THE LOWER PENNSYLVANIAN NEW RIVER FORMATION: A
NONMARINE RECORD OF GLACIOEUSTASY IN A FORELAND BASIN

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ABSTRACT

Lower Pennsylvanian siliciclastic sedimentary rocks of the central Appalachian Basin consist predominantly of nonmarine, coal-bearing facies that developed within a fluvio-estuarine, trunk-tributary drainage system in a foreland-basin setting. Sheet-like, sandstone-mudstone bodies (up to 100 km wide and 70 m thick) developed in an axial trunk drainage system, whereas channel-like, sandstone-mudstone bodies (up to several km wide and 30 m thick) developed in tributaries oriented transverse to the thrust front. The origin of these strata has been debated largely because the paleogeomorphology and facies architecture of the New River Formation (NRF) are poorly understood.

A sequence stratigraphic framework for the NRF, based on a combination of outcrop mapping and subsurface well-log analysis, reveals: 1) regionally significant erosional surfaces along the bases of sheet-like and channel-like sandstone bodies (sequence-boundaries), 2) fluvial- to estuarine-facies transitions (marine flooding surfaces), 3) erosionaly based, framework-supported, quartz-pebble conglomerates (ravinement beds), and 4) regionally traceable, coarsening-upward intervals of strata (highstand deposits above maximum flooding surfaces). Using these criteria, both 3rd- and 4th-order sequences have been identified. An idealized 4th-order sequence consists of deeply incised, fluvial channel sandstone separated from overlying tidally modified estuarine sandstone and mudrock by a ravinement bed, and capped by coarsening-upward bayhead delta facies. The relative thickness of fluvial versus estuarine facies within a fourth-order sequence reflects a balance between accommodation and sediment supply within a 3rd-order relative sea level cycle. Lowermost 4th-order sequences are dominated by fluvial facies, whereas the uppermost sequences are dominated by estuarine facies. Therefore, 3rd-order sequence boundaries are interpreted to lie at the bases of the lowermost, fluvial-dominated fourth-order sequences. Coarsening-upward intervals that record the maximum landward extent of marine conditions are interpreted as highstand deposits of the composite third order sequence. Thus, the NRF consists of thick, superimposed fluvial sandstone of the lowstand systems tracts and anomalously thin transgressive and highstand systems tracts. Asymmetrical subsidence within the foreland basin resulted in westward amalgamation of multiple, 4th-order, fluvial valley-fill successions and sequence boundaries.

The Early Pennsylvanian time period was characterized by global icehouse conditions and the tectonic assembly of Pangea. These events affected the geometry of the overall stratigraphic package, which can be attributed to high-magnitude, high-frequency, glacioeustatic sea-level fluctuations superimposed on asymmetric tectonic subsidence.
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INTRODUCTION

Nonmarine stratigraphic sequences in foreland basins have the potential to provide information on the interplay between tectonics, eustasy, and climate. To date, most studies of nonmarine sequence stratigraphy have been conducted in Mesozoic foreland basins of the U.S. western interior (e.g. Shanley and McCabe, 1993, 1995; Olsen et al., 1995; Van Wagoner, 1995; Martinsen et al., 1999; Pedersen and Steel, 1999; Willis, 2000; Yoshida, 2000; Miall and Arush, 2001), which formed under the influence of eustatic and climatic conditions in a greenhouse world (Fischer, 1982; Berner, 1991). Far fewer studies have been conducted on foreland-basin stratigraphic intervals that developed during icehouse times (e.g. Aitken and Flint, 1995; Miller and Eriksson, 2000).

Although thrust loading is the dominant control on foreland basin subsidence, facies patterns, and unconformities at the scale of the basin fill (1 my – 100 my, 1,000 m – 10,000 m; Price, 1973; Dickinson, 1974; Quinlan and Beaumont, 1984; Covey, 1986; Heller et al., 1988; Flemings and Jordan, 1990; Leeder, 1993; Castle, 2001), eustatic, climatic, and tectonic influences overlap in time and space at the meso-architectural scale of a basin (1 ky – 1 my, 10 m – 100 m; Leeder, 1993). This is particularly true for fluvial and marginal marine depositional systems which respond to changes in the ratio between accommodation and sediment supply (A/S) brought about by short-term eustatic and climatic changes within the basin and its source area, superimposed on episodic tectonic pulses (Shanley and McCabe, 1994; Ethridge et al., 1998). The stratigraphic expression of changing A/S ratio should be expected to vary in accordance with 1) magnitude and rates of eustatic sea level fluctuations, 2) in-phase versus out-of-phase relationships between climatically controlled sediment supply and eustatically
controlled accommodation, 3) the relative importance of estuarine processes, including tides, waves, and fluvial currents, 4) the degree of valley incision and/or paleosol formation, and 5) the degree of erosional removal of strata during incision. Therefore, foreland basins formed during greenhouse versus icehouse times should record important differences in the stratigraphic architecture of nonmarine deposits (Frakes et al., 1992; Blum and Tornqvist, 2000).

Recognition of the relative importance of tectonic, eustatic, and climatic controls at various spatial and temporal scales is the focus of many recent studies in nonmarine basins (Shanley and McCabe, 1994, 1998; Blum and Tornqvist, 2000), and sequence stratigraphy has become the standard methodological framework for such work (e.g. Wright and Marriot, 1993; Shanley and McCabe, 1994; Currie, 1997; Legarreta and Uliana, 1998; Martinsen et al., 1999). These models are based on the recognition of facies and surfaces indicative of changes in A/S ratio, including regionally-extensive erosional unconformities, changes in alluvial architecture, and various estuarine, tidal, coal, and/or lacustrine facies. In order to refine sequence stratigraphic models for nonmarine rocks and evaluate the importance of external controls on fluvial and marginal marine architecture, there is a need for studies in basins within different spatial, temporal, and environmental settings.

The Lower Pennsylvanian New River Formation is a predominantly nonmarine, siliciclastic interval of strata that was developed in the central Appalachian foreland basin during a time of global icehouse conditions and the tectonic assembly of Pangea. This unique setting, in combination with abundant outcrop and subsurface data throughout the basin, make the New River Formation an ideal unit in which to study the effects of external forcing mechanisms on nonmarine sequence stratigraphy. The purpose of this paper is to: 1) present a combined subsurface- and outcrop-based sequence stratigraphic framework for the New River Formation,
and 2) use this framework to evaluate the importance of tectonic, eustatic, and climatic controls on the paleogeomorphology and facies architecture of Lower Pennsylvanian strata of the Alleghenian foreland basin.

**GEOLOGIC AND STRATIGRAPHIC SETTING**

The Lower Pennsylvanian New River Formation occupies the central Appalachian Basin, an elongate (~600 km long, ~180 km wide) foreland basin that formed through multiple episodes of Paleozoic collisional tectonics (Quinland and Beaumont, 1984). As much as 7 km of Mid-Ordovician to Lower Permian strata were developed in the foreland basin due to subsidence and deposition related to thrust loading in the hinterland during the Taconic, Acadian, and Alleghenian orogenies (Quinland and Beaumont, 1984). The central Appalachian Basin is bounded on the east by the Appalachian fold and thrust belt, and on the west by two main structural features, the Cincinnati Arch and a hingeline formed along the northern margin of the Rome Trough (NMRT in Fig. 1, inset).

During the Carboniferous, the basin was filled by an eastward-thickening clastic wedge associated with the onset of Alleghenian tectonism (Ettensohn, 1994). These deposits are characterized by various scales of stratigraphic cyclicity. Tankard (1986) and Klein and Willard (1989) infer both large- and small-scale cyclicity as the result of thrusting and lithospheric flexure. The Carboniferous global icehouse, however, is one of the most well documented pre-Quaternary glacial periods in earth history (Crowell, 1978; Veevers and Powell, 1987), and some authors infer glacioeustasy as the dominant control on cyclicity (Heckel, 1986; Miller and Eriksson, 2000). Other authors consider climate as the main control on the alternation between
Figure 1- Location of study area. Inset map shows the central Appalachian basin and its major bounding structures; the Allegheny thrust front, the Cincinnati Arch, and the northern margin of the Rome Trough (NMRT). Also shown is the trace of the NW-SE cross section of figure 2. Large map of West Virginia shows outcrop of New River Formation (shaded), well logs used for sub-surface correlation (black dots), and the trace of cross sections A-A' (Fig. 3, top), B-B' (Fig. 3, bottom), and C-C' (Fig. 11).
siliciclastic and chemical sedimentary deposits (Cecil et al., 1985; Cecil, 1990; Miller et al., 1996).

The New River Formation (Fig. 2) in West Virginia consists of as much as 300 meters of predominantly nonmarine, coal-bearing siliciclastics that filled the foreland basin following the development of the widespread Lower Pennsylvanian unconformity. This formation and equivalent strata in Kentucky (lower part of Breathitt Group) and Virginia (Lee Formation) can be grouped into two main facies belts: a western belt dominated by thick (up to 70 m), tabular (up to 90 km wide, ~500 km long) quartz arenites, and an eastern belt dominated by shale, siltstone, coal, and discontinuous sandstone bodies. In a study of equivalent strata in eastern Kentucky, Chesnut (1988) showed that these facies belts advanced northwestward through time, such that successive sandstone bodies progressively onlapped the western side of the basin. This is also the case for the New River Formation, and as shown in figure 3, the eastward-dipping unconformity was progressively overlain by stratigraphically younger sandstone bodies.

The Lower Pennsylvanian sandstones can be grouped into four main bodies. In Kentucky these are known as the Warren Point, Sewanee, Bee Rock, and Corbin Sandstone Formations of the Breathitt Group (Chesnut, 1994). In West Virginia they are informally known as the ‘salt sands.’ Each major sandstone body typically is composed of several, thinner sandstone bodies separated by thin veneers of underclay, coal, shale and/or siltstone. In West Virginia, these thinner sandstone bodies are named (from bottom to top) the Pineville, Lower Raleigh, Upper Raleigh, Guyandot, Lower Nuttall, and Upper Nuttall Sandstones of the New River Formation (Fig. 2). The sandstone bodies pinch out into fine-grained facies in the eastern part of the study area, but amalgamate to the northwest to form thick sandstone bodies (salt sands) in the subsurface.
Figure 2- A) Generalized lithostratigraphic chart for the Carboniferous record of the central Appalachian basin. Detailed column shows typical lithology and gamma-ray signature of the New River Formation and uppermost part of the Pocahontas Formation. The names of major sandstone bodies and mineable coal seams are given. B) Cross section through the central Appalachian foreland basin showing the eastward-thickening wedge of Carboniferous strata (see figure 1 for location). Note angular truncation of strata along the base of the New River Formation. The western-eastern facies zonation within the New River Formation represents the predominance of sheet-like sandstone bodies in the west and the predominance of mud-rock, coal, and discontinuous sandstone bodies in the east (Modified from Englund and Thomas, 1990).
Sheet sandstones of the New River Formation are similar in scale and depositional setting to those of the Cretaceous western interior basins (Rice, 1985; Van Wagoner, 1995). However, the direction of facies gradation from coarse-grained fluvial to fine-grained marginal marine is different. Whereas Cretaceous fluvial sandsheets are attached to proximal facies and grade basinward into marginal marine facies, sandsheets of the New River Formation are part of the distal foreland basin fill, and interfinger towards the thrust front (Fig. 1, inset) with fine-grained, marginal marine and subordinate nonmarine strata. Existing depositional models (Donaldson, 1974; Ferm, 1974; Hobday and Horne, 1977; Presley, 1979; Houseknecht, 1980; Staub et al., 1991) fail to adequately explain this anomalous distribution of facies within a modern stratigraphic framework.

Time constraints are poor for the studied interval due to the paucity of fossils and absolute age dates, but an estimate can be made based on megafloral biostratigraphy by Blake (1997) and correlation with western European stages (Riley and Turner, 1995). These studies indicate that the interval between the base of the New River Formation and the base of the Betsie Shale Member of the Kanawha Formation (Fig. 2) corresponds to the Westphalian A (Langsettian). The Carboniferous time scales provided by Menning et al. (1997) provide maximum and minimum estimates for the lower boundary – between 316.5 and 309 Ma – and the upper boundary – between 313.5 and 307 Ma – for this stage. Therefore, the duration of the study interval is estimated at between 2 and 3 million years.
METHODS

Subsurface and outcrop data (Fig. 1) were combined to develop a three-dimensional sequence stratigraphic framework for the New River Formation. Strike and dip-oriented cross sections were constructed (Fig. 3) and tied into measured sections and cores at key localities. In outcrop, five facies associations were defined based on lithology, sedimentary structures, trace fossils, and paleocurrents (Table 1). For subsurface correlation, these units were grouped into three main facies associations based on gamma-ray well log expression: blocky, low-radioactivity; fining-upward; and coarsening-upward. The sharp-based, blocky pattern is typical of the low-radioactivity quartz arenites. Fining-upward well log patterns are most common at the tops of sandstone bodies, and are rarely present at the tops of coarsening-upward units. Coarsening-upward well log patterns are developed at several distinctive stratigraphic levels, but they are thickest and most extensive on top of the four major (‘salt sand’) sandstone bodies (Fig. 3A, 3B). These are the easiest patterns to recognize and trace from well to well because the base of each coarsening-upward unit is defined by a ‘hot’ radioactive kick in the well log. One such interval is developed on top of the Guyandot Sandstone. Because of its stratigraphic location in the middle of the formation, the base of this interval is used as a datum upon which to hang the cross sections.
Figure 3- Detailed cross sections through the New River Formation in southern West Virginia (see figure 1 for locations). Correlations were made based on three gamma-ray well log patterns - blocky/low radioactivity, fining-upward, and coarsening-upward - which were calibrated to lithology in core and outcrop. Datum is the shale above the Guyandot Sandstone or, where absent, the shale above the Nuttall Sandstone. Note the progressive westward stacking of successive sandstone bodies and the amalgamation of sandstone facies to the west. 'Unnamed' sandstone at the top of the section is known as the Corbin Sandstone in Kentucky.
<table>
<thead>
<tr>
<th>Lithology</th>
<th>Sedimentary structures</th>
<th>Fossils</th>
<th>Sand body geometry</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine- to very coarse-grained sandstone Local quartz &amp; siderite pebble conglomerate</td>
<td>Upward-thinning sets of tabular &amp; trough cross beds, 0.1 – 3 m thick Subordinate ripple cross laminae, plane beds, &amp; massive bodies</td>
<td>Rare</td>
<td>Channel-fills with up to 5 m of basal relief</td>
<td>Trunk fluvial: Bedload-dominated, high-energy, low-sinuosity fluvial systems</td>
</tr>
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<td></td>
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<td>Sheet-like (100km wide, 70 m thick) channel complexes</td>
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<td></td>
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<td>Channel complexes (several km wide, 30 m thick)</td>
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</tr>
<tr>
<td>Fine- to medium-grained sandstone</td>
<td>Sigmoidal cross-beds with rare, eastward-oriented paleoflow Planar, trough, &amp; sigmoidal cross beds that grade into clay-draped toesets</td>
<td>Rare skolithos &amp; diplocraterion</td>
<td>Occurs on top of channel complexes</td>
<td>Tidally influenced, upper estuarine fluvial channels Tidal sand bodies/sand flats</td>
</tr>
<tr>
<td>Interlaminated mudrock &amp; fine-grained sandstone</td>
<td>Lenticular, wavy, &amp; flaser bedding, commonly grades into cross beds</td>
<td>Rare</td>
<td></td>
<td>Tidally-influenced, upper estuarine fluvial channels Tidal sand/mud flat</td>
</tr>
<tr>
<td>Sandstone bodies with basal, intraformational conglomerate</td>
<td>Massive at base, grades upward into plane beds</td>
<td>Absent</td>
<td>Isolated channel-fills with 1-5 m basal relief, 10-40 m wide</td>
<td>Mass flow deposits</td>
</tr>
<tr>
<td>Shale, mudrock, siltstone, very fine- to fine-grained sandstone Interlaminated mudrock &amp; fine-grained sandstone</td>
<td>Lenticular, wavy, &amp; flaser bedding, arranged into repetitive, decimeter-scale packages of muddier to sandier intervals. Centimeter-scale packages of thickening &amp; thinning, sandstone/mudstone couplets (laminae)</td>
<td>Lockeia, Planolites, Teichichnus, Palaeophycus, rare Rosselia, Thallassanoides, &amp; Asterosoma. Occasional ostracoda, pelycypoda, &amp; lingula</td>
<td>Thin (&lt;0.5 m) sandstone lenses</td>
<td>Tidally influenced, central estuarine deposits</td>
</tr>
<tr>
<td>Interlaminated mudrock &amp; fine-grained sandstone</td>
<td>Lenticular, wavy, &amp; flaser bedding Ripple cross-laminae, trough cross-bedding Rare hummocky cross-strata &amp; symmetrical, form-discordant ripples</td>
<td>Same trace fossil assemblage as mudrock (estuarine) facies above Some very intense bioturbation</td>
<td>Laterally extensive, coarsening-upward sandstone bodies, up to 5 m thick Thin (&lt;0.3 m) sandstone lenses</td>
<td>Bayhead deltas, progradational complexes, mixed tide, wave, and fluvial influence</td>
</tr>
<tr>
<td>Mudrock, siltstone, coal Very fine- to medium-grained sandstone</td>
<td>Diffuse laminae Ripple cross-strata &amp; tabular, upward-thinning cross-bed sets (30 cm to 3 cm) Gently inclined (~10°) beds of heterolithic strata (rare)</td>
<td>Various plant fossils, roots</td>
<td>Thin (&lt;1.5 m) sandstone sheets</td>
<td>Floodplain paleosols, peat mires Rare, low energy, mixed bedload/suspended load, high-sinuosity fluvial</td>
</tr>
</tbody>
</table>

Table 1 Facies descriptions and interpretations
FACIES ASSOCIATIONS AND DEPOSITIONAL ENVIRONMENTS

Fluvial sandstone association

The most common facies association within the New River Formation consists of coarse-, medium-, and fine-grained sandstone with local quartz-pebble and siderite-pebble conglomerates. In some exposures it is possible to recognize a four-fold hierarchy of bounding surfaces within sandstone bodies in which upward-thinning, medium- to large-scale tabular and trough cross-bed sets (Fig. 4A), plane beds, and ripple cross strata are superimposed on gently inclined surfaces. Multiple inclined beds are developed within larger-scale channel-fills with as much as 5 meters of local relief. Basal lags of intraformational siderite, woody plant fragments, and coal rip-ups are developed along channel bases. Individual channel-fills are vertically and laterally amalgamated to form two main types of channel complexes: channel-like (several km wide, 30 m thick) and sheet-like (up to 90 km wide, 70 m thick). Channel-like sandstone bodies with more than 20 meters of basal relief (Fig. 5) occur in the eastern facies belt, whereas relatively flat-based, sheet-like sandstone bodies predominate in the western facies belt (Fig. 3A, 3B). The orientations of paleocurrent indicators are north-northwest in the channel-like sandstone bodies, and south-southwest in the sheet-like sandstone bodies (Fig. 6).

These facies are interpreted as the deposits of bedload-dominated, low sinuosity, high-energy fluvial systems based on the architecture of bounding surfaces observed in outcrop (cf. Miall, 1985). Deposition occurred through bedform migration over sandy, downstream-accreting macroforms and, to a lesser extent, across bank-attached, laterally accreting macroforms. Several macroforms were superimposed during the infilling of small-scale channels. Channel migration resulted in vertical and lateral amalgamation of small-scale
Figure 4- A) Large-scale tabular/planar cross beds in fluvial sandstone facies. B) Sigmoidal cross bedding of tidal sandstone facies. Paleocurrents are commonly landward-oriented (east). Note hammer for scale. C) Rhythmically-laminated sandstone/mudstone of tidal facies. D) Upward-coarsening bayhead delta facies. Scale bar is 5 feet.
Figure 5- Outcrop photograph of a deeply-incised paleovalley: the Upper Raleigh Sandstone near Beckley, West Virginia.
Figure 6- Paleocurrent data from Upper Raleigh Sandstone in the New River Gorge area. All data collected from fluvial sandstone facies, except for those used in rose diagram marked 'tidal,' which were collected from tidal sandstone facies. Note the differences in paleoflow directions between southern and northern locations. This change reflects north/northwest-flowing tributary streams which drained into south/southwest-flowing trunk rivers. Note eastward (landward) orientation of paleoflow in 'tidal' rose diagram.
channels to form the larger, channel-like and sheet-like channel complexes. Wizevich (1992) used lateral profile analysis to infer a similar depositional history for equivalent sandstone units in Kentucky, and fluvial deposition has been inferred for thick sandstone bodies in other parts of the basin as well (Rice, 1985; Barnhill, 1994; Greb and Chesnut, 1996).

_Tidal sandstone-mudrock association_

These facies comprise fine- to medium-grained sandstone and minor amounts of mudrock. This association is distinguished by one or both of the following characteristics: sigmoidal cross-beds, and/or interfingering between cross-bedded sandstone and lenticular, wavy, and flaser bedding. Both facies are commonly associated with 1 – 5 m thick, isolated, massive, sandstone channel-fills.

**Sigmoidal cross-bedded sandstone.**---The cross-bedded sandstone facies is characterized by distinctive sigmoidal shapes and multiple reactivation surfaces (Fig. 4B). The amount of mudrock within these facies is variable. Where mudrock content is high, it is most common as mudstone drapes within ripple-bedded toesets. Trace fossils are rare, but some vertical burrows have been observed on sandstone cross-bed foresets. Paleocurrent trends are mainly oriented west/southwest. However, in some localities paleoflow directions are oriented east. These trends are oriented $180^\circ$ to underlying paleocurrents of the cross-bedded (fluvial) sandstone facies (see rose diagrams between Beckley and Mount Hope on figure 6). This facies is commonly separated from cross-bedded sandstone facies (fluvial sandstone) by a sharp contact defined by a thin, clast-supported, quartz-pebble conglomerate bed.

The internal structures, paleocurrent trends, and close association with muddy facies, are suggestive of a tidally-influenced origin. These sandstones are comparable to both modern
(Visser, 1980) and ancient (Kreisa and Moiola, 1986) examples of tidal deposits. Internal structures of these deposits are consistent with those predicted by Allen (1980) for sand waves formed by tidal currents with significant time-velocity asymmetries. Particularly strong evidence for tides is given by the landward-oriented paleocurrents. Such evidence has been used by Shanley et al. (1992) to infer tidal influence in otherwise fluvially dominated successions. The thin conglomerate beds that separate tidally influenced facies from underlying cross-bedded, fluvial sandstone are interpreted as reworked deposits above a tidal ravinement surface (cf. Shanley et al., 1992).

**Interfingering sandstone/mudrock.**---Both small-scale and large-scale interfingering relationships exist between the sandstone and mudrock facies. Small-scale interfingering relationships occur within cross bed sets as: 1) rhythmically laminated, trough-filling toesets of large-scale, trough cross-bed foresets (Fig. 4C), 2) wavy bedded toesets that grade into planar cross-beds, superimposed on inclined heterolithic strata, and 3) lenticular bedding that grades laterally into thin beds of current ripple cross strata. Large-scale interfingering occurs between 1-2 m thick units of interlaminated sandstone-mudrock and 1-2 m thick cosets of tabular-planar to sigmoidal cross-bedded sandstone. Each mudrock unit consists of alternating, 2-3 cm thick beds of sandstone-dominated and mudrock-dominated laminae with abundant current ripples. Grain size and bedding thickness typically increases upward within these intervals.

Although not diagnostic of tidal settings, lenticular, wavy, and planar bedding is suggestive of alternating current flow and slack water periods (Reineck and Wunderlich, 1968). The intricate association of these mudrock facies with sigmoidal cross beds provides strong evidence for a tidally influenced depositional environment. In addition, some facies show a crude rhythmicity in the alternation between sandstone-dominated (flaser) and mudrock-
dominated (lenticular) bedding, which is suggestive of spring-neap variations in tidal current velocities (Greb and Archer, 1995).

The most convincing evidence for tidal influence is found in the rhythmically laminated facies of muddy, trough cross-bed toesets. The outcrop expression of these facies is similar to other Pennsylvanian-age tidal deposits of the Appalachian and Illinois basins. Thick to thin variations in laminae thicknesses within these deposits are commonly interpreted as the result of variations in tidal velocities from spring to neap tides (Kvale et al., 1989; Kvale and Archer, 1990; Archer et al., 1995; Miller and Eriksson, 1997; Adkins and Eriksson, 1998; Greb and Archer, 1998). Detailed examination of these facies, however, indicates that a single thickening-to-thinning package of sandstone-mudstone couplets grades laterally into a single, trough-shaped, ~3 cm-thick sandstone foreset. It is likely that foreset migration during a spring to neap tidal cycle would have been on the order of several meters, rather than centimeters (Visser, 1980). This observation suggests that thickening and thinning packages of laminae were deposited during one tidal event. The sandstone/mudstone couplets were probably generated by sediment size partitioning from random flow separation and variable flow velocities across the top of the dune during a single tidal flow (R. Boersma, A. Van Gelder, and J.H. Van den Berg, personal communication, 2001).

As a whole, the sandstone-mudrock facies represent tidally influenced fluvial deposition in inner estuarine environments (c.f. Dalrymple et al., 1992). The subtle evidence for tidal influence throughout this association suggests that these deposits represent the first occurrence of marine processes near the fluvial/tidal transition in the estuaries.

**Massive sandstone.**---Massive, channelized sandstone bodies are common near the contact between mudrock units and the planar cross bedded sandstone sets. These sandstone
bodies are 1 – 5 meters thick and 10 – 40 meters wide, contain basal lags of intraformational conglomerate, and have cross-sections orientated perpendicular to the paleocurrent modes in the cross stratified sandstone. Plane beds commonly are present towards the tops of massive sandstone bodies.

These sandstone bodies are interpreted as the deposits of mass-flows that developed due to bank collapse of channel margins. A similar depositional model was inferred by Turner and Monro (1987) for massive, channelized sandstones from the Carboniferous of England. In their model, bank collapse was initiated by an increase in bank slope in front of an approaching dune. This model is particularly appropriate for the massive sandstones of the New River Formation because they occur immediately below cross-bed sets, and thus, were formed just prior to the approach of the advancing bedform.

*Estuarine mudrock association*

This facies association comprises shale, mudrock, and lenticular, wavy, and flaser bedding with abundant horizontal and vertical burrows. Heterolithic, interlaminated mudstone-sandstone facies are commonly organized into repetitive, cyclic, decimeter-scale packages that change from lenticular bedding to wavy/flaser bedding, and back into lenticular bedding. In rare cases, mudstones consist of rhythmic, centimeter-scale packages of thickening and thinning laminae. Ichnofossils include *Lockeia, Planolites, Teichichnus, Palaeophycus, Helminthopsis (?)*, and more rarely, *Rosselia, Thallassanoides*, and *Asterosoma*. Ostracod body fossils have been observed in some black shale facies, and some authors have reported other fresh- and brackish-water invertebrate body fossils, including *Pelecypoda* and *Lingula*, from shales of the

These facies are interpreted as central estuarine basin deposits. The relatively high abundance and diversity of ichnofossils suggests the presence of marine-restricted, brackish-water environments. In addition, the abundance of lenticular, wavy, and flaser bedding and the rhythmic alternation between muddier and sandier laminae suggests that tidal deposition was predominant. Based on the model of Dalrymple et al. (1992), the low-energy setting of the central estuarine basin should result in the greatest amounts of mud deposition and bioturbation. These facies represent the maximum landward advance of marine processes during the deposition of the New River Formation.

*Deltaic mudrock-sandstone association*

These facies comprise upward-coarsening, 1.5 – 18 m-thick units of mudrock, siltstone, and fine-grained sandstone (Fig. 4D). Sedimentary structures include lenticular, wavy, and flaser bedding, ripple cross laminae, and trough cross bedding. In rare cases, hummocky cross stratification and symmetrical, form-discordant ripples are present. In general, the scale of cross-bedding increases upward, and ripple cross strata change from symmetrical, form-discordant and mudstone-draped, round-crested forms, to asymmetrical, sharp-crested forms within a single coarsening-upward interval. Sharp-based, cross-bedded sandstone lenses are common near the tops of these units. Rarely, thin (<30 cm) sandstone lenses with inverse grading are present. These lenses become conglomeratic upward, with intraformational mudstone clasts near their tops. The trace fossil assemblage is similar to that of the estuarine mudrock association.
although, at some locations, bioturbation is intense enough to obscure all primary sedimentary structures.

The average thickness of individual coarsening-upward units varies with respect to geographic location and stratigraphic position. For example, those above the Upper Raleigh Sandstone are 1.5 – 2 meters thick in northwestern areas, but are 6 – 9 meters thick at the same stratigraphic interval in southeastern areas. Those developed in mudrock-dominated intervals (i.e. above the Guyandot Sandstone, Fig. 3) are as much as 18 meters thick. Coarsening-upward units are generally stacked into sets, with the uppermost unit in contact with a thick, mineable coal seam (i.e. Sewell coal or Iager coal).

This association of facies is interpreted as consisting of both small-scale and large-scale progradational complexes. Thin, coarsening-upward successions, were formed by progradation of bayhead deltas and estuary mouth bars during the early infilling of estuaries. These are similar in scale and morphology to some modern progradational deposits in the Gironde estuary (Fenies and Tastet, 1998). Thicker coarsening-upward successions, such as those above the Guyandot Sandstone (Fig. 2), were formed as prograding deltaic complexes. The distinction is made primarily based on thickness and the degree of bioturbation. The presence of inverse graded, conglomeratic sandstone lenses suggests that locally, delta-front slopes were sufficiently steep to generate debris flows.

**Floodplain mudrock-coal association**

Facies association E consists of sideritic mudrock, coal, and thin (<1 m) very fine- to medium-grained sandstone lenses. Mudock facies are red/gray to brown in color, and are mostly massive and blocky, although relict laminae are locally preserved. Thin (1 – 10 cm) coal beds
are common above rooted mudrock horizons that contain finely-preserved plant fossils. Sandstone lenses contain sets of tabular cross-strata that thin from 30 cm at the base to 3 cm at the top. Some facies consist of 3 meter-thick, gently-inclined (~10°) beds of heterolithic strata. These facies represent rare floodplain and low-energy fluvial environments. The thin coals, paleosols, and sandstone lenses were developed as floodplain deposits. Gently inclined, heterolithic strata reflect lateral accretion of low-energy, mixed-load, highly sinuous fluvial settings (Allen, 1965).

**INTER-RELATIONSHIPS OF FACIES ASSOCIATIONS**

Vertical and lateral relationships between facies associations were studied using lateral profiles and photomosaics from road cuts near Beckley, West Virginia (Fig. 7). Three vertically-stacked channel complexes are identified, each of which is composed of two or more channel fills of similar architectural style. Both amalgamated and non-amalgamated types of Sprague et al. (2002) are present.

The lowermost channel complex is non-amalgamated and consists of at least three channel fills. Each channel-fill is composed of tidal sandstone-mudrock, estuarine mudrock, and deltaic mudrock-sandstone facies associations. Lower parts of channel-fills contain facies tidal sandstone-mudrock facies, which is both vertically and laterally gradational into estuarine mudrock facies. Vertical gradation from sandstone to mudrock is observed in the channel-fill immediately below the Upper Raleigh Sandstone on the right side of profile 2. Lateral gradation
Figure 7- Lateral profile of highway exposures near Beckley, West Virginia, based on closely-spaced measured sections (vertical lines). Dashed line connects right side of western road cut (1) with left side of eastern road cut (2). Heterolithic channel fills below and above the Upper Raleigh Sandstone consist of tidally influenced estuarine deposits. The Upper Raleigh Sandstone consists of fluvial sandstone facies that truncate the Little Raleigh coal seam to the east. This surface is interpreted as a composite 3rd- and 4th-order sequence boundary (SB). Ostracod-bearing black shale on left side of profile 1 is interpreted as a 4th-order maximum flooding surface (mfs). Some parts of profile are 'mirror images' of the actual exposure because data was collected from both sides of highway. Regional dip is ~1° northwest. 3) Interpretation of facies architecture within Upper Raleigh Sandstone, showing amalgamated fluvial channels. Data partially supplied by Erik P. Kvale, Indiana Geological Survey.
from sandstone to mudrock is observed over a distance of ~75 m near the middle of profile 2. Upward within the channel-fills, estuarine mudrock is vertically gradational into deltaic sandstone-mudrock. The upper part of the channel complex (below the Little Raleigh coal) is comprised of tidal sandstone-mudrock facies. Thus, the typical channel fill at this location consists of a repetitive succession of facies from tidal sandstone-mudrock, to estuarine mudrock, to deltaic mudrock-sandstone, and back to tidal sandstone-mudrock.

The middle channel complex consists primarily of fluvial sandstone within amalgamated sandstone channel-fills. The channel fills are recognized by changes in the scale and style of cross stratification across erosional boundaries (Fig. 7, profile 3). The middle complex is deeply incised (~18 m) into the lower channel complex, with contorted and slumped beds present along the sides of the channel-fill. A very thin interval of tidal sandstone is present near the top of the channel complex, but its relationship with the fluvial facies is unclear because of limited exposure in that location.

The non-amalgamated facies architecture of the uppermost channel complex (Fig. 7, profile 1) is similar to the lower channel complex. However, channel-fills are smaller-scale and are commonly draped by thin, basal coals. A typical channel-fill facies succession begins with tidal sandstone-mudrock or estuarine mudrock, and is vertically gradational estuarine mudrock or deltaic mudrock-sandstone, respectively. The channel complex is capped by tidal sandstone-mudrock facies in the uppermost channel-fill.

The facies relationships described above are similar to fluvial- to estuarine-facies successions of idealized paleovalley fills (Dalrymple et al., 1992). The lowermost channel complex is interpreted as the estuarine-fill of a larger-scale paleovalley (Lower Raleigh).
middle and uppermost channel complexes represent a single, fluvial-to-estuarine, paleovalley fill succession (Upper Raleigh).

**PALEOGEOOMORPHOLOGY**

Discrepancies between outcrop paleocurrent data and subsurface trends of sandstone body thickness have been the source of much confusion and misinterpretation of Lower Pennsylvanian paleogeography in the central Appalachian Basin. Paleocurrents throughout most of the outcrop belt indicate generally northwest transport, whereas sheet-like sandstone bodies are oriented roughly perpendicular (northeast-southwest) to these trends. Paleocurrent data from this study are from sheet sandstones in the northwest and channel-like bodies to the southeast. The New River Gorge – which cuts nearly 250 meters down into the New River Formation near Fayetteville – exposes sandstone bodies that are normally only present in the subsurface. The change in mean paleocurrent direction of cross-bedded facies (fluvial, excluding the ‘tidal’ rose diagram) within the Upper Raleigh Sandstone is coincident with the change from the eastern facies belt to the western facies belt, and thus, the change from channel-like to sheet-like sandstone bodies (Fig. 6).

Some workers have attributed the trends in paleocurrent directions and sandstone body thicknesses to a northwest-oriented fluvial drainage system that delivered sediment to a northeast-southwest oriented shoreline where sediments were reworked by longshore currents in shelf and nearshore marine environments (Presley, 1979; Houseknecht, 1980; Staub et al., 1991). Conversely, authors working in other parts of the basin have recognized that the thick, sheet-like sandstone bodies are predominantly fluvial in origin (Rice and Schwietering, 1988; Greb and
Paleocurrent data from this study (Fig. 6) support a fluvial drainage system hypothesis, where channel-like and sheet-like sandstone bodies represent deposition in transverse- and axially oriented fluvial environments, respectively.

Early Pennsylvanian paleogeomorphology and drainage networks were further studied by combining cross sections and paleocurrent data (Figs. 3 and 6) with coal cut-out maps (Fig. 8). The regional cross section in figure 3 shows that the Sewell coal seam is erosionally removed to the northwest by the Guyandot Sandstone. Similar patterns of northwestern coal truncation are observed in other cross sections as well. Thus, the western limit of a coal bed roughly corresponds with the eastern limit of a sheet-like sandstone body. In contrast, the eastern facies belt contains well-preserved coal beds that are locally truncated. Figure 8 shows two subsurface coal mine maps that delineate erosional surfaces in the eastern facies belt. Unshaded regions show areas where coal was not mined due to uneconomic thickness and/or truncation by sandstone. These maps are interpreted to show the geometry of northwesterly oriented erosional surfaces along the bases of channel-like sandstone bodies in the roofs above the coals and their northwest transition into sheet sandstone bodies. This type of erosional surface can be observed in road-side exposures near Beckley, West Virginia (Figs. 5, 7). In this area, the Upper Raleigh Sandstone truncates the Little Raleigh coal seam and is deeply incised (~18 m) into underlying deposits (Fig. 7).

The cross-sectional and plan-view geometries described above, in combination with the paleocurrent data of this and previous studies, show that fluvial systems occupied paleovalleys in which tributary streams flowed northwestward into southwest-flowing trunk streams. This trunk/tributary paleovalley system was developed repeatedly in response to periodic erosion
Figure 8- Underground maps of A) Pocahontas #4 coal seam, and B) Sewell coal seam, showing mined-out coal (shaded). Unshaded portions show areas where coal is not present due to erosional truncation by overlying sandstone bodies. Small arrows show tributary paleovalleys, large arrow shows trend of trunk paleovalley. A - from Padgett and Ehrlich (1978), B - courtesy of West Virginia Geologic and Economic Survey.
throughout the basin. The tributaries acted as transport paths for coarse sediment into the distal trunk paleovalleys.

**SEQUENCE STRATIGRAPHY**

An objective, rock-based approach is used to define sequences and systems tracts in this study. The terminology used here is independent of the thickness and duration of a stratigraphic interval and does not imply a specific period of time or position on a eustatic or relative sea level cycle (Van Wagoner et al., 1988, p. 42). A sequence is defined as a genetically related succession of relatively conformable strata bounded by unconformities or their relative conformities (Mitchum, 1977, p. 53). Systems tracts are defined according to their position in relation to sequence boundaries, flooding surfaces, and parasequence stacking patterns. The lowstand systems tract extends from the sequence boundary to the initial flooding surface, the transgressive systems tract lies between the initial flooding surface and the maximum flooding surface, and the highstand systems tract extends from the maximum flooding surface to the overlying sequence boundary (Van Wagoner et al., 1988).

The application of systems tract terminology to predominantly nonmarine strata is appropriate only where a linkage between fluvial and shoreline lithosomes can be demonstrated (Ethridge et al., 1998; McLaurin and Steel, 2000). Sequences in the New River Formation are divided into systems tracts because flooding surfaces can be correlated in the subsurface from predominantly nonmarine strata to coeval marginal marine strata, and in some cases, parasequence stacking patterns can be identified.
The recognition of sequence boundaries in predominantly nonmarine strata is problematic. As discussed by Aitken and Flint (1995) and Best and Ashworth (1997), localized channel scours can be easily mistaken for sequence boundaries. Several criteria for the recognition of sequence boundaries were outlined by Shanley and McCabe (1994) and further developed by Aitken and Flint (1995) and Miall and Arush (2001). These criteria include: 1) abrupt facies tract dislocation, 2) regional incision on a scale greater than that of associated channels, 3) presence of multilateral, multistory sand bodies, 4) major changes in paleocurrent directions, and 5) upward changes in grain size and petrographic composition.

Based on the above criteria, both 3rd- and 4th-order sequences can be identified in the New River Formation. As shown on figure 9, third-order sequence boundaries lie at the bases of each of the four major sandstone bodies (Pineville, Upper Raleigh, Lower Nuttall, and unnamed sandstone – shown on Fig. 3), and fourth-order sequence boundaries lie at the bases of the thinner sandstone bodies (Lower Raleigh, Guyandot, Upper Nuttall, and several other unnamed sandstones). Both 3rd- and 4th-order sequence boundaries can be recognized in outcrop. The base of the Upper Raleigh Sandstone near Beckley, West Virginia (Fig. 5, 7) is an example of a 3rd-order sequence boundary. This sandstone body is composed of amalgamated, fluvial, sandstone channel-fills and is deeply incised (~18 m) into underlying tidally-influenced estuarine strata. The juxtaposition of fluvial on tidal deposits marks a basinward shift in facies tracts. This boundary is also accompanied by a major change in petrographic composition, from the underlying, lithic-rich Lower Raleigh Sandstone into the overlying, quartz-rich Upper Raleigh Sandstone (Houseknecht, 1980). In addition to the other 3rd-order sequence boundaries identified in this study, this sequence boundary can be correlated across the entire study area (Fig. 10). Fourth-order sequence boundaries cannot be traced for large distances in the
Figure 9- Sequence stratigraphic interpretation of the New River Formation. Fourth-order sequences stack into composite 3rd-order sequences. Note the upward decrease in thickness of 4th-order fluvial facies (stippled) within 3rd-order sequences, especially sequence 2. Also note the absence of thick, 4th-order highstand deposits.
Figure 10- Third-order sequence stratigraphy of the New River Formation based figure 3. Third-order sequence boundaries lie below the four major sandstone bodies (Pineville Sandstone is significantly thicker to the southwest). Third-order maximum flooding surfaces lie at the bases of regionally-extensive, coarsening-upward units. Note the predominance of lowstand systems tract deposits and the absence of thick highstand systems tract deposits.
subsurface because sandstone bodies amalgamate to the west (see Raleigh-Guyandot interval in Fig. 10).

Although sequence boundaries are the most readily identifiable stratigraphic surfaces in outcrop, correlation of sequences in the subsurface is aided by the recognition of maximum flooding surface deposits. Maximum flooding surfaces were identified based on the recognition of central estuarine basin facies which mark the most landward extent of the shoreline. These facies are overlain by regionally traceable, coarsening-upward intervals of progradational strata. On gamma-ray well logs, the maximum flooding surface is a ‘hot’ kick at the base of a coarsening-upward pattern (figure 3). Third- and fourth-order maximum flooding surfaces can be identified in the New River Formation. Third-order surfaces are present on the tops of major sandstone bodies and are generally traceable across the length of the basin. As shown in figure 11, the maximum flooding surface above the Guyandot Sandstone can be traced from the base of a thick, progradational parasequence set in downdip sections, to a thin stratigraphic interval marked by a ‘hot’ shale in updip sections. Parasequences above this surface downlap onto the maximum flooding surface. Fourth-order maximum flooding surfaces are present on the tops of thinner sandstone bodies and commonly pinch out over short distances. For example, the coarsening-upward well log pattern between the Upper Raleigh Sandstone and the Sewell coal (figure 3) pinches out to the west over a distance of ~30 km.

Recognition of initial marine flooding surfaces is based on the change from the fluvial association to tidally influenced facies within paleovalleys. In the subsurface, this stratigraphic interval is marked by the change from the blocky, low-radioactivity pattern to the fining-upward pattern. The initial flooding surface is commonly marked by a thin, (<1 m) quartz- and siderite-pebble conglomerate above a tidal ravinement surface.
Figure 11- Cross section C-C' (see figure 1 for location) showing two 4th-order sequences. Note progradational and downlapping parasequence stacking patterns above maximum flooding surfaces.
A typical 4\textsuperscript{th}-order sequence consists of deeply incised, fluvial channel sandstone separated from overlying tidally modified estuarine sandstone and mudrock by a ravinement bed, and capped by central basin deposits and coarsening-upward delta/bayhead delta facies. The relative thickness of fluvial versus estuarine facies within a fourth-order sequence varies with respect to its position within a 3\textsuperscript{rd}-order sequence. Lowermost 4\textsuperscript{th}-order sequences are dominated by fluvial facies, whereas the uppermost sequences are dominated by estuarine facies (Fig. 9).

**DEPOSITIONAL MODEL**

Figure 12 illustrates the development of an idealized 4\textsuperscript{th}-order sequence, and shows how several sequences stack into a composite 3\textsuperscript{rd}-order sequence. This model is based primarily on the facies architecture and geometry of the Raleigh-Guyandot sequence in figure 10. At relative highstands of sea level, west/southwest-prograding deltaic complexes filled the estuaries and resulted in highstand depositional shorelines along the margins of the axial trunk valleys (Fig. 12A-1). The highstand deltas were subsequently eroded by narrowly-confined fluvial systems during relative falls in sea level, which resulted in tributary valleys that routed coarse sediment into the distal parts of the basin (Fig. 12A-2). Fluvial deposition during relative lowstands of sea level resulted in an extensive sandstone sheet that filled the trunk valley, and multiple, channel-like sandstone bodies that filled the tributary valleys (Fig. 12A-3). Relative rises in sea level caused drowning of the paleovalleys along with tidal ravinement and tidally-influenced fluvial deposition in the elongate estuaries (Fig. 12A-4). Finally, central basin muds were deposited, marking the maximum flooding surface.
Figure 12- A) Simplified paleogeographic/depositional reconstruction for the New River Formation during: 1) progradation of highstand deltas, 2) fluvial incision during relative lowstand of sea level, 3) fluvial infilling of valleys, and 4) marine flooding and estuarine development. B) Idealized cross sections depicting evolution of a 3rd-order sequence, based on geometry of Raleigh/Guyandot sequence from figures 3 and 11.
Composite, 3rd-order sequences were developed by the vertical amalgamation of multiple 4th-order sequences (Fig. 12B). Fluvial deposits of the lowstand systems tract within the lowermost 4th-order sequence overlie a composite 3rd- and 4th-order sequence boundary. Likewise, the uppermost central estuarine basin facies represent a composite 3rd- and 4th-order maximum flooding surface. This model can be compared to the sequence stratigraphic model of Posamentier and Allen (1993) for foreland basin deposits. The predominance of type 1 sequence boundaries throughout the studied interval suggests that maximum rates of sea level fall consistently exceeded basin subsidence. Thus, the preserved parts of the basin were developed within zone B of Posamentier and Allen (1993).

The sequence stratigraphic model developed here provides an explanation for the anomalous facies distribution (coarsening toward the craton) in the New River Formation. During relative lowstands of sea level, sands were delivered to the distal part of the basin via the tributary paleovalley system. Through time, high sediment yields relative to accommodation resulted in westward amalgamation of successive lowstand systems tracts in the axial trunk system. Thus, the major, sheet-like, fluvial sandstone bodies interfinger with fine-grained estuarine and subordinate fluvial facies to the east, causing them to be detached from any proximal, coarse-grained foreland basin deposits that may have existed.

DISCUSSION

Differentiating between upstream and downstream controls on nonmarine sequence stratigraphy is a difficult challenge, but it has important implications for the prediction of reservoir-scale facies architecture within predominantly continental settings (Shanley and
McCabe, 1994). There is general agreement amongst the sedimentological community that, in an upstream direction, the effects of eustasy are gradually replaced by tectonic and climatic controls on accommodation and sediment supply (Shanley and McCabe, 1994). What is not agreed upon, however, is the spatial scale of these effects and the temporal scales over which each of these controls operates.

Blum and Tornqvist (2000) define the landward limit of sea level control as the upstream extent of coastal onlap related to sea-level rise. Based on Quaternary systems, this limit appears to be controlled by hinterland sediment supply and the gradient of the onlapped floodplain surface. The landward extent of onlap may be an order of magnitude greater in low-gradient, high sediment-yield rivers than in high-gradient, low sediment-yield rivers. It is important to note, however, that the landward extent of coastal onlap does not necessarily correspond to the landward extent of incision related to sea-level fall.

One way to evaluate whether upstream or downstream changes controlled stratigraphic stacking patterns is the recognition of ‘downfilled’ versus ‘backfilled’ paleovalleys (Schumm, 1993). Paleovalleys are downfilled when hinterland sediment supply controls deposition, and are backfilled when sea level rise is the primary cause of aggradation. Each style of valley filling should produce vertical trends in grain size that can be recognized in the rock record. Downfilled valleys should coarsen upward, whereas backfilled valleys should fine upward.

Paleovalley-fills that form in response to relative rises in sea level should consist of predictable facies successions that reflect time-transgressive fluvial and estuarine depositional environments (Dalrymple et al., 1992; Zaitlin et al., 1994). In the middle segment of a valley-fill system, a fluvial- to estuarine-facies transition will mark the initial flooding surface along which relatively thin fluvial facies of the lowstand systems tract are separated from relatively thick
Estuarine facies of the overlying transgressive systems tract. Estuarine deposits will pinch out updip into entirely nonmarine deposits of the inner valley-fill system. In this realm, lowstand systems tracts will consist of amalgamated channel sandstones, whereas transgressive systems tracts will consist of isolated channel sandstones encased in overbank mudrock facies. This upward change may also be accompanied by a change in the style of fluvial deposition (e.g. braided to anastamosed or meandering).

Based on the experimental and theoretical models above, it is possible to evaluate the importance of upstream versus downstream controls on sequence development and facies architecture in the New River Formation. The presence of estuarine facies above fluvial deposits suggests that paleovalleys were well within the realm of coastal onlap during the development of 4th-order sequences. The lack of marine shales and outer estuarine barrier and/or tidal inlet facies within these valley fills indicates that the valley-fills were formed in middle- to inner-estuarine settings (c.f. Zaitlin et al., 1994). Based on comparison with the estuarine facies models described above, the vertical successions of facies within 4th-order paleovalley fills of the New River Formation generally suggest depositional responses to relative rises in sea level.

There are, however, some important differences between the general models and the sequences within the studied interval which suggest that downstream controls were not the only factors that influenced erosion and deposition. First, the lowstand systems tracts are anomalously thick relative to the transgressive systems tracts. The ratio of fluvial to estuarine facies within valley fills that form entirely due to relative changes in sea level can be up to an order of magnitude less than what is observed in the New River sequences (Greb and Chesnut, 1996). Second, the fining upward patterns that are predicted to form in backfilled valleys (Schumm, 1993) are rare to absent within the New River paleovalleys. It is only within the
uppermost parts of the lowstand systems tract and in the lowermost parts of the transgressive systems tracts that fining-upward patterns are locally observed (Fig. 3). Fluvial portions of the valley fills, both in middle and inner parts of the valley system, tend to be consistent in grain size. For example, cross section B-B’ in figure 3 shows that below the maximum flooding surface in landward positions, there is no marked upward decrease in grain size. Outcrop observations confirm that, in many locations, central basin deposits directly overlie fluvial deposits, with no intervening fining-upward facies, and that the low sinuosity fluvial style persisted throughout the early infilling of the valleys. Finally, highstand systems tracts are anomalously thin throughout the New River Formation. These observations are suggestive of upstream controls on deposition.

Overall, stratal patterns in the New River Formation appear to have been affected by both upstream and downstream controls. The following discussions address glacioeustatic, climatic, and tectonic mechanisms as possible controls on sequence development, facies architecture, and basin geometry within the studied interval.

**Eustasy**

In order to evaluate eustasy as a control on sequence development, an estimate of the duration of 4th-order sequences is needed. However, amalgamation of sandstone bodies in the subsurface makes the recognition of the total number of sequences difficult. In addition, it is primarily the eastern facies belt of the Raleigh-Guyandot interval that is exposed in the study area, so the number of 4th-order sequences in the entire New River Formation can only be estimated. At least 10 sequences can be recognized in well logs and cores that penetrate the thickest parts of the basin. In comparison, Chesnut (1994) identified 18 ‘coal-clastic cycles’
based on excellent exposures of equivalent strata in Kentucky. For purposes of this discussion, the number of sequences is estimated to be between 10 and 18. The approximate duration of the interval in which the New River Formation was deposited is between 2 and 3 my. Thus, a minimum sequence duration of 100 ky is given by using the minimum age constraints and maximum number of sequences (2 m.y./18 sequences). Alternatively, a maximum sequence duration of 300 ky is given by using the maximum age constraints and minimum number of sequences (3 m.y./10 sequences). In comparison, Pashin (1994) calculated an average duration of 200 – 500 ky for coarsening upward cycles of the broadly time-equivalent, Lower Pennsylvanian Pottsville Formation of Alabama. The calculated durations are within the range of periodicities for orbital eccentricity that are known to drive glacioeustasy during icehouse times (Hays et al., 1976; Imbrie, 1985).

The average duration of 3rd-order sequences in the New River Formation is estimated at between 500 and 750 ky based on the recognition of four 3rd-order sequences within the 2 – 3 m.y. interval of study. These time scales are beyond the range of known orbital periodicities, so 3rd-order sequence development does not appear to be linked to glacioeustasy. Tectono-eustatic fluctuations could have operated at these time scales (Cloetingh, 1988; Harrison, 1990), and may have been responsible for the development of some 3rd-order Carboniferous sequences (Miller and Eriksson, 2000) although the origin of Lower Pennsylvanian 3rd-order sequences remains problematic.

Climate

The stratigraphic repetition of coal and siliciclastic sedimentary rocks in Lower Pennsylvanian strata has been attributed to climatic fluctuations between tropical and wet-dry
conditions (Cecil, 1990). The quartz-rich composition of the New River sandstones may be explained by intense weathering during prolonged periods of tropical climate, as happens in the modern Orinoco drainage system (Johnsson et al., 1988). In contrast, Gill and Yemane (1996) described a paleoultisol profile from northeastern Pennsylvania that provides evidence for seasonal conditions that may have persisted for hundreds of thousands of years. The time scale of this inferred cyclicity is similar to the calculated duration of 4th-order sequences in the New River Formation. However, fluvial response to climate change at these time scales is poorly understood (Blum and Price, 1998). Some studies suggest that climatically driven fluvial responses may operate at 100 ky time scales (Veldkamp and Van den Berg, 1993), but few Quaternary or pre-Quaternary examples have thus far been documented (e.g. Olsen, 1990).

Although it is unclear whether or not climate change was a direct control on sequence development, fluvial response to high-frequency climate changes were probably highly effective in contributing to the sheet-like nature and anomalous thickness of the New River sandstone bodies. Quaternary records provide convincing and abundant evidence for high-frequency (<100 ky), icehouse-style climate changes that affected aggradation and degradation in actively subsiding alluvial basins (Blum and Price, 1998; Tornqvist et al., 2000). Icehouse-style conditions similar to the Quaternary are inferred for the Carboniferous by numerous authors (i.e. Crowell, 1978; Veevers and Powell, 1987; Heckel, 1994; Miller and Eriksson, 1999), so it is reasonable to assume that high-frequency climatic fluctuations would have affected fluvial systems in the Early Pennsylvanian. Multiple episodes of lateral migration, aggradation and degradation due to high-frequency climatic fluctuations, coupled with overall high sediment yields during the early to middle stages of valley filling, could have resulted in thick, laterally persistent sandstone bodies with multiple, internal erosional surfaces. Given the complex history
of Quaternary analogs that reflect repeated responses to climate change (e.g. Blum and Price, 1998), this scenario is more plausible than a single episode of valley incision followed by a prolonged period of infilling, punctuated only by autocyclic channel switching. Although this model is not based on direct evidence, further investigations may seek to document ‘cryptic’ sequences boundaries (Miall and Arush, 2001) and/or composite valley-fill unconformities (Blum and Price, 1998) within and at the bases of the seemingly homogeneous sandstone bodies.

Whether or not the above model is correct, the thickness of fluvial facies in the lowstand systems tract was likely the result of overall high sediment yields to the fluvial system. High sediment yields at the sequence scale may have been related to numerous upstream controls such as climate, tectonics, and/or high denudation rates within the source area.

**Tectonics**

There is abundant evidence in the central Appalachian Basin for syndepositional deformation in the Early Pennsylvanian. Padgett and Ehrlich (1978) demonstrated that the trellis-like pattern of paleodrainage nets in fluvial systems of the Pocahontas Formation (Fig. 2) was controlled by northeast/southwest oriented joint trends. Further, they demonstrated a link between dominant paleoflow directions and the trends of fold axes in the basin. Other authors have documented fault-controlled sedimentation patterns in coals, sandstones, and conglomerates of the New River Formation and equivalents (Greb et al., 1990; Staub, 1994). These studies point toward tectonic control on local drainage patterns and point-sourced sediment supply within the foreland depozone. Over large time scales, tectonic uplift within the hinterland may have contributed to high sediment yields and progradation of the basin depocenter, which resulted in the progressive onlap of successively younger 3rd-order sequences onto the basin.
margin. Therefore, it is possible that episodic tectonic pulses could have contributed to the origin of 3rd-order sequences.

The most obvious tectonic effect on Lower Pennsylvanian stratal patterns is the southeastward-thickening wedge of strata in which sheet sandstones progressively onlap the western basin-margin unconformity (Greb and Chesnut, 1996). This geometric configuration strongly resembles the model of Flemings and Jordan (1990) for basins undergoing active subsidence due to thrust loading of an elastic lithosphere. The westward migration of the depocenter through time suggests that the New River Formation was deposited during a transition from an underfilled basin in the Early Pennsylvanian to an overfilled basin in the Middle Pennsylvanian during the northwest migration of the thrust front (Tankard, 1986).

**CONCLUSIONS**

1) The New River Formation is divisible into five facies associations that represent a variety of fluvial and estuarine depositional environments. The majority of the formation was deposited by bedload-dominated, high-energy, low-sinuosity fluvial systems. These deposits are transitional upward into tidally influenced, inner estuarine fluvial channels, central basin deposits, delta/bayhead delta deposits, and rare floodplain and mixed-load, low-energy fluvial environments.

2) A trunk-tributary paleovalley system persisted throughout the Early Pennsylvanian. Fluvial systems in the tributary paleovalleys transported coarse sediment into the axial trunk paleovalleys. Fluvial- to estuarine-facies transitions within the paleovalley fills represent depositional responses to relative rises in sea level. Flooded valleys were filled with central
basin mudrock and deltaic deposits, which were subsequently incised by the younger paleovalley fluvial systems.

3) Both 3\textsuperscript{rd}- and 4\textsuperscript{th}-order sequences can be recognized in the New River Formation. Fourth-order sequences consist of deeply incised, fluvial channel sandstone separated from overlying tidally modified estuarine sandstone and mudrock by a ravinement deposit, and capped by central basin mudrock and coarsening-upward delta/bayhead delta facies. Within composite 3\textsuperscript{rd}-order sequences, lowermost 4\textsuperscript{th}-order paleovalley fills are dominated by fluvial facies, and uppermost paleovalley fills are dominated by estuarine facies. The ‘salt sands’ of the New River Formation consist of superimposed lowstand systems tracts that were formed due to the amalgamation of multiple 4\textsuperscript{th}-order sequences, superimposed on asymmetric subsidence.

4) Both upstream and downstream controls influenced erosional and depositional patterns in the New River Formation. The anomalous thickness of the lowstand systems tract reflects high sediment yields from the hinterland, whereas fluvial- to estuarine-facies successions reflect relative rises in sea level.

5) Tectonic, eustatic, and climatic controls can be inferred for the New River Formation based on the proposed sequence stratigraphic framework. Subsidence due to thrust loading appears to have been the over-riding control on basin geometry. The westward onlap of successive sandstone bodies reflects overall high sediment yields during the Early Pennsylvanian. Third-order sequence development may have been controlled by tectonoeustatic fluctuations and/or tectonic uplift in the hinterland. Glacioeustatic fluctuations are inferred as the principal control on 4\textsuperscript{th}-order sequence development based on sequence duration. Climate, in addition to high relief and tectonic uplift in the hinterland, may have contributed to high
sediment yields that led to the development of laterally persistent sandstone bodies within the lowstand systems tracts of 4th-order sequences.

6) The anomalous facies distribution, sequence architecture, and paleogeomorphicology in the New River Formation reflects high-frequency glacioeustatic fluctuations superimposed on asymmetric foreland basin subsidence.
REFERENCES


Presley, M.W., 1979, Facies and depositional systems of upper Mississippian and Pennsylvanian strata in the central Appalachains: Carboniferous Coal Guidebook, 50 p.


VITA

JESSE T. KORUS

EDUCATION

<table>
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<tr>
<th>Year</th>
<th>Institution</th>
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<td>2002</td>
<td>Virginia Tech</td>
<td>Blacksburg, VA</td>
<td>M.S. Geology</td>
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<td>2000</td>
<td>University of Nebraska-Lincoln</td>
<td>Lincoln, NE</td>
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AWARDS RECEIVED

- 2001 AAPG Energy Minerals Grant
- Spring 2000 BP/Amoco Foundation Fellowship
- 1998-2000 Rex Monahan Scholarship Recipient
- 1998 L. Austin Weeks Undergraduate Grant Recipient
- Nebraska Geological Society Undergraduate Research Grant
- Nebraska Academy of Sciences Best Undergraduate Presentation
- Dean’s List Six Semesters

WORK EXPERIENCE

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<tr>
<td>August 2000 – present</td>
<td>Virginia Tech</td>
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</tr>
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Abstracts:

Korus, J.T., 2000, Estuarine deposition and tidal rhythmites of the Dakota Formation (Upper Albian), southeastern Nebraska: Symposium on Nebraska Stratigraphy, 120th Nebraska Academy of Sciences, Programs and Proceedings, p. 67.


Korus, J.T., and Eriksson, K.A., 2002, A stratigraphic framework for predicting sandstone body geometry in fluvial and estuarine deposits of the New River Formation, West Virginia: North-Central/Southeastern GSA Joint Annual Meeting