upper Seaboard A, Tiller, Jawbone Rider, and the Aily coal (Fig. 10a-f). Individual highstand coal beds occur above minor upward-fining intervals within the broadly upward-coarsening highstand systems tract. Bodek (2006) attributed the thin coal-capped upward-fining intervals to autocyclic processes. These processes include channel avulsion and delta lobe switching and were due to local changes in accommodation rate and sediment supply. Post-abandonment dewatering and compaction may provide the necessary accommodation for the accumulation and preservation of peat within the highstand systems tract, thus making highstand coals a product of autocyclic processes (O'Mara and Turner, 1999).

Most of the coals within the Pocahontas Formation are developed within transgressive systems tracts - which is consistent with the findings of Bodek (2006). In the Pocahontas Formation, highstand deposits are much thinner or even completely removed (Fig. 10a-c; 10e-f) as a result of low accommodation during deposition, ridding the Pocahontas Formation of what *might* have been highstand coal beds. What remains in the rock record are the uneroded transgressive coal beds. The close association of transgressive coals to the maximum flooding surface indicates that they formed during the latest stages of transgression (Bohacs and Suter, 1997; Bodek, 2006). According to Bohacs and Suter (1997) this would suggest that the rate of accommodation increase and the rate of peat production were approximately the same during late stages of transgression.

Both allocyclic and autocyclic processes played a role in the formation and preservation of regionally extensive economic coal seams in Lower Pennsylvanian strata of the central Appalachian basin. The close association of transgressive coal seams to both composite 3rd-order maximum flooding surfaces along with 4th-order maximum flooding surfaces supports an allocyclic origin to their deposition. Whereas Chesnut (1994) inferred post-tectonic induced subsidence for the 2.5 m.y., 3rd-order maximum flooding surfaces, recent work has shown that it is more likely a higher-order, low-frequency (2.4 ± 0.4 m.y.) orbital eccentricity signature (Matthews and Frohlich, 2002). Therefore, deposition of transgressive coals is attributed to Milankovitch orbital eccentricity cycles of both 4th-order (400 k.y.; Plint et al., 1992; Read, 1995) and 3rd-order (2.5 m.y.). This is consistent with the findings of Bodek (2006). Highstand coals are a function of mainly autocyclic delta processes and are of a much higher frequency than their transgressive counterparts.

7 **CONCLUSIONS**

1. Early Pennsylvanian coal-bearing strata in the central Appalachian Basin of southwestern Virginia represent a trunk-tributary drainage system characterized by sublithic and quartz-rich incised valley fills. The trunk drainage system, draining a northerly cratonic source, is characterized by quartz-rich incised valley fills and is oriented NE-SW. The tributary drainage network is aligned orthogonal to the trunk system, draining the metamorphic terrain of the Alleghanian orogen towards the southeast, and is characterized by sublithic incised valley fills.
2. Early Pennsylvanian incised valley fill deposits are both fluvial and estuarine in origin. High-magnitude sea level fluctuations played a major role in the incision

and backfilling of early Pennsylvanian paleovalleys. During sea level lowstand, valley incision commenced until the sea transgressed, causing backfilling of the paleovalleys and the formation of estuaries. These eustuarine fills cap both quartz-rich and sublithic incised valley fills and represent a fluvial to estuarine transition within the trunk-tributary drainage network.

3. Early Pennsylvanian strata of the Breathitt Group contain both 3^{rd}- and 4^{th}-order sequences. Third-order composite sequences are built of multiple stacked 4^{th}-order sequences and reflect major sea level fluctuations. These major, 3^{rd}-order sea level fluctuations have been traditionally attributed to tectonic forces, but are more likely a product of lower-frequency orbital eccentricity cycles. Fourth-order sequences are attributed to Milankovitch driven glacio-eustacy.
4. Coals within the early Pennsylvanian occur in the transgressive and highstand systems tracts. Coal beds within the transgressive systems tract occur in close association with 4^{th}-order flooding surface, while coal beds within the highstand systems tract occur within high-frequency deltaic autocycles. Therefore, transgressive coal beds can be attributed to Milankovitch driven glacio-eustacy while highstand coal beds may have more of an autocyclic deltaic influence.

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