SEQUENCE STRATIGRAPHIC ARCHITECTURE OF EARLY PENNSYLVANIAN, COAL-BEARING STRATA OF THE CUMBERLAND BLOCK: A CASE STUDY FROM DICKENSON COUNTY, VIRGINIA

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ABSTRACT

Lower Pennsylvanian, coal-bearing, siliciclastic strata of the central Appalachian foreland basin were deposited in continental to marginal marine environments influenced by high-amplitude relative sea level fluctuations. Sediment was derived from both the low-grade metamorphic terrain of the emergent Alleghanian orogen towards the southeast, and the cratonic Archean Superior Province in the north. Immature sediments derived proximally from the Alleghanian orogen, including sublithic sandstone bodies, were deposited as a southeasterly-thickening clastic wedge within a southeast-northwest oriented transverse drainage system. Texturally and mineralogically mature quartzarenites were deposited in strike-parallel elongate belts along the western periphery of the basin. These mature quartzarenites are braided fluvial in origin and were deposited within northeast-southwest oriented axial drainage head-watered in a northerly cratonic source area. The contemporaneity of transverse and axial fluvial systems defines a trunk – tributary drainage system operating in the central Appalachian foreland basin during the early Pennsylvanian.

Detailed analysis of core, gamma ray logs, and cross-sections reveals a hierarchy of bounding discontinuities and architectural elements within the study interval. Discontinuities are both erosional and depositional (condensed) surfaces of interpreted 3rd-order (~ 2.5 Ma) and 4th-order (~ 400 k.y.) origin. Architectural elements within 4th-order sequences consist of upward-fining lowstand and transgressive incised valley fill, alluvial, and estuarine deposits, and upward-coarsening highstand deltaic deposits that are separated by condensed sections. 4th-order sequences are stacked into 3rd-order composite sequences. Sequence stratigraphic architecture in the central Appalachian basin can therefore be attributed to 4th-order Milankovitch orbital eccentricity cycles superimposed on 3rd-order orogenically driven subsidence, or more likely, 4th-order Milankovitch orbital eccentricity cycles superimposed on a lower-frequency eccentricity cycle. The widespread nature of both 3rd- and 4th-order marine flooding zones and sequence boundaries enables both genetic and depositional sequence stratigraphy to be applied to terrigenous to marginal marine coal-bearing strata of the central Appalachian basin.

Regionally extensive coal beds occur in close association with both 4th-order condensed sections as well as within highstand deltaic deposits. Formation of coal beds in the central Appalachian basin of southwest Virginia is therefore attributed to both an allocyclic glacio-eustatic mechanism, associated with Milankovitch orbital eccentricity cycles, and autocyclic deltaic processes related to channel avulsion and delta lobe switching.

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CONTENTS

LIST OF FIGURES

INTRODUCTION

The early Pennsylvanian record of the central Appalachian basin is characterized by immature mixed siliciclastic strata and coal beds intercalated with major quartzarenite bodies. Coal-bearing siliciclastic strata comprise a hinterland-thickening wedge that was derived from uplift and erosion of the Alleghanian orogen along the southeastern margin of the basin. Quartz-rich sand bodies were developed along the cratonward periphery of the basin and are aligned parallel to strike. The mixed siliciclastic facies and coals have been traditionally assigned to fluvio-deltaic settings (Donaldson, 1974; Englund, 1974; Ferm, 1974; Donaldson et al., 1985; England et al., 1986; England and Thomas, 1990; Allen, 1993) whereas both marine (e.g. 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) paleoenvironmental models have been proposed for the quartzarenite bodies**.** Earlier studies were successful in determining the temporal and spatial extent of the quartzarenite bodies and the coal-bearing mixed siliciclastics. However, stratigraphic relationships between the two lithological associations remains poorly understood. The lateral transition from quartzarenites into mixed siliciclastics has been described as “intertonguing,” or “gradational” (Englund and DeLaney, 1966; Englund, 1974; Miller, 1974) whereas the quartz arenites are said to “truncate,” or “wedge-out” into coal-bearing units (Englund, 1974; Englund, 1979; Chesnut, 1994; Greb et al., 2004).

The principal objective of this study is to develop a sequence stratigraphic model to elucidate the relationships between early Pennsylvanian quartzarenites and coal-bearing siliciclastic units and their collective relationship to the mid-Carboniferous unconformity. Particular emphasis will be placed on differentiating texturally and mineralogically immature from mature sandstone bodies and understanding their three-dimensional architectural relationships in space and time.

The Carboniferous rock record in Laurasia developed during a climatic transition from greenhouse conditions (with small global ice volumes) to icehouse conditions (associated with the buildup of the Gondwana continental glaciation in the southern hemisphere) (e.g. Miller and Eriksson, 2000; Smith and Read, 2000; Wright and

Vanstone, 2001; Isbell et al., 2003; Butts, 2005). Thus, a secondary objective of the study is to evaluate controls on sequence development with specific reference to the influence of Milankovitch orbital eccentricity driven glacio-eustatic sea level fluctuations.

GEOLOGIC BACKGROUND

Tectonic Setting

The Appalachian basin formed as a product of collisional tectonics from the cumulative effects of the Taconic, Acadian, and Alleghanian orogenies (Quinlan and Beaumont, 1984). The resultant basin is a northeast-southwest trending foreland basin approximately 1,075 miles in length extending from New York to Alabama and with a maximum width of 310 miles in the north and an overall southerly narrowing trend (Fig. 1; Ryder, 1995). The central Appalachian basin is located in parts of southern West

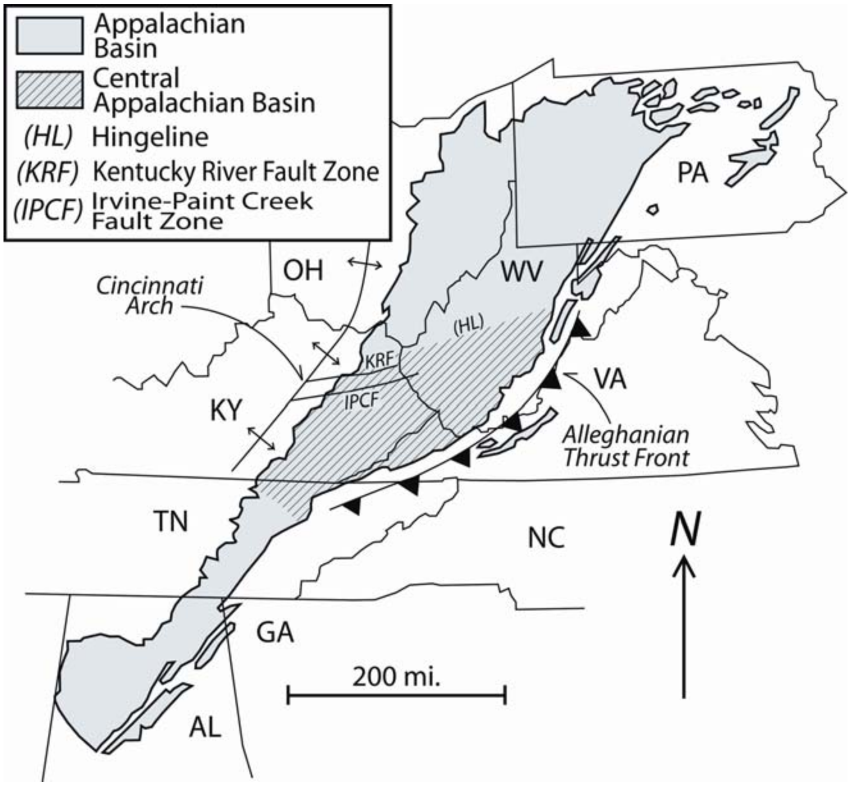


Figure 1: Map showing the aerial extent of Carboniferous deposits (shaded region) in the Appalachian basin, including the areas of the central Appalachian basin (hatched region), with bounding structures. (Adapted from Cecil et al., 1985; Chesnut, 1994; Greb and Chesnut, 1996; Korus, 2002; Greb et al., 2004; Greb and Martino, 2005)

Virginia, southwestern Virginia, eastern Kentucky, and northeastern Tennessee, and is largely delineated on the basis of bounding structures (Fig. 1). The Appalachian fold-and-thrust belt demarcates the southeastern margin of the basin, whereas the Cincinnati arch and associated rheologic uplifts define the cratonward periphery (Greb and Martino, 2005). The northern margin of the central Appalachian basin is delineated by the Kentucky River Fault System, the Irvine – Paint Creek Fault System, and a structural east-west trending hingeline in central West Virginia (Greb and Martino, 2005). Thrust loading in the Appalachian fold-and-thrust belt during the early Pennsylvanian through early Permian Alleghanian orogeny initiated subsidence in a central Appalachian basinal depocenter (Rice and Schwietering, 1988), and provided accommodation for up to 9,500 feet of early Pennsylvanian through early Permian predominantly terrestrial and marginal-marine siliciclastic rocks (Ettensohn, 2004). Due to the increasing flexural rigidity of the lithosphere, achieved through earlier episodes of orogenesis, the Alleghanian orogeny was characterized by a relatively broad, shallow foreland basin (Tankard, 1986; Willard and Klein, 1990; Ettensohn, 1994) largely lacking deep water, flysch-like sedimentary strata (Ettensohn, 2004).

Mid-Carboniferous Stratigraphy

Incipient stratigraphic models of Carboniferous strata in the central Appalachian basin depicted units as essentially tabular bodies. This model, popularly termed the "layer-cake" model, envisioned individual sediment bodies as being laterally continuous and deposited during discreet time intervals. Additionally, conventional interpretations suggested that the Mississippian and Pennsylvanian systems were separated by a widespread unconformity (Ettensohn, 1980). In the latter part of the 20th century, as roadcuts became more abundant, and hydrocarbon and coal production increased, it became apparent that some Carboniferous units were not as widespread throughout the basin as previously thought. It was realized that some units were truncated, intertongue, or grade laterally into underlying or overlying strata (Miller, 1974). Clearly a more reliable stratigraphic framework was needed to properly characterize Carboniferous strata of the Appalachian basin.

Coal-bearing siliciclastic strata of the lower and middle Pennsylvanian Breathitt Group consist predominantly of sublithic sandstone with subordinate amounts of siltstone, shale, underclay, and coal (Englund et al., 1986). Sublithic sandstone bodies predominantly show evidence of westerly paleoflow and were derived from the south-southeasterly, low-grade metamorphic terrain of the Alleghanian orogen (Rice, 1985; Rice and Schwietering, 1988). Overall, the Breathitt clastic wedge thickens toward the thrust-loaded hinterland (Englund, 1979; Englund and Thomas, 1990; Chesnut, 1988, 1996). Comparison with previous studies has indicated that early and middle Pennsylvanian strata reaches a maximum thickness of approximately 2,400 ft along the southeast margin of the basin and thins to the northwest (Miller, 1974; Englund, 1979; Englund et al, 1986; Englund and Thomas, 1990; Chesnut, 1994; Nolde, 1994a; Korus, 2002). Quartzarenite formations of the Breathitt Group occur as northeast – southwest oriented bodies that are lenticular in cross-section. Individual quartz sandstone formations are approximately 37-50 miles wide (Greb et al., 2004), up to 500 feet thick and often composed of numerous thinner 70 – 100 foot thick individual beds (Chesnut, 1994). These sandstone bodies show evidence of southwesterly paleoflow (Wizevich, 1992). Lithologically, quartz sandstone formations are dominated by quartzarenite with localized lenses of quartz-pebble conglomerate and pebbly quartzarenite. Individual beds are often separated by fining-upward intervals of siltstone, shale, underclay, and coal. These quartz sandstone belts are arranged *en echelon*, such that they onlap and amalgamate cratonward (Wizevich, 1992; Greb and Chesnut, 1996; Greb et al., 2004). In more axial positions within the basin, quartz sandstones are found to bifurcate, pinch-out, truncate, and grade laterally to the southeast into coal-bearing facies. Quartzarenite belts appear to be topographically confined between coal-bearing clastics wedges to the southeast, and uplifted upper Mississippian units along the Cincinnati arch to the northwest (Rice and Schwietering, 1988).

In recent decades, stratigraphic studies have shown that upper Mississippian and lower Pennsylvanian strata display marked lithological differences that have been attributed to: 1) a climatic change from semi-arid to ever-wet conditions (Cecil et al., 1985; Donaldson et al., 1985; Cecil, 1990); 2) the onset of Alleghanian tectonism (Tankard, 1986; Klein and Willard, 1989; Willard and Klein, 1990); and 3) an increase in amplitude of eustatic changes associated with progressive growth of the Gondwana glaciation (Saunders and Ramsbottom, 1986; Veevers and Powell, 1987; Ross and Ross, 1988).

Early and Middle Pennsylvanian Lithostratigraphic Nomenclature

Formalized Kentucky nomenclature:

Stratigraphic nomenclature used in this thesis corresponds to the formalized Kentucky nomenclature (see review in Chesnut, 1994, 1996). In the central Appalachian basin of eastern North America, the early and middle Pennsylvanian Breathitt Group consists of eight formations (Chesnut, 1994, 1996; Greb et al., 2004). The early Pennsylvanian section consists, in ascending order, of the Pocahontas, Bottom Creek, and Alvy Creek Formations whereas the middle Pennsylvanian consists, in ascending order, of the Grundy, Pikeville, Hyden, Four Corners, and Princess Formations (Chesnut, 1994). Individual formations of the Breathitt Group are separated by widespread marine horizons (Chesnut, 1994, 1996). The Breathitt Group is dominated by texturally and mineralogically immature siliciclastics and intercalated coal beds. However, quartzarenite formations occur as westerly facies equivalents to the lower Pennsylvanian Pocahontas, Bottom Creek, Alvy Creek Formations as well as to the lowest middle Pennsylvanian Grundy Formation (Fig. 2). These quartz sandstone bodies, in ascending order, are the Warren Point, Sewanee, Bee Rock and Corbin Formations of the Breathitt Group (Chesnut, 1994; Greb et al., 2004).

Correlation into Virginia:

In Virginia, the Warren Point and Sewanee Formations are collectively termed the upper and lower tongues of the Middlesboro Member of the Lee Formation, respectively (Miller, 1974; Nolde, 1994a). The Bee Rock nomenclature is utilized in both Virginia and Kentucky. The Corbin sandstone, though widespread in eastern Kentucky, is confined to the extreme southwestern corner of Virginia in Lee County, and is referred to locally as the Nease Sandstone Member (Nolde, 1994a). The Pocahontas Formation is widely developed in Virginia and West Virginia but is largely absent in eastern

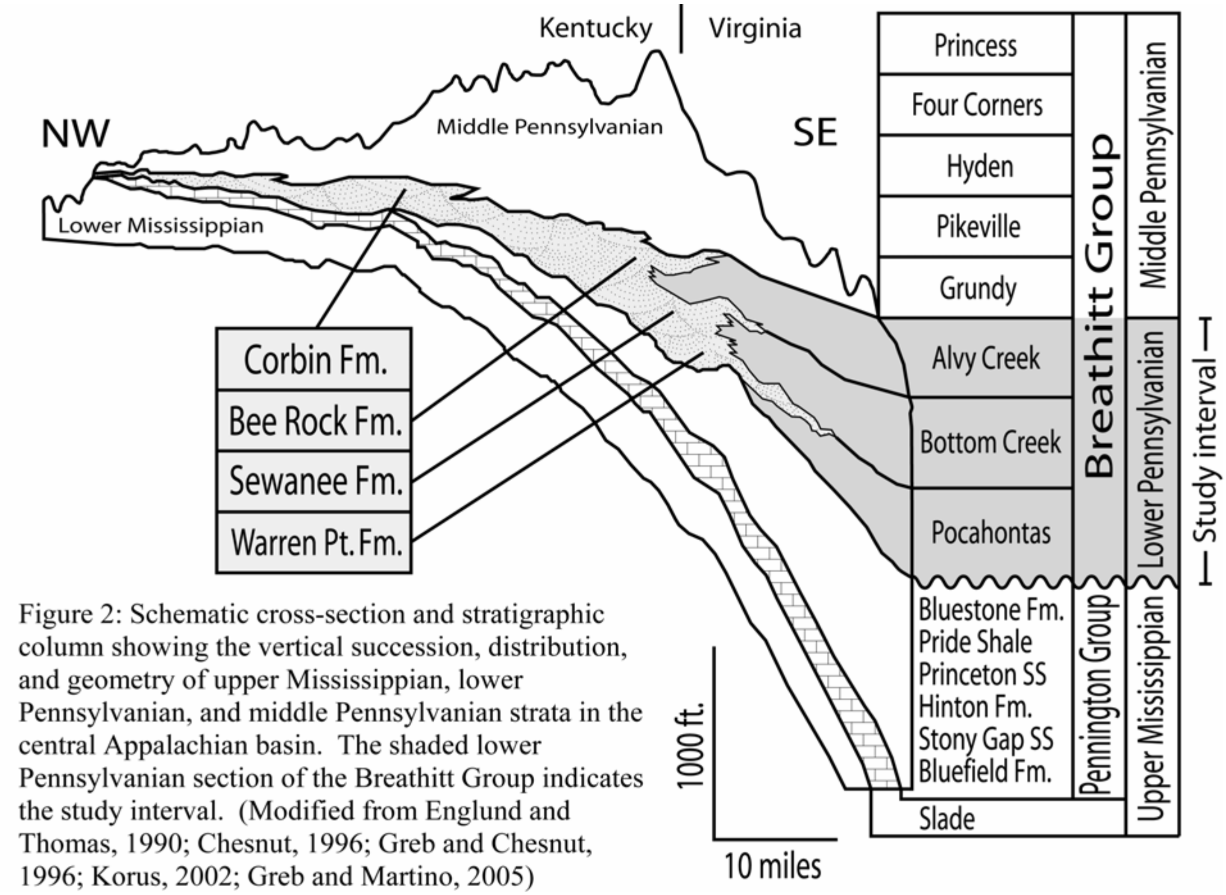


Figure 2: Schematic cross-section and stratigraphic column showing the vertical succession, distribution, and geometry of upper Mississippian, lower Pennsylvanian, and middle Pennsylvanian strata in the central Appalachian basin. The shaded lower Pennsylvanian section of the Breathitt Group indicates the study interval. (Modified from Englund and Thomas, 1990; Chesnut, 1996; Greb and Chesnut, 1996; Korus, 2002; Greb and Martino, 2005)

Kentucky. The coal-bearing Bottom Creek and Alvy Creek Formations in Virginia, where accompanied in vertical succession by quartzose sandstones of the Middlesboro and/or Bee Rock Members are collectively included within the Lee Formation (Nolde et al., 1988; Nolde, 1994a). Towards the southeast margin of the central Appalachian basin in southwest Virginia, quartz sandstones of the Middlesboro and Bee Rock members pinch-out (Fig. 2). Correlation of proximal, coal-bearing facies in the absence of readily recognizable quartz sandstones is tenuous at best. The top of the Pocahontas Formation is placed at the top of the Flattop Sandstone Member (Nolde, 1994a), which also correlates with the base of the Pocahontas #8 coal bed (Englund, 1974). The interval of strata between the top of the Flattop Sandstone member and the top of the McClure Sandstone Member is classified as the New River Formation. The Flattop and McClure sandstone members are roughly laterally equivalent to the lower tongue of the Middleboro and the Bee Rock members, respectively (Nolde, 1994a).

Correlation into West Virginia

In Virginia, the New River Formation refers to coal-bearing units of the Bottom Creek and Alvy Creek formations that lack major quartzarenite bodies. To the northwest, where quartzarenite bodies are developed within coal-bearing strata, the term Lee Formation is used for time equivalent units (Nolde, 1994a). The New River Formation nomenclature is therefore of limited usage in Virginia because quartzarenites are absent only in eastern Buchanan and northeastern Russell counties and in coal-bearing parts of Tazewell County (Nolde, 1994a).

In West Virginia the New River Formation refers to coal-bearing units of the combined Bottom Creek and Alvy Creek formations of the Breathitt Group that comprise the southeastern facies belt (Korus, 2002). Major sandstone bodies in this belt include the Pineville, Lower Raleigh, Upper Raleigh, and Guyandot sandstone members. The northwestern facies belt is dominated by amalgamated quartzarenite bodies (Korus, 2002). Multi-storied to amalgamated sandstone bodies of the combined Warren Point and Sewanee Formations in Kentucky are informally known in West Virginia driller's terminology as the 'Salt Sands.' The quartzose Bee Rock Formation of Kentucky is correlated to the Nuttall Member in West Virginia.

Early Pennsylvanian Global Correlations

In an attempt to establish an international classification for the Carboniferous Period, the Mississippian and Pennsylvanian subsystems were subdivided by the Eighth International Congress on Carboniferous Stratigraphy and Geology (International Geological Congress, 1975; cf. Davydov et al., 2004), into early, middle, and upper periods. This subdivision allowed for the correlation of established Russian stages with stratotypes in North America (Davydov et al., 2004). In terms of Pennsylvanian global stages, the early and middle Pennsylvanian correspond to the international Bashkirian and Moscovian stages, respectively (Fig. 3; Davydov et al., 2004, p. 228). In this thesis, the international Bashkirian Stage will be referred to as its equivalent, the early Pennsylvanian, and the Moscovian Stage will be referred to as the middle Pennsylvanian.

In terms of western European stages, the base of the early Pennsylvanian is correlated to the base of the Namurian B Stage (Fig. 3). The early Pennsylvanian spans through the Westphalian B stage. The early – middle Pennsylvanian boundary is therefore placed at the Westphalian B – C boundary (Fig. 3; Groves et al., 1999). The base of the North American Morrowan Stage is placed at the Mississippian – Pennsylvanian systematic boundary and spans the Namurian B and C stages. The basal boundary of the overlying North American Atokan Stage is placed at the base of the European Westphalian A Stage. The early – middle Pennsylvanian boundary is therefore Lower Atokan in age (Groves et al., 1999; Davydov et al., 2004). In sum, the early Pennsylvanian time period, in terms of North American stages, spans the entire Morrowan and basal Atokan stages.

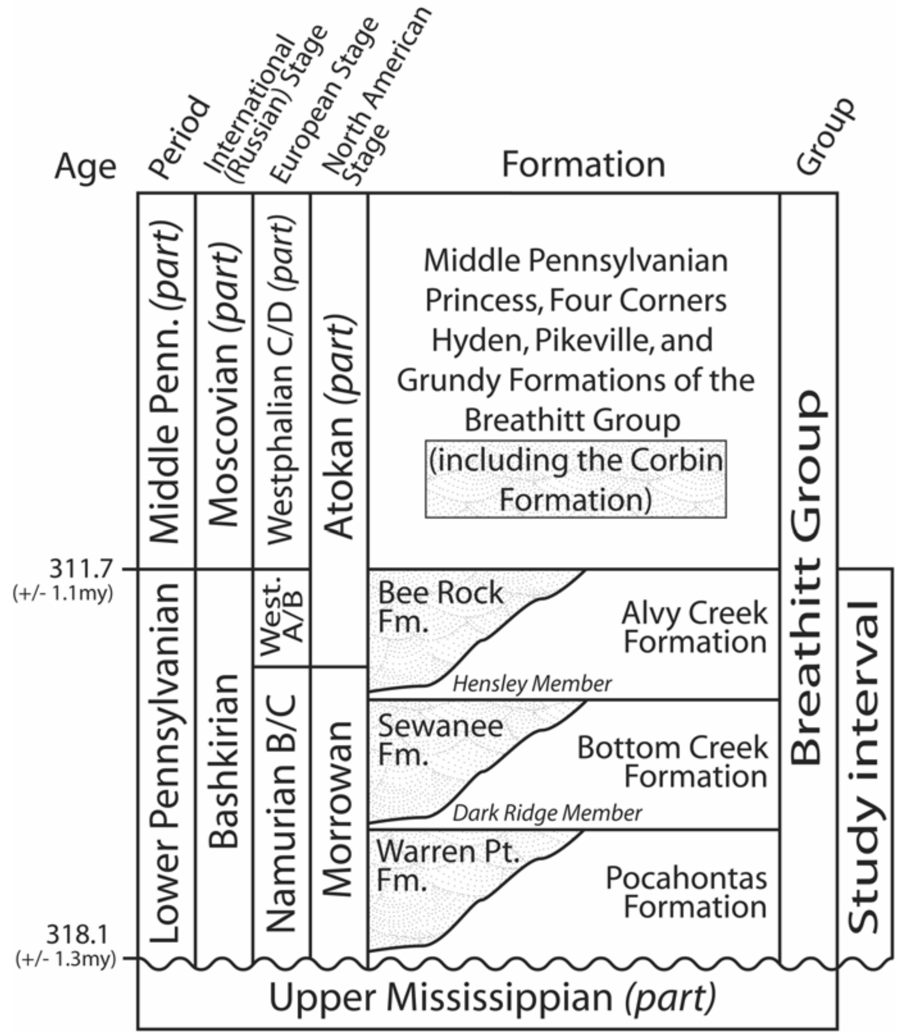


Figure 3: Relationship of lower and middle Pennsylvanian strata in the central Appalachian basin to period and global stage boundaries. Note the age estimates for the upper and lower boundaries of the early Pennsylvanian period (Bashkirian Stage) (Davydov et al., 2004). (Modified from Chesnut, 1994)

In many global Carboniferous successions, a prominent mid-Carboniferous unconformity is present (Davydov et al., 2004). This boundary has been widely attributed to a mid-Carboniferous eustatic lowstand lasting approximately 1.9 m.y. (Saunders and Ramsbottom, 1986). Based upon floral biostratigraphy from southern West Virginia, Beuthin (1994, 1997) suggested that the mid-Carboniferous unconformity is largely manifested as an upper Mississippian (Chokerian through Alportian stages of the Namurian A Series) hiatus in the central Appalachian basin, indicating that any earliest Pennsylvanian hiatus was minimal (Beuthin, 1997; Groves et al., 1999). The base of the Pennsylvanian system in the central Appalachian basin therefore occurs near the systemic mid-Carboniferous boundary, corresponding to the base of the Absaroka Sequence of Sloss (1963).

Based upon a suite of Carboniferous radiometric dates, Davydov et al. (2004, p. 246) applied a regression line to extrapolate the age of Carboniferous stage boundaries from existing age dates scattered throughout the Carboniferous. The base of the Pennsylvanian is estimated at 318.1 +/- 1.3 m.y., whereas the top of the early Pennsylvanian is estimated at 311.7 +/- 1.1 m.y., giving the early Pennsylvanian time period a duration of 4 – 8.8 m.y .with a mean of 6.4 m.y. (Fig. 3; Davydov et al., 2004). The duration of the entire Pennsylvanian Period is estimated at approximately 19 m.y. (Klein, 1990; Davydov et al., 2004).

Depositional Environments

As stratigraphic relationships became better understood, it was necessary to define a paleoenvironmental model to explain the lateral facies variability observed in outcrop and in the subsurface. It was important for models to take into account the perceived stratal relationships of Breathitt quartzarenites and juxtaposed coal-bearing siliciclastic strata, and underlying Upper Mississippian siliciclastic and carbonate strata. Ambiguity over the existence, and the position of a mid-Carboniferous unconformity relative to the Mississippian – Pennsylvanian systemic boundary gave rise to divergent paleoenvironmental interpretations.

Marine Model

Workers advocating a conformable relationship between the Mississippian and Pennsylvanian systems in the Appalachian basin (e.g. – Ferm and Cavaroc, 1969; Ferm, 1974; Horne et al., 1974) envisioned a time-transgressive environmental continuum between Mississippian and Pennsylvanian strata (Fig. 2). In this model, upper Mississippian limestones of the Slade Formation were interpreted as offshore carbonate build-ups whereas mixed siliciclastics of the Pennington-Mauch Chunk Group were interpreted as deeper-water and lagoonal mudstones. Pennsylvanian coal-bearing strata of the Breathitt Group were interpreted as fluvio-deltaic deposits built along the southeastern margin of a shallow cratonic sea. Pennsylvanian quartz sandstones were considered to be intermediate between offshore "Mississippian" marine units and fluvio-deltaic "Pennsylvanian" units. The well-washed character of the quartzarenites as well as their apparent parallel relationship to an inferred shoreline gave rise to their interpretation as barrier-bar deposits (Horne et al., 1974; Hobday and Horne, 1977). In this model, the terms "Mississippian" and "Pennsylvanian" were used in a lithostratigraphic sense only as the mid-Carboniferous boundary was considered to be diachronous (Horne et al., 1974). The boundary was therefore arbitrarily placed at the contact between "Pennsylvanian" barrier-bar quartzarenites and "Mississippian" marine units.

The above model gained popularity due to its seeming ability to predict lateral facies changes down the dip of the basin (Ferm and Cavaroc, 1969). However, further stratigraphic and sedimentological work began to reveal evidence of disconformity between the early Pennsylvanian quartz sandstones, and the underlying upper Mississippian mixed siliciclastics and carbonates. Subtle indicators of unconformities such as paleokarst and paleochannels along basement-activated structural highs (Haney, 1979; Rice and Schwietering, 1988), aided in the recognition of a widespread mid-Carboniferous hiatus. The recognition of such an unconformity temporally decoupled Mississippian "marine" units from Pennsylvanian "terrigenous" units, thus negating the proposed time-transgressive continuum (Chesnut, 1988).

Further studies have since identified a widespread unconformity at the base of the quartzose Warren Point Formation. When this surface is traced cratonward, it is found to truncate progressively older upper Mississippian strata to the west that were uplifted along the southeastern flank of the Cincinnati Arch. Near the Virginia – Kentucky border, this truncation has completely removed the upper Mississippian Bluestone Formation such that basal Pennsylvanian quartz sandstones of the Warren Point Formation directly overly the basal Pride Shale Member of the Bluestone Formation (Englund, 1979). This progressive truncation continues into eastern Kentucky where further truncation is manifested as Pennsylvanian quartz sandstone belts directly overlying early Mississippian units. When this contact is traced to the southeast into more axial positions in the basin, it is found to overlie the early Pennsylvanian Pocahontas Formation of the Breathitt Group. Based on this observation, the unconformity is early Pennsylvanian in age (Chesnut, 1991). Cratonward, where the Pocahontas Formation wedges out in the subsurface, the unconformity is projected at the level of the Mississippian - Pennsylvanian systemic boundary. Many workers maintain that the systemic boundary between the early Pennsylvanian Pocahontas Formation and upper Mississippian Bluestone Formation is intertonguing and conformable in southeastern areas of the basin (Miller, 1974; Englund, 1979).

Despite an improved stratigraphic framework, the origin of Pennsylvanian quartz sandstone belts continued to be debated. Studies advocating a barrier-bar depositional environment for the Pennsylvanian quartz sandstones (e.g. Englund, 1974; Ferm, 1974; Horne et al., 1974; Miller, 1974; Hobday and Horne, 1977; Englund, 1979; Englund et al., 1986) suggested that sediment was derived from the southeasterly Alleghanian orogen and reworked in an epicontinental marine environment, herein referred to as the "marine" model. The mid-Carboniferous unconformity resulted from the subaqueous and/or subaerial reworking of the Upper Mississippian / Pocahontas surface that was uplifted following the deposition of the Pocahontas Formation (Englund, 1979; Chesnut, 1991). After the development of the mid-Carboniferous unconformity, barrier quartz sandstones continued to be deposited throughout the early Pennsylvanian as dictated by periodic eustatic still-stands and shoreline stabilization (Englund et al., 1986). Similar alternatives to the marine model include reworking of quartz sands into shoreline-parallel tidal channels or in an ocean straits environment (Cecil and Englund, 1985). Variations of the marine model share commonalities of a southeasterly (orogenic) sediment source area with re-working in a nearshore marine environment influenced by overall southwesterly longshore drift or ebb-dominated southwesterly tidal flow (e.g. Hobday and Horne, 1977).

The marine model was highly popularized due to the seeming appropriateness of quartzose barrier-bars aligned orthogonal to the inferred fluvio-deltaic siliciclastics (Englund et al., 1986; Englund and Thomas, 1990). However, opponents to the “marine” model cited various lines of sedimentological evidence that would contradict the “marine” model in favor of a fluvial model for Early Pennsylvanian quartzarenite belts.

Fluvial Model

Many lines of field-based evidence contradict the notion of a marine origin for Pennsylvanian quartz sandstone formations in favor of a terrigenous/fluvial model. These observations include: channelized scour and fining-upward channel-fill sequences (Wizevich, 1992), unidirectional southwesterly paleocurrents (Chesnut, 1988; Rice and Schwietering, 1988; Wizevich, 1992), large basal bedforms, atypical of tidal processes (Rice, 1984), ubiquitous basal quartz-pebble conglomeritic lags (Bement, 1976; Rice, 1984), paucity of shelly body fossils (Miller, 1974; Wizevich, 1992), atypically steep gradients for a barrier-bar environment (Chesnut, 1988), *in-situ* tree roots, abundant plant debris, and close association with peat deposits (Wizevich, 1992).

Prior to the late Mississippian, southerly-flowing river systems, draining from the southern Canadian Shield (Rice, 1985), were diverted cratonward west of the Cincinnati Arch. These river systems carried a coarse quartz-rich bed load and were largely funneled through the Eastern Interior basin via the Sharon-Brownsville paleovalley (Rice and Schwietering, 1988). In the latest Mississippian, during the onset of Alleghanian orogenesis, the downwarping of the Appalachian basin was accompanied by uplift of the Cincinnati arch (Quinlan and Beaumont, 1984). Headward erosion along the northwest margin of the uplifted Cincinnati arch captured these northwesterly fluvial systems and diverted drainage into a rapidly subsiding early Pennsylvanian depocenter in the central Appalachian basin. Rapid aggradation deposited quartzose sandstone bodies axially along the western margin of the Appalachian basin (Rice and Schwietering, 1988). Deposition of these fluvial sandbelts continued until the early stages of the middle

Pennsylvanian when the topographic low of the Appalachian trough was alluviated and abandoned (Rice and Schwietering, 1988).

In sum, the fluvial model suggests that lithologically diverse sediment was introduced into the basin from two source areas. Quartz sand and gravel were introduced from a northerly cratonic source, whereas texturally and mineralogically immature coal-bearing molasse including feldspathic and/or micaceous sandstones, were derived from the low-grade metamorphic terrain of the Alleghanian orogen to the southeast (Greb and Chesnut, 1996). Recent studies in the central Appalachian basin have sought to understand the stratal relationships of quartzose sandbelts with coal-bearing units within the Breathitt Group. Understanding the stratigraphy and extrabasinal processes dictating stratal architecture has proven crucial in developing a predictive model to understand the basin-wide coal bed quality, distribution, and mine roof conditions. Many recent workers now support a model which integrates the two source areas.

Trunk – tributary model

A trunk – tributary model depicts the interaction of two fluvial systems draining contrasting terrains. During lowstands of sea level, tributary fluvial systems draining the Appalachian fold and thrust belt to the southeast flowed westerly (Rice and Schwietering, 1988) eventually merging into large bedload-dominated trunk streams carrying a quartzose bedload and flowing down the axis of the Appalachian foreland from a northerly cratonic terrain toward the southwest (Archer and Greb, 1995; Greb and Chesnut, 1996; Korus, 2002). During subsequent sea level rise, these fluvial systems were transgressed, drowning both incised trunk and tributary river valleys, and forming estuaries (Greb and Chesnut, 1996; Korus, 2002; Greb and Martino, 2005). Following drowning, bay-head deltas prograded into estuaries at highstand to form coarsening-upward deltaic successions capping coal-bearing estuarine and marginal marine facies (cf. Petersen and Andsbjerg, 1996; Korus, 2002). Bay-head delta formation was followed by relative sea level fall beginning the next eustatic cycle.

Recognition of the above facies successions has resulted in many questions concerning driving forces on relative sea level oscillations in the Appalachian basin. Some workers have cited tectonic (subsidence) related cyclicity (Tankard, 1986) whereas others have advocated orbitally driven glacial cycles (Milankovitch cycles). Chesnut (1994) advocates a combination of glacially driven eustatic cycles superimposed on periodic tectonic subsidence. A more complete understanding of spatial and temporal relationships between tributary and trunk facies will help to better understand controls on stratal architecture.

Sequence Stratigraphy

Whereas much earlier work in the Carboniferous of the central Appalachian basin was directed towards understanding large-scale stratigraphic relationships and associated depositional environments, recent worked has focused on explaining observed stratal relationships in a sequence stratigraphic framework. Coal-bearing cyclic depositional packages, or ‘cyclothems’, have long been recognized in the Pennsylvanian system of the Appalachian basin (e.g. Weller, 1930; Wanless and Shepard, 1936) and have been described in both a genetic and depositional context. Chesnut (1994) described cyclothems, or ‘coal-clastic’ cycles in a genetic context (e.g. Galloway, 1989) by identifying major coal beds and closely associated marine flooding zones. A typical genetic cyclothem succession begins at the top of a major coal bed and is overlain by a coarsening upward succession of mudstone, heterolithic, and sandstone. This coarsening-upward package is in turn overlain by a fining-upward succession typically beginning with an interval of cross-bedded sandstone fining upwards to a rooted paleosol and accompanying overlying coal that marks the top of the genetic cyclothemic succession (Chesnut, 1994). A widespread disconformity, often demarcated by an erosionally based, channel-fill sandstone or interfluve paleosol commonly separates the coarsening-upward package from the fining-upward package (Chesnut, 1994). Other workers (e.g. Klein and Willard, 1989; Aitken and Flint, 1994, 1995; Heckel et al., 1998), citing this aforementioned widespread disconformity separating coarsening- from fining-upward successions, described cyclothems in a depositional framework where cyclothemic successions are bound by sequence boundaries at the bases of fluvial sandstone bodies interpreted as incised valley fill deposits.

In reference to a genetic approach, mapping throughout the Appalachian basin has revealed the occurrence of widespread marine horizons throughout the Breathitt Group.

Seven major marine zones have been identified and used to subdivide the Breathitt Group into eight formations of approximate equal thickness (Chesnut, 1994; Greb et al., 2004). Based on a suite of age estimates for the top and base of the Breathitt Group, Chesnut (1994) estimated the duration of flooding surface-demarcated 'major-transgression cycles' within the Breathitt Group to be approximately 2.5 m.y. in duration. Within these flooding-surface-bounded packages, five to six 'coal-clastic cycles' (Chesnut, 1994) were recognized (Greb et al., 2004). Based upon a 2.5 m.y. estimated duration for major-transgression cycles, coal-clastic cycles were estimated to be approximately 400 k.y. in duration. Cycles of 2.5 m.y. duration were attributed to post-tectophase marine incursion following episodic thrust-loading-induced foreland subsidence in the Alleghanian orogen. Coal-clastic cycles with an estimated 400 k.y. duration correspond to long-term Milankovitch orbital eccentricity cycles (Plint et al., 1992; Read, 1995). In sum, two orders of hierarchical depositional sequences were identified based upon a hierarchy of flooding surfaces. Coal-clastic cycles correspond to 4th-order orbital eccentricity cycles. These 4th-order cycles are found to comprise tectonically induced 3rd-order composite sequences. In general, lowermost 4th-order sequences of the 3rd-order composite sequence tend to be fluvial-dominated whereas uppermost 4th-order sequences tend to be estuarine-dominated (Korus, 2002). Lowstand, transgressive, and highstand 4th-order sequence sets have been identified based on the amount of incision, stacking of basal valley-fill sandbodies, and amount of fine-grained facies preserved within a sequence (Aitken and Flint, 1995). Pennsylvanian stratal architecture in the Appalachian basin is therefore attributed to glacio-eustasy superimposed on periodic thrust-loading-induced subsidence (Chesnut, 1994; Greb et al., 2004).

METHODS

Many studies of the Carboniferous rock record in the Appalachian basin have sought to reconcile broad structural and stratigraphic relationships on a basinwide scale. Such studies have typically utilized borehole data from adjoining states in constructing cross-sections through the Appalachian basin (e.g. Tankard, 1986; Chesnut, 1994; Greb and Chesnut, 1996; Korus, 2002). This study focuses on a single county in southwestern Virginia (Fig. 4) to investigate, on a local scale, the stratigraphic and genetic relationships between quartz sandstone formations and coal-bearing formations of the Breathitt Group Dickenson County is ideally suited for this study because it is located along the southeastern margin of the central Appalachian basin. Dickenson County has been a location of conventional gas recovery since the middle of the 20th century and, in recent years, has been further developed as a site for coal bed methane production. Extensive natural gas development in the area has provided for a dense framework of tightly-spaced borehole data points. In this study, a suite of approximately 75 coal bed methane and conventional gas wells distributed throughout Dickenson County were utilized.

This study is based on wire-line logs complemented by a complete (~1,800') core with accompanying gamma and density log data through the entire lower Pennsylvanian section. Hereafter, this will be referred to as the 'core log.' Within the core itself, mineralogy, grain-size trends, and physical and biogenic structures have been recorded and coordinated with gamma ray motifs observed in the corresponding log (Appendix A). This core log was further incorporated as an intersection log such that it is included within both a dip- and strike-oriented cross-section. The lithologic features observed and recorded in the core (Appendix A) were used to determine and/or affirm the position of flooding surfaces, sequence boundaries, and fining- and coarsening-upward successions.

While conventional gas and coal bed methane well logs have proved to be different, each comes with distinct advantages and disadvantages. Whereas both conventional gas and coal bed methane wells have complete gamma ray logs, coal bed methane wells also have density logs that can be utilized to identify coal beds. Many Pennsylvanian coals are laterally pervasive and extensively mined beyond the scope of the study area, and therefore serve as a set of isochronous marker beds that can be used for correlating and constraining cross-sections. The limited total depth of coal bed methane wells is, however, a drawback. Oftentimes coal bed methane wells were not of sufficient depth to capture the entire study interval. Lowermost Pennsylvanian coals as well as the top of the underlying upper Mississippian surface are often not penetrated by the well borehole leaving gaps in the borehole data near the often controversial Mississippian-Pennsylvanian contact. In contrast, conventional gas well logs typically extend into the latest Devonian Berea Sandstone. These logs have complete gamma ray data throughout the Pennsylvanian and Mississippian sections, making imaging of the

Mississippian-Pennsylvanian contact possible. This is accomplished through the recognition of diagnostic gamma ray log motifs associated with upper Mississippian units such as the Princeton Formation and overlying Pride Shale. However, conventional wells typically do not have density log data within the Pennsylvanian sections, inhibiting the recognition of coals. Constraining the stratigraphy of the Mississippian – Pennsylvanian contact as well as the early Pennsylvanian section was made possible through the integration of both conventional gas and coal bed methane well logs.

Construction of cross-sections

In this study, four cross-sections were constructed in transects across Dickenson County (Fig. 4). Each cross-section contains between 14 and 18 data points with log spacing averaging 0.5 to 1.0 miles. Two cross-sections were oriented approximately parallel to basin strike (transects A – A', and B – B' on Fig. 4), whereas two cross-sections were oriented along transects parallel to the dip of the basin (transects X – X' and Y – Y' on Fig. 4). The cross-sections were arranged such that they intersect at common well data points. The marine flooding zone within the early Pennsylvanian (Hensley Member) has been used as a datum from which to hang logs in each cross-section. This well-constrained datum has been placed atop the Sewanee Formation closely associated with the Upper Seaboard coal bed.

LOWER PENNSYLVANIAN - DESCRIPTIONS

Facies

Facies descriptions are based on observations made from the continuous core through the study interval (Fig. 2). Figure 5 illustrates logs of representative intervals from this core. The following descriptions are based mostly on these logs but also incorporate observations from other sections of the core.

Quartz-pebble conglomerate

Quartz-pebble conglomerates are light- to medium-gray in color and occur in thin (1-3 ft), sharp-based beds (Fig. 6a). These conglomerates are typically found as coarse-grained concentrations within quartzarenite bodies. Quartz is the dominant pebble lithology with pebble size typically ranging from 0.25 – 0.5 inches in diameter. Overall, quartz-pebble conglomerates are grain-supported with a quartzose, medium-grained sand to granule matrix. Heavy minerals are a common matrix constituent and define distinctive horizons. Sedimentary structures are generally lacking such that this facies is typically massive. Some discreet (0.5 – 1 inch) thick beds show weak, graded bedding. Gamma ray values of quartz-pebble conglomerate intervals are similar to bounding lithologies.

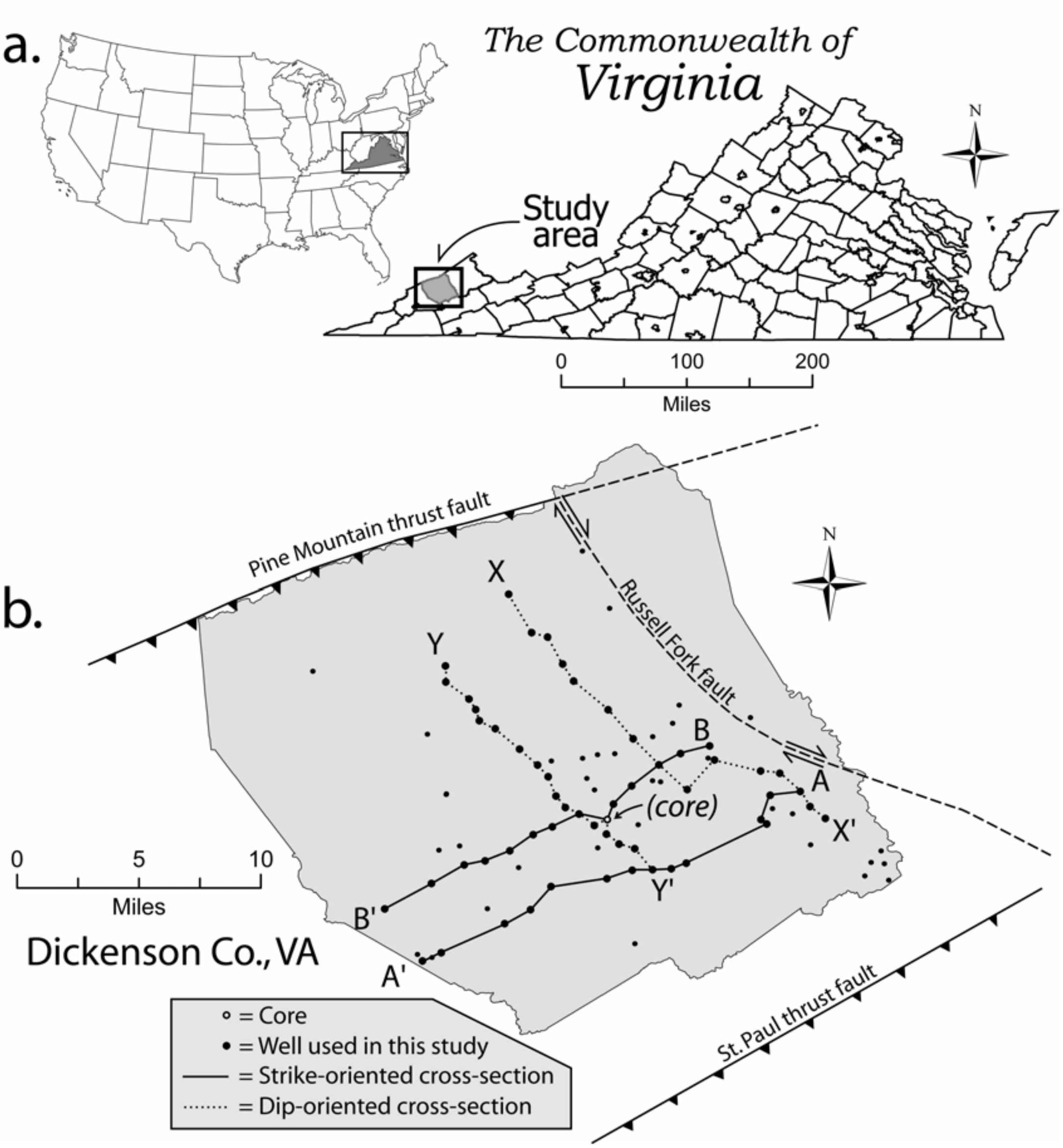


Figure 4: a) Study area map showing the location of Dickenson Co., Virginia. b) Map of Dickenson Co., Virginia, indicating the location of well data points including the core log, strike-oriented cross-sections (A – A' & B – B'), dip-oriented cross-sections (X – X' & Y – Y'), and major faults.

Siderite-pebble conglomerate

Siderite-pebble conglomerates occur as thin (less than 1 ft), sharp-based beds typically at or near the base of sublitharenite bodies (Fig. 6b). Siderite pebbles are 0.25 – 0.5 inches in diameter, are sub-angular to sub-rounded and typically elongate. Pebbles are medium-brown to brown-orange in color and occur in a medium-gray sublitharenite matrix. Siderite-pebble conglomerate intervals are structureless and massive. In general, both siderite- and quartz-pebble conglomerates are sufficiently thin as to not provide a diagnostic gamma ray response. Gamma ray values of siderite-pebble conglomerate intervals are similar to bounding lithologies.

Quartzarenite

Quartz–rich sandstones and intercalated quartz-pebble conglomerate beds are diagnostic constituents of the quartzose Warren Point, Sewanee, and Bee Rock formations. Of these three formations, the Warren Point and Sewanee formations are contained within the studied core. Petrographic studies by Reed (2003) and Reed et. al. (2005) on the Upper Raleigh Sandstone Member of the New River Formation in Raleigh County, southern West Virginia allow for a comparison with the correlative Sewanee Formation in the study area. The Upper Raleigh Sandstone Member is a quartzarenite (*sensu* McBride, 1963; Dott, 1964) consisting of 96% quartz, 3% lithics, and 1% feldspar (average of 21 samples). The quartz fraction consists predominantly (>95%) of monocrystalline quartz.

Quartzarenites are white to light gray in color (Fig. 6c) and occur as 30 – 50 ft thick beds that are cross-bedded in core. Sharp basal contacts typically are defined by quartz-pebble conglomerate and/or pebbly quartzarenite often containing coal and/or mudstone rip-up clasts (Fig. 6d). Quartzarenites are characterized by a distinctive low, blocky gamma-ray signature with a well-defined sharp base. In general, quartzarenite bodies become ‘dirtier’ upward as fines and immature mineralogic constituents increase. The upper parts of quartzarenites often consist of interbedded quartzarenite and heterolithic facies. This ‘dirtying’ or ‘muddying’ upward is manifested as a gradual increase in gamma ray value towards the top of the quartzarenite units (Fig. 5).

Sublitharenite

Lithic sandstones are abundant throughout the coal-bearing units of the Pocahontas, Bottom Creek, and Alvy Creek formations of the Breathitt Group. Petrographic studies on two litharenite intervals by Reed (2003) and Reed et al. (2005) in Buchanan County, Virginia provide a basis for estimating framework grain composition in correlative sandstones in adjacent Dickenson County, Virginia. The first sublitharenite is referred to as the Council Sandstone and is present below the Jawbone Coal zone whereas the second litharenite is laterally correlative to the Bee Rock quartzarenite and may represent the McClure Sandstone that is typically present above the Aily Coal bed. Petrographic analysis of 13 samples reveals that the samples are sublitharenites (*sensu* McBride, 1963; Dott, 1964) consisting on average of 77% quartz, 15% lithics and 8% feldspar. The quartz fraction is predominantly monocrystalline quartz whereas sedimentary and metamorphic clasts dominate the lithic fraction. Feldspar consists nearly exclusively of potassium feldspar.

Sublitharenites are medium gray in color along fresh surfaces (Fig. 7a) and typically occur as 10 – 50 ft thick beds of fine- to coarse-grained sandstone that display cross-bedding in core. These sandstone units contain siderite lags with or without mudstone and coaly rip-ups and, like quartzarenites, typically have sharp bases (Fig. 7b). Rare internal reactivation surfaces are defined by coaly stringers, muddy interbeds and rooted horizons. Sublitharenites are developed in sharp-based, fining-upward intervals up to 60 ft thick, and as 5 – 10 ft-thick units that display gradational upper and lower contacts within finer-grained facies. Thicker sublitharenite intervals are characterized by a medium-low, sharp-based, blocky gamma ray motif that, like quartzarenites, increase upward as the sandstone bodies become muddier (Fig. 5). The thinner sublitharenite units typically display gradational upper and lower contacts (Fig. 5).

Sandy and muddy heterolithic

The term heterolithic is used to describe facies that contain discernable quantities of interlaminated sandstone, siltstone, and mudstone. A heterolithic distinction is prefaced by ‘sandy’ if a given sample contains greater than 50% sandstone with subordinate amounts of mudstone and ‘muddy’ if it contains greater than 50% mudstone with subordinate amounts of sandstone. Sandy heterolithic facies are light- to medium-gray with dark-gray muddy interbeds, whereas muddy heterolithic facies are dark- to very dark-gray with light- to medium-gray sandy intervals (Figs. 7c and d). Heterolithic facies are found within intervals of mudstone, carbonaceous mudstone and coal, and occur intercalated within 30 – 100 ft thick fine-grained intervals between quartzarenites and/or sublitharenites.

Sandy heterolithic facies are characterized by flaser and wavy bedding (Fig. 7c), and rhythmic graded beds (Fig. 8). Planolites are rarely observed within mudstone interbeds. Muddy heterolithic facies are characterized by lenticular to wavy bedding and, in common with sandy heterolithic facies, also display local rhythmic graded bedding. Muddy heterolithic facies locally contain abundant plant debris and burrows including planolites (Fig. 7d).

The gamma ray response of heterolithic facies is highly dependent on the amount of mudstone present within a given interval. Sand-dominated heterolithic facies are characterized by a moderate gamma ray response whereas mud-dominated heterolithic facies are typified by a moderate to high gamma ray response. Common interbedded sandy and muddy heterolithic facies are expressed as a medium to medium-high serrated, or 'saw-toothed,' gamma ray motif (Fig. 5).

Mudstone and carbonaceous mudstone

Mudstone occurs as 1 – 30 ft-thick beds, whereas carbonaceous mudstone occurs as 1 – 3 ft-thick beds and is typically closely associated with coal. Both mudstone varieties are typically intercalated with thin heterolithic facies as described above. Mudstones are dark-gray to very dark-gray in color and typically contain abundant scattered plant debris**,** siderite bands or nodules, and coaly streaks. Carbonaceous mudstones are very-dark gray to almost black and contain abundant plant debris and common coaly streaks. Where closely associated with coal, carbonaceous mudstones are frequently cleated.

Mudstones are characterized by moderately-high to high, fairly uniform, gamma-ray responses whereas carbonaceous mudstones, if sufficiently thick to register a gamma reading, are represented by a sharp, high reading or 'hot kick'(Fig. 5). Typically carbonaceous mudstones are insufficiently thick to register a gamma ray response in which case gamma ray values are similar to vertically adjacent mudstones.

Coal

The core evaluated in this study was drilled in part to assess the desorbed methane content of approximately 20 economically significant lower Pennsylvanian coal beds. As a result, coal beds greater than 3" thick were removed for analysis and excluded from the 'complete' core. Many coal beds are of insufficient thickness to register a gamma ray response. In these instances, coal adopts a similar gamma value to bounding lithologies. Coal beds greater than a few feet in thickness (i.e. Pocahontas #5, Jawbone, and Jawbone Rider coal (see Appendix A)) are characterized by a low gamma spike that is distinguishable from juxtaposed mudstone and/or carbonaceous shale. Coal beds are best identified by means of the bulk density log and are characterized by an exceeding low spike.

Based on the thickness of missing core, coupled with the density log for the 'complete' core, most coal beds in the study interval range in thickness between 0.5 and 2 feet. However, thicker coal beds include the Pocahontas #5 (5 ft), Jawbone (6 ft), and Jawbone Rider (5 ft) (see Fig. 5, and Appendix A). Some of the thinner (less than 0.5 ft) coals are developed within thick, sharp-based quartzarenite or sublitharenite bodies. Most thicker, and therefore more economically viable, coals are found within finer-grained facies preserved between the sandstone bodies.

Coal beds and carbonaceous mudstones are typically interbedded within intervals of mudstone and muddy heterolithic facies and represent *in situ* accumulations of organic matter (cf. Hampson et al., 1999). Underlying mudstone facies are characteristically rooted, contain coaly stringers, ubiquitous plant debris, and commonly show signs of pedogenesis including blocky soil structure. Overlying facies, though lithologically similar, are not rooted and lack evidence of soil structure. In some instances, coal beds are sharply overlain by a sharp, erosionally based quartzarenite or sublitharenite. In these cases, coaly rip-up clasts are often present at the base of overlying sandstone bodies (Fig. 6d).

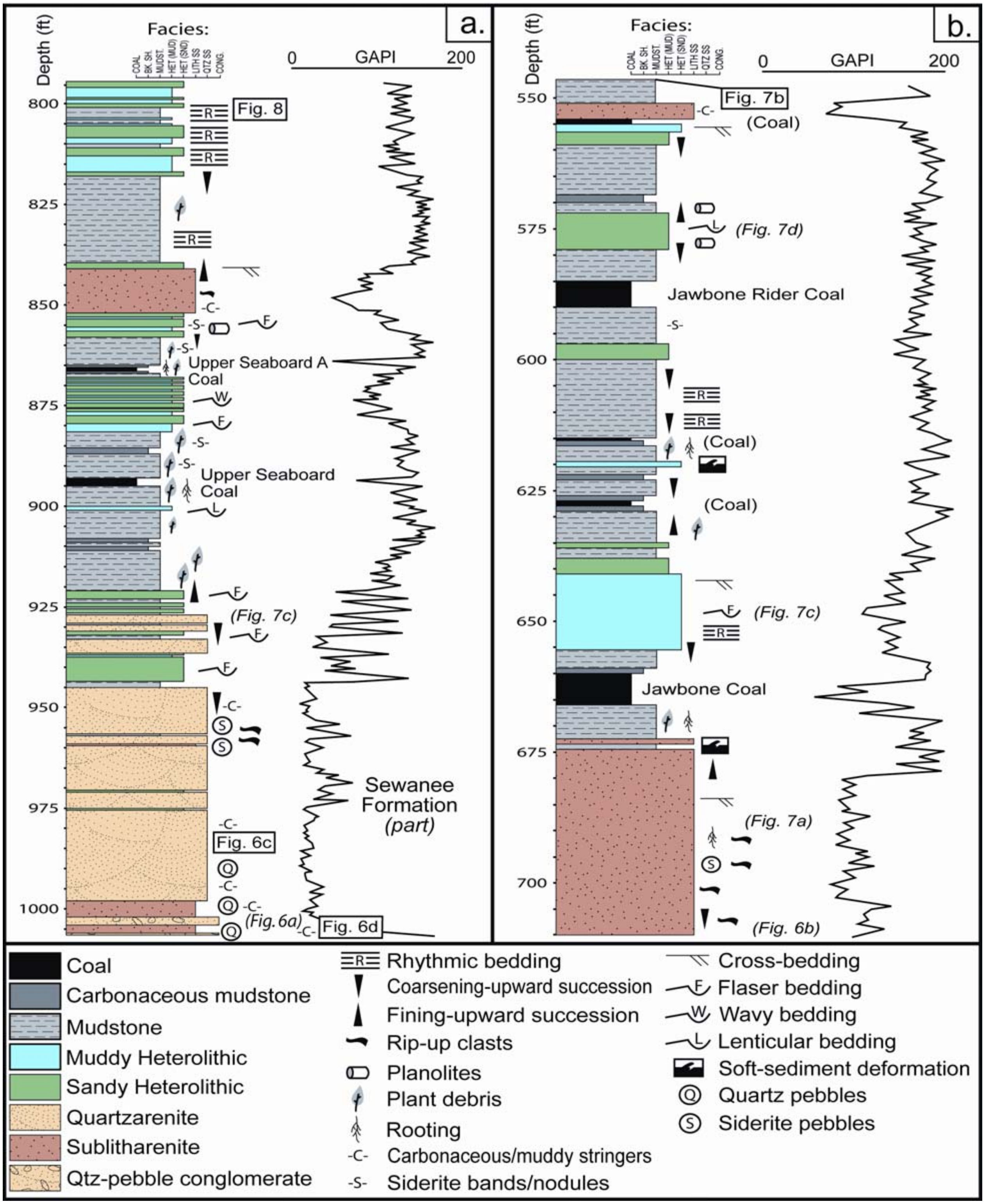


Figure 5: Representative log intervals from core descriptions including facies, sedimentary structures, selected nomenclature, and gamma ray curve. Boxed figure references indicate actual core samples photographed from representative log intervals. Figure references in italic parentheses indicate the likely occurrence of a given facies and/or structure within a comparable vertical succession. a) Quartzarenite-based log interval. b) Sublitharenite-based log interval.

Coals of the southwest Virginia coal field are ranked as high-volatile bituminous. Lower and middle Pennsylvanian coals average between 1.9 to 48.60 percent ash, and 0.4 to 5.2 percent sulfur (Wilkes et. al., 1992; *in* Nolde, 1994b)). More specifically, lower Pennsylvanian coals including the Pocahontas #3, Cove Creek (Pocahontas #7), Tiller, Jawbone / Jawbone Rider, Raven, and Aily coal beds range from 5.88 – 21.28% ash with a mean of 10.94%, and 0.56 – 0.84% sulfur with a mean of 0.72% (Wilkes et. al., 1992). In general, sulfur content of southwest Virginia coals averages 1.1% with typically less than 10% ash content (EIA, 1994), making lower Pennsylvanian Virginia coals amongst the highest quality in the Appalachians (Milici and Campbell, 1997).

Facies successions

Cursory examination of the core log (Fig. 5 and appendix 1) reveals gamma-ray log patterns that are predictable and vertically repetitive. Several gamma ray characteristics, such as abrupt 'shoulders,' and 'spikes,' in addition to increasing- and decreasing-upward trends, provide a diagnostic gamma signature that corresponds to a particular lithofacie or vertical succession of lithofacies.

In the following section, characteristic gamma ray motifs will be discussed in relation to core descriptions. The most apparent gamma ray response throughout the core log is that of abrupt 'shoulders' at the base of quartzarenites and sublitharenites. Both of these sandstone lithologies produce a diagnostic abrupt decrease in gamma values relative to underlying finer-grained facies. Quartzarenites are characterized by noticeably lower gamma values and therefore a more drastic negative deflection.

Fining-upward successions

Both quartzarenite and sublitharenite sandstone bodies become finer-grained upwards from coarse sandstone and/or conglomeratic facies to sandy heterolithic facies (Fig. 5a, 1007 – 893 ft; and Fig. 5b, 710-660 ft). This gradation is manifested as a gradual increase in gamma ray values. The transition from arenilitic to sandy heterolithic facies is often gradational resulting in a jagged or 'saw-toothed' gamma ray response. Continued fining-upward is recorded by a gradational facies change from sandy heterolithic to muddy heterolithic to mudstone. The fining-upward succession typically is capped by thick mudstone intercalated with carbonaceous black shale and coal. If sufficiently thick, carbonaceous black shale is reflected by a high gamma-ray spike within mudstone facies with moderately high gamma-ray values.

Coarsening-upward successions

Coarsening-upward successions of facies commence above the coal-bearing mudstone facies (Fig. 5a, 893 – 794 ft; and Fig. 5b, 660 – 546 ft). A gradual decrease in gamma-ray value is associated with a progressive increase in coarser sediments. Whereas fining-upward successions tend to be similar and predictable in both thickness and facies progression, coarsening-upward successions are more variable. An idealized coarsening-upward succession progresses from muddy/carbonaceous facies to heterolithic facies to sublitharenite. In many instances, however, thinner, higher-frequency coarsening- to fining-upward intervals are observed within an overall coarsening-upward succession (e.g. Fig. 5a, 893 – 865, and 865 – 817). These thinner coarsening- to fining-upward intervals typically commence at the base of a mudstone that overlies a regionally persistent coal bed and coarsens upward to mixed heterolithic and/or sublitharenite facies. The interval then fines upward to mudstone typically characterized by abundant plant debris, rooting, and overlain by a laterally persistent coal bed. In general, up to two higher-frequency coarsening- to fining-upward intervals are developed within the overall broader coarsening-upward succession. In the core log, the degree of upward-coarsening, as well as the thickness of coarsening-upward successions, varies amongst superimposed successions.

Architectural elements

Based on the above discussion, stratal patterns in the core log correspond with predictable vertical successions of lithofacies. The association between gamma ray motifs and lithofacies recognized in the core log enables correlation to adjacent well locations that lack core data core data. In this way, cross sections have been constructed (Fig. 9a-d) showing the architecture of major building blocks that consist of associations of facies.

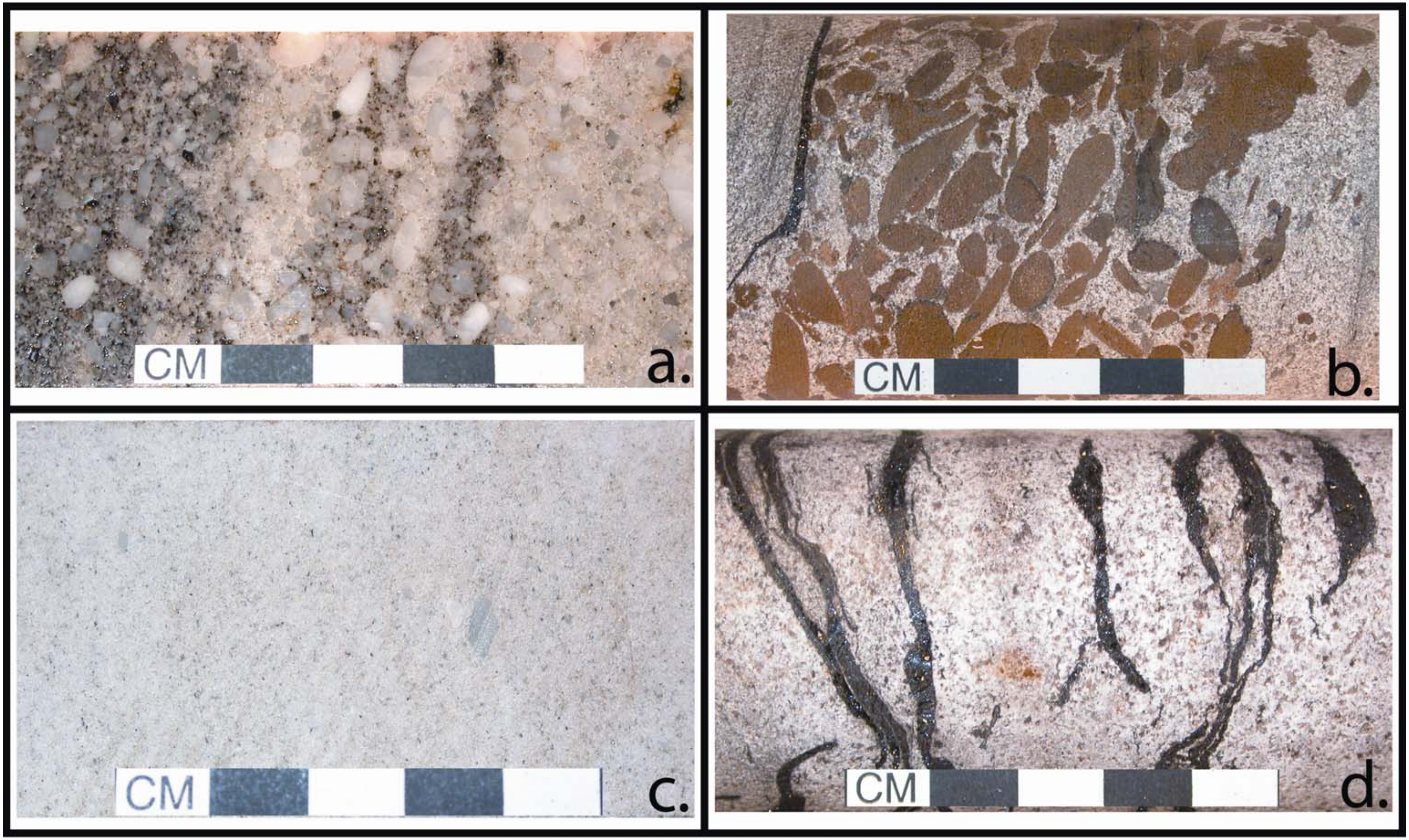


Figure 6: Core photographs of : a) Quartz-pebble conglomerate in a quartzarenite / heavy mineral matrix. b) Siderite-pebble conglomerate in a sublitharenite matrix. c) Quartzarenite. d) Quartzarenite with rip-ups derived from an underlying coal. The right side of each frame is the 'up' direction.

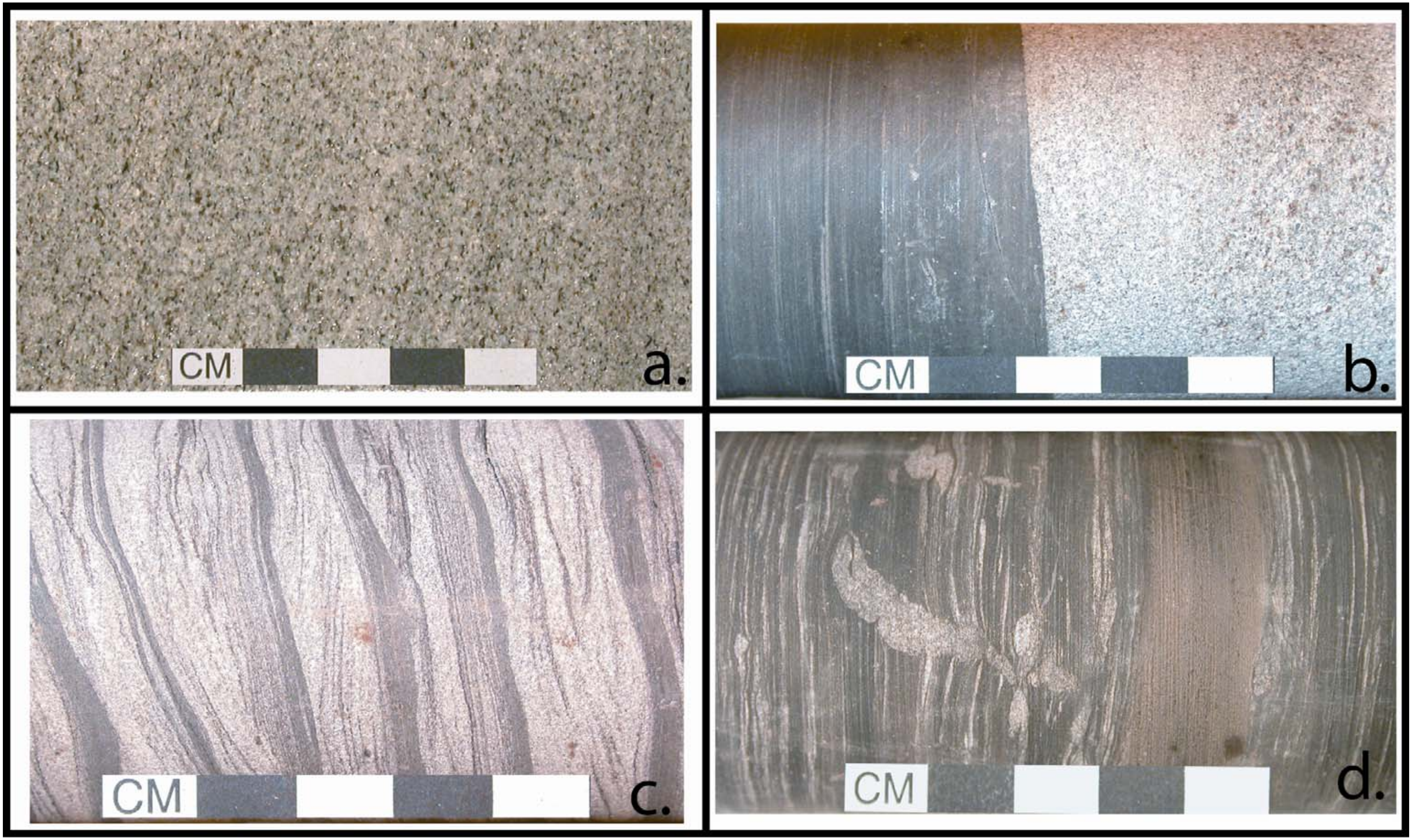


Figure 7: Core photographs of: a) Sublitharenite. b) Sharp contact between sublitharenite and underlying mudstone. c) Flaser-bedded sandy heterolithic facies. Note the rhythmicity of sand-shale couplets and mud drapes on crossbed foresets. d) Lenticular-bedded muddy heterolithic facies with planolites. The right side of each frame is the 'up' direction.

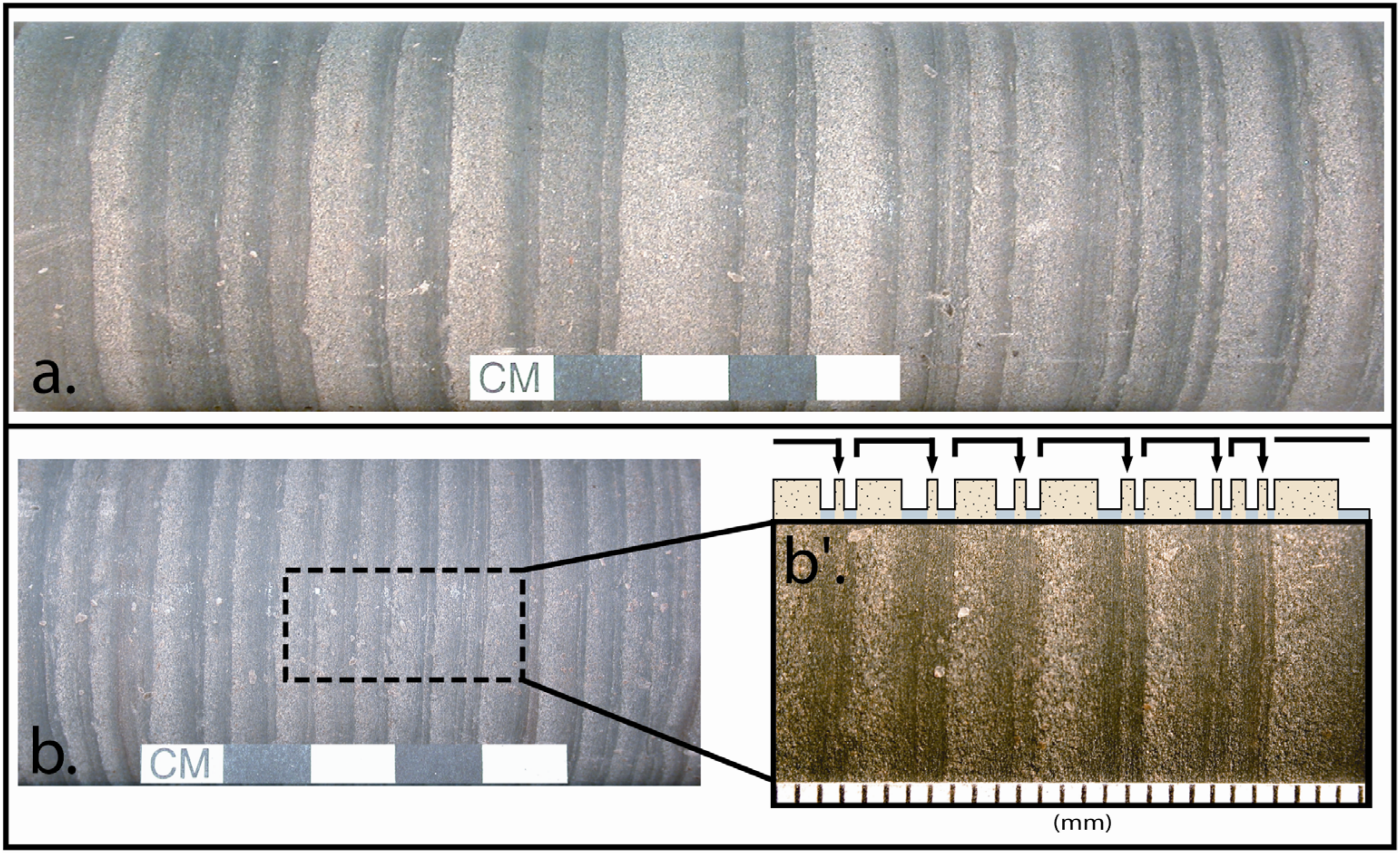


Figure 8: Core photographs of: a) Sandy heterolithic facies with thickening (left to center) and thinning (center to right) sets of graded beds. b) Sandy heterolithic facies with thick-thin couplets of graded beds. b') Magnification of thick-thin couplets within boxed area of Fig. 8b. Arrow-tipped brackets represent individual thick-thin couplets. The right side of each frame is the 'up' direction.

Sheet-like sandstone elements

These sandstone bodies are comprised exclusively of quartzarenite and are most prominent along the along the northwestern margin of the study area (cratonward) (Fig. 9c, d). The sandstone bodies have sharp bases characterized by conglomeratic lags and rip-up clasts, and display an overall fining-upward of grain size. Sheet-like quartzarenite sandstone bodies are tabular in cross-section, typically range from 50 – 100 feet in thickness, and are developed throughout the study area. These sheet-like quartzarenite bodies sharply overlie finer-grained facies including sandy heterolithic, muddy heterolithic, mudstone, carbonaceous mudstone, and coal. In rare instances, underlying finer-grained facies have been completely removed such that sheet-like quartzarenite bodies are amalgamated (Fig. 9a-d). The sheet-like sandstone bodies are gradational into overlying heterolithic facies.

Lenticular sandstone elements

These sandstone bodies typically range from 25 – 75 feet in thickness, 1 to over 10 miles in width, and consist of both quartzarenite and sublitharenite (Fig 9a-d). Lenticular quartzarenite sandstone bodies are most common along the northwestern margin of the study area (cratonward) whereas sublitharenite bodies are most prevalent toward the southeast (orogenward). Lenticular sandstone bodies are multi-lateral with quartzarenite and sublitharenite bodies occurring within common stratigraphic intervals. Similar to sheet-like sandstone bodies, lenticular sandstone bodies are characterized by sharp bases typically defined by conglomeratic lenses and rip-up clasts. Whereas quartz-pebble conglomerate and pebbly quartz sandstone comprises the coarse lag constituent of quartzarenite bodies, siderite-pebble conglomerate is characteristically developed at the base of sublitharenite bodies. In common with sheet-like quartzarenite bodies, lenticular sandstone bodies sharply overlie finer-grained faces and display fining-upward gradational tops. Where lenticular sandstone bodies wedge-out laterally into finer-grained facies, they are replaced by a broadly coarsening-upward succession of facies.

Upward-fining elements

Upward-fining architectural elements consist of sandy and muddy heterolithic, mudstone, carbonaceous mudstone, and coal facies that gradationally overlie both sheet-like and lenticular sandstone bodies (Fig. 9a-d). In addition, fining-upward successions directly underlie coarsening-upward successions where lenticular sandstone bodies are absent. Fining-upward successions are typically 10 – 20 feet thick, but can be as thick as 50 feet (Fig. 5a), and typically are capped by a regionally persistent coal bed.

Tabular mudstone-dominated elements

These elements typically overlie the fining-upward elements. This architectural element is variable in both lithology and thickness, but in general, consists of a 5 - 20 foot of mudstone and/or muddy heterolithic above a laterally persistent coal bed. Bases of these muddy intervals are typically gradational from coal, to carbonaceous black shale, to mudstone over an interval of a few feet. Upper contacts of these mudstone intervals are gradational into coarser heterolithic facies.

Upward-coarsening elements

Upward-coarsening architectural elements are the most spatially and temporally variable of the architectural elements. Coarsening-upward successions occur as tabular intervals of coal, overlain by carbonaceous mudstone, mudstone, heterolithic, and sublitharenite facies and typically overlie fining-upward successions. Coarsening-upward successions are highly variable in thickness and range from less than ten to 150 feet thick. In general, the thickness of individual coarsening-upward successions are consistent along the strike of the basin (Fig. 9a, b), and become thinner in a northwesterly dip direction (Fig. 9c, d). Higher-frequency, coarsening- to fining-upward intervals within the overall coarsening-upward succession are 10 – 50 foot thick, lenticular in cross-section and range from 1 to over 10 miles in width. The lenticular geometry of the higher-frequency intervals is dictated by the spatial and temporal extent of constituent coarse-grained facies. Where coarse-grained facies pinch-out laterally into muddier facies, fining- and coarsening-upward trends are not apparent within broadly coarsening-upward successions of muddier facies. Coal beds typically cap the fining-upward component of higher-frequency successions and are laterally persistent independent of the extent of the underlying coarse-grained facies. Coarsening-upward successions are truncated along sharp contacts at the base of overlying sheet-like or lenticular sandstone bodies.

Bounding discontinuities

Architectural elements identified on the cross sections (Fig. 9a-d) are defined by bounding discontinuities that are either erosional (unconformable) and depositional (condensed) (cf. Walker, 1992). Both major and minor erosional discontinuities can be recognized (Fig. 9a-d). These discontinuities can be traced laterally throughout the study area in both strike and dip directions. Minor discontinuities typically have comparatively large thicknesses of fine-grained facies preserved between the erosional discontinuity and the basal sandstone body of the underlying succession. In contrast, major discontinuities have comparatively less fine-grained facies preserved beneath them and, in rare cases, complete erosive removal of fine-grained facies results in the amalgamation of sandstone bodies.

Minor erosional discontinuities are best exemplified at the bases of lenticular sublitharenite bodies throughout most of the study interval, and at the bases of lenticular quartzarenite bodies in the northwest portion of the study area (Fig. 9a, b). In cases where a lenticular sublitharenite body pinches out laterally, it is often replaced in adjacent logs by a coarsening-upward succession. In these instances, the discontinuity is placed at the top of the coarsening-upward succession that typically corresponds with a regionally persistent coal (cf. Aitken and Flint, 1995; Greb at al., 2004). Major discontinuities are found at the base of the widespread, sheet-like quartzarenite bodies of the uppermost tongues of the Warren Point and Sewanee Formations (Fig. 9a-d). A similar hierarchy of major and minor discontinuities has been recognized in correlative strata of the central Appalachian basin (Fig. 1) by Aitken and Flint (1994; 1995) and Korus (2002).

In addition to erosional discontinuities, major and minor “marine zones” have also been identified in cross-section (Fig. 9a-d). The major marine zones correspond with the bottom three regional marine zones recognized in the Breathitt Group by Chesnut (1994). In the study area, the major marine zones are named the Dark Ridge and Hensley members at the base of the Bottom Creek and Alvy Creek formations, respectively (Fig. 3). These two marine zones extend to the northwest where they overly the Warren Point and Sewanee/Bottom Creek Formations, respectively (Figs. 3 and 9). A third unnamed marine zone occurs above the Bee Rock/Alvy Creek Formations (Fig. 3) and is assigned to the middle Pennsylvanian Grundy Formation of the Breathitt Group (Chesnut, 1994).

The major marine zones have been identified in cross-section based on their position above the major quartzarenite sheets of the uppermost tongues of the Warren Point and Sewanee Formations (Fig. 9). These marine zones occur as thick, coal-bearing intervals of mudstone and carbonaceous shale that locally contain planolites. In core, the upper marine zone (Hensley Member) is a thicker mudstone interval (up to 100 ft) than is the lower marine zone (Dark Ridge Member). However, gamma ray responses in adjacent logs indicate that the Dark Ridge Member is thicker elsewhere in the study area. The Pocahontas #9 and X Seam coal beds are closely associated with the Dark Ridge Member whereas the Upper Seaboard and Upper Seaboard A coal beds are present within the Hensley Member marine zone.

In addition to major marine zones, minor marine zones have been identified at the top of fining-upward successions that overlie minor discontinuities. Minor marine zones are thinner (25-75 ft) than major marine zones, and typically occur above sublitharenites as opposed to sheet-like quartzarenites. In common with major marine zones, the minor marine zones are characterized by associations of mudstone, carbonaceous shale, and coal. The thickest coals in the core log (Pocahontas #5, Jawbone, and Jawbone Rider) are associated with minor marine zones.

LOWER PENNSYLVANIAN – INTERPRETATION

Architectural elements - depositional environments

Sheet-like sandstone elements

The depositional environments of sheet-like quartzarenite bodies in the central Appalachian basin, as exemplified by the uppermost tongues of the Warren Point and Sewanee Formations of the Breathitt Group, have been much debated. 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) models have been proposed for these quartzarenite bodies. The provenance of quartzarenites has also been a subject of much debate. Advocates of the marine model suggest sediment derivation from a low-grade metamorphic terrain of the emergent Alleghanian orogen towards the southeast and reworking in a nearshore environment. Conversely, proponents of the fluvial model suggest that quartzarenites were derived from a northerly cratonic source and deposited by bedload-dominated braided streams flowing axially down the Alleghanian foreland.

Recent studies (e.g. Rice and Schwietering, 1988; Beuthin, 1994; Archer and Greb, 1995) have inferred broad northeast – southwest trending incised valleys at the bases of the major quartzarenite bodies, supporting a fluvial interpretation. Data from this study confirms the interpretations by Rice and Schwietering (1988) and Archer and Greb (1995) from elsewhere in the central Appalachian basin that sheet-like quartzarenite bodies in Dickenson County, Virginia were deposited in broad, low-sinuosity, bedload-dominated braided streams that flowed in a southwesterly direction along the axis of the Alleghanian foreland basin. Similar sandstones bodies in Kentucky were attributed by Wizevich (1992) to down-dip accretion of individual bedforms, macroforms, and channel-fill elements during high to waning flow stages. Coarse-grained conglomeritic lags associated with the bases of channels and reactivation surfaces are interpreted as lag deposits that accumulated in subaqueous scours or along longitudinal bars (cf. Miall, 1985). The sheet-like sandstone bodies are interpreted as major, incised valley fill deposits that developed as a result of incision and back-filling of valleys due to fluctuations in base level.

Lenticular sandstone elements

Lenticular quartzarenite bodies are texturally and mineralogically similar to sheet-like quartzarenites indicating a similar source area and depositional environment. Lenticular quartzarenite bodies are most prevalent along the northwest margin of the study area. Sublitharenite bodies of the Pocahontas, Bottom Creek, and Alvy Creek formations consist predominantly of quartz, but metamorphic fragments including mica schist are the second most common constituent (Reed 2003; Reed et al., 2005) and indicate a metamorphic provenance.

Lenticular sublitharenite bodies were derived from the low-grade metamorphic terrain of the Alleghanian orogen to the southeast. These sandstone bodies were deposited in bedload-dominated, multilateral, low-sinuosity channels of a transverse drainage system flowing to the northwest from the emergent Alleghanian orogen. The occurrence of quartzarenite and sublitharenite sandstone bodies above common erosional discontinuities indicates that transverse draining rivers merged into longitudinal draining rivers towards the northwest margin of the basin (Korus, 2002). Lenticular sandstone bodies are interpreted as minor, incised valley fill deposits that developed as a result of incision and back-filling of valleys due to fluctuations in base level.

Fining-upward elements

Both quartzarenite and sublitharenite sandstone bodies are upward fining, indicating waning flow conditions related to a decrease in gradient associated with base level rise. Continued base level rise resulted in back-flooding of incised valleys and the formation of estuaries. Sandy and muddy heterolithic facies (Fig. 7c, d) and rhythmically interbedded sandstones and mudstones (Fig. 8) are indicative of tidally influenced sedimentation, and marine incursion into a fluvial dominated environment (cf. Petersen and Andsbjerg, 1996; Greb and Martino, 2005). Coal beds that cap the fining-upward successions above the sheet-like and lenticular incised valley fills indicate widespread peat accumulation during the latest stages of estuarine infill. The presence of coal beds both above lenticular incised valley fills and, where lenticular incised valley fills wedge out laterally, above adjacent coarsening-upward successions indicates that extensive peat swamps developed above both incised valleys and adjacent interfluve areas implying that marine incursion was sufficient to back-flood both incised valleys and interfluves (cf. Shanley and McCabe, 1994).

Tabular mudstone-dominated elements

Laterally persistent coal beds that typically demarcate the top of the fining-upward successions are interpreted by Greb and Martino (2005) to have formed as topogenous and omborogenous peat mires that were established above estuarine facies in response to base level rise. Overlying 5 – 20 foot thick intervals of carbonaceous mudstone, mudstone, and muddy heterolithic facies record continued base level rise and drowning of peat mires (cf. Tibert and Gibling, 1999). These muddy facies often contain burrowing and abundant plant debris, and compare well with suspension deposits of the central basin region of estuaries described by Dalrymple et al. (1992).

Coarsening-upward elements

The broadly coarsening-upward elements are interpreted as the deposits of deltas that prograded into the Appalachian seaway towards the northwest during late stages of base level rise through early base level fall (cf. Korus, 2002; Greb and Martino, 2005). Coarsening- to fining-upward intervals developed within the overall coarsening-upward successions may be a product of intrinsic processes such as channel avulsion, delta lobe switching, and growth faulting The laterally restricted sandy heterolithic and/or sublitharenite facies that cap some coarsening-upward intervals represent distal bar, mouth bar, channel and/or beach deposits (cf. Coleman, 1976; Bhattacharya and Walker, 1992; Reading and Collinson, 1996; O'Mara and Turner, 1999). Overlying fining-upward intervals capped by coals are indicative of overbank and crevasse splay deposition followed by the establishment of peat mires on abandoned delta lobes (cf. Coleman, 1976). Accommodation necessary for peat accumulation was accomplished through localized transgressions driven by dewatering and compaction induced subsidence. Similar processes are observed in St. Bernard lobe of the modern Mississippi River delta where post-abandonment subsidence has led to gradual transgression (Coleman, 1976; Bhattacharya and Walker, 1992; Demko and Gastaldo, 1996). Stacked upward-coarsening to upward-fining intervals are related to further subsidence and reactivation of delta lobes.

Trunk-tributary relationships

Recent studies (e.g. Korus, 2002; Greb et al., 2004) have sought to explain the lateral relationships between quartzarenite and sublitharenite sandstone bodies. However, due to the broad scope of these studies, fine-scale stratigraphic relationships were not well constrained. This study is unique in that it incorporates a large dataset of wells within a limited area spanning the transition from quartzarenite facies along the northwest margin of the basin to sublitharenite facies towards the southeast.

Lenticular quartzarenite and sublitharenite sandstone bodies overlie common stratigraphic surfaces (Fig. 9c, d; Sequences: P4, P5, P8, B1, B2, B3, B5, & A4). Furthermore, where these two sandstone body types merge laterally, the gamma ray response indicates an intermediate sandstone composition or interfingering relationship between quartzarenite and sublitharenite sandstone bodies reflecting a gradational transition between the two sandstone facies. These observations indicate that quartzarenite, and laterally juxtaposed sublitharenite developed contemporaneously.

The quartzarenite and sublitharenite sandstone bodies were interpreted above as incised valley fill deposits of axial and transverse drainage systems, respectively (Korus, 2002). During base level fall, both axial and transverse streams down-cut to form trunk and tributary incised valleys. Subsequence base level rise back-filled both trunk and tributary streams with quartzose and sublithic bedloads, respectively. Continued base level rise formed estuaries above both trunk and tributary channels. The establishment of widespread peat mires above trunk, tributary, and associated interfluves indicates flooding of both channel and interfluve areas (Shanley and McCabe, 1994). Continued base level rise resulted in formation of peat mires and deposition of a succession of brackish to marine mudstone (cf. O'Mara and Turner, 1999; Van Heeswijck, 2001; Greb and Martino, 2005). During subsequent slowing of base level rise and early base level fall, deltaic deposits prograded over fluvial, estuarine, coal-bearing, and marginal marine facies. Deltaic deposits broadly coarsen upward whereas intercalated, thinner upward-coarsening and upward-fining intervals record autogenic processes such as delta switching and abandonment (e.g. - O'Mara and Turner, 1999). Continued base level fall initiated fluvial incision of coarsening-upward deltaic facies.

Overview of sequence stratigraphy

Sequence stratigraphy is defined as the study of chronologically significant frameworks of genetically related, unconformity-bound intervals of sedimentary strata (Van Wagoner et al., 1988; 1990). The basic building blocks of sequence stratigraphy are individual sequences, which are defined as relatively conformable, genetically related, and unconformity-bound successions of strata (Mitchum, 1977). Within an overall sequence stratigraphic framework, the smallest scale stratal units including lamina, laminasets, beds and bedsets are found to comprise progressively larger-scale stratal units including parasequences (shoaling-upward successions bound by flooding surfaces (Van Wagoner et al., 1988)) and ultimately sequences. This internal packaging of progressively thicker stratal units representing increasingly greater amounts of time ultimately defines a chronostratigraphic hierarchy. (Van Wagoner et al., 1990; Mitchum and Van Wagoner, 1991). Lower-order sequences, including parasequences, are found to stack within higher-order sequences in an often repetitive and predictable fashion. For example, lower-order sequences that are arranged within a higher-order sequence oftentimes will predictably vary in facies stacking patterns, sediment body geometry, and position along depositional dip (Van Wagoner et al., 1988). The stacking pattern, distribution, and sediment body geometry of lower-order stratal units within a higher-order sequence enables assessments to be made regarding controls operating within a given depositional system. Depositional controls including, but not limited to, eustasy, tectonism, climate, sediment supply dictates base level variability which in turn governs sequence development. An understanding of depositional controls and resultant sequence architecture enables the prediction of individual facies within an overall depositional system (Posamentier et al., 1988; Holz et al., 2002). This is particularly pertinent in the oil and gas industry in predicting the distribution of reservoir facies.

The direction and magnitude of local sea-level changes is a result of the combined effects of eustasy and tectonism (Posamentier et al., 1988; Holz et al., 2002). This is referred to as relative sea level change, as tectonism (uplift/subsidence) can influence local sea level such that it accentuates, retards, or even rarely counteracts the direction of global eustatic change (Plint et al., 1992). Direction and magnitude of relative sea level change, and associated driving forces, exerts the greatest control on hierarchical sequence development and internal stacking patterns. Diagnostic stacking patterns and sediment body geometries of stratal units within larger-scale sequences discriminates successions of strata that are formed in response to specific relative sea level changes. These packages of sedimentary strata within sequences are referred to as systems tracts (Posamentier et al., 1988; Van Wagoner et al., 1988; 1990).

Periods of sea level change can be linked to the development of systems tracts and bounding discontinuities within individual sequences. Sequence boundaries are formed during times of maximum rate of sea level fall. Two types of sequence boundaries are recognized. Type I sequence boundaries are formed where the rate of eustatic fall exceeds basin subsidence at the depositional shoreline break, and are characterized by erosive subaerial exposure, stream rejuvenation, incised valley formation, and sediment bypass (Van Wagoner et al., 1988; Reading and Levell, 1996). Type II sequence boundaries are associated with rates of subsidence exceeding rates of eustatic fall and are not associated with stream rejuvenation and incised valley formation (Posamentier et al., 1988; Van Wagoner et al., 1988; Posamentier and Allen, 1993). Lowstand systems tracts are only found atop type I sequence boundaries, and are formed during late stages of relative sea level fall through incipient sea level rise. Lowstand systems tracts are mainly characterized by aggradation as sediments being delivered to the basin via incised fluvial systems progressively onlap the basal sequence boundary in a landward direction (Shanley and McCabe, 1994). The lowstand systems tract is culminated by early sea level rise and the backfilling of incised valleys (Van Wagoner et al., 1988; 1990). The upper boundary of the lowstand systems tract is demarcated by the transgressive surface, separating aggradational lowstand deposits from retrogradational transgressive deposits (Van Wagoner et al., 1988). However, the transgressive surface is often difficult to recognize as it typically is not accentuated by a vertical facies change (Reading and Collinson, 1996). The initial flooding surface marks a change from fluvial to estuarine sedimentation and is typically associated with a facies change and is therefore more recognizable (Allen and Posamentier, 1993; Zaitlin et al., 1994; Reading and Collinson, 1996). However, the initial flooding surface is a diachronous feature and not constrained within a sequence stratigraphic framework (Zaitlin et al., 1994).

Continued relative sea level rise floods incised valleys, forming estuaries, and causes the landward migration of the shoreline (Boyd et al., 1992; Zaitlin et al., 1994). The upper limit of retrogradational transgressive deposits is delineated by the maximum flooding surface. In marine strata, the maximum flooding surface is easily recognized as a condensed interval of strata characterized by a high radioactivity black shale horizon that is deposited during periods of suppressed clastic input (Galloway, 1989; Shanley and McCabe, 1994; Holz et al., 2002). However, in dominantly alluvial strata recognition of the maximum flooding surface is represented by the onset of marine processes, including tidal sedimentation, in previously fluvial dominated areas (Shanley and McCabe, 1994). The maximum flooding surface is typically contained within the muddy central basin deposits of the middle estuary (Zaitlin et al., 1994). Introduction of tidal processes into fluvial landscapes may roughly be the up-dip equivalent of marine condensed sections (Greb and Martino, 2005). The magnitude of such transgressions often dictates the degree of backflooding in main incised valleys and/or lower order tributaries (Shanley and McCabe, 1994).

The highstand systems tract is initiated by a gradual decrease in the rate of relative sea level rise following maximum flooding conditions (Reading and Levell, 1996). This is accompanied by a progressive change from retrogradational transgressive deposits through a period of aggradation and ultimately the progradation of upward-coarsening facies over underlying transgressive deposits (Van Wagoner et al., 1988). This includes the progradation of bayhead delta facies into estuaries (Zaitlin et al., 1994). The highstand systems tract is terminated as sea level reaches its maximum rate of relative sea level fall and the formation of the next overlying sequence boundary is initiated.

Sequence stratigraphic interpretation of discontinuities

A framework of major and minor discontinuities including erosional (unconformable) horizons and marine zones correlated across the study area (cross-sections A-A’, B-B’, X-X’, and Y-Y’) provides a basis for evaluating the lower Pennsylvanian strata of Dickenson Co., VA in both a depositional and genetic framework. In a genetic framework (e.g. Galloway, 1989), Chesnut (1994) identified major marine zones as major marine flooding surfaces in the Breathitt Group. These marine zones were attributed to post-tectophase subsidence and marine incursion. These marine zones in the lower Pennsylvanian section separate the Pocahontas, Bottom Creek and Alvy Creek formations of the Breathitt Group into three separate entities of near equal thickness. Based upon a suite of age estimates for the lower and middle

Pennsylvanian as a whole, Chesnut (1994) estimated the duration of each flooding surface bound formation to be approximately 2.5 m.y. each (Chesnut, 1994; Greb at al., 2004), corresponding to an accepted periodicity of 3rd order cyclicity (Plint at al., 1992; Read, 1995). Chesnut (1994, Fig. 5, p. 56) utilized a wide variety of age estimates to establish a 20 million year duration for the combined lower and middle Pennsylvanian. Davydov et al. (2004) suggests that the entire duration of the Pennsylvanian Period was only 19 m.y., an apparent contradiction with the derived estimates of Chesnut (1994, Fig. 5, p. 56). However, a closer evaluation of the lower Pennsylvanian (Bashkirian Stage) suggests a duration of 4 – 8.8 m.y, with an average duration of 6.4 million years (Davydov et al., 2004). The range of these age estimates fits the assertion of Chesnut (1994) that the lower Pennsylvanian section of the Breathitt Group is comprised of three formations of approximately 2.5 m.y. duration each (approximately 7.5 m.y. total). Based on the overall age estimates for Pennsylvanian as a whole by Davydov et al. (2004), Chesnut's (1994) estimation of the duration of the middle Pennsylvanian (Moscovian Stage) may be overestimated. Davydov et al. (2004) suggests a 5.2 m.y. average duration for the middle Pennsylvanian (Moscovian Stage), whereas Chesnut (1994) suggests a duration of 12.5 m.y. in the form of five 2.5 m.y. 3rd-order sequences. Nonetheless, estimates for the duration of the lower Pennsylvanian appear to be in agreement.

Recognition of major marine flooding zones as third-order maximum flooding surfaces leads to the interpretation of underlying major discontinuities at the bases of sheet-like quartzarenites as third-order sequence boundaries. From a depositional sequence stratigraphy standpoint (e.g. Vail et al., 1977), widespread sheet-like quartzarenite belts of the upper units of the Warren Point and Sewanee formations are interpreted as incised valley fills, the bases of which demarcate third-order sequence boundaries. Third-order marine flooding surfaces are found stratigraphically above these major sequence boundaries, and separate the lower Pennsylvanian Pocahontas, Bottom Creek, and Alvy Creek formations into separate third-order genetic sequences.

Minor erosional discontinuities are found at the bases of multi-lateral, lenticular sublitharenite sandbodies. These sandbodies show an abrupt grain-size transition as they are typically incised into underlying muddy facies. The degree of incision, contrasting grain size across the discontinuity, and regional extent of the surface indicates genesis from a regional base level fall and leads to their interpretation as sequence boundaries (Aitken and Flint, 1994). In accompanying cross-sections, five to seven minor sequence boundaries are found within major third-order sequences. In total, 18 minor sequence boundaries are found within the lower Pennsylvanian section as a whole. Taking into account an estimated 7.5 m.y. duration for the lower Pennsylvanian (Chesnut, 1994; Davydov et al., 2004), each minor sequence, bound by minor sequence boundaries, is estimated at approximately 400 k.y. duration. A 400 k.y. duration for minor sequences is comparable to the duration of Milankovitch long-term global eccentricity cycles (Plint, 1992; Read, 1995) This duration suggests that minor sequence boundaries are fourth-order sequence boundaries, and minor sequences are fourth-order cycles.

Minor flooding zones are found atop fining-upward successions within fourth-order sequences. These flooding zones typically contain successions of mudstone, carbonaceous mudstone and a regionally persistent coal. They are lithologically and spatially similar to third-order maximum flooding zones, though typically thinner. Minor flooding zones are interpreted as fourth-order flooding surfaces.

Fourth-order sequence boundaries and flooding surfaces comprise larger-third order sequences, thus defining third-order composite sequences. A similar sequence hierarchy was recognized in correlative strata by Chesnut (1994), Korus (2002), and Greb et al. (2004), in the upper Mississippian of southern West Virginia by Miller and Eriksson (2000), and extending into the middle Mississippian by Smith and Read (2000). Additionally, fourth-order sequences have been recognized as comprising lowstand, transgressive, and highstand sequence sets within composite 3rd-order composite sequences, in the Middle Pennsylvanian of eastern Kentucky by Aitken and Flint (1994).

Sharp, erosional bases, beneath incised valley fill deposits of cross-bedded sandstone and conglomerate are interpreted as type I sequence boundaries (Van Wagoner et al., 1988). Multi-lateral, coarse-grained incised valley fill and correlative interfluve areas are included within the lowstand systems tract (Van Wagoner et al., 1988; Aitken and Flint, 1995; Zaitlin et al., 1994; Petersen and Andsbjerg, 1996). Lowstand wedges are not observed as they are probably developed along the distal shelf margin to the southwest in the Ouachita foredeep. The lowstand systems tract is culminated at the transgressive surface. As previously mentioned, this is a cryptic surface probably within the upper portions of alluvial incised valley fill (Posamentier et al., 1988; Reading and Collinson, 1996), and may be exemplified by paleocurrent reversals in the upper parts of alluvial sandbodies (Korus, 2002). The more recognizable initial flooding surface, though not recognized in a sequence stratigraphic framework, is roughly equivalent to the transgressive surface (Allen and Posamentier, 1993; Zaitlin et al., 1994) and is expressed as a change from coarse fluvial facies to muddier estuarine facies (Greb and Martino, 2005). These fluvial to estuarine transitions are roughly correlative to down-dip marine flooding zones (Greb and Martino, 2005) In core, this transition is typically manifested as a vertical facies change from quartzarenite or sublitharenite to heterolithic facies with tidal indicators such as slack water-induced ripple bedding, and rhythmic sedimentation (e.g. Petersen and Andsbjerg, 1996).

The transgressive systems tract is represented by a fining-upward succession of sandy and muddy heterolithic facies, and mudstone that is commonly overlain by a regionally persistent coal bed. Transgressive coal beds typically demarcate the top of the transgressive systems tracts as the maximum flooding surface is typically placed at the base of an overlying mudstone (Greb and Martino, 2005). A thick brackish water mudstone overlying widespread coal beds is indicative of deeper central estuarine conditions developed as estuaries were transgressed following peat accumulation during maximum flooding conditions (Zaitlin et al., 1994; Greb and Martino, 2005). In cross-section, fourth-order maximum flooding surfaces are indicated at the transition from fining-upward to coarsening-upward successions (Fig 9a-d).

The highstand systems tract typically begins at the base of a relatively persistent mudstone and proceeds to coarsen upward as estuaries are transgressed. One or more coal beds are also typically encountered in the early highstand systems tract. These coal beds are found to be laterally persistent and typically cap small-scale fining-upward sequences in an overall coarsening-upward succession. The highstand systems tract is terminated at the overlying sequence boundary.

In the central Appalachian basin, both erosional (sequence boundaries) and condensed (marine flooding surfaces) bounding discontinuities have been recognized and have led to both depositional (*sensu* Vail et al., 1977) and genetic (*sensu* Galloway, 1989) sequence stratigraphic interpretations. In a genetic sense, Chesnut (1994) identified a hierarchy of marine zones within both 'coal-clastic' 4th-order cycles and third-order composite tectono-cycles. Other workers (e.g. Aitken and Flint, 1994, 1995; Korus, 2002) have characterized Pennsylvanian strata in a depositional sequence stratigraphic sense (e.g. Vail et al., 1977) by identifying erosional disconformities at the bases of fluvial sandstone bodies interpreted as incised valley fill deposits.

This study utilizes elements of both depositional and genetic sequence stratigraphy. In up-dip terrigenous settings, evidence of marine incursion is often subtle. Partitioning of lower Pennsylvanian strata into depositional sequences is best accomplished by defining allostratigraphic units bounded below by disconformities at the base of fluvial valley-fill sandstone bodies, and above by marine flooding zones. In this depositional context, apparent marine zones of allocyclic origin can be predicted and differentiated from minor flooding surfaces of intrabasinal origin. Whereas depositional sequence stratigraphy is best suited for discriminating allocycles within the overall sequence hierarchy, regionally persistent coal beds are often found closely associated with a hierarchy of marine flooding surfaces. Therefore, an awareness of both genetic and depositional sequence stratigraphy is paramount in understanding both the overall sequence stratigraphic framework and origin of economically important coal beds.

The mid-Carboniferous boundary

The mid-Carboniferous systemic boundary in the central Appalachian basin has been a subject of much debate. While earliest models predicted an unconformity separating the Mississippian and Pennsylvanian systems, many workers, beginning in the late 1960's, suggested a conformable mid-Carboniferous boundary (e.g. Ferm and Cavaroc, 1969; Ferm, 1974; Horne et al., 1974). This model suggested that "marine" upper Mississippian units of the Slade (Newman/Greenbriar) and Pennington (Mauch Chunk) Formations were laterally equivalent to the "terrigenous" coal-bearing units of the Breathitt Group. Quartzarenite belts were interpreted as barrier bar deposits medial to aforementioned "marine" and "terrigenous" units. The mid-Carboniferous boundary was arbitrarily placed at localized unconformities at the bases of quartzarenite belts. The "marine" to "terrigenous" transition represented a time-transgressive environmental continuum, thus making the mid-Carboniferous boundary a diachronous feature.

As natural gas production, road-cuts, and regional mapping became more pervasive throughout the central Appalachian basin, it became apparent that a significant unconformity existed at the base of the Pennsylvanian (Chesnut, 1988). Along the northwest margin of the basin (Fig. 1), basal quartzarenite belts of the Warren Point Formation are found to truncate progressively older Mississippian units toward the northwest. Where this erosional juxtaposition of quartzarenites atop upper Mississippian units is observed, the mid-Carboniferous boundary is readily identified (cross-sections X-X' and Y-Y'). However, in deeper parts of the basin toward the southeast (Fig. 1) the nature of the mid-Carboniferous boundary becomes more problematic.

In general, two different interpretations have been proposed, in which the mid-Carboniferous boundary is placed either at the base of (at the systemic mid-Carboniferous boundary), or atop the Pocahontas Formation. In the case of the latter, the base of the Warren Point Formation (basal quartzarenite belt) is projected orogenward where the contact of the lowermost quartzarenite apparently onlaps the Pocahontas Formation. In this scenario, the unconformity is therefore early Pennsylvanian in age. When the Pocahontas wedges out toward the northwest, the unconformity surface is projected at the systemic boundary. The mid-Carboniferous boundary is therefore an apparent "Mississippian – Pennsylvanian" unconformity in the absence of the Pocahontas Formation (Chesnut, 1994). Additionally, this scenario typically assumes an intertonguing and therefore conformable relationship between the Pocahontas and the uppermost Mississippian Bluestone Formation in southeastern reaches of the central Appalachian basin (Englund, 1979).

The aforementioned scenario suggests that upper Mississippian clastics, and the lowest Pennsylvanian Pocahontas Formation, were deposited in a depositional continuum. Following deposition, tectonic uplift associated with incipient Alleghanian tectonism caused the denudation of the Pocahontas surface and subsequent onlap of early Pennsylvanian quartzarenites (Englund, 1979). However, paleodrainage considerations (e.g. Beuthin, 1994) and paleopedological and floral biostratigraphic evidence (e.g. Beuthin, 1997), indicate a significant depositional hiatus occurring at the systemic mid-

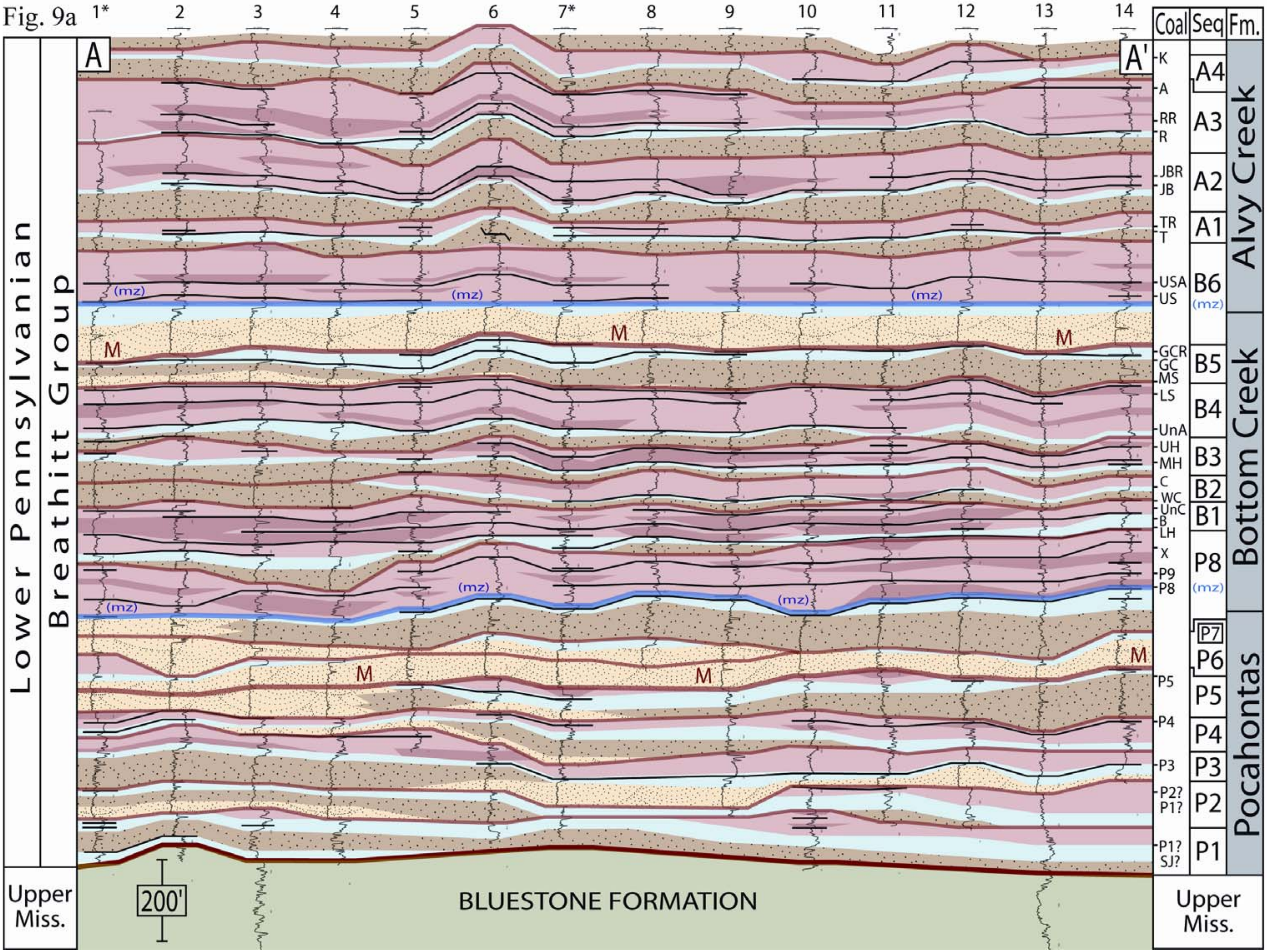
Carboniferous boundary at the base of the Pocahontas Formation. While the earlier model suggests a tectonic mechanism for the formation of the “mid-Carboniferous” unconformity, this model advocates a eustatic mechanism for unconformity genesis associated with a global eustatic lowstand (Saunders and Ramsbottom, 1986; Beuthin, 1994). Deposition of basal Pennsylvanian quartzarenites was therefore roughly equivalent to the deposition of the Pocahontas Formation.

While ample outcrop exposure in shallow, northwestern reaches of the central Appalachian basin has allowed extensive mapping of the mid-Carboniferous unconformity, lack ofexposure to the southeast in deeper parts of the basin has inhibited characterization of the mid-Carboniferous boundary and associated stratigraphic relationships. This study, in part, attempts to characterize the nature of the mid-Carboniferous unconformity in southwestern Virginia (Fig. 4) using a series of well logs penetrating both the upper and lower Pocahontas boundaries.

The northwestern extent of dip-oriented cross-sections X-X’ and Y-Y’ (Fig. 9c-d) shows the progressive truncation of the upper Mississippian Bluestone to the northwest. This truncation continues to the northwest such that the basal quartzarenite of the Warren Point Formation is in direct erosional contact with the Pride Shale Member of the Bluestone Formation near the Kentucky – Virginia border (Englund, 1979). In reference to the northwestern extent of dip-oriented cross-sections X-X’ and Y-Y’, the contact between the upper Mississippian and lower Pennsylvanian occurs at the base of the P4 4th-order sequence. When this sequence boundary is projected toward the southeast, it is found to occur two 4th-order sequences below the “basal” unit of the Warren Point Formation. Therefore, the “basal” unit of the Warren Point Formation is a diachronous feature across the study area and should not be considered a regional unconformity surface. Dip-cross sections show that quartzarenite belts, common in the northwest, and lenticular sublitharenite bodies, common in the southeastern coal-bearing facies, occur contemporaneously atop common sequence boundaries. Furthermore, individual 4th-order sequences within the Pocahontas Formation are found to angularly onlap towards the northwest onto the southeasterly-dipping upper Mississippian surface. These findings support Beuthin’s (1994, 1997) assertion that the mid-Carboniferous unconformity occurs at the systemic Mississippian - Pennsylvanian boundary at the base of the Pocahontas

Figure 9a: Cross-section A – A’

Fig. 9a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A'
Coal
Seq
Fm.
K
A
RR
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USA
US
GCR
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UH
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C
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UnC
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LH
X
P9
P8
P5
P4
P3
P2?
P1?
P1?
SJ?
A4
A3
A2
A1
B6
(mz)
B5
B4
B3
B2
B1
P8
(mz)
P7
P6
P5
P4
P3
P2
P1
Alvy Creek
Bottom Creek
Pocahontas
Lower Pennsylvanian
Breathitt Group
Upper Miss.
Upper Miss.
(mz)
(mz)
(mz)
(mz)
(mz)
(mz)
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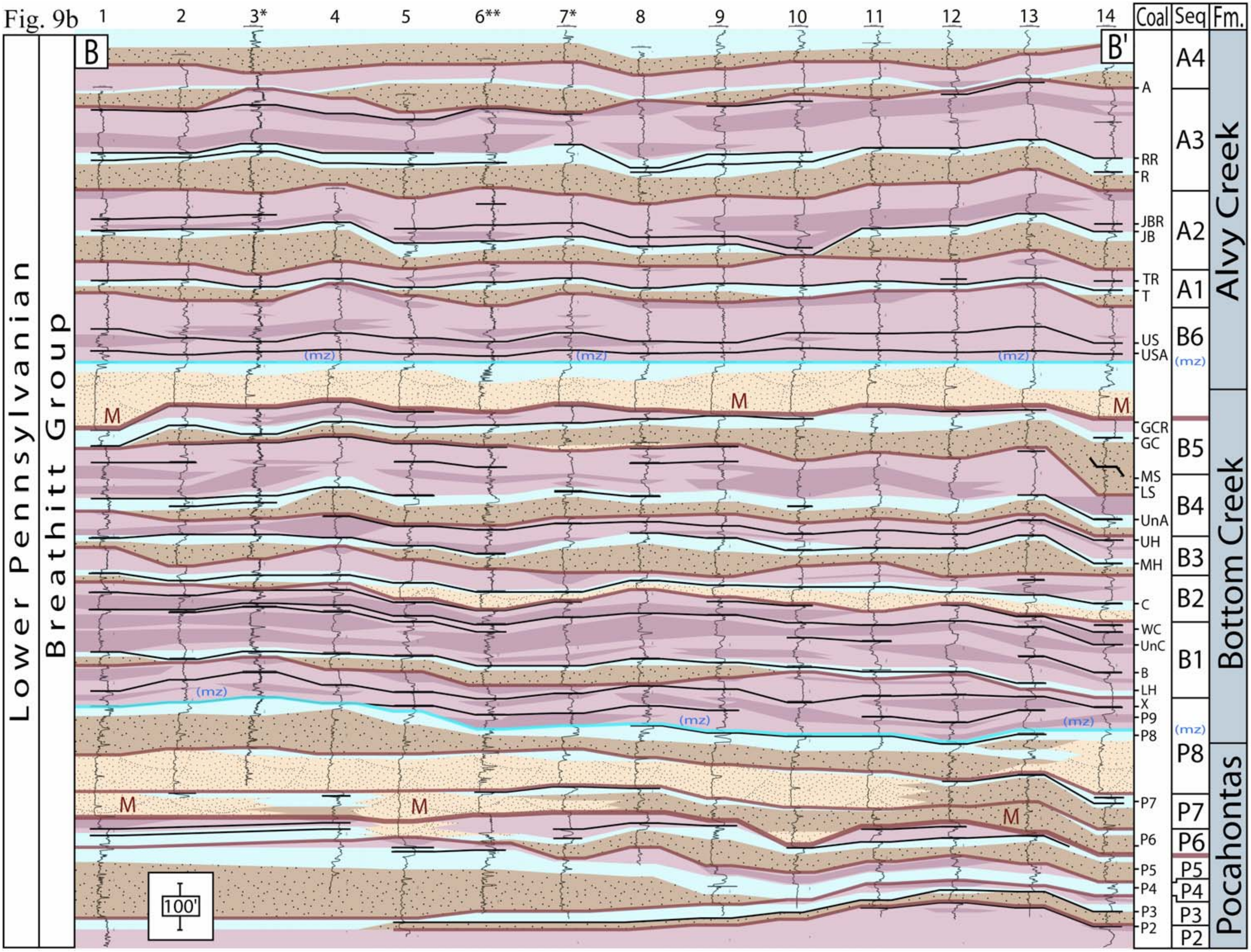
M
200'
BLUESTONE FORMATION

Figure 9b: Cross-section B – B’

Fig. 9b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Lower Pennsylvanian
Breathitt Group
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A3
A2
A1
B6
(mz)
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B4
B3
B2
B1
(mz)
P8
P7
P6
P5
P4
P3
P2
Alvy Creek
Bottom Creek
Pocahontas
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M
M
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M
M
(mz)
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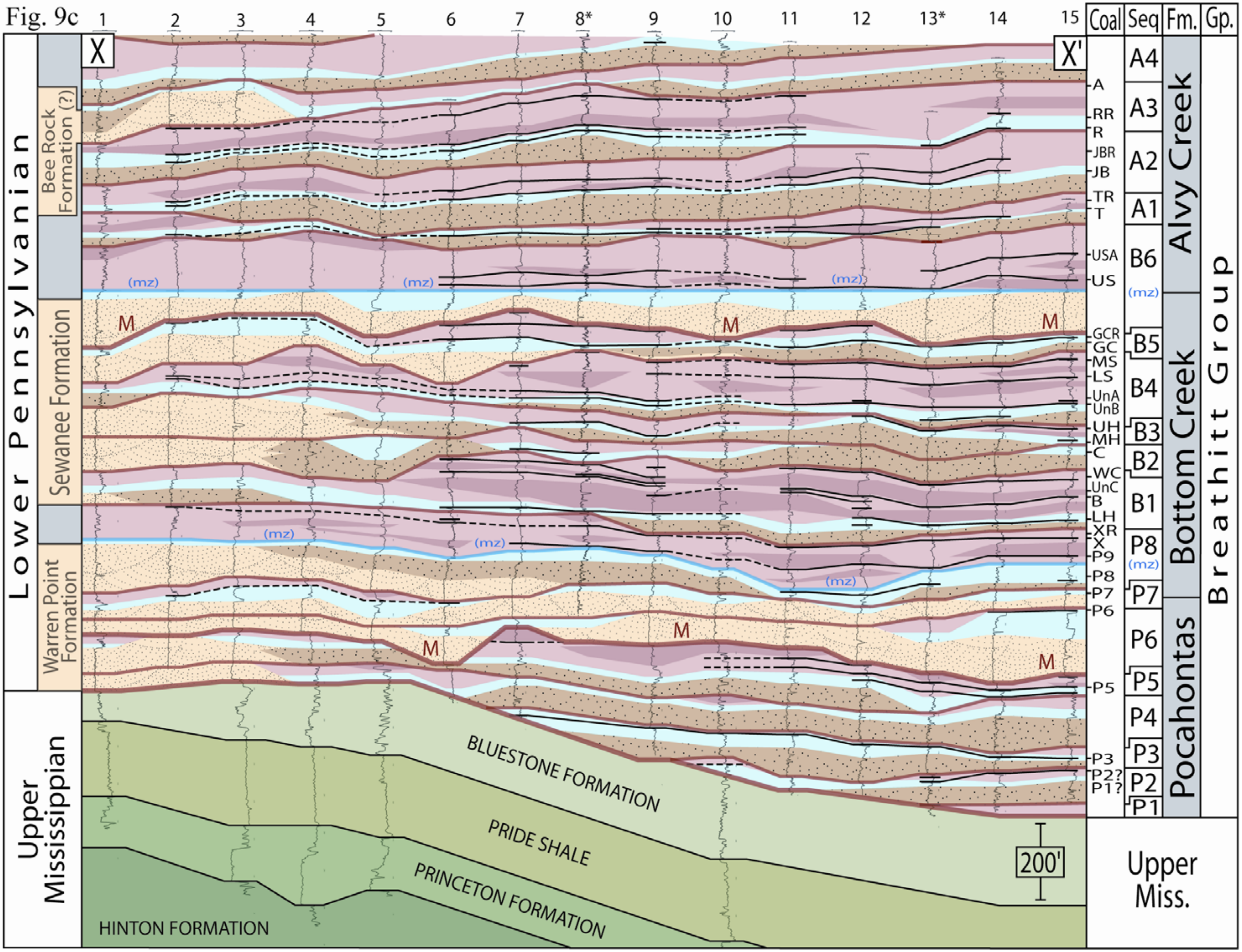
100'

Figure 9c: Cross-section X – X’

Fig. 9c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15
Coal
Seq
Fm.
Gp.
X
X'
Lower Pennsylvanian
Bee Rock Formation (?)
Sewanee Formation
Warren Point Formation
Upper Mississippian
(mz)
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RR
R
JBR
JB
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USA
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P2?
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P3
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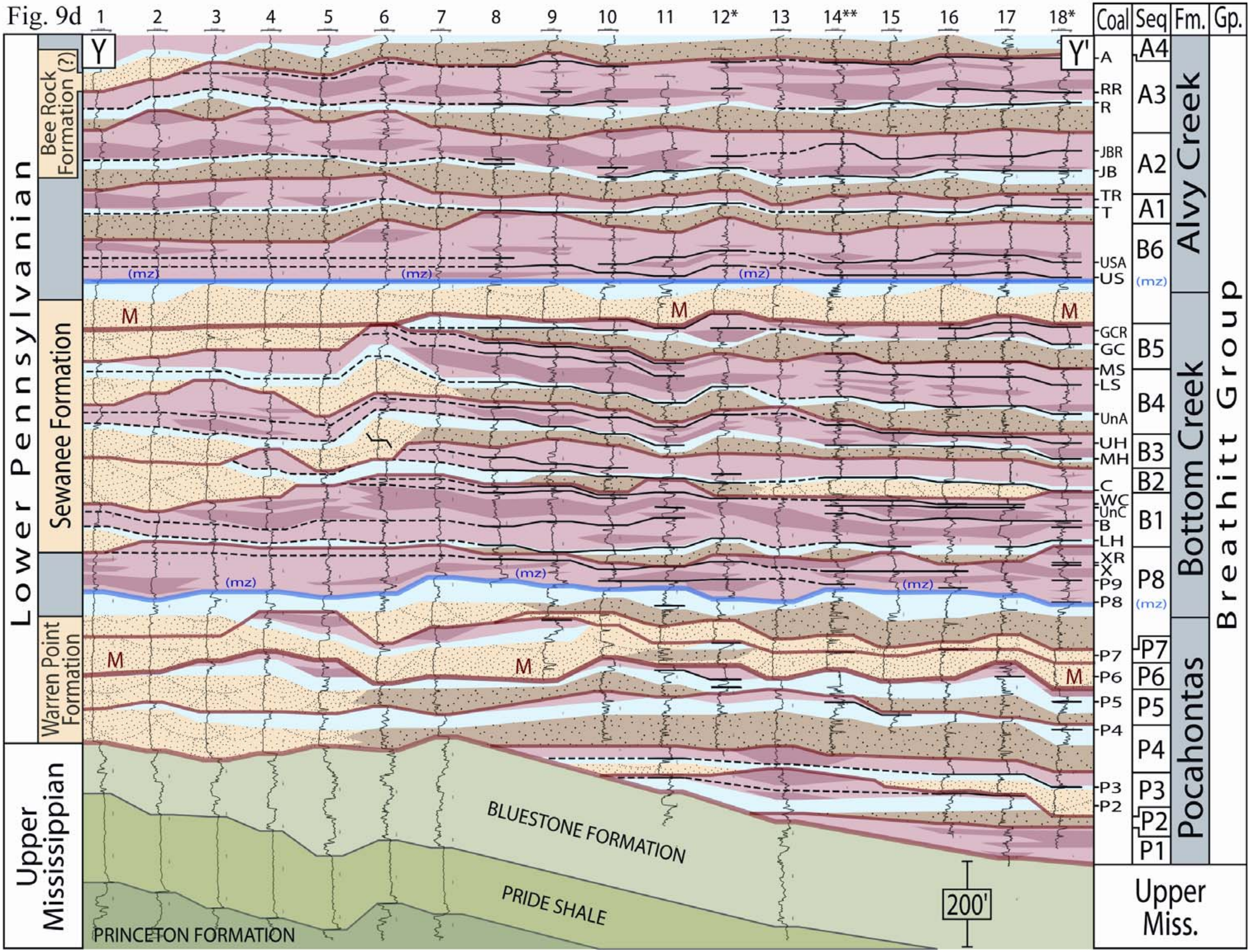
P1
Alvy Creek
Bottom Creek
Pocahontas
Breathitt Group
Upper Miss.
BLUESTONE FORMATION
PRIDE SHALE
PRINCETON FORMATION
HINTON FORMATION
200'

Figure 9d: Cross-section Y – Y’

Fig. 9d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Coal
Seq
Fm.
Gp.
Y
Y'
Lower Pennsylvanian
Bee Rock Formation (?)
Sewanee Formation
Warren Point Formation
Upper Mississippian
(mz)
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P2
P1
Alvy Creek
Bottom Creek
Pocahontas
Breathitt Group
Upper Miss.
BLUESTONE FORMATION
PRIDE SHALE
PRINCETON FORMATION
200'

Cross-section Legend:

- ▨ Quartzarenite
- ▨ Sublitharenite
- ▥ Coarsening-upward succession
- ☐ Fining-upward succession
- ─── Coal bed
- - - - Inferred coal bed
- ─── Minor discontinuity
- M Major discontinuity
- ─── Marine zone
- * Intersection well
- ** Core well

Coal Bed Nomenclature

K	Kennedy	**C**	C Seam
A	Aily	**WC**	War Creek
RR	Raven Rider	**UnC**	Unnamed C
R	Raven	**B**	Beckley
JBR	Jawbone Rider	**LH**	Lower Horsepen
JB	Jawbone	**XR**	X Seam Rider
TR	Tiller Rider	**X**	X Seam
T	Tiller	**P9**	Pocahontas 9
USA	Upper Seaboard A	**P8**	Pocahontas 8
US	Upper Seaboard	**P7**	Pocahontas 7
GCR	Greasy Creek Rider	**P6**	Pocahontas 6
GC	Greasy Creek	**P5**	Pocahontas 5
MS	Middle Seaboard	**P4**	Pocahontas 4
LS	Lower Seaboard	**P3**	Pocahontas 3
UnA	Unnamed A	**P2**	Pocahontas 2
UnB	Unnamed B	**P1**	Pocahontas 1
UH	Upper Horsepen	**SJ**	Squire Jim
MH	Middle Horsepen		

Figure 9a: Strike-oriented cross-section A - A'
Figure 9b: Strike-oriented cross-section B - B'
Figure 9c: Dip-oriented cross-section X - X'
Figure 9d: Dip-oriented cross-section Y - Y'

Formation. While a eustatic component to the mid-Carboniferous unconformity is supported by a contemporaneous global eustatic lowstand (Saunders and Ramsbottom, 1986), the angular relationship between the upper Mississippian and lower Pennsylvanian strata would indicate a tectonic influence on unconformity development. This tectonic influence can be attributed to earliest Alleghanian tectonism, or post tectophase isostatic rebound (Quinlan and Beaumont, 1984; Tankard, 1986).

DISCUSSION

Sequence stratigraphic principles were originally developed for shallow marine strata where marine flooding surfaces are readily observed and separate genetically related, unconformity-bound depositional packages (e.g. Galloway, 1989). Maximum flooding surfaces are easily recognized as condensed intervals of strata, whereas sequence boundaries typically are sharp, erosive contacts between lithologically dissimilar muddy marine facies and overlying coarse terrigenous clastics. Key stratal features such as marine flooding zones and sequence boundaries are less obvious up-dip where the affects of marine processes become more subtle, and where sequence boundaries are often cryptic within amalgamated fluvial sandstone bodies (Miall and Arush, 2001). In the absence of readily recognizable key stratal surfaces, it has been difficult to develop a genetic framework for dominantly terrestrial strata.

Many studies in predominantly non-marine sedimentary basins have utilized laterally extensive coal beds as proxies for isochronous discontinuities such as condensed sections and sequence boundaries. The use of coal beds to constrain paralic stratigraphy has become increasingly commonplace as coal beds have been documented in a wide variety of sedimentary basins including: foreland basins (e.g. Gastaldo, 1993; Aitken and Flint, 1994, 1995; Chesnut, 1994; Demko and Gastaldo, 1996; Bohacs and Suter, 1997; Hampson et al., 1999; Tibert and Gibling, 1999; Michaelsen and Henderson, 2000), rift basins (e.g. Petersen and Andsbjerg, 1996; Petersen et al., 1998; O'Mara and Turner, 1999; Van Heeswijck, 2001), intracratonic basins (e.g. Alves and Ade, 1996; Holz, 1998) and passive margins (e.g. Bohacs and Suter, 1997). In addition to a wide variety of tectonic regimes, coal beds are found to form under conditions of both icehouse (e.g. Gastaldo, 1993; Aitken and Flint, 1994, 1995; Chesnut, 1994; Hampson et al., 1999;

O’Mara and Turner, 1999; Tibert and Gibling, 1999) and greenhouse (e.g. Cross, 1988; Kalkreuth and Leckie, 1989; Petersen and Andsbjerg, 1996; Bohacs and Suter, 1997; Petersen et al., 1998) global eustatic conditions. As an added caveat, the occurrence, geometry, and quality (percentage of ash and sulfur) of coal beds also can be highly influenced by prevailing climatic conditions during times of peat accumulation (e.g. Cecil et al., 1985; Cecil, 1990; Cecil et al., 1993; Holz, 1998).

Whereas coal beds are formed in diverse geologic settings, as dictated by the interplay of tectonic, eustatic, and climatic controls, all paralic coal-bearing environments share a commonality of requisite increases in accommodation to facilitate peat accumulation. Accommodation in nearshore environments is dictated by relative sea level change. Relative sea level change is the local change in sea level produced by the combined effects of tectonism, eustasy, and sedimentation rates (Plint et al., 1992). While the creation of accommodation space is important in creating a peat forming environment, it is the rate of accommodation increase versus the rate of peat accumulation that ultimately dictates the buildup and preservation of organic matter, and the geometry and quality of resultant coal beds (Bohacs and Suter, 1997; Diessel et al., 2000; Holz et al., 2002). The most substantial accumulations of peat are found to occur where the rate of accommodation increase approximately equals the rate of peat production (Bohacs and Suter, 1997).

Rates of accommodation increase favorable to peat accumulation are closely related to the relative sea level curve. The maximum flooding surface is defined as a widespread marine flooding surface that separates retrogradational, transgressive facies from progradational, highstand facies (Read, 1995; Reading and Collinson, 1998). In this sense, the maximum flooding surface is closely associated with the inflection point on a curve depicting relative sea level rise with time. Incipient relative sea level rise to maximum flooding conditions is characterized by an increasing slope on the relative sea level curve accompanied by a gradual increase in the *rate* of relative sea level rise, whereas maximum flooding conditions to incipient relative sea level fall is characterized by a decreasing slope on the relative sea level curve accompanied by a gradual decrease in the *rate* of relative sea level rise. In this sense, similar *rates* of relative sea level rise can be attained prior to, and following maximum flooding conditions. Therefore, rates of accommodation increase favorable to peat accumulation can be encountered within aggradational to retrogradational transgressive facies, and aggradational to progradational highstand facies (Bohacs and Suter, 1997; Diessel et al., 2000; Holz et al., 2002).

In lower Pennsylvanian successions of southwest Virginia, the aforementioned generalization holds true in that laterally extensive, economically viable coal beds occur within both fining-upward transgressive facies, and coarsening-upward highstand facies. Lowstand systems tracts in the study interval consist of quartzarenite and sublitharenite incised valley fills of axial and transverse fluvial origin, respectively, and correlative hiatal interfluve areas (Van Wagoner et al., 1988, 1990). The overlying transgressive systems tract initiates at the transgressive surface that, in marine realms, is commonly characterized by a distinct facies translation. However, in up-dip settings, the transgressive surface is commonly cryptic within upper parts of incised valley fills and may only be distinguishable by subtle indicators such as paleocurrent reversals or ravinement deposits (Miller and Eriksson, 2000; Korus, 2002). The transgressive systems tract consists of a fining-upward succession of facies spanning a fluvial to estuarine transition as incised-valleys are back-flooded (Zaitlin et al., 1994). Transgressive coal beds occur between fining-upward estuarine facies, and overlying brackish to marine mudstones interpreted as maximum flooding deposits of the central estuarine basin. Transgressive coal beds in the study interval include most of the coal beds of the Pocahontas Formation, in addition to the Lower Horsepen, C Seam, Middle Horsepen, Unnamed A, Greasy Creek, Upper Seaboard, Tiller, Jawbone, and Raven coal beds (Fig. 9a - d). The Pocahontas Formation as a whole is more difficult to assess in that it contains a higher percentage of sandstone than the Bottom Creek and Alvy Creek formations. Lower accommodation during the deposition of the Pocahontas Formation led to common amalgamation of basal incised valley fills, and erosive removal of greater thicknesses of highstand deposits below sequence boundaries, thus preferentially preserving transgressive coal beds over highstand coal beds. The position of transgressive coals between underlying estuarine facies and overlying maximum flooding-associated mudstones indicates that transgressive coal beds formed during the late stages of transgression just prior to maximum flooding conditions (cf. Bohacs and Suter, 1997). This suggests that rates of accommodation increase relative to rates of peat production were optimal during the latest stages of transgression. Subsequent increasing rates of sea level rise associated with maximum flooding conditions proved to be too high relative to peat production rates resulting in peat mires being inundated by brackish to marine water as indicated by overlying marginal marine mudstones (e.g. Greb and Martino, 2005). Interpretation of transgressive coals is straightforward in that coal beds are developed above widespread, predictable, and repetitive fining-upward successions in close conjunction with interpreted 4th-order maximum flooding surfaces (Chesnut, 1994). Formation of transgressive coals is therefore attributed to eustatic sea level rise driven by 4th-order Milankovitch orbital eccentricity cycles.

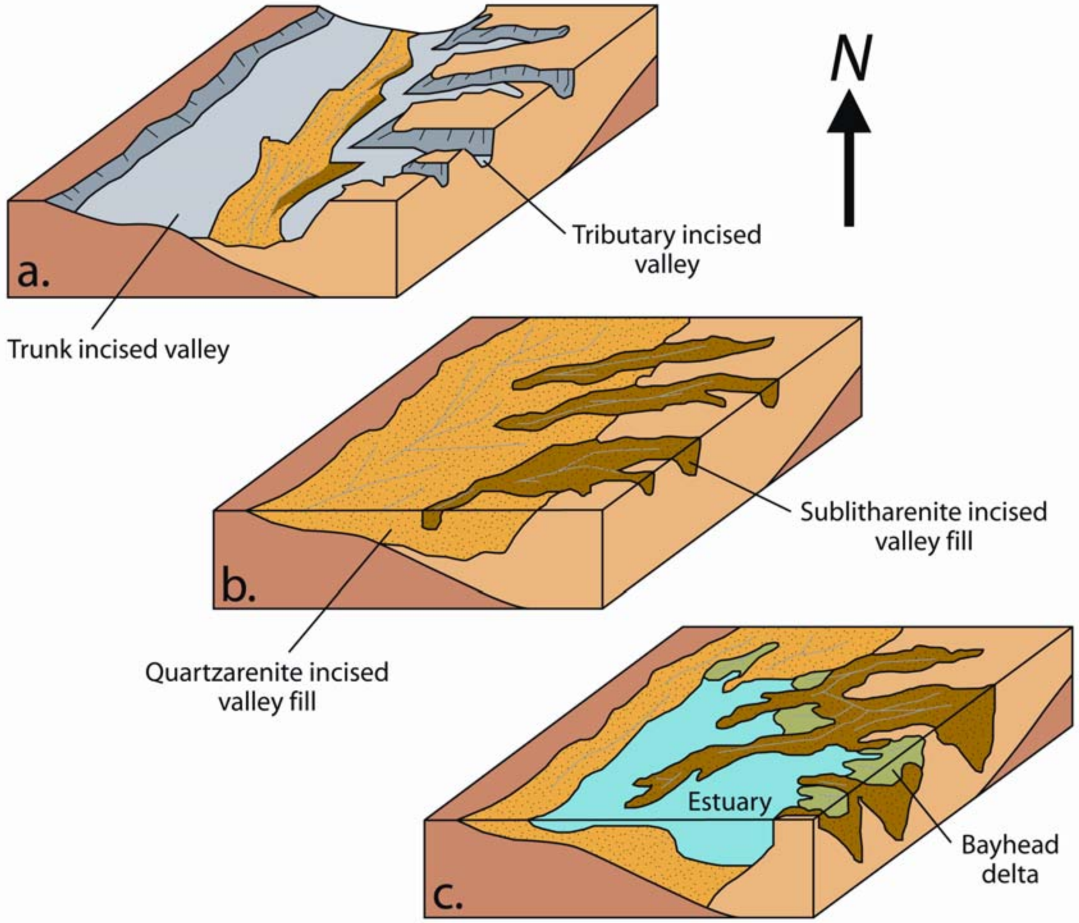

Figure 10: Paleogeographic reconstruction depicting: a) relative sea level fall and incision of axial (trunk) and transverse (tributary) valleys, b) relative sea level rise and contemporaneous back-filling of trunk and tributary incised valleys with quartzose and sublithic valley fill, respectively, 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).

Although highstand coal beds occur within broadly coarsening-upward 4th-order highstand systems tract deposits, their origin is more complex than transgressive coals in that they do not appear to closely correspond with 4th-order bounding discontinuities. Whereas transgressive coal beds typically occur as a single coal bed beneath a maximum flooding horizon within a given 4th-order sequence, highstand coal beds often occur as sets of two to three coal beds within 4th-order highstand systems tract deposits. Lower Pennsylvanian coal beds assigned to 4th-order highstand systems tracts include the Pocahontas #9, X Seam, X Seam Rider, Beckley, Unnamed C, War Creek, Upper Horsepen, Lower Seaboard, Middle Seaboard, Upper Seaboard A, Jawbone Rider, Raven Rider, and Aily coal beds (Fig. 9a - d). As discussed previously, broadly coarsening-upward 4th-order highstand systems tract deposits often are comprised of coarsening- to fining-upward intervals commonly capped by coal beds. These thinner intervals within the overall coarsening-upward 4th-order highstand systems tract are ascribed to autocyclic processes such as channel avulsion and delta lobe switching. In this sense, accommodation necessary for peat development is a product of post-abandonment dewatering and compaction (cf. O'Mara and Turner, 1999).

Lower Pennsylvanian coal beds in the central Appalachian basin of southwest Virginia were formed from a combination of allocyclic and autocyclic processes. In total, three orders of marine flooding surfaces are observed. The highest order flooding surfaces correspond to 3rd-order maximum flooding surfaces and are recognized as widespread marine horizons separating the Pocahontas, Bottom Creek, and Alvy Creek Formations of the Breathitt Group. Third-order maximum flooding surfaces of approximately 2.5 m.y. periodicity are attributed to post-tectophase marine incursion and are therefore a product of Alleghanian tectonism (Chesnut, 1994). However, 2.5 m.y. periodicity cycles have been recognized by Matthews and Frohlich (2002), that were attributed to a higher-order, low-frequency (2.4 +/- 0.4 my) orbital eccentricity cycles. Five to seven 4th-order maximum flooding surfaces and corresponding 4th-order sequences comprise 3rd-order composite sequences. The average periodicity of interpreted 4th-order sequences is approximately 400 k.y., corresponding to long-term Milankovitch orbital eccentricity cycles (Plint et al., 1992; Read, 1995). Transgressive coals are closely associated with 4th-order maximum flooding surfaces and consistently occur above fining-upward fluvial to estuarine transitions. Formation of transgressive coals is therefore attributed to Milankovitch driven glacio-eustasy. The lowest-order flooding surfaces occur within 4th-order highstand systems tract deposits. These high-frequency flooding surfaces cap deltaic elements and are ascribed to compaction and dewatering induced subsidence followed by marine incursion over abandoned delta lobes. Accommodation for peat accumulation in 4th-order highstand regimes was produced from the combined effects autogenic deltaic processes and eustatic sea level rise within 4th-order highstand systems tracts. A similar tripartite hierarchy of flooding surfaces was recognized by O'Mara and Turner (1999) in the lower Pennsylvanian of northern England.

CONCLUSIONS

1) Lower Pennsylvanian coal-bearing strata of the central Appalachian basin are characterized by sublithic and quartzose incised valley fills with subordinate amounts of heterolithic facies, mudstone, carbonaceous mudstone and coal. The juxtapostion of sublithic and quartzose incised valley fill deposits, aligned orthogonal to each other defines a trunk-tributary drainage system operating in a foreland basin. Tributary drainage was derived from the low-grade metamorphic terrain of the emergent Alleghanian orogen towards the southeast, whereas axial drainage flowed parallel to the strike of the basin and was derived from a northerly cratonic source.
2) Deposition of lower Pennsylvanian strata was influenced by high-magnitude sea level fluctuations. In general, relative sea level lowstand to early transgression is represented by the incision and backfilling of axial (trunk) and transverse (tributary) incised valleys with quartzose and sublithic incised valley fill, respectively. Continued transgression led to the back-flooding of trunk and tributary incised valleys forming estuaries. During relative sea-level fall, progradational deltaic facies developed above underlying fluvial, estuarine, and marginal marine facies.

3) Major sea level fluctuations have been attributed to both tectonic and eustatic mechanisms. Third-order composite sequences have been attributed to tectonic mechanisms, but more likely, represent a lower-frequency orbital eccentricity cycle. Third-order sequences consist of higher-frequency 4th-order cycles attributed to Milankovitch driven glacio-eustasy. 4th-order sequences contain fluvial to marginal marine facies that comprise lowstand, transgressive, and highstand systems tracts. Higher-frequency autocycles are associated with deltaic facies within 4th-order highstand systems tracts.
4) Coal beds developed within both late transgressive facies closely associated with 4th-order maximum flooding surfaces, and in association with higher-frequency deltaic autocycles of 4th-order highstands, thus discriminating transgressive from highstand coal beds in a sequence stratigraphic context. Formation of coal beds is therefore attributed to glacio-eustatic, and autocyclic deltaic mechanisms within 4th-order genetic sequences.
5) Lower Pennsylvanian strata, beginning with incipient deposition of the Pocahontas Formation, display northwesterly onlap onto the southeasterly dipping hiatal upper Mississippian surface. This supports the notion that the mid-Carboniferous unconformity occurs at the systemic Mississippian – Pennsylvanian boundary

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