FLUVIAL ARCHITECTURE OF THE INTERVAL SPANNING THE PITTSBURGH AND FISHPOT LIMESTONES (LATE PENNSYLVANIAN), SOUTHEASTERN OHIO

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M. Ryan King
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Abstract

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FLUVIAL ARCHITECTURE OF THE INTERVAL SPANNING THE PITTSBURGH AND FISHPOT LIMESTONES (LATE PENNSYLVANIAN), SOUTHEASTERN OHIO (144 pp.)

Detailed measured sections from the short stratigraphic interval spanning the Pittsburgh to Fishpot Limestone (Late Pennsylvanian) in Athens County, Ohio contain a range of lithologies that are interpreted as a complex suite of continental environments including fluvial (braided, meandering, and anastomosed) and palustrine deposits. Five 4th-order sequences are present based on a model in which interfluve paleosol profiles representing both Falling Stage and Lowstand Systems Tracts, are adjacent to incised braided fluvial deposits representing Lowstand and early Transgressive Systems Tracts (TST). Limestone deposition is mainly restricted to the late TST and was followed by either anastomosed or meandering fluvial deposits of the Highstand Systems Tracts. This model of continental sequence stratigraphy is broadly consistent with a previously published model for 3rd-order relative sea level changes on a passive margin. The variations between the models result from differences in tectonic setting and 3rd-order and 4th-order eustatic rates.

Approved: ________________________________

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Associate Professor of Geological Sciences
To my parents, Bob and Tina, for supporting me unconditionally.
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Chapter 1

Introduction

Fluvial systems respond to auto- and allocyclic forces, such as climate and base level changes of tectonic and eustatic origin, by changing channel pattern (Schumm 1993). Over time these changes result in the vertical stacking of different fluvial styles that reflect the forcing functions, which is referred to as architecture, (Miall 1996). An analysis of fluvial architecture therefore can provide insight into the large-scale controls affecting the terrestrial component of a basin. Recognition of these controls in the distal portions of a basin are particularly valuable in trying to apply sequence stratigraphic methodology to fluvial sediments (Miall 1996). Sequence stratigraphy has been successfully applied to sedimentary rocks with a tidal component (Shanley and McCabe 1994), however, fluvial sequence stratigraphy is still a matter of considerable debate (e.g., Wright and Marriott 1993; Dalrymple et al. 1998; Ethridge et al. 1998; Heckel et al. 1998; Posamentier and Allen 1999). The goal of this study was to place the fluvial and lacustrine deposits of a Late Paleozoic foreland basin fill into a sequence stratigraphic context by application of fluvial architectural analysis.

The Late Pennsylvanian deposits from the western (distal) margin of the central Appalachian foreland basin are well exposed in Athens County, Ohio (Sturgeon 1958; Donaldson et al. 1985; Castle 2001). During the Late Pennsylvanian, the Appalachian basin was subsiding due to flexural loading from the thrusting of the Alleghanian Orogeny (Quinlan and Beaumont 1984; Klein and Kupperman 1992). Southeast Ohio was at approximately 5°S to 10°S paleolatitude (Figure 1.1; Scotese et al. 1999; Vai 2003). The paleogeographic location of the study area is an important factor because it is a first-order control on climate, which affects the hydrologic character of fluvial systems and the maturity of paleosols on floodplains (Cecil 1990; Kraus 1999). The Late Pennsylvanian was also a time of a global icehouse climate (Crowell...
Figure 1.1: Paleogeographic map of the Pennsylvanian (approximately 300 Ma) showing simplified ocean circulation patterns (arrows) and extent of glaciation (modified from Saltzman 2003). Ohio was situated at approximately 5-10° S latitude. Changes in ice volume affected glacio-eustatic sea level.
The sea level changes associated with the growth and melting of continental ice sheets on Gondwana produced changes in base level that influenced the style of fluvial systems on the Laurasian supercontinent (Heckel 1994; Miall 1996; Blum and Tornqvist 2000).

The Pennsylvanian System in Ohio is divided into four groups based on coal-economic interest. In ascending stratigraphic order these groups are termed Pottsville, Alleghany, Conemaugh, and Monongahela. This study examined the interval bracketed by the top of the Conemaugh Group and the Fishpot Limestone of the basal Monongahela Group (Figure 1.2). The upper Conemaugh and Monongahela Groups of Athens County are composed of sandstones, shales, freshwater limestones, and coals (Sturgeon 1958). The Conemaugh Group represents the upper barren coal measures that lack an appreciable amount of economic coals; whereas the Monongahela is the upper (productive) coal measure (Sturgeon 1958, Kelafant et al. 1988, Larsen 1991). The contact between the two groups is placed at the base of the Pittsburgh Coal (Sturgeon 1958; Kelafant et al. 1988; Larsen 1991), which is thickest (average 1.8 to 2.4 m) and most extensive (over 28,389 km²) of the five coals in the Monongahela Group (Ruppert et al. 1999).

Donaldson and Shumaker (1981) attribute the formation of this broad coal to isolation from sedimentation whereas Ruppert et al. (1999) suggested formation was a result of an increase in accommodation from tectonic loading or eustasy.

Examination of the style and architecture of fluvial deposits allow inferences to be made concerning the major controls of sediment deposition in continental basins (Leeder 1993; Miall 1996; Dalrymple et al. 1998; Ethridge et al. 1998). Fluvial style refers to the specific type of river system that generated the deposit; whereas architecture may refer to either the three-dimensional arrangement of facies associations within a style or the arrangement of styles within a basin fill. The influence of tectonic, climatic, and eustatic controls on the style of river deposits
Figure 1.2: The study interval is located between the base of the Lower Pittsburgh Redbed (Casselman Formation; Conemaugh Group) and the sediments cross-cutting the Fishpot Limestone (Monongahela Group). The names refer to components of cyclothems named in Sturgeon (1958). Thicknesses are mean values.
have been inferred from foreland basins of North America from the Jurassic to the Tertiary (e.g., Nadon 1994; Talling et al. 1995; Currie 1997; Martinsen et al. 1999; Plint and Wadsworth 2003).

In this study a series of detailed measured sections along a well-exposed highway cut in east-central Athens County provide the data to test five hypotheses:

1) Anastomosing and braided fluvial systems deposited the siliciclastic portion of the section.

2) The current anastomosing/carbonate lake models explain the lateral facies variations within the study area.

3) The sequence stratigraphic model for a 3rd-order change in relative sea level proposed by Wright and Marriott (1993) explains the changes in fluvial architecture as well as facies relationships within the study area.

4) Glacial-eustasy had an influence on the facies distributions.

5) Tectonic subsidence was the greatest influence on accommodation and hence fluvial architecture.
Chapter 2

Previous Work

2.1 Stratigraphic Overview

The methodology used to study Late Paleozoic deposits has changed significantly over the last 50 years. The cyclothem concept (Wanless and Weller 1932), where each cyclothem was considered as a mappable lithostratigraphic unit equivalent to a formation (Larsen 1991), was applied to deposits in Athens County by Sturgeon (1958). Sturgeon (1958) not only recognized the Upper Pittsburgh and the Redstone Cyclothems between the Pittsburgh Coal and the Fishpot Limestone, but also named all the beds in the section. This proliferation of nomenclature led to confusion because unit boundaries were inconsistently located. The lack of a rigid definition for placement of the cyclothem boundary lead to the multiplication and duplication of terms and the eventual abandonment of this methodology as a lithostratigraphic classification (Larsen 1991).

Cyclothem stratigraphy was replaced by process depositional models, specifically, the river dominated delta model (e.g., Ferm 1974; Donaldson and Shumaker 1981; Donaldson et al. 1985) to explain the rapid and complex lateral facies changes within the Late Paleozoic strata. Using the deltaic model, workers concluded that during the Middle Pennsylvanian, deltas building northwestward overfilled the Pocahontas Basin and began to onlap the Cincinnati Arch (Donaldson and Shumaker 1981; Donaldson et al. 1985). Marine deposits decrease in abundance up-section. Evidence of the last major transgression is the Ames Limestone in the middle of the Conemaugh Group (Sturgeon 1958). The upper Conemaugh Group and entire Monongahela Group contain deposits of extensive swamps and lakes as the connection with the epeiric sea was cut off when the deltaic deposits prograded westward. These lacustrine deltas were recognized by the presence of thick coals and limestones that lack marine fauna (Donaldson and Shumaker 1981).
No formations are presently recognized within the Monongahela Group. The key beds relative to the study area from southeastern Ohio are the Pittsburgh Coal, the Pomeroy-Redstone Coal, and the Fishpot Limestone (Slucher 2004). The Pittsburgh Limestone lies below the Pittsburgh Coal, the Redstone Limestone lies almost a meter below the Redstone Coal and can extend down almost to the Pittsburgh Coal, and the Fishpot Limestone is present in the interval between the Redstone Coal and an overlying coal (Figure 1.2; Lamborn 1951).

The Pittsburgh and Redstone Limestones commonly appear to be nodular on weathered surfaces (Condit 1912; Lamborn 1951) but may differ in color. The Pittsburgh Limestone is brown to buff or blackish in appearance because of carbonaceous material while the Redstone Limestone weathers a buff red (Condit 1912; Lamborn 1951; Eggleston 1994). Lamborn (1951) reported that the thickest and most continuous beds of the Pittsburgh Limestone occur from Athens County northeast to Belmont County (Figure 2.1). In the same publication, Lamborn noted that the Fishpot probably followed the same trend as the other two limestones but differed in appearance from these two because it is the most extensive and well bedded of the Monongahela limestones in eastern Ohio. Workers have repeatedly correlated all three of these limestones over thousands of square kilometers even though the beds are not continuous (Stout 1931; Eggleston 1994).

All three limestone intervals are considered to be freshwater to brackish deposits based on the absence of marine fauna (Lamborn 1951) and the presence of clastic textures (Berryhill et al. 1971; Eggleston 1994; Nadon et al. 1998; Cassle 2005). None of these studies reported fauna within the Fishpot Limestone. All of the authors above have noted the argillaceous, siliceous, and dolomitic nature of the limestones. Berryhill et al. (1971) reported that that the conglomeratic top of beds were sometimes dolomitic and that the microcrystalline base of beds contained very little magnesium.
Thin or poorly developed limestones
Thick or best developed limestones
Primarily shale and shaly sandstones
Primarily sandstone

Boundary of Pennsylvanian Outcrops
County Boundaries
Sandstone Split within the Fishpot

Figure 2.1: Distribution of limestones in eastern Ohio as described by Lamborn (1951) (modified from Lamborn 1951). Athens County is indicated in the black shaded portion of the Ohio map by diagonal stripes.
Berryhill et al. (1971) noted three types of sand bodies in strata from the Monongahela and overlying Dunkard Groups. These were sheet-like, elongate, and lobate or pod. Pod-like bodies were considerably smaller than the other two and interfingered with siltstone and mudstones. Nadon et al. (1998) suggested that there were both anastomosed and braided fluvial deposits in the study interval but provided only a single measured section that included no major sandstones. Edwards (2001) examined four measured sections in the eastern portion of the study and concluded that the interval was the product of an anastomosing fluvial system overlain by a braided system. The juxtaposition of these two styles also has major stratigraphic implications since deep fluvial incision may result in the deposition of lithologies from significantly different time periods and different environments adjacent to one another.

Recent local models of the Pennsylvanian lacustrine systems proposed by Valero Garces et al. (1994) and based on the work of Weedman (1988, 1994) used a lacustrine/alluvial complex to explain the presence of freshwater carbonates interbedded with siliciclastics. In the Valero Garces et al. (1994) model, an anastomosed system evolves into a single channel system between tectonic pulses with a floodplain consisting of laterally extensive soils and swamps. Eggleston (1994) also noted the similarities between the upper Pennsylvanian limestones and the Everglade palustrine deposits of Platt and Wright (1992). Both Valero Garces et al. (1994) and Eggleston (1994) suggested that the thickest sequences of limestone represent the deepest part of the lake. Cassle (2005) concurred with the palustrine interpretation of the limestones in the study area. His facies analysis of the Pittsburgh Limestone, although based on petrographic and fossil data, was unable to resolve the issue of proximity of the marine realm. He was able to establish that these lake systems were shallow, no more than three meters deep.
2.2 Fluvial Architecture

Eustatic, climatic, and tectonic factors result in large-scale changes in fluvial systems within foreland basins over time (Miall 2000). These large-scale changes create stacking patterns of different fluvial styles in a basin referred to as fluvial architecture. Fluvial architecture was defined by Miall (1983, p. 282) as “the three-dimensional geometry and interrelationships of the deposits of the channel, levee, crevasse, floodplain and other sub-environments of a fluvial depositional system”. However, this architecture can be evaluated over a range of spatial and temporal scales. For example, Leeder (1993) divided fluvial architecture into micro- ($10^2$-$10^3$ years), meso- ($10^3$-$10^6$ years), and macro-architecture ($10^6$-$10^8$ years) based on scale, controls, and time.

The fluvial architecture of a deposit is constructed by first employing architectural element analysis to determine the fluvial style. Architectural element analysis is an alternative method of facies analysis proposed by Miall (1985) based on the recognition of up to eight orders of bounding surfaces and architectural elements (Table 1.1). Miall (1996, p., 91) defined an architectural element as “a component of a depositional system equivalent in size to, or smaller than a channel fill, and larger than an individual facies unit, characterized by a distinctive facies assemblage, internal geometry, external form, and in (some instances) vertical profile.” The cross-cutting of surfaces defines elements where low-order surfaces are truncated by higher order surfaces.

Sedimentary structures within fluvial deposits are classified using the microform, mesoform, and macroform categories proposed by Jackson (1975). Microforms are the product of the migration of small-scale bedforms such as ripples. The migration of larger bedforms, such as dunes, generates mesoforms (Miall 1985). Macroforms are the largest features of fluvial channels
<table>
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<tr>
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<th>Characteristics of Bounding Surfaces</th>
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<td>set bounding surface</td>
<td>Microform (e.g., ripple)</td>
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<td>Macroform growth increment</td>
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<td>4th-order</td>
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</tr>
<tr>
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<td>Channel or mature paleosol</td>
<td>Long-term geomorphic processes (e.g., channel avulsion)</td>
</tr>
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<td>6th-order</td>
<td>flat, regionally extensive, or base of incised valley</td>
<td>Channel belt</td>
<td>5th-order (Milankovitch) cycles, response to fault pulse</td>
</tr>
<tr>
<td>7th-order</td>
<td>sequence boundary; flat, regionally extensive, or base of incised valley</td>
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<td>8th-order</td>
<td>regional disconformity</td>
<td>Basin-fill complex</td>
<td>3rd-order cycles. Tectonic and eustatic processes</td>
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</table>

Table 2.1: Hierarchy of depositional units in fluvial deposits (modified from Miall 1996)
and correspond to bars. These large features represent deposition over tens to thousands of years (Jackson 1975; Miall 1985). Variation among macroform elements permits differentiation of river deposits into fluvial styles (Miall 1985).

Micro-architecture utilizing mesoforms and to a lesser extent microforms can be constructed using the conventional method of vertical measured section that illustrate variations in grain size and sedimentary structures with depth (Figure 2.2). The changes in grain size and sedimentary structures, which are related to changes in flow regime (e.g., Allen 1970; Cant and Walker 1976; Miall 1978), allow definition of lithofacies, which can then used to interpret the type of fluvial deposit (Friend 1983; Miall 1985; Walker 1992) (Figure 2.3 a-c). An analysis of macroforms requires exceptional outcrop and the use of either photomosaics or closely spaced measured sections to capture the complexity of the meso-scale architecture. Although such analysis is not always possible, it allows construction of a more complete picture of the fluvial style (Miall 1996).

2.3 Fluvial Styles

The three primary fluvial styles, braided, meandering, and anastomosing (Rust 1978a), are end-members of a continuum that vary along different reaches of the same system as the controlling variables change (Leopold and Wolman 1957). Lateral and vertical differences in fluvial style therefore reflect changes in fluvial parameters on either a local or regional scale (Keighley and Pickerill 1996; Miall 1996). The fluvial styles can be distinguished from one another in outcrop using conventional measured sections by considering the vertical changes in grain size, sedimentary structures, and associated facies.
Figure 2.2: An example of a vertical profile (modified after Miall 1996). Facies codes: 
S=sand sized grains; r=rippled; t=trough cross-bedded; p=planar cross-bedded; e=highly erosional. Numbers refer to cross-cutting bounding surface orders.
Figure 2.3: a) Lateral and vertical facies in the Old Red Sandstone interpreted to be a meandering river deposit (modified from Allen 1970). b) Lateral variation of facies within a meandering river system (modified from Miall 1992). c) Vertical succession of facies (modified from Miall 1992).
2.3.1 Style 1: Braided Fluvial

Braided rivers (Figure 2.4) are bed-load systems that typically have the highest slopes and multiple, low sinuosity channels (Leopold and Wolman 1957). Braided deposits generally contain small amounts of fine-grained sediments, although this criterion is not considered definitive (Miall 1978; Rust 1978b; Friend 1983; Bristow and Best 1993; Bridge 1993; Lorenz and Nadon 2002). The channels are separated by bars (macroforms) that can migrate down stream (down-stream accretion; DA) or laterally (lateral accretion; LA). Flow in the deeper portions of the channels transport the coarsest grain sizes as 3-D dunes that form trough crossbeds (Miall 1996). Lateral migration of bars produces 2-D bedforms that form planar-tabular crossbeds with current directions perpendicular to the trough crossbeds of the main channels (Cant and Walker 1976). Down-stream accretion of the macroforms produces low-angle, parallel lamination (Bristow 1993; Miall 1996). The tops of macroforms are commonly rippled and contain a limited amount of floodplain fines (Cant and Walker 1976). Variations in flow strength can produce upper flow regime plane beds at any position within a macroform element. The low cohesion of channel margins results in rapid lateral erosion of the channels as flow in the river increases resulting in laterally extensive sand bodies (Friend 1983). Miall (1996) illustrated five sub-types of braided fluvial system based on clast size, and variations in the abundance of different sedimentary structures.

Braided fluvial deposits are commonly sandstone or conglomerates that display little or no fining upward grain size trend within channels. The lithosomes typically have width/thickness ratios >300 (Miall 1996). Paleoflow directions measured from the two most common sedimentary structures are typically at right angles to each other with the trough crossbeds indicating the actual downstream direction (Cant and Walker 1976). Ripple cross-lamination and
Figure 2.4: Architectural model for a deep, perennial, sand-bed braided river (modified from Miall 1996). This fluvial style is characterized by the presence of planar tabular cross-beds and down-stream accretion macroforms.
floodplain deposits representing the top of macroforms are seldom reported because of low preservation potential.

2.3.2 Meandering Fluvial

Meandering rivers (Figure 2.5) typically occur in regions of lower slopes than braided systems and are distinguished by the presence of a single channel (Leopold and Wolman 1957; Schumm 1985). The sediment transported by meandering rivers is termed mixed load because of the presence of sand and/or gravel and cohesive mud. Floods deposit mud on the adjacent floodplains, which then restrict the expansion of the channel during higher flows and cause more overbank sedimentation. Bank erosion in single thread rivers creates a locally wider channel that then fills as a point bar along one side while forming a characteristic cut bank. Water depth increases gradually down the point bar to the thalweg or deepest point in the river (Allen 1970).

Sedimentary structures within a meandering river channels follows a predictable pattern of 3-D dunes in the coarsest sediment along the thalweg to ripples near the top of the point bar (Figure 2.5). Upper flow regime plane bed deposition can occur at any point during high water flows and 2-D dunes form in intermediate water depths but are much less common than in braided systems. The adjacent floodplain consists of muds and thin sands deposited during flood events. The rapid deceleration of flow as the water leaves the channel results in deposition of the coarsest sediment near the channel as levees, which serve to further constrain flow within the channel (Allen 1970; Miall 1996). Point-source breaks in levees are termed crevasses and the sediment transported to the floodplain through these breaks typically forms a thin sheet termed a crevasse splay. Subaerial exposure of the floodplain is common resulting in pedogenic modification of the sediment. Lateral migration of the channel makes preservation of floodplain
Figure 2.5: Architectural model for a sand-meandering stream (modified from Miall 1996). Continued migration of the point bars will result in a dominance of the macroform lateral accretion elements in the preserved record as well as the low potential of the preservation of levee deposits, crevasse splays, and floodplain fines.
deposits problematic unless subsidence rates are high. A distinctive feature marking meandering floodplains is the presence of ox-bow lakes formed by neck cut-off of the channel over time.

Grain size within measured sections through meandering river deposits typically fines upward from an erosional base to the floodplain mudstones. Mudstone intraclast conglomerates are common at the base as a result of caving along the cutbanks (Allen 1970; Miall 1996). Sedimentary structures vary up-section from trough crossbeds at the base to ripples at the top of the sandstone. The migration of the point-bar results in the formation of a macroform element characterized by lateral accretion (LA) surfaces, which are not always present (Figure 2.5). Sandstone body geometry is typically thin and wide but with width/ thickness ratios in the range of 100-200 (e.g., Gibling 2006). Floodplain deposits, where preserved, commonly consist of paleosols with thin sandstones interpreted as crevasse splay deposits.

2.3.3 Anastomosed Fluvial

Anastomosing fluvial systems (Figure 2.6) typically occur in regions of very low slope and are composed of multiple, laterally stable channels that carry mainly suspended load (Smith and Smith 1980; Nadon 1994). Anastomosed systems differ from braided by the presence of topographic lows between channels in the former and interchannel bars in the latter (Leopold and Wolman 1957; Nadon 1994). Anastomosed channels commonly contain sand-sized material that form 3-D and 2-D dunes along the channel floor. The low gradient and mud on the adjacent floodplains prevents lateral migration of the channels. However, there is commonly a sinuous thalweg that results in the formation of lateral bars.

Floods result in formation of levees that are typically sand-prone with much of the suspended load deposited on the floodplain. Stabilization of levees by vegetation (Smith 1976)
Figure 2.6: Architectural model of an anastomosed river (modified from Miall 1996). Note the high preservation potential for levees. Fine-grained sediments comprise the majority of the fluvial architecture. Crevasse splay elements are common within this system; whereas lateral accretion is minimal.
and mud results in a vertical accretion of the river channels. Crevasse breaks in levees are common, producing abundant crevasse splays on the floodplain. River channel avulsion through a crevasse depends on a number of factors but, in general, occurs when the local gradient within the crevasse is greater than the local channel slope. Channel abandonment is a gradual process and abandoned sections of a channel tend to fill almost completely with sand. The lower elevation of most of the floodplains allows the presence of lake systems of variable duration (Smith and Smith 1980).

Anastomosed fluvial deposits consist of ribbon sandstones encased in mudstones with thin sandstones (e.g., Nadon 1994). The channel sandstones have scoured bases and flat tops, a slight fining-upward trend, and width/thickness ratios generally <30. Sedimentary structures include trough and planar-tabular crossbedding, parallel lamination, and ripple cross-lamination (Nadon 1994). The levees consist of sandstone of the same grain size as the channel. The progradation of the levees into the adjacent floodplain typically gives the sandstones a characteristic 'wing' (Stear 1983). The adjacent floodplain deposits commonly contain laminated mudstones formed in shallow siliciclastic lakes (e.g., Nadon 1994) or carbonate lake deposits (e.g., Valero Garces et al. 1994) interbedded with blocky mudstones, representing paleosols, and thin sheet sandstones deposited by crevasse splay processes. Lenticular sandstones, the preservation of levees, and greater abundance of floodplain sedimentation characterize anastomosed deposits (Miall 1996).

2.4 Basin Architecture

Fluvial architecture at the scale of a basin is a function of the accommodation generated by 1) subsidence (tectonics and compaction), 2) eustasy (base level), and 3) the sediment supply, which is a proxy for climate (Dalrymple et al. 1998). Fluvial styles adjust to these three regional controls (Miall 1996; Dalrymple et al. 1998).
Eustasy is a major influence on base level, which affects gradient and hence fluvial style (Heckel 1994; Miall 1996; Dalrymple et al. 1998; Blum and Tornqvist 2000). Eustatic control on sedimentation progressively decreases from the coast to approximately 300 km up-river (Blum and Tornqvist 2000). Eustasy operates at time scales of $10^4$ to $10^5$ years (Blum and Tornqvist, 2000). A rise in base level reduces gradient and results in a shift in fluvial style toward the anastomosed end member. A drop in sea level shifts the style toward the braided fluvial style and may result in incision and sediment bypass (Wright and Marriott 1993; Gibling and Wightman 1994; Plint and Nummedal 2000).

In the study area, eustasy is typically not considered because of the lack of marine sediments within the upper Conemaugh and Monongahela Groups. Data from the Mid-continent (Ross and Ross 1988) show that there was a 3rd-order relative sea level fall during the time the study interval was deposited (Figure 2.7). However, the report of brackish water fauna by Cassle (2005) from the Pittsburgh Limestone suggests that eustasy must be considered in any model attempting to explain the fluvial styles of the basal Monongahela Group.

Climate is the primary allocyclic control on sediment flux by its influence on the amount and variability of discharge, the types and density of vegetation, and weathering characteristics (Smith 1976; Miall 1983; Cecil 1990). These factors combine to determine sediment load and supply (Miall 1983; Ethridge et al. 1998). Climate change affecting fluvial successions occur at time scales of $10^4$ to $10^5$ years (Blum and Tornqvist 2000) and are linked to eustatic sea level changes. The local climate becomes more humid during transgressions because of the proximity of the seaway (Rankey 1997). Increases in seasonality lead to increases in the heterogeneity between lithofacies as well as increases in the frequency of second- and third-order bounding surfaces (Miall 1996). Changes in hydraulic regime inferred from variations in grain size provide
Figure 2.7: Variations in 3\textsuperscript{rd} and 4\textsuperscript{th}-order changes in coastal onlap during the Pennsylvanian. The Ames limestone is the most widespread lithosome in the study area (after Nadon et al. 1998). Sea level curve after Ross and Ross (1988). Absolute age dates after Menning et al. (2006). Ames limestone location after Heckel et al. (2007).
one means of interpreting changes in climate (Cecil 1990). In addition, the presence and type of paleosols, evaporites, and lacustrine deposits are key indicators of climate because they point to the ratio of evaporation to precipitation (Miall 1996, Kraus 1999).

The presence of vertic paleosols in the Late Pennsylvanian deposits of the Appalachian basin suggests that the regional climate on average had a seasonal rainfall (Tandon and Gibling 1994; Caudill et al. 1996, 1997; Wright 1999). Cecil (1990) postulated semi-arid conditions were present during deposition of the Monongahela Group based on the presence of the numerous lacustrine limestones. However, Cassle (2005) demonstrated that, although the lakes were commonly desiccated, they formed during wet periods in the local climate.

Tectonics affects both total accommodation and base level (Ethridge et al. 1998). Variations in tectonic subsidence or uplift can increase or decrease the effect of eustatic base level fall (Heckel et al. 1998). The rates of tectonic subsidence operate over time scales ranging from $10^4$ to $10^7$ years (Miall 1996). The effect of tectonics on basin architecture depends on the scale of observation.

In Ohio, low amplitude, contemporaneous folding that might have influenced sedimentation on a local scale was reported from eastern Athens County by Ver Steeg (1944). Lamborn (1951) reported the presence of structures described as “anticline noses” 3 to 30 kilometers in length, <1 to > 12 meters high, and with axes that typically trend 35-40 degrees west of north in Athens County. Donaldson and Shumaker (1981) considered “sub-block differential subsidence” by Alleghenian tectonic and sedimentary loading of the underlying faults responsible for creating structural lows that influenced the thickness, facies, and dispersal directions of fluvial sediments. Geophysical studies by Lucius and von Frese (1988) and von Frese et al. (1997) identified a gravity low and magnetic anomaly just to the west of Athens.
County. Subsequent seismic work by Steigerwalt (2002) and Harbi (2005) suggested that this complex acted as a rigid body during westward thrusting that may have produced Late Paleozoic deformation.

Recent studies of the lower Conemaugh Group in Athens County by McNamara (2006) and Klasen (2007) suggested that local changes in accommodation were a response to penecontemporaneous, low amplitude structures. Such changes could produce both lateral and vertical variations in fluvial style, paleosol development, and sequence bounding unconformities.
Chapter 3
Methodology

The data collected for this study consisted of detailed measured sections and photomosaics of the outcrop (Figure 3.1). A total of nine vertical sections were measured along US highway 32/50 west of Guysville. Sections were precisely located using a Garmin E-trex GPS unit. Many portions of the section were hand trenched to prevent an excess of covered intervals. A composite section was constructed where the cover was too thick.

A physical description including color, lithology, sedimentary structures, paleocurrents, bed thickness, contacts, clasts or nodule character, bioturbation, and fossil content was made of each bed in the field. Each bed was sampled and later examined under a microscope to determine texture, grain size, sorting, composition, type and size of micas, organic and fossil content. Samples from both the top and base were collected from beds greater than a decimeter in thickness, as well as middle portions from beds several decimeters in thickness. Nodules were collected and samples were broken open in lab to observe fresh surfaces and to test for reaction with hydrochloric acid. Since the fresh surfaces of limestone typically appeared massive, all limestones were slabbed. Approximately one-third of the nearly two hundred slabbed limestone samples were then polished on a lap grinder. Other lithologies and clast or nodules were also cut to examine the internal structure for soft sediment deformation and bioturbation.

Several attempts to extract conodonts from the Pittsburgh Limestone and the Fishpot using methods of Jeppsson and Anechus, (1995) failed to produce results. This method uses a solution of 10% formic acid buffered by calcium carbonate and calcium triphosphate to dissolve the limestones and has been reported to be able to recover conodonts even from dolomites.
Figure 3.1: Location of measured sections within the study area (modified from Stewart Quadrangle, USGS 1961).
A photomosaic was constructed of sections RK01 to RK05 and RK06 to RK09. While photomosaics are not as useful in mudstone lithologies as they are in areas of sandstones, the photomosaics add confidence to the datums as well as the placement of section RK09. Smaller photomosaics were constructed to aid in the interpretation of larger features such as architectural elements.

Each measured section was drafted and correlated using the Pittsburgh Coal as the datum for sections RK01-RK06 and the uppermost sand as a datum for sections RK06 and RK07. Section RK09 was oriented using a total station and by the aid of photomosaics. The base of the sandstone in section RK09 lies 5 meters below the top of the sandstone marking the top of RK08. Facies descriptions and interpretations for each section were made in the field. The facies were then grouped into facies associations to determine depositional environments and ultimately fluvial style. The vertical changes in fluvial style, or architecture, were evaluated with respect to changes in the rate and amount of accommodation during deposition. The fluvial architecture was then compared to a published model of expected style changes within a continental sequence stratigraphic framework to assess the applicability of the model to this tectonic setting.
Chapter 4

Facies Descriptions and Interpretations

4.1 Introduction

Facies are bodies of rock characterized by a distinct combination of lithology, physical, and biological structures that confer an aspect different from the surrounding and juxtaposed lithosomes (Walker 1992). Facies can be defined on many different scales, and subdivision is tailored to the scope and focus of a project. Genetically related facies form facies associations that have environmental significance (Walker 1992). Since architectural elements are also defined on many scales, they can either be contained within a facies association or be equivalent to a facies association. The 14 facies defined in this study are described and interpreted below, and are arranged in order of increasing grain size from mudstones and shales to sandstones and limestones (Table 4.1). The facies are subsequently grouped into six facies associations described in detail in Chapter 5.

4.2 Facies Fbl: Blocky Mudstone

*Description:* Blocky mudstones vary in grain size from claystone to mudstone and are distinguished by an angular, blocky texture (Figure 4.1a; Retallack, 1988). This facies ranges in thickness up to 2.56 meters. The thickest intervals of facies Fbl occur directly below the Pittsburgh Limestone and bracket the Fishpot Limestone. The blocks range from several millimeters to several centimeters in diameter and vary in size upward within beds but with no consistent trend. The blocks commonly exhibit slickensides on surfaces and large curvilinear fracture planes (Figure 4.1b) are present in beds greater than a decimeter thick. The base of the thicker beds may contain layers up to a few decimeters in thickness that are much harder than the surrounding mudstones in which most of the cementation is calcareous. Silica cement is present
Table 4.1: Facies and facies associations from the study area. Colors generally correspond to those used in later facies association figures. Dark shades represent the dominant facies in each facies association, whereas the lighter shades represent the minor or rare constituents.
Figure 4.1: Structures within Facies Fbl (Blocky Mudstones). a) Typical blocky texture consistent with a paleosol, scale bar represents approximately 60 cm. b) Large curved fracture planes common with vertic paleosols, scale bar represents approximately 10 cm. c) Long dark mottle formed by rooting d) Branching white mottles also interpreted as rhizoliths. Black scale box is 1 cm.
within the redbeds between the Fishpot Limestone and the underlying coal as well as in the large fractures below the Pittsburgh Limestone.

Color of Fbl beds ranges from maroon, gray, to various shades of green and beds can vary in color and texture laterally and vertically (Figure 4.2). The most prominent lateral variation in color type is from shades of red to shades of gray. This transition takes place over tens of meters and is typically marked by a mottled zone combining both colors, except in one instance where the colors alternated. Maroon to red mudstones typically overlie green colored mudstones with small carbonate nodules and occur most commonly within 1.2 meters of the upper limestone beds. The gray to bluish or greenish gray mudstone most commonly occurs between thin beds of limestone. Beneath the Pittsburgh Limestone this facies is a complex assemblage varying in color from grays to reds and in amount of sand grains, and carbonate nodules present. The base is covered and the upper 1 to 1.5 m contains meter-scale, curvilinear fractures.

Contacts between facies Fbl and other facies are typically abrupt whereas contacts between different colors within Fbl are often gradational and mottled, especially where a gray bed overlies red mudstones. Mottling of colors is common. Bifurcating mottles that range in size from 1-10 mm in diameter, organics, and iron-stained halos are present in some beds (Figure 4.1c). The larger mottles occur below the coal and are up to 10 cm in length. Sub-millimeter size nodules that are reddish black and equally spaced are present in the gray mudstones. Green mudstone beds commonly contain carbonate nodules ranging from 0.1 - 2 cm in diameter. Red iron nodules 3 to 4 cm in diameter occur in one bed within section RK01. The maroon beds in section RK05 contain large, irregular limestone masses often with white halos around them and white bifurcations structures at the very top (Figure 4.1d). Gray blocky mudstones may be present within the limestone masses.
Figure 4.2: Vertical and lateral variations in paleosol colors within the study interval. Note the appearance of the red colors only in the upper third of the section. Detailed measured sections are located in Appendix A.
Interpretation: The beds of Facies Fbl are interpreted as paleosols based on the presence of rhizoliths, blocky texture, curvilinear fracture planes, and the horizonation. The preserved organics are the remnants of roots and the small bifurcating mottles and iron halos are interpreted as the product of changes in chemistry connected with roots (Retallack 1988). The red coloration of the micronodules indicates oxidation of iron, which together with the equal spacing, suggests these formed as sphaerosiderite associated with roots (e.g., Retallack 1988). The presence of the larger hematite nodules in section RK01 indicates oxic conditions even though there is organic matter within the bed. The blocks formed as peds in a soil profile (Retallack 1988). The curvilinear fractures (Figure 4.1b) are interpreted to be limbs of antiforms associated with mukkara structures during the formation of gilgai microrelief (Retallack 2001).

Beds of facies Fbl can be subdivided into horizons defined by color and structure. Gray colors and the presence of the various iron nodules and micronodules suggest a gleyed Bg horizon (Kraus 1999, Retallack 2001). The red and reddish brown colors indicate oxidation typical of Bt or Bw horizons. The slickensided surfaces are evidence of structural Bt horizons (Retallack 2001) and the zones with carbonate nodules are interpreted to be Bk horizons. The large irregular masses of limestone in section RK05, coupled with the red blocky mudstones and the capping white roots, suggest the development of terra rosa or C horizon. The hard calcareous mudstones suggest the development of hardpans and the hard, noncalcareous portions of the red mudstones are interpreted as a fragipan (Bx horizon) cemented by silica (Retallack 2001). The source of the silica is unknown, but two possibilities are phytoliths from plants (e.g., Clarke 2003) or a devitrified volcanic ash horizon, which in concordance with other occurrences in the Appalachian basin is associated with an organic rich horizon (e.g., Lyons et al. 2006).

The gray paleosols indicate poorly drained conditions, whereas the reds indicate well-drained conditions. These two environments may designate small-scale relief on a floodplain or
the change from distal levee to floodplain. The mottling, thickness, and changes in ped size suggest a complex history for many of the beds of facies Fbl. The mottled transition of gray down into red in some beds represents secondary gley overprinting an originally oxidized horizon (Kraus 1999; Driese and Ober 2005). The thicker paleosols suggest accumulation over long periods of time. In a single soil profile the size of the peds should decrease regularly up section. The variations in ped size, therefore, indicate the presence of composite soils that represent multiple aggradational events overprinted by pedogenesis (Kraus 1999). The complex changes within the measured sections indicate repeated truncation of soil profiles. These variations in ped size suggest changes in paleosol maturity. The slickensides and large curvilinear fractures indicate that this facies represents mainly vertic paleosols (Caudill et al. 1997). Vertisols commonly form in regions with seasonal changes in moisture. The presence of the hardpans in the upper parts of the sections indicates an increase in evaporation that may be associated with increased aridity (Wright 1999).

4.3 Facies Fpl - Platy mudstone

*Description:* Facies Fpl are siliceous, laminated mudstones present between the Pittsburgh Coal and the Fishpot Limestone that have a platy shape (*sensu* Retallack 1988) with sharp edges when broken (Figure 4.3a). Facies Fpl ranges in color from dark green to maroon. The upper and lower contacts of this facies are often gradational and sometimes marked by bulbous structures. Facies Fpl is not calcareous, but often contains small, flat, white, round, calcareous disks, typically less than a cm wide, which can be present in large numbers. Small slickensides may be present but are not as common as within Facies Fbl. The abundant, non-carbonized plant remains, which appear similar to slickensides, are mainly composed of leaf impressions (*Lepidodendron* ?), an unknown seed fern, and *Calamites* up to 18 cm in length (cf. Cross et al. 1996). Carbonized plant debris is rare in these mudstones.
Figure 4.3: Concretions and fossils within Facies Fl (laminated mudstones): a) vertical iron nodules, b) internal brecciation within iron nodules, c) *Microconchus* (*Spirorbis*). Scale bar is approximately 1 mm.
Nodules can occur singly or as layers within this facies. The nodules exhibit four main forms: elongate, relatively round, large flattened ovate, and vertically amalgamated. The elongate nodules are typically 1 cm in diameter and a maximum of 10 cm in length. Long axes are typically horizontal, often oriented with similar strikes, although some larger examples are vertical (Figure 4.3b). The surfaces of the round and ovate nodules may be smooth or have elongate curving ridges. The large flattened ovate nodules can exceed 30 cm in diameter parallel or perpendicular to bedding. The nodules are commonly stained red to brown, although the interiors are most often light tan but are sometimes a dull red color. Internally the nodules are massive to brecciated or have concentric rings (Figure 4.3c) and calcite-filled fractures.

Interpretation: This facies represents a siliciclastic lacustrine environment that was lightly overprinted by pedogenesis based on the platy texture and the iron nodules, which are interpreted to indicate rooting. The hardness, lack of carbonate cement, and the close relationship with iron suggest silica precipitation, possibly due to podzolization (Boggs 2001). Phytoliths from plants or sponge spicules (Clarke 2003) are considered the most likely silica source because of the lack of defined horizons and the large amount of associated plant impressions. The horizontal and vertical nature nodules suggest that they may be related to root systems.

4.4 Facies Fi: Mudstones with Intraclasts

Description: Facies Fi consists of mudstone beds that contain clasts composed of claystone, laminated mudstones, siltstone, and limestone interbedded with Facies L, Fl, Fp, or below Si. The clasts are subangular to subrounded and average a few centimeters in width can be up to 18 cm long. The mudstone clasts are typically elongate, and the carbonate clasts are more oval. The clasts are often iron stained. Carbonate clasts vary from mudstones to packstones that internally can be laminated or brecciated and contain ostracodes or small aligned, millimeter-sized, string-
like, branching allochems of unknown affinity. In general, the size shape, size, and abundance of clasts have no vertical trend. In some cases, however, the clasts become more angular and less abundant upward. Carbonate clasts are sometimes coated with ostracodes, other smaller clasts, or quartz grains up to 0.25 mm in diameter.

The mudstone matrix of beds containing limestone, angular mudstone, and siltstone clasts typically has a subangular to blocky texture, slickensides on surfaces, and, in decimeter thick beds, large curvilinear fractures. In many cases, the blocky texture is smaller at the top of the beds although in thicker intervals the size of the blocks may vary within beds. The thickest bed of this facies (approximately 1m) occurs near the top of the Pittsburgh Limestone. The blocky matrix often contains an appreciable amount of other constituents such as shells or other clasts. Most shell material consists of broken pieces of ostracodes, possible bivalves, and Microconchus (Spirorbis; Taylor and Vinn 2006).

The non-carbonate clasts include small, green, flat, angular mudstones with distinct boundaries and subrounded to rounded siltstone fragments. Plant impressions are present in some siltstone clasts. Plant debris, plant impressions, and branching rod-like organics are present locally, usually near the top of beds. Some beds have a cap of thin laminated mudstones or millimeter thick, iron-rich laminations that contain fish teeth and abundant crushed Microconchus. Muscovite is often abundant, and the grains can be up to 0.4 mm wide.

Light green angular mudstone clasts also occur in laminated beds of hard, calcareous, dark greenish to gray mudstone <10 cm thick between carbonates of the Pittsburgh Limestone. Slabbed hand samples of Facies Fi show that the laminations are wavy, anastomosing, or flaser bedded. These mudstones sometimes occur as triangular shaped wedges with the apex oriented
either up or down. The degree of cementation makes these wedges are difficult to distinguish from the adjacent limestones. Organics are rare and occur as small carbonized rods.

**Interpretation:** Facies Fi was deposited within a lacustrine to floodplain setting based on adjacent facies (described below). The presence of clasts indicates transport although the distance of transport is difficult to determine and was likely highly variable. The more rounded clasts imply a greater distance of transport, however, the lithologies are not resistant and can round easily. The blocky texture of the matrix was a result of pedogenic modification similar to Facies Fbl. *Microconchus* has been used as evidence of a marine influence (Cassle 2005) but Taylor and Vinn (2006) suggest that *Microconchus* was also formed by organisms within freshwater, brackish, and hypersaline environments.

4.5 Facies Fl: Laminated Mudstones

**Description:** Laminated mudstones have relatively horizontal, parallel to sub-parallel laminations in layers ranging from a few millimeters to a little over a meter in thickness. Facies Fl occurs throughout the study interval but is most common in the siliciclastic interval between the Pittsburgh and Fishpot Limestones. The variations within beds of Fl within the siliciclastic and carbonate intervals are described separately beginning with the latter.

Beds of Facies Fl within the Fishpot and Pittsburgh limestones are typically only a few centimeters thick and have a high clay content. The color is usually gray but this facies is red at two places within and above the Fishpot Limestone. Within the Fishpot Limestone, Facies Fl may contain carbonate nodules that are thin, isolated, several centimeters in diameter, or lenticular and wavy bedded (*sensu* Reineck and Wunderlich 1968). Laminations within the latter are defined by silt or ostracode shells occur within the laminated mudstones. Other morphologies include long rounded branching structures around which the beds are deformed (Figure 4.4a).
Figure 4.4: Nodules and trace fossils within Facies Fl: a) deformation around iron nodules, b) red striping often associated with nodules, c) vertical burrow approximately 1 cm long, d) parallel trackways with small grooves or scours (g).
Within the Pittsburgh Limestone, Facies Fl contains organics on bedding planes, but some thin coaly stringers are nearly vertical. Large amounts of orange, iron stain and dense concentrations of Microconchus with some conical fish teeth are present at the top of some beds. Facies Fl within the Fishpot Limestone may contain rare (10%) ooids or spar-cemented pellets (sensu Boggs 2001).

Facies Fl in the siliciclastic portion of the sections is typically shades of green, gray, or tan and calcite cement is very rare. Locally, thin beds of siltstone with climbing ripples are present. Thicker beds often contain portions with a high silt component that can be correlated into laterally adjacent siltstones. The amount of mica present is a function of grain size with the clay-rich beds containing little to none and the coarser mudstones containing large quantities. Iron or carbonate nodules are common and laminations are typically deformed around the larger nodules. Centimeter thick iron stained horizons commonly occur with nodules (Figure 4.4b). Pyrite is commonly associated with these horizons. Facies Fl is typically overlain by platy mudstones (Facies Fbl) or laminated, rippled, or hummocky siltstones (Facies Slt). Contacts with platy mudstone are commonly highly irregular.

Body fossils are relatively rare and include Microconchus, ostracodes, bivalves, and Spinicaudatans (A. Stigall, pers. com.) as both preserved hard parts and impressions. Plant material is common as both impressions and carbon films. Ichnofossils are the most common evidence of life in Facies Fl. Trace fauna appear to be exclusive to the coarser mudstones and intervals below burrowed siltstone and sandstone. Bioturbation on bedding planes occurs as round structures in concave epirelief up to 1 cm in diameter and as horizontal tube epichnion and hypichnion structures (Martinsson 1965, 1970 in Pemberton 1992) of similar diameter. Some round structures are bordered by crescent shaped convex epirelief traces. Within beds vertical structures are present as endichnion (Martinsson 1965, 1970, in Pemberton 1992) with mainly
parallel walls although a few are slightly undulatory. The vertical structures cross-cutting bedding planes (Figure 4.4c), and deform sedimentary structures. The typical infill of bioturbation structures appears to be the same as the surrounding bed, except for one instance where a coarser fill was present (section RK07 at 8 meters). Parallel trackways (Figure 4.4d) occur as a negative and positive set of lenticular concave epirelief impressions on bed tops. The impressions can be are up to a few millimeters long and less than a millimeter wide. Relatively straight tool or groove marks, which are up to 5 cm long, may lie perpendicular to the trackways. Less common are black vertical structures that are typically only 1 to 2 mm thick and < 2 cm deep. In one locality a large, (4 cm wide, 30 cm long) curved nearly horizontal black structure was found.

Bioturbation is almost absent within Facies Fl in the first 5 meters above the Pittsburgh Coal. Traces in this interval occur as parallel trackways in sections RK07 and section RK03. Between 5 and 8 meters above the coal the section contains small, < 0.5 cm diameter, circular structures on bedding planes and vertical structures (Figure 4.4c). The amount of bioturbation in sections RK02, 03, 04, and 07 becomes moderate to intense (Reineck 1967, in Pemberton, 1992) at approximately 8 meters above the coal. Within section RK07 the maximum size of burrows increases from 0.2 cm to 1 cm over a vertical distance of 0.25 m and diminishes to 0.4 cm in the last half of the interval.

Three prominent clay-rich zones are present in the sections measured. The clay-rich interval above the Pittsburgh Coal is gray, has a sharp or gradational base, and coarsens upward. This unit is traceable between sections RK01 and RK06. Many surfaces of this interval contain Spinicaudatans except in sections RK02 and RK09 where they are replaced by bivalve impressions up to 2.4 cm in length (A. Stigall, pers. comm.). White ostracodes with original shell material are present near the base and generally decrease in abundance up section. Fish scales,
plant material, and nodular or platy pyrite are also present but rare. The clay-rich beds below the thick sandstone and above the Fishpot Limestone both contain well preserved, intact fern leaves still attached to stems (referring to the fact that the leaves have not separated at their diastem).

**Interpretation:** Laminated mudstone in this study represent deposits of mainly suspended load sediment in a lacustrine setting with the more clay-rich intervals indicating the least energetic conditions. Within the siliciclastic interval the deposition of the laminated mudstones on Facies Fbl is indicative of a sustained rise in the water table. The presence of the thin siltstones containing ripples and climbing ripples indicate brief periods of rapid sedimentation that interrupted normal lacustrine deposition. The presence of Facies Fpl above and below the Facies Fl is an indication of varying water table heights. The bulbous contacts at the base of some Fl beds may represent compressional loading. Shoaling events in the lake system deposited the overlying siltstones. Within the Pittsburgh and Fishpot Limestones the presence of the laminated mudstones above beds of limestone that were subjected to subaerial exposure indicates that Facies Fl was a product of a rapid increase in water depth. In general, the absence of paleosol structures points to an increase in rate of formation of accommodation where aggradation occurred faster than pedogenesis (Wright and Marriott 1993).

The numerous body fossils present above the Pittsburgh Coal is present in many of the sections contained in Sturgeon (1958) who referred to this horizon the pelecypod zone and described it as a clay-shale that coarsened upward. The presence of *Microconchus* in the Pittsburgh Limestone indicates brackish conditions, whereas the Spinicaudatans above the coal indicate a freshwater environment. The change up-section from the Spinicaudata and ostracode dominated environment to one dominated by larger bivalves indicates a shift to a more persistent lacustrine environment. At the other end of the spectrum the branching rod-like structures, iron nodules, and branching calcium carbonate structures are interpreted as rhizoliths indicating times
of either subaerial exposure or at least a lower water table. The vertical changes in style of preservation from organic roots in both the Pittsburgh Limestone and siliciclastic interval, and iron in the lower two thirds of the siliciclastic interval, and calcium carbonate rhizoliths in the Fishpot Limestone suggests an increase in oxidation and a regionally lower water table. An alternate interpretation for the rhizoliths is that are branching decopod crustacean burrows, which can be of similar size and morphology in modern sediments (e.g., Ziebis et al. 1996). The rhizolith interpretation is considered more likely because they are similar to the structures that occur within paleosols.

One reason for the variations in the style of bioturbation above the bivalve zone may be that the lacustrine system became subject to increasing sedimentation and desiccation. The parallel track ways were probably formed by arthropods. The tool marks associated with the trackways could be a result of sedimentation or ichnofossils, such as swim traces attributed to acanthodians in arthropod dominated environments (Wisshak et al. 2004). The proliferation and diversity of traces near the top of the siliciclastic section of Facies Fl indicates that the environment was optimal for burrowers. The passive infill of the traces within this interval suggests that there was a sudden sediment influx.

The different modes of preservation of plant material also suggest a wide range of energy conditions. The lack of completeness, the disarticulated nature of the plant impressions and of the smaller carbonized organics, the defined rounding on larger fragments, and the association of the grains with silt-rich beds indicates higher energy transport. By contrast, the preservation of entire leaves suggests both limited transport and exposure.
4.6 Facies Fo: Organic-Rich Shale

*Description:* Facies Fo contains more than 50% organics and is black in color. These mudstone beds are typically only a few centimeters thick. Facies Fo is generally fissile but is well cemented at the top of the Pittsburgh Limestone. Muscovite and biotite are rare in hand samples but small, black rods are common. Facies Fo occurs at five horizons within the measured sections (Appendix). All examples consist of centimeter-scale beds except at the top of the Pittsburgh Limestone where it is sometimes a decimeter-thick bed. The base of the horizons 1, 4 and 5 overlie beds of gray, nodular Fbl, which are commonly darker colored near the contact. Horizons 1 and 4 are interbedded with Facies Fbl, whereas horizon 5 is overlain by laminated mudstone.

At the top of the Pittsburgh Limestone, horizon 2 is underlain by limestone or blocky mudstone and overlain by limestone or laminated mudstone. The mudstone that rests upon the Pittsburgh Limestone laterally appears to replace the coal east of section RK05. This mudstone in hand sample contained greater than 20% diamond-shaped fish scales. The third bed, which lies between the two limestone intervals, typically rests on a bioturbated siltstone or sandstone and under a laminated mudstone.

The calcite cemented beds within the top 0.5 meters of the Pittsburgh Limestone are laminated with an undulatory appearance caused by drape over the limestone beds below. The contacts between the calcareous mudstone and the adjacent limestone are sometimes gradational, although they are usually visible on well weather surfaces. The mudstones commonly contain a large amount of disarticulated shell material, which is often white, that consists mainly of ostracodes, possibly bivalves, and may contain *Microconchus* pieces (section RK05). These shells can locally be as much as 50% of the bed. In some cases, such as in section RK03, the shells are oriented within the layers. Plant fossils, and even a large tree impression that is now partially vitreous coal, are present on the base of some beds. Pyrite nodules are locally present.
Interpretation: Facies Fo represents thin, siliciclastic lacustrine deposits in which organic material (plants and shells) accumulated in large numbers due to low sedimentation rates. The small size of the fossils suggests an environmental stress by one or more parameters, such as salinity, subaerial exposure, or turbidity.

4.7 Facies C: Coal

Description: Coal is present in the sections as a black bed typically 10-12 cm thick. The coal is commonly laminated and vitreous and may contain fish scales, conical fish teeth, shark teeth, millimeter- to centimeter-size, angular, calcareous clasts, and rare brown angular/subangular, non-calcareous clasts less than 2 cm in diameter. No muscovite or biotite were seen but pyrite is common, and very small slickenside surfaces are present locally. Coal occurs in only one interval within the western five measured sections above the Pittsburgh Limestone and below Facies Fl. Within section RK06 the coal is replaced by 2 centimeters of mudstones of Facies Fo. The basal contact with the limestone is abrupt lithologically, but shells grade upwards into the base of the coal, and a conglomerate composed of angular limestone pieces up to 3 to 4 cm in diameter, coal clasts, and sand grains is present at the base of the coal section RK03. The top contact of the coal with the overlying mudstone can be gradational or abrupt. Pyrite veins extend upward from the coal into the overlying Facies Fl beds in section RK02.

Interpretation: Coal formed from allochthonous material is termed cannel coal (Boggs, 2001). The stratigraphic position indicates that this facies is the Pittsburgh Coal (Sturgeon 1958) although atypical in appearance. North and south of the study area the Pittsburgh Coal was thick enough to be stripped mined (Sturgeon 1958). The thin, laminated nature of the coal and the presence of the limestone and coal conglomerate at the base of Facies C in section RK03 suggest a high energy environment, at least locally. The shells in the base of the coal elsewhere suggest a gradational shift from an open water environment such as the floating bogs. The thin nature of
the coal in the study area suggests the organic matter necessary to form a coal was absent because of environmental factors, such as water depth.

4.8 Facies Slt: Siltstone

*Description:* Facies Slt is composed of thin beds of poorly sorted siltstones present mainly between the two main limestone intervals. Facies Slt is absent within the Pittsburgh Limestone, and rare within the Fishpot Limestone. Beds of this facies vary in thickness from 1 cm to 1.7 meters and the grain size within individual beds can vary more laterally than vertically (e.g., between sections RK03 and RK07). Facies Slt is slightly coarser in top of the Pittsburgh Sandstone than at the base. Bedding contacts are sharp to gradational and colors include tan, yellow, gray and green. Organics (<40%) can be present as carbonized debris or impressions. These beds typically contain muscovite and biotite grains up to 1 mm in diameter. Ovate iron nodules up to 11 cm in diameter are present in some beds.

Primary structures within most beds are composed of climbing ripples (Figure 4.5a), ripple cross-lamination, and parallel lamination. In plan view, the ripples are most often low-angle 3-D ripples. Small-scale (decimeter), low-angle, divergent lamination similar to hummocky cross stratification (HCS) is present in thin interbeds mostly of very fine sandstone (Figure 4.5b) occur above bed 3 of Facies Fo, which is a local marker bed than is used to divide the siliciclastic section between the Pittsburgh and Fishpot Limestones into a lower and upper interval. The base of one bed (section RK02 at 14 meters) has flute marks a few decimeters wide and almost two decimeters deep indicating flow was toward 243°. Soft sediment deformation including loading structures, overturned antiforms (Figure 4.5c), and pillows (Figure 4.5d) are common. Pillow structures are common at the same horizon within sections RK02, 03, and 07. Tool marks are present along the base in section RK02 with an orientation of 060°/240°.
Figure 4.5: Sedimentary structures within Facies Slt (siltstones):  a) climbing ripples, b) hummocky cross stratification  scale bar equals approximately 15 cm, c) overturned anticlines (black and white), d) pillow structures scale bar approximately 10 cm.
Bioturbation is present within all beds in facies Slt although the degree and type of bioturbation is variable. The degree of bioturbation in many cases has completely overprinted primary sedimentary structures. Biogenic structures were identified by the presence of clearly defined structures or repetitive structures of the same nature, shape, or affinity. Traces on bedding planes and vertical faces consists of the predominantly the same structures as are present in facies Fl with a few notable additions. These additional traces include a funnel-shape burrow (Figure 4.6a), passively filled bean-shape burrows (Figure 4.6b), and large burrows up to 3 cm in diameter (Figure 4.6c). Vertical burrows range up to 3 cm wide in calcareous areas, but are mainly < 1 cm (e.g., Figure 4.4c).

An arthropod track dominated area occurs 1-2 meters above the coal and a more diverse heavily burrowed horizon is present 8 m above the coal. Within Facies Slt, however, there are two distinct horizons at 5 and 7 meters above the coal that are intensely bioturbated. The upper half of the siliciclastic interval is commonly heavily bioturbated and many times the traces overprint sedimentary structures leaving only a bumpy appearance when broken. The largest burrows, which are up to several centimeters wide, are present within the siliciclastic portion of the Fishpot Limestone.

Plant fossils within Facies Slt are much less common than in Facies Fl and typically consist of molds of complete compound leaf sets of smaller ferns, and *Calamites (?)* (Figure 4.6d) present along clay partings. The upper beds of the Pittsburgh Sandstone contain abundant, often complete ferns in positive relief. Small, shallow dipping, oriented, rod-like structures composed of siltstone commonly protrude from these beds. Large tree impressions are present at the base of large flutes in section RK02 at 14.5 meters. Large vertical, branching structures that cut through several sets of beds are present in section RK07 approximately 5.5 m above the coal. These
Figure 4.6: Biogenic structures within Facies Slt: a) conical burrows, b) bean shaped, c) large burrow, d) moldic tree impression, e) large vertically branching structures.
structures are heavily weathered but striations are still visible on the inside of some and one *in situ* branching portion contains an impression similar to *Calamites*. The main or trunk portion of all vertical structures dips slightly to the east. The basal portion of each structure is about 4-5 cm in diameter and the structures are 41-43 cm in length.

Carbonized organics in Facies Slt are limited to three areas and usually occur as vertical branching rods or as grains and clasts up to several centimeters in diameter. The lower half of section RK03 contains largest vertical distribution of this type of plant fossil between 1.5 and 4 meters above the Pittsburgh Coal. This fossil material is present in the western three sections approximately 3.5 meters above the Pittsburgh coal.

*Interpretation*: Beds of Facies Slt were deposited in a shallow lacustrine setting with lateral change in grain size suggesting an overall fining of beds away from a sediment source. The presence of climbing ripples and preservation of abundant plant material show the sediments within both the lower and upper intervals aggraded rapidly. The large vertical structures with striations are interpreted to be *in situ* tree trunks buried by a rapid influx of silt. However, the presence of HCS and the disappearance of the iron nodules point to a fundamental change in the depositional environment in the upper interval. The change is also reflected in the type of ichnofossils present.

Organisms make traces in response to eight main factors (MacEachern et al. 2005) and the change in bioturbation from epifaunal to infaunal implies a change in one or more of these controls. Four of the factors (food resource type, water salinity, temperature, and oxygenation) cannot be evaluated based on the present information. Another factor, substrate consistency, is assumed to be constant because the lithology is the same and the substrate stiffness is a product of two other factors, subaerial exposure and substrate moisture. Therefore, the changes in style of
trace fossils in the study area are considered the product of the three variables that could be constrained, energy conditions, subaerial exposure, and substrate moisture.

The preservation of the tracks and the compaction of the burrows indicate that the substrate in both intervals was moist. The change to burrows from tracks and the presence of HCS in the upper interval is interpreted as an increase in energy levels impacting the substrate. The reworking of facies Slt within the Fishpot Limestone by larger burrowers could represent a change in substrate consistency resulting from periodic desiccation of the palustrine limestones (see below).

4.9 Facies Sl-r: Laminated to Rippled Sandstone

*Description:* Thick laminated to rippled sandstones is present in bedsets up to 5.5 m thick. Colors vary from tan to gray and grain size ranges from lower very fine to upper medium sand. Muscovite and biotite grains are typically abundant and up to 1 mm in diameter. Bright green, white, black and pink clasts up to several millimeters in diameter are present locally. Rippled bedsets bounded by sharp near horizontal surfaces are the norm with two exceptions contained in localized fining upwards lenses. Climbing ripples are present locally. Bedsets composed of parallel laminations typically have low dips of less than 7°. Plant fossils and iron nodules are rare in this facies, except at the base of section RK08 and a few meters above the base in section RK09 where carbonized organics are abundant. Minor bioturbation is present in section RK09 as small, round, epi relief burrows.

*Interpretation:* Facies Sl-r is interpreted as the product of rapid sedimentation near a source of relatively coarse silicilastics, such as a river or splay channel. The current ripples indicate either slow moving or relatively shallow flow while the isolated climbing ripples formed during periods of rapid deceleration of flow, probably into standing water. The low-angle, parallel laminations
are also indicative or rapid and/or shallow flow (Boggs, 2001). The overall lack of bioturbation present suggests higher stress environmental conditions than the adjacent finer grained beds of Facies Fl or Slt.

4.10 Facies Sla: Low-angle laminated Sandstone

*Description:* Facies Sla is present in the lower and upper portion of section RK09 as tan colored sandstone beds and a small gray lens a few meters below the Fishpot Limestone with grain size varying from lower medium to upper very fine, and mica grains (both muscovite and biotite) up to 0.4 cm in diameter (Figure 4.7a). Beds are typically only a few centimeters thick and form multiple, small-scale, fining upward successions with similar dip directions vertically, variable dips laterally. Dip angles are often greater than 7°. Large burrows within this facies were observed in float but not found in place.

*Interpretation:* Facies Sla is present only at the top of the thickest sandstone in the study area. The variable dip of the low-angle laminations suggests deposition at the top of a macroform, such as a mid-channel bar, in a fluvial channel (Bristow 1993). Changes in flow strength during deposition are indicated by the grain size variations within the bedsets.

4.11 Facies Sp: Planar Tabular Crossbedded Sandstone

*Description:* Facies Sp (Figure 4.7b) is only present in section RK09 as a single bed 0.21 m thick composed of white, upper medium-grained sandstone that contains elongate flat light and dark gray mudstone clasts < 2.5 cm in diameter that ranges from 10-30%. Green clasts less than a couple of millimeters in diameter appear as less than 10% of the bottom portion. This facies has upper very coarse-grained muscovite and rare biotite. Three measurements of the crossbedding indicates paleoflow was between 021° and 345°.
Figure 4.7: Sedimentary structures that define two of the sandstone facies: 
a) Facies Sla, low angle sandstone b) Facies Sp, planar trough crossbedded sandstone.
Interpretation: Planar tabular crossbedded sandstone forms by the migration of relatively low energy 2-D dune forms. This facies can form in any environment with unidirectional flow. The incorporation of the mudstone intraclasts suggests erosion from a local source, such as the collapse of a riverbank.

4.12 Facies St: Trough Cross-bedded Sandstone

Description: Trough cross-bedded sandstone beds are present up to a meter in thickness, vary from lower medium- to upper coarse grained, and are tan or white in color. Muscovite and biotite are usually present and can reach 1.5 mm in diameter. Facies St is present only in the interval between the two limestones and in the upper portion of section RK09. In sections RK06 and RK09 facies St is bracketed by beds of Facies Sm. Elsewhere, Facies St is commonly overlain by the Facies Slr. Facies St in section RK09 differs significantly from the other examples. Clasts are most common within the thick sandstone in section RK09 and are most abundant in the bottom half of that sandstone. The base of this exposure contains small (< 2 cm), subangular to subrounded clasts of gray mudstone and tan to white limestone. The overlying sandstone contains similar sized tan to white, and orange limestone clasts as well as flat mudstone clasts up 5 cm long. This upper exposure is coarse-grained with correspondingly larger mica grains.

Interpretation: Facies St formed by the migration of 3-D dunes under slightly higher flow velocities or water depths than Facies Sp. Although no specific depositional environment is indicated by this facies the coarse grain sizes present in section RK09 indicate significantly higher flow velocities, which is consistent with channelized flow, occurred in this section compared to the rest of the study area.
4.13 Facies Sm: Massive Sandstone

*Description:* Facies Sm includes all beds of sand-sized grains that lacked primary sedimentary structures. Grain size varies from upper fine-to lower coarse-grained sand and colors ranged from tan, to gray, to white. Muscovite and biotite grains (> 1 mm in diameter) are common.

*Interpretation:* True massive sandstones are the product of movement with dispersive pressures such as subaqueous debris flows (Boggs, 2001). More commonly, this facies is simply a product of weathering that has removed evidence of internal structures. With no evidence to the contrary the latter interpretation is preferred here.

4.14 Facies Si: Sandstones with Intraclasts

*Description:* Facies Si is defined by the presence of mudstone intraclasts in a sandstone matrix. Within sections RK04, 05, and 06 flat, millimeter-sized, gray to maroon mudstone intraclasts make up almost 40% of the base of the beds. Clast size ranges up to 5 cm in length. The Facies Si at the base of section RK06 also contains blocks of laminated mudstone up to 10 cm long and up to 3 cm high. Iron nodules up to 1.5 mm in diameter are present but rare. Orange and white limestone clasts occur near the base of RK09, as well as vertical, organic rods, and plant fragments 1 mm in diameter, along with rare, 0.3 cm diameter, round, concave, epirelief burrows.

*Interpretation:* The sandstone with intraclast facies was deposited in a relatively high energy environment near an area undergoing active erosion of a variety of lithologies.

4.15 Facies L: Limestone

Limestone occurs in two zones named the Pittsburgh (lower) and Fishpot Limestones (upper) that share many characteristics but differ enough in appearance that they can be distinguished in the field (Figure 4.8a-c). The Pittsburgh Limestone and the upper Fishpot appear
Figure 4.8: Variations in appearance between the Pittsburgh and Fishpot Limestones: a) Pittsburgh Limestone, b) upper portion of the Fishpot Limestone [pencil for scale], c) lower portion of the Fishpot Limestone. Basal limestone bed is approximately 5 cm thick.
similar, however, the lower Fishpot is typically white in color composed of thin beds that weather orange and spongy with a boxwork texture (Figure 4.9). The two limestone intervals contain four subfacies defined based on texture described in detail below; massive (Facies Lm), laminated (Facies Ll), floatstone (Facies Lf), and rudstone (Lr).

4.15.1. Subfacies Lm: Massive Limestone

*Description:* Beds of massive limestone vary from mudstone to grainstone (Dunham 1962 in Boggs 2001). Allochems are visible on weathered surfaces but fresh surfaces appear homogenous. Beds typically contain more than forty percent allochems > 0.3 mm and < 2 mm in diameter (Figure 4.10a). Allochems range in color from green to tan, or to black or white and mottling of gray or cream colors is common. One hand sample was a mottled dark red color. The lighter color mottling usually surrounds calcite spar, typically < 2 mm thick and rounded in plan view. Thin, vertical veins of calcite up to 3-4 cm in length are present as downward thinning wedges in some hand samples. Small horizontal calcite veins similar to birdseye texture are present but are much less common than the vertical veins. The surfaces of some beds have a polygonal pattern of fractures infilled with the same material as the vertical veins. Burrows are present only along bedding planes. One horizon of oolitic grainstone is present in the basal Fishpot Limestone.

*Interpretation:* Facies Lm is interpreted to be shallow lacustrine limestone based on the repeated subaerial exposure indicated by the presence of desiccation cracks. The grainstones and packstones suggest a relatively high energy environment. The mottling is interpreted as a product of the burrowing seen along the bedding contacts and rooting that destroyed the original texture of these rocks. Cassle (2005) interpreted the mottling as a product of marmorization, which occurs when water levels fluctuate and the iron content of the sediment is greater than 2%. Red mottling represents the fixing of migrating ferric iron and the gray and white colors represent
Figure 4.9: Boxwork texture within limestones: a) an example of modern boxwork limestone from Marion Lake, South Australia (modified from Warren, 1982; Kendall and Warren, 1987), b) boxwork texture from the Fishpot Limestone.
Figure 4.10: Limestone Subfacies Lm (massive) and Ll (laminated): a) Subfacies Lm, scale bar in centimeters, b) Subfacies Ll (Type 1 - inclined), c) Subfacies Ll (Type 2 - mudstone to packstone) with tepee structure.
iron-depleted areas (Freytet and Verrecchia 2002). The wedge-shape vertical veins and polygonal surface pattern represent desiccation cracks with secondary calcite infilling.

4.15.2 Subfacies Ll: Laminated Limestone

*Description:* Limestones that display lamination make up facies Ll. Mottling is much less common in Facies Ll than in Lm, but the former typically contains more calcite veins. Two types of lamination are visible. Type 1 laminations (Ll₁; Figure 4.10b) are often slightly inclined and contain a large number of grains of amorphous or laminated calcium carbonate or mainly disarticulated bivalve and ostracode shells, which may be oriented either perpendicular or parallel to the laminations. The grain-dominated laminations are typically interspersed with thin green lamina in an anastomosing manner. Type 2 laminations (Ll₂; Figure 4.10c) are defined by alternating mudstone and packstone with distinctive variations in color between the laminations, which can be undulatory. The shells present within Ll₂, which were likely ostracode, are typically articulated. Vertical microfaults, veins of calcite or organics commonly cut the laminations. Wedge-like structures were visible in beds containing Ll₂ laminations on slabbed surfaces.

*Interpretation:* The two types of laminated limestones are interpreted to be deposits of a freshwater lake system based on the presence of only bivalves and ostracodes. The disarticulated shells and grains within Ll₁ laminations indicate higher energy and some local transport. Ll₂ laminations formed as algal accumulations in quiet water based on the combination of color variation, texture, and undulation (Freytet and Verrecchia 2002). The algal laminations suggest minimal sediment influx. The wedge-like structures are interpreted to be tepee structures (Assereto and Kendall 1977, Kendall and Warren 1987), which indicate periodic desiccation. Microfaulting probably was a result of compaction (Berryhill et al. 1971).
4.15.3 Subfacies Lf: Intraclastic Floatstone

*Description:* Floatstone (Embry and Klovan 1972) consists of beds with > 10% carbonate clasts or allochems > 2 mm in diameter in matrix support (Figure 4.11a). Clasts are usually subangular to rounded and are commonly laminated and most common in the Pittsburgh Limestone. This facies corresponds to part of the intraclastic microbreccia facies of Cassle (2005). Larger clasts may be composed of smaller clasts, debris, or shells of bivalves and ostracodes. Portions of beds with fewer clasts have small rod like allochems of unknown affinity making up 10% to 20% of the rock. The weathered upper surface and sometimes sides have irregularities similar in size to the clasts within the bed. The few floatstones present in the Fishpot are usually homogeneous in color and faint clast outlines could only be determined in cut samples. One hand sample from the Pittsburgh Limestone contained a structure referred to as a pedotubule by Freytet and Plazat (1982).

*Interpretation:* The ostracode and bivalve fossils imply lacustrine deposition of Facies Lf. The presence of a floatstone indicates deposition by mass wasting events such as debris flows or hyperconcentrated flows (e.g., Zahela and Wiesemann 2005). The long stringy transparent allochems may represent fenestral textures that are associated with drying events (Alonzo-Zarza 2003). A few of the Lf facies suggest some pedogenic modification based on clastic textures and root structures.

4.15.4 Subfacies Lr: Intraclastic Rudstone

*Description:* Rudstones (Embry and Klovan 1972) consist of clasts or allochems > 2 mm diameter in grain support. In some instances, the weathered upper surfaces of beds of Facies Lr can appear similar to beds of weathered Facies Lf. Based on slabbbed hand samples Facies Lr is divided into two general types, is a monomictic breccia and a polymictic conglomerate to breccia.
Figure 4.11: Limestone Subfacies Lf (floatstone) and Lr (rudstone): a) Subfacies Lf, b) Subfacies Lr (Type A - monomictic breccia), c) Subfacies Lr (Type B - polymictic conglomerate or breccia).
(LrB; Figure 4.11c). This facies corresponds in part to the intraclastic microbreccia facies of Cassle (2005).

Facies LrA weathers either gray or orange with fresh surfaces appearing largely homogenous because all the clasts are similar in composition to each other and the matrix. Only slight changes in color from grays to tans occur within the beds. On slabbed surfaces white rinds, or white or clear calcite filled veins sometimes define clast borders termed craze planes by Freytet and Plazat (1982). Clast edges can be matched between adjacent clasts in most cases. In some slabbed hand samples of apparently homogenous limestone there are faint subangular to angular outlines with the same dimensions and shapes of clasts present in other beds of this facies. No fauna were visible in either clasts or matrix.

Facies LrB differs from LrA in that the clast edges can not be matched and clast density is lower. Individual clasts may be brecciated, but can be defined by some combination of color, shape and roundness, presence of laminations, or lithology. Clasts may be composed of smaller clasts. Color is more variable in this subfacies ranging from shades of green to gray to black. The color of the matrix in some beds is substantially different from the clasts, which helps identify the clast margins. The upper surface of LrB beds that cap the Pittsburgh Limestone contain *Microconchus*, shark teeth, bivalves, and ostracodes. These Pittsburgh Lr beds have a similar appearance to the polyphase transport breccias of Freytet and Plazat (1982). Weathered LrB bed surfaces in the Fishpot Limestone exhibit acanthodian spines (Dr. Mapes, pers. comm.), fish scales, oncolites, and, in section RK01, crushed calcareous tubular structures. Branching, subvertical organics approximately 1 mm in diameter are present in some LrB beds at the base of the Fishpot Limestone.
Interpretation: The similar color and matching edges of Facies LrA clasts indicate little displacement and no transport within the environment. The cause of brecciation was periodic desiccation (Cassle 2005). The faint outlines in the essentially homogenous beds are interpreted as clasts that have undergone recrystallization based on the angular to subangular shapes. The recrystallization of clasts and the multiple episodes of calcite infilling between clasts points to several diagenetic events, probably related to repeated wetting and drying. The fauna within these beds is consistent with a freshwater depositional environment.

The more rounded clasts and greater variety of clast textures within Facies LrB indicate somewhat longer distances of transport and different source beds compared to LrA. The more angular clasts within this facies are more homogenous suggesting larger or maximum amounts of brecciation or very local transport. The more angular clasts include green mudstone granules that may be pedogenic mud aggregates, although this is considered unlikely because transport with the carbonate clasts should have destroyed the aggregates. The presence of multiple clasts within one another suggests a complex history of multiple deposition, brecciation, and transport events.

The Microconchus, shark teeth, bivalves, and ostracodes at the top of the Pittsburgh Limestone may be indicators of marine influence. Acanthodian spines, fish scales, and calcareous tubes, which are the remains of sponges or plant material, in the Fishpot Limestone do not provide an unequivocal interpretation of environment. The branching organic remains are interpreted as roots that show that these beds were subaerial exposed prior to deposition of the overlying coal.
Chapter 5

Facies Associations

5.1 Introduction

Facies can be interpreted in terms of small-scale variations in the processes that occur within a depositional setting. Interpretation of a depositional environment, such as a specific type of river system, requires recognition of groups, or associations of facies that are genetically related. A total of five facies associations that include palustrine, lacustrine, floodplain, fluvial, and interfluve environments are described and interpreted in this chapter based on the facies described in Chapter 4. A synthesis of the allocyclic controls on deposition interpreted from the vertical and lateral variations in the facies associations is presented at the end of this chapter.

5.2 Facies Association 1: Palustrine to Lacustrine Carbonate

*Description* The two intervals that comprise the regionally extensive Pittsburgh and Fishpot Limestones (Figure 2.1; Lamborn 1951) belong to Facies Association 1. Facies Associations 6 and 2 bracket the Pittsburgh interval. The Fishpot zone is bounded above and below by Facies Association 3 (Figure 5.1). The limestones are composed of combinations of the four carbonate subfacies interbedded with Facies Fbl, Fl, and Fi (Table 4.1). Each limestone interval contains a significantly different proportion of facies. The Pittsburgh contains a greater proportion of ostracodes and organics compared to the Fishpot and, at least locally, is more faunally diverse. Sturgeon (1958) reported *Microconchus* from the Fishpot Limestone, but none were observed within the study area.

A cross-section of the Pittsburgh Limestone using the coal as a datum shows that there was at least 1.9 m of pre-existing topography on the top of Facies Association 6 (Figure 5.2). The
Figure 5.1: Lateral and vertical distribution of facies associations in the study area.
Figure 5.2: Lateral and vertical variations in Facies L within the study interval. Note the limestone beds are more continuous at the top of the Pittsburgh and at the base of the Fishpot.
limestone/siliciclastic ratio decreases up-section but limestone beds become generally more continuous toward the top of the Pittsburgh. The lateral restriction of facies can be interpreted as either a function of a limited extent of the primary depositional environments or as a function of disruption by small-scale erosional events. A facies sequence of Lm-Ll-Lf or Lr is common particularly in section RK01 through RK03. The upper beds of the Pittsburgh, which typically contain Facies Lf and Lr, lie above an equally extensive unit composed primarily of Facies Fi.

The Fishpot Limestone varies substantially in thickness from west to east but, unlike the Pittsburgh Limestone, the basal beds are the most continuous (Figure 5.2). The lower Fishpot is typically white in color and composed of thin beds in which Facies Ll₂ is typically overlain by Lrₐ with minor amounts of Facies Ll₁, Lrₐ, and Lf also present. Weathered surfaces are orange and spongy with a boxwork texture (Figure 4.11). These beds are typically sugary textured on broken surfaces, often highly fractured and more rarely contain slickensides or fossils. The beds of Lr, Lm (grainstones), and Lf contain organic stringers, fish scales, conical fish teeth, glauconite, oncolites, an acanthodian spine (Dr. Mapes, pers. comm.), oolites, isolated quartz grains, and unnamed algal-coated tubular structures.

No small-scale trends were observed in this portion of the section but overall the amount of limestone within the Fishpot decreases up-section. The major change in limestone facies is the predominance of Facies Lr. Type A (monomictic breccia) is most common but Type B (polymictic breccia-conglomerate) is also present. Facies Lm and Lf occur only in the lower 2/3 of this unit. Distinctive changes within the siliciclastic component include the presence of maroon to red paleosols of Facies Fbl as well as siltstones that separate beds of limestone. The lower limestone beds containing oolites can be traced across the exposure whereas the upper beds cannot. The upper limestone beds passes laterally into carbonates containing a significant amount of siliciclastics and rhizoliths.
Interpretation: The depositional setting of the limestones is interpreted to be lacustrine to palustrine with possibly some marine influence at the top of the Pittsburgh and the base of the Fishpot Limestones. The areal extent of the limestones eliminates deposition by springs but it also makes it difficult to reconcile deposition in a fluvial setting if the only means to prevent siliciclastic sediment influx was natural levees. The lack of normal marine fauna in the limestones is generally cited as evidence of lacustrine deposition (e.g., Sturgeon 1958; Cassle 2005). The vertical infilled cracks, which occur in all subfacies to varying degrees, the intense brecciation, nodular texture, and boxwork structure are all evidence of periods of dehydration. Pseudo-anticlines, or tepees, and boxwork structure are common in lacustrine, tidal, and back-barrier environments (Warren 1982; Kendall and Warren 1987), however, characteristic tidal indicators, such as birds-eye structures, are not abundant.

The largely unfossiliferous limestones of the Monongahela Group are commonly referred to as freshwater, lacustrine, and palustrine (Sturgeon 1958; Cassle 2005). Modern palustrine systems, such as marshes, swamps, fens and bogs, are defined as being < 8 ha (20 acres) in size and with < 2 m of water depth at low water (Cowardin et al. 1979). The depth of standing bodies of water changes with time because of variations in the water budget, which is primarily affected by evaporation, inflow from rivers, and precipitation. Wide, shallow lake basins tend to desiccate rapidly if inflow is restricted because of the large surface area for evaporation relative to the total water volume (Carroll and Bohacs 1999). Although the limestone zones as a whole are far more extensive than modern palustrine environments, individual beds likely fall within the size limit. There is evidence of exposure in both the limestones and interbedded mudstones. Therefore, the limestones in this study area should be classified as palustrine.
The vertical facies successions within the Pittsburgh Limestone are interpreted as a product of shoaling and are consistent with depths on the order of 3 m or less proposed by Cassle (2005). Some beds contain evidence of multiple episodes of brecciation. The amount of transport of the clasts is more difficult to assess because brecciation can cause up to 15% expansion between clasts (Assereto and Kendall 1977). The many textures and structures, such as the flaser and ribbon bedding, the ooids, and oncolites, point to deposition in an environment of variable energy and water levels at the same time the Microconchus may indicate a nearby marine influence. Regardless of the specific environment, the presence of the limestones required rapid, short-term formation of accommodation and a means to limit coarse siliciclastic input.

Several depositional scenarios could lead to the mixture of carbonate and siliciclastic facies seen in the Pittsburgh and Fishpot Limestones depending on whether or not deposition of the two lithologies was linked or decoupled. The mudstones could represent the initial deposits as the water levels rose with the carbonates precipitated during periods of water level highstand. Desiccation then produced the clastic textures within the limestones and the pedogenic overprint in the mudstones at the same time. Alternatively, the limestones were the initial deposits with the mudstones entering the system terminating carbonate deposition as water levels fell. Again, desiccation produced pedogenic overprinting in both lithologies simultaneously. A third option is to consider the two lithologies are largely unrelated. At different times, either limestone or mudstone deposition occurred in the palustrine system depending on proximity to a fluvial source. Pedogenesis then modified the deposits of each water cycle. The irregular distribution of beds and the variations in maturity of the pedogenesis suggests that the third option is more realistic. There is no regular vertical distribution of the mudstones and limestones that would indicate both occurred within the rise and fall of water level. The pedogenic overprint of the mudstones and the presence and degree of brecciation in the limestones are both irregular and variable implying a wide range of wet/dry combinations during deposition.
The occurrence of the Pittsburgh Limestone above a major interfluve represented by Facies Association 6 indicates a significant elevation of the regional water table in response to some combination of glacial-eustatic transgression and tectonic subsidence. Compaction is not an issue here since the terrestrial deposits of Facies Association 6 were largely compacted prior to deposition of the Pittsburgh Limestone (cf. Nadon and Issler 1998). The widespread formation and preservation of the limestones (Figure 2.1) during an overall 3rd-order relative sea level fall (Ross and Ross 1988) requires a regional increase in total accommodation and demonstrates that an increase in subsidence rate occurred. The upward decrease in the amount of limestone should signal a general reduction in rate of formation of accommodation, however, the lateral continuity of the beds suggests the reverse is true. The upward decrease in Facies L1 and Lm within the Fishpot Limestone when combined with the occurrence of oolites at the base and the predominance of Facies LrA at the top is interpreted as an indication of increasing desiccation up section consistent with a decrease in the rate of formation of accommodation.

The formation and preservation of the Fishpot Limestone requires a high water table like the Pittsburgh below, however, the overall facies trend is one of base level fall up-section based on the presence of Facies Fbl associated with the upper limestones. The presence of the oolite bed indicates a rapid increase in base level from the Facies Association 3 mudstones below. The presence of the increased amount of coarser siliciclastics within the Fishpot compared to the Pittsburgh suggests some combination of closer proximity to a fluvial source (Figure 2.1) and a lower degree of tectonic subsidence providing less overall accommodation.

The only previously reported fauna from these limestones was *Microconchus* and ostracodes (Cassle 2005), which are present in abundance. Numerous other body fossils and a variety of burrows can now be added to the list. The diversity of fauna are consistent with lacustrine deposition. The only brackish water indicator may be *Microconchus*. The texture of
smooth ostracode carapaces is similar to marine species described by Fohrer and Samankassou (2005), but similar shell textures also occur in freshwater (e.g., Cassle 2005).

5.3 Facies Association 2: Siliciclastic Lake

*Description* Facies Association 2 is present between the two carbonate lake deposits and composed of facies Fl, Fpl, Fo, Fi, C, and Slt. Fine-grained sediment, extensive burrowed horizons, and beds that contain both plant and shell fossils of a freshwater to brackish affinity characterize this facies association. The laminated mudstones and shales of Facies Fl comprise most of the sediment. Root structures and immature paleosol overprinting, which formed the nodules in Facies Fl and resulted in Facies Fpl, occurs scattered throughout the interval. Thin but laterally continuous beds of Facies Slt occur throughout this association. This coarser grain material commonly rests on Facies Fl with a sharp base to erosional and then fines upward into Fl. Facies Association 2 encloses the coarser ribbon sandstones of Facies Association 4. The contact with the underlying Facies Association 1 (palustrine/lacustrine limestone) is abrupt, whereas the upper contact with Facies Association 3 (Floodplain) is gradational.

*Interpretation:* The predominance of Facies Fl in this association is indicative of deposition from suspension in lakes or ponds. The presence of roots and Facies Fpl points to periodic very shallow water conditions if not complete desiccation. The fossil plants, shells and burrows are all consistent with freshwater conditions, except for the basal sediments near the Pittsburgh Coal that are likely brackish. The sharp base, continuity and coarser grain size of the siltstones indicates they are crevasse splay deposits introduced into the lake system during flood events (Farrell 2001). The absence of mature paleosols is indicative of rapid aggradation and consequently, a high rate of formation of accommodation.
The abrupt basal contact with the Pittsburgh Limestone indicates a rapid shift in depositional regime to siliciclastics either by progradation or by river avulsion (e.g., Ghosh 1977; Weedman 1988; Farrell 2001). Simple progradation is considered unlikely because facies Fbl is absent in Association 2 implying that the rate of formation of accommodation was higher than in Facies Association 1. River avulsion is an autocyclic phenomenon that occurs when a channel or channel belt becomes elevated relative to an adjacent portion of the floodplain (Slingerland and Smith 1998). River flow is diverted through a levee crevasse because of the local increase in gradient.

5.4 Facies Association 3: Floodplain

*Description:* Facies Association 3 brackets and interfingers with the upper limestones of Facies Association 1 and contains primarily the fine-grained sediments of Facies Fbl, Fi, Fl, Fpl, and Fo. The most conspicuous aspect of Facies Association 3 is the presence of beds of red and mottled red-gray paleosols (Facies Fbl) that are traceable between most of the sections. Gray paleosols are common and laterally extensive. Intraclasts (Facies Fi) are common within beds in section RK09.

*Interpretation:* Facies Association 3 represents floodplain sedimentation. The heavy pedogenic overprint is the primary factor that differentiates Association 3 from Association 2. The vertic paleosols of Facies Fbl suggest a seasonal wet/dry climate, however, the development of the red coloration shows that, on average, Association 3 was deposited in a setting with a lower water table compared to either Associations 1 or 2. The presence of the calcite nodules within the paleosols (Bk Horizon) supports high levels of evaporation (Wright 1999). The occurrence of catenas, represented by the lateral change in paleosol colors generally indicates the presence of some primary depositional slope on the floodplain, such as a distal levee (e.g., Kraus 1999). The higher energy deposits of Facies Fi in section RK09 occur adjacent to lacustrine deposits of
Facies Association 2. These beds are interpreted as a product of valley wall collapse associated with the incision of the sheet sandstone of Facies Association 5 (see below).

The occurrence of Association 3 above lake systems of Association 1 and 2 is interpreted to be the result of a decrease in the rate of formation of accommodation. The decrease in available space to deposit sediment allowed the siliciclastic sediment to aggrade above the regional water table. The interfingering of Association 3 with the upper unit of Association 1 (the Fishpot Limestone) indicates that the carbonate lake system could exist relatively close to a siliciclastic sediment source during times are relatively low rates of formation of accommodation. The absence of limestone clasts within the siliciclastic component argues for in situ precipitation of the carbonate to allow the complete partitioning of the chemical and siliciclastic components.

5.5 Facies Association 4: Ribbon Sandstones

*Description:* Facies Association 4 is composed of fine- to medium-grained sandstones of facies Si, Sm, Sl-r, St, Slt, and Sla in packages that range in thickness from 0.5 m to 6 m. Sandstone ribbons are defined as those with width/thickness values either less than 15 (e.g., Friend 1983) or <30 (Nadon 1994). The margins of most of the sandstones are covered, however, the lack of lateral continuity and sand body orientation relative to paleoflow indicators show that they have a ribbon geometry.

Three classes of ribbon sandstones are present in the study area: thin, intermediate, and thick. Two thin sandstones are present that are < 0.5m thick and only up to a few meters wide with sharp bases overlying Facies Fl. Soft sediment deformation is sometimes present below the sandstone. The sandstones fine upward from fine-grained sandstone to siltstone and typically contain Facies Slr or Sla. The paleoflow direction for the thin ribbon in Section RK07 based on the dip of beds in Facies Sla was north-south (001°/181°; Figure 5.3). One sandstone of
Figure 5.3: Paleocurrent measurements in sections RK01 through RK08.
intermediate thickness (> 0.5 and < 2m in thick) is present in section RK01. The sharp base of the sandstone overlies Facies Slt. Sedimentary structures within the sandstone vary from climbing ripples (Facies Srl) changing upward to Facies Sm and then a fining upward (medium-to fine-grained) portion Facies St, which is most of the sandstone, with paleoflow toward the east-southeast (Figure 5.3).

The largest class of ribbon sandstones in this study varies from 2 to 6m in thickness. There are two or three of these thick sandstones present depending on correlation. The sandstones typically have a sharp base that is often marked by soft sediment deformation, flutes, tool marks, and contain tree trunks. At one exposure between sections RK05 and RK06 the base of the sandstone has convex hyporelief burrows up to 2 cm in diameter that are rounded, mostly massive, but display elongate lenticular convex features in multiple orientations. The thick sandstone in section RK06 is bordered to the east by Facies Srl that steps up and offlaps to the east before it finally grades into Facies Fl over a distance of 1-2 meters.

The sediments fine upward from Facies Si at the base to Facies Sm, St and, at the top, Facies Srl. Paleocurrent data from Facies St at the base the sandstone in sections RK04 and RK06 show toward the southwest that is consistent with the dip of Facies Srl in sections RK04 and RK05 and the tool marks at the base of section RK06. However, tool marks and flutes at the base of RK05 and a few decimeters above the base in RK06 show a northwest-southeast transport direction. Data from the top of Facies St in section RK06, which show the flow was toward the NW-SE (Figure 5.3), is the same as that of the climbing ripples in the upper part of sections RK04 and RK05.

*Interpretation:* The sharp to erosive base and fining-upward of the sandstones is consistent with deposition within fluvial channels of various scales that are encased in lacustrine-prone deposits.
of Facies Association 2. There is minimal erosion at the base of most of the sandstones and perhaps none in the case of the sandstone with the traces preserved at the base. The offlapping of the Slr facies in section RK06 is interpreted as a levee that prograded into a shallow lake or pond. This levee deposit is similar in appearance to the wings reported from other ribbon sandstones (e.g., Stear 1983; Nadon 1994). Although this is the only exposed margin of this type of sandstone, the lack of lateral continuity, the range in sandstone thickness, and the absence of lateral accretion deposits indicates that these channels were not part of a meandering river system. The presence of the levees and contemporaneous lacustrine deposits eliminates a braided fluvial origin.

The various aspects of both the ribbons and the enclosing Facies Association 2 siliciclastic lake deposits containing thin, crevasse splay siltstones and sandstones are consistent with deposition by an anastomosed river. The preservation of a levee forms the wings on the margins of the ribbon sandstones (Nadon 1994). The three sizes of sandstone bodies in an anastomosed fluvial deposit represent distal (thin) and proximal (intermediate) splay channels fed by a main (thick) channel. These are equivalent to the small-scale, flood-basin channels, the crevasse channel, and the trunk channel of Farrell (2001). The limited to absent incision at the base of the channels is similar to the description from the anastomosed deposits within the St. Mary River Formation in Alberta (Nadon 1994).

Anastomosed rivers are very low-gradient, suspended load systems that typically form in climates with a strong seasonality in rainfall (Nadon 1994). Floods quickly overtop the levees and create what is essentially a large, slow moving lake during the rainy season. During the dry season the interchannel areas are dotted with small ponds (Smith and Smith 1980). Only regions where the rivers are strongly aggradational, experience rapid rates of formation of accommodation, contain anastomosed fluvial deposits. The facies that comprise an anastomosed
system are virtually identical to those of a river-dominated delta (Nadon 1994). The juxtaposition of Association 2 with Association 1 below is interpreted to reflect a decrease in rate of formation of accommodation that allowed the progradation of the low-gradient fluvial system into the basin. The presence of Association 3 above Association 4 is consistent with a continual reduction in rate of accommodation.

5.6 Facies Association 5: Thick Sheet Sandstone

*Description* The 12-m thick sandstone recorded in section RK09 has an erosional base and fines upward slightly. More than a meter of relief occurs along the basal contact with a poorly exposed suite of lithologies including sandstones (Facies Sla) and mudstones (Facies Fi and Fl) of Facies Association 3. Internally, the sandstone contains a highly varied assemblage of facies with Facies Si, Sm, Sp, and S, at the base, Facies St and Sm in the middle Facies Sla and Sm at the top. Paleocurrent data from Facies Sp rends toward 342° whereas the low-angle, dipping surfaces at the top indicate flow was toward 086° and 278° (Figure 5.4). A conspicuous lens of Facies Fl and Fi occurs within the sandstone that is several meters in height and width. The intraclasts within this sandstone contain the most varied assemblage of lithologies in the study (see section 4.14). The width of the sandstone is not known precisely. The western margin occurs within the dry creek between sections RK08 and RK09. The eastern margin is not exposed, however, sandstone of similar thickness, grain size, and stratigraphic position is present in highway exposures 2 km farther east. The sheet designation for the thick sandstone in RK09 assumes the two exposures contain the same lithosome.

*Interpretation:* The coarse grain size in an overall fining upward grain size trend indicates deposition in a fluvial channel. The limited amount of coarsening upward and the presence of a wide range of sedimentary structures with divergent paleoflow directions are consistent with deposition by a braided fluvial system. This interpretation provides a reasonable explanation of
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Figure 5.4: Paleocurrent data for RK09 generated using Rosietm: a) surfaces of Facies Sp, b) left dipping Sla surfaces, c) right dipping Sla surfaces.
the small lens of Facies Sm within the sandstone as a hollow formed where two braid channels converged (Miall, 1996). The presence of Facies Association 1 deposits west of the sandstone presents an apparently contradictory facies juxtaposition that can be resolved if the braided fluvial system was incised (e.g., deep perennial sand-bed braided river model of Miall 1996; Edwards 2001). Cormany (2001) and Flemming (2003) found similar deposits in Athens County in the Conemaugh and Allegheny Groups. Incision of the braided system explains several features within this exposure. First, incision would isolate the coarse-grained sandstones from Associations 1, 2, 3, and 4 present at the same stratigraphic horizons farther west. Second, bank collapse associated with incision explains the presence of the diverse assemblage of intraclast lithologies within the sandstone. Finally, incision can explain the presence of the Facies Association 3 lithologies directly below the sandstone. The incision of the river was initiated by a drop in base level, whereas deposition occurred during base level rise. The presence of a terrace within the valley during base level rise provided the local accommodation necessary to deposit and preserve the floodplain facies.

5.7 Facies Association 6: Interfluve

*Description:* The sediments at the base of section RK02 are exposed continuously along the western outcrop belt as a complex assemblage of variegated red, gray, green, and mudstones and sandstones. These Pittsburgh Redbeds are a laterally extensive unit composed of semi-flint clays and sandstones (Sturgeon 1958). These sediments are clearly different from the facies present above the base of the Pittsburgh Limestone. The sediments at the base of section RK02 include multiple beds of Facies Fbl that are both red and gray with the best developed large fractures. Thin carbonates and zones of carbonate nodules are also present.

*Interpretation:* The dominant characteristic within the Pittsburgh Redbeds is the heavy pedogenic overprinting of all the lithologies. The thick and laterally extensive nature of this unit suggest it
formed as an interfluve in response to incision of fluvial systems during a regional drop in base level. Such interfluves are known to be complex with both aggradation and erosion occurring in very small, local drainages, and all deposits heavily overprinted by pedogenesis (Gibling 2006).

5.8: Fluvial Architecture

The vertical and lateral variations in the six facies associations point to a systematic variation in the rate and total amount of accommodation formed from the onset of deposition at the base of the Pittsburgh Limestone to the sediments that cap the Fishpot Limestone. Different combinations of the facies associations combine to form the three main fluvial styles (Figure 5.5). There is no evidence in the study area that allows a definitive interpretation of the fluvial styles associated with the interfluve (6) and the palustrine (1) deposits.

The braided fluvial deposit of style 1 consists primarily of Facies Association 5 (Miall 1996). Facies Association 3 below the channel sandstones in section RK09 is included in this style because the high energy intraclast facies at this location are inconsistent with the laterally adjacent lacustrine deposits. The meandering fluvial style is interpreted to be present as Facies Association 3 bracketing the Fishpot Limestone. Although there are no channel sandstones present the paleosols within the floodplain deposits are indicative of a mixed load fluvial system that underwent moderate aggradation (Kraus 1999). The anastomosed fluvial deposits are composed of Facies Associations 2 and 4. The juxtaposition of the lacustrine fines and ribbon sandstones in both suites of facies is a result of rapid aggradation (Smith and Smith 1980).

A rise in base level produced by a combination of accelerated subsidence and a glacial-eustatic transgression led to the deposition of the basal palustrine beds of Facies Association 1 (Pittsburgh Limestone) on top of an interfluve (Facies Association 6). The decrease in amount of limestone up-section that accompanies the increase in lateral continuity of the beds may indicate a
Figure 5.5: Fluvial architecture of the study interval. The presence of the meandering style is inferred from the presence of slowly aggrading floodplain deposits.
climate shift or the increased proximity of a fluvial system. The maximum rate of formation of accommodation occurred during, or soon after, deposition of the Pittsburgh Coal based on the presence of the brackish water fauna.

Siliciclastic sediments inundated the area after deposition of the Pittsburgh Coal. The anastomosed fluvial style requires a relatively rapid increase in accommodation. However, the rate of increase was decelerating based on the renewed formation of paleosols of meandering fluvial style directly above. The recurrence of palustrine limestones (Fishpot) bracketed by meandering fluvial deposits at the top of the section indicates a less dramatic increase in base level than was present at the base of the section. This base level rise can be explained by the continual decrease in subsidence rate accompanied by another glacial-eustatic transgressive pulse. The braided fluvial sandstone in section RK09 is an anomalously high-energy deposit within the study area. The drop in base level necessary to produce the incision interpreted for this deposit requires either tectonic uplift of the area or a significant glacial-eustatic sea level drop.

The conventional facies analysis of the study interval illustrates the existence of variations in magnitude and type of external driver for the rate of formation of accommodation through time. An alternative means of evaluating the allocyclic controls on deposition is to use sequence stratigraphy (Van Wagoner et al. 1990). Although most generally applied to shallow marine deposits, this methodology has been applied with success to continental deposits in regions influenced by eustatic base level changes.
6.1 Introduction

Sequence stratigraphy is a method of interpreting a stratigraphic section in terms of chronostratigraphy rather than lithostratigraphy. The primary advantage of using a chronostratigraphic approach is the ability to correlate sediments of different lithologies and depositional environments. Examination of the lateral distribution of the different facies deposited at approximately the same time leads to the identification of the fundamental controls on sedimentation in a region. The three main controls on deposition are typically considered to be some combination of eustasy, tectonics, and climate that vary depending on factors such as the type of basin, proximity to marine influence, and paleolatitude. Although this is a powerful tool, there are limitations (outlined below) when applying this technique to terrestrial deposits (Shanley and McCabe 1994).

6.2 Sequence Stratigraphic Concepts

A sequence is defined as “a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities” (Mitchum 1977, in Catuneanu 2002, p. 5). Sequences are subdivided into systems tracts that contain parasequence sets composed of parasequences (Van Wagoner et al. 1990). The key operational concept is that the distribution of sediment within a sequence is controlled by changes in relative sea level. Relative sea level is defined as the amount of accommodation, or space to deposit sediment, produced by the combination of changes in eustatic sea level, tectonic subsidence or uplift, and sediment compaction.
Parasequences are the sedimentary response to the highest frequency changes in sea level in a basin. A parasequence consists of a coarsening upward succession bounded by marine flooding surfaces forming an apparent progressive decrease and then increase in water level (Van Wagoner et al. 1990). These coarsening upward units form by both eustatic relative sea level changes and short-term changes in sedimentation. Parasequences occur in larger scale packages termed parasequence sets that are the sedimentary response to changes in relative sea level. Three types of parasequence set occur: progradational, retrogradational, and aggradational (Van Wagoner 1990). A vertical section through a progradational parasequence set (PPS) contains progressively coarser and thicker parasequences up-section. Each high frequency sea level oscillation results in a package that represents progressively more proximal deposits that form a regressive package. A PPS is formed as the rate of relative sea level is low allowing the sediment flux to fill the accommodation (Van Wagoner et al. 1990). Conversely, a retrogradational parasequence set (RPS) consists of a series of thinning and fining upward units that form a transgressive deposit. A RPS deposit indicates a continuing increase in rate of formation of accommodation that overwhelms the sediment flux. An aggradational parasequence set forms when sediment flux just matches the rate of formation of accommodation forming a vertical stack of identical parasequences.

A systems tract is “a linkage of contemporaneous depositional systems” (Brown and Fischer 1977, in Posamentier et al. 1988, p. 110). There are four commonly used systems tracts defined by their position on a relative sea level curve (Figure 6.1). A rapid increase in formation of accommodation results in deposition of an RPS forming a Transgressive Systems Tract (TST). The overlying sedimentary package, which is composed of a PPS, forms the Highstand Systems Tract (HST). Accommodation is still forming during deposition of the HST but at a decreasing rate. The Maximum Flooding Surface (MFS), represents the maximum transgression, separates the TST and HST. Eventually the rate of formation of accommodation becomes negative. At this
Stage 1  From bottom inflection point to accelerating rising limb
Relative Sea level rising
Increasing accommodation
Relative slow rate of formation of accommodation
results in formation of a progradational parasequence set (regression)
= LOWSTAND SYSTEMS TRACT (LST)

Stage 2  Maximum rates of sea level rise
Rate of formation of accommodation exceeds sedimentation rate
Retrogradational Parasequence Set (Transgression)
TRANSGRESSION SYSTEMS TRACT (TST)

Stage 3  Decreasing rates of relative sea level rise until sea level maximum
Decrease in rate of formation of accommodation and less than sedimentation rate
Progradational Parasequence Set
HIGHSTAND SYSTEMS TRACT (HST)

Stage 4  Drop in relative sea level
Rate of formation of accommodation negative
No space to deposit sediment so the formation of a Forced Regression
 FALLING STAGE SYSTEMS TRACT (FSST)

Figure 6.1: Definition diagram of sequence stratigraphic terminology used in the text (modified from Nadon and Hembree 2007).
point the space available for sedimentation is so limited that the shoreline moves basinward in a series of steps termed a forced regression or a Falling Stage Systems Tract (FSST; Plint and Nummedal 2000). Ultimately, subaerial exposure of the HST and FSST form an unconformity and sequence boundary. Rivers begin to incise in response to base level fall during the FSST. The subsequent increase in accommodation space begins slowly allowing sediment to prograde into the basin for a short time in a progradational parasequence set within the Lowstand System Tract (LST) before transgression forms a TST. In cases where differentiation of the HST and FSST is not possible Catuneanu (2002) advocated using the more generic term Regressive Systems Tract (RST).

6.3 Continental Sequence Stratigraphic Model

Sequence stratigraphy was developed to explain the controls on sedimentation within marine sections and there is still no widespread agreement on what constitutes the equivalents to parasequences and parasequence sets in continental deposits. Posamentier and Vail (1988) suggested using fluvial stacking patterns to define systems tracts in terrestrial settings. Wright and Marriott (1993) incorporated the channel stacking patterns with related pedogenic responses and redefined the systems tracts in terms of fluvial architecture related to accommodation. Wright and Marriott (1993) acknowledged that geomorphic and climatic factors would complicate or modify their sequence model. The purpose of building a model, however, is not to account for local factors presented in a system, but to distill away local variations in order to focus on the primary processes driving the system (Walker 1992).

The model of the fluvial response to a 3rd-order base-level change proposed by Wright and Marriott (1993) was predicated on the formation of what was then termed a Type 1 sequence boundary, which included river incision during a relative sea level fall. The fluvial deposits in the model were partitioned between the LST, TST, and HST. Recognition of the sequence boundary
was based on the high degree of paleosol maturity formed on the interfluve during almost half of a relative sea level cycle. In the current systems tract nomenclature, the sequence boundary is represented by the development of mature, well-drained soil and fluvial incision formed during the FSST and some, or all, of the LST depending on distance from the shoreline.

The elevation in base level produced by the rise in relative sea level results in accommodation that allows fluvial aggradation. The model predicts an upward change in fluvial style within the LST from amalgamated, multistory fluvial sandstones deposited by either braided or meandering systems (Style I, Figure 6.2) at the base to belts of channel sandstones deposited with hydromorphic soils at the top (Style II). If the resulting base level rise did not overtop the interfluve, then a more complex fill may be present within the incised valley.

The increased rates of formation of accommodation during the TST were expected to produce high aggradation rates and deposition of anastomosed ribbon sandstones with a low channel connectivity adjacent to floodplains consisting of thick, weakly developed paleosols (Style III). The model suggests that the slower rates of formation of accommodation within the HST result in meandering fluvial deposits that show an upward increase in both channel connectivity and floodplain soil maturity as the rate of formation of accommodation steadily decreased (Style IV). Ultimately the upper HST deposits would be overprinted by either a composite or very mature paleosol profile formed under the overlying sequence boundary. Wright and Marriott (1993) inferred that the reduction in gradient during the HST could result in a finer grain size within the channel sandstones and shallow lakes on the floodplain.
Figure 6.2: Simple fluvial architecture model for a sequence deposited during a 3rd-order base level fall-rise (modified from Wright and Marriott 1993). LST = Lowstand systems tract; TST = Transgressive systems tract; HST = Highstand systems tract. The different styles of fluvial deposits predicted in this model (I-IV) as the rate of accommodation changes are described in more detail in the text.
6.4 Application of the Wright and Marriott Model

The vertical and lateral distribution of the six facies associations recognized in this area provide the means to evaluate the predictions of the sequence model of Wright and Marriott (1993) and to determine the causes of changes in base level, which was one of the main goals of the study. A total of one complete and three partial sequences are present and described separately below (Figure 6.3).

6.4.1 Sequence 1

Sequence 1 is present in measured sections RK02, RK04, and RK05 as the Facies Association 6 interfluve deposits (Figure 6.3). The abrupt change from a suite of multicolored, stacked paleosols to Facies Association 1 palustrine limestones and low maturity of the gray paleosols defines the sequence boundary. The heavy pedogenic modification of the siltstones, limestones, and sandstones of Facies Association 6 is consistent with a reduction in rate of formation of accommodation associated with the late HST and then long-term exposure as an interfluve adjacent to an incised valley system.

6.4.2 Sequence 2

Sequence 2 extends from the base of the lower Facies Association 1 deposits (Pittsburgh Limestone) to the top of the lower group of beds representing Facies Association 3 beneath the Fishpot Limestone. The gleyed paleosols and palustrine limestones of Facies Association 1 indicate increasing accommodation associated with a TST. The presence of the zone of very thin Facies Fi near the top of the Pittsburgh Limestone may indicate the presence of higher order sequences within the section (see Discussion below). The faunal content within the limestones and mudstones directly below the Pittsburgh Coal may indicate a marine influence and the MFS is placed within the brackish water deposits above the coal. This placement of the MFS is
Figure 6.3: The five sequences present in the study interval in relation to the fluvial architecture. The base of sequence 4 is placed at the top of the prograding siliciclastics within the Fishpot Limestone. Sequence 5 is composed primarily of the incised braided fluvial sandstone, however, the sequence boundary is placed at the base of the intraclast sediments that are occur lateral to lacustrine deposits within the anastomosed fluvial style. The MFS of sequence 2 lies directly above the Pittsburgh Coal whereas those of sequence 3 and 4 occur within palustrine limestones. The palustrine limestones occur primarily within the TST. The anastomosed fluvial style forms the bulk of the HST of sequence 2. The meandering style was deposited during the late HST.
consistent with the location of the zone of maximum marine influence within cyclothems of the underlying Conemaugh Group, which there are represented by marine limestones (e.g., Nadon and Kelley 2004).

The location of the MFS and the shift to siliciclastic claystone deposits at the base of Facies Association 3 above the coal indicate the onset of base level fall and deposition of the HST. Although the deposition of the poorly drained floodplain of Facies Association 2 and the anastomosed fluvial deposits of Facies Association 4 both indicate rapid aggradation, the progradation of the siliciclastic-dominated system over Facies Association 1 deposits indicates an overall reduction in rate of formation of accommodation (Figure 6.4). The overall decrease in rate of formation in accommodation resulted in the more mature paleosols of Facies Association 3 at the top of sequence 2.

Variations in grain size and organic content within the siliciclastic units provide data that allow the subdivision of the HST (Figure 6.4). The widespread mudstone unit in the middle of the unit associated with an organic-rich horizon and a transition in type of burrowing, nodule, and sedimentary structures is interpreted as evidence of a flooding surface and possibly a higher order MFS surface (Horizon A). The absence of horizon A within the channels is not unexpected. A local rise in base level would temporary decrease channel energy but as soon as base level fell the channels would scour any thin mud deposit left by the transgression. A second minor transgressive surface at the top of the siliciclastic unit (Horizon B) is marked by a return of Facies Fo.

6.4.3 Sequence 3

The base of sequence 3 is located at the base of the Fishpot Limestone. This sequence boundary marks the start of an interval that lacks any significant amount of siltstones. The
Figure 6.4: Relative grain size, organic content, bioturbation, and biotite content within the siliciclastic units above the Pittsburgh Coal excluding section RK09. Horizon A is a flooding surface of a 5th-order sequence. Horizon B marks the end of coarse siliciclastics below the Fishpot Limestone. Horizon C at the base of the Fishpot Limestone is a flooding surface and sequence boundary capping sequence 2. Horizon D marks the top of the siliciclastic interval within the HST of sequence 3.
presence of the overlying palustrine limestones indicates the region was isolated from a siliciclastic source and the simplest explanation for this is a base level rise. The absence of Facies Association 6 below sequence 3 means that there was no significant incision accompanying the relative sea level fall that terminated sequence 2. Facies Association 1 limestones are interbedded with more mature paleosol horizons and contain more evidence of exposures (Facies Lr) than the limestones near the base of sequence 1. This difference in paleosol maturity is a result of a lower rate of formation of accommodation within sequence 3. The continuous basal oolitic limestones are interbedded with Facies Fl near the base of the sequence marks the MFS. The overlying HST is capped by the siltstone interval that can be traced across the study area (Figure 6.4, Horizon D). The upper boundary of sequence 3 occurs directly below the limestones at the top of sections RK01 and RK03.

6.4.4. Sequence 4

Only the basal portion of sequence 4 occurs within the study interval. The two limestone beds mark the TST of sequence 4. Although neither bed can be traced across the study area and both are rudstones, they are also nodular and contain slickensides that make them appear more similar to the beds of the Pittsburgh Limestone than the Fishpot. In addition, the rhizoliths within these two beds are smaller and less numerous than within the Fishpot Limestone below. The MFS horizon occurs above the thin Facies Fo capped by a claystone. This claystone marks the only measured portion of the HST within sequence 4.

6.4.5. Sequence 5

Sequence 5, which is not completely exposed, is composed of Facies Associations 3 and 5 and present only within section RK09. The braided fluvial sandstones of Facies Association 5 represent deposition within an incised valley of undetermined lateral and vertical extent, and the basal sequence boundary is not coincident with the base of the sandstone. Although Facies Fl is
present directly below the sandstones it overlies Facies Si and Fi of Facies Association 3, which imply high energy depositional events inconsistent with lacustrine deposition. These two intraclast facies are also at the same stratigraphic location as Facies Fl on the western side of the modern erosional gully that formed at the margin of the thick sandstones only 50 m to the west. These intraclast beds are interpreted to be the result of bank collapse of the valley wall now marked by the gully. The laminated mudstones directly below the Facies Association 5 sandstones indicate quiet water deposition on a pond or lake that formed adjacent to the braided systems during base level rise. The sandstones of Facies Association 5 are placed within the TST based on overall stratigraphic location (see Discussion below).

The assignment of the sandstones of Facies Association 5 to the LST or TST is largely a matter of timing that cannot be resolved completely with the data from this study. Technically, the LST is deposited only until the rate of formation of accommodation increases to the point where a retrogradational parasequence set develops (Figure 6.1). This scenario places the base of valley fill within the TST with the exception of the palimpsest LST deposits.

6.5 Discussion

The pattern of systems tracts and sequences within the study interval is one of a rapid increase in total accommodation (sequence 2) followed by progressively less accumulation (sequences 3 and 4). Evidence of significant incision of fluvial systems occurs only at the base of sequence 2 and sequence 5 (Figure 6.5). The best explanation of this pattern lies in a combination of tectonic subsidence and glacial-eustasy controlling relative sea level.

Sections from the Mid-continent of the U.S. show that the trend of the 3rd-order relative sea curve during deposition of the basal Monongahela Group was negative (Figure 2.7). If the 3rd-order eustatic curve were the only control on fluvial style (e.g., Wright and Marriott 1993),
Figure 6.5: Generalized stratigraphic column of the study area with interpretation of relative sea level and the basic interpretation of tectonic and eustatic controls on deposition. A total of 5, 4th-order sequences are represented in the interval of study. Sequence 2 is further subdivided into two 5th-order changes in relative sea level.
then the deposits in the study area would be primarily interfluve facies. The presence of brackish water deposits at the top of the Pittsburgh Limestone indicates that the 4th-order, glacial-eustatic, relative sea level curve played an important role in determining the facies stacking patterns in the study area. The overall base level fall associated with the 3rd-order relative sea level curve explains the variations in the thickness and extent between the Pittsburgh and Fishpot Limestones. The formation of the Facies Association 6 interfluve and the Facies Association 5 incised valley fill also indicate a significant drop in relative sea level consistent with a eustatic fall (Figure 6.5). However, a eustatic driver alone cannot explain the variation in sequence thickness or the pattern of higher order transgressions within the HST of sequence 2.

Tectonic subsidence occurred throughout deposition of the study interval otherwise no section would be preserved. The subsidence was likely low amplitude and widely distributed based on the location of study area outboard of the moat formed by thrust loading in the Appalachian Mountains during this time interval and the lateral extent of the Pittsburgh Limestone (Figure 2.1). An increase in the rate of tectonic subsidence just prior to and during the deposition of sequence 2 explains the differences in limestone thickness and facies compared to sequence 3 (Figure 6.5).

The presence of Facies Association 1 within the TST of sequence 2 and the HST of sequence 3 suggests that the latter formed by eustatic accommodation not augmented by accelerated tectonic subsidence. The anastomosed fluvial deposits within the HST of sequence 2 are consistent with a rapid development of accommodation that could be explained by eustasy alone. However, figures depicting the retrogradational parasequence set of an HST commonly show a progressive increase in thickness and amount of coarse siliciclastics up section (Figure 6.1) whereas the thickness and grain size decrease with height in sequence 2. These anomalies are functions of the formation of accommodation by tectonic subsidence and geographic location.
The rapid decrease in formation of total accommodation as subsidence rate decreased provided less space for the sediment to fill. The geographic location of the facies compared with a typical shallow marine setting is significant because the fluvial system within the area requires a finite amount space in which to deposit sediments. Too little accommodation results in diversion of the fluvial channels elsewhere and aggradation of fine-grained floodplain deposits. The high frequency 5th-order sequences within sequence 2 have not previously been reported from the terrestrial deposits but have been recognized recently from marine sections (Algeo et al. 2004; Huffer et al. 2007).

The subdivision of the sections into sequences is consistent with the variations in fluvial architecture of the study area. The top of sequence 1 is a surface of regional exposure that should be laterally adjacent to an incised valley. Sequences 2, 3, and 4 contain palustrine limestones within the TST. Highstand deposits are composed of both anastomosed and meandering fluvial styles, however, the former was a function of the increased rate of tectonic subsidence within sequence 2.

The sequence stratigraphic fluvial architecture of the study interval is broadly similar to the model of Wright and Marriott (1993). The palustrine deposits are equivalent to hydromorphic soils of the model (Figure 6.6; Table 6.1). Braided fluvial and meandering fluvial deposits occur in the same position within both models, although there is no meandering river deposit in the TST. Differences between this study and the published model include 1) the scale of relative sea level change, 2) the presence of anastomosed fluvial deposits within the HST rather than the TST, and 3) the occurrence of palustrine deposits in both TST and HST deposits. These anomalies are explained by differences in the controls on the rate and amount of formation of accommodation produced by some combination of glacial-eustatic sea level change and tectonic subsidence, which were the primary controls on formation and preservation facies architecture. The
Figure 6.6: Modified model of Wright and Marriott (1993) to explain 4th-order changes in relative sea level. LST=Lowstand systems tract; TST= Transgressive systems tract; HST= Highstand Systems Tract; FSST= Falling stage systems tract.

* represented by the sequence boundary surface.

Table 6.1: A comparison of the facies associations and systems tracts found in this study to the model proposed by Wright and Marriott (1993).
possibility that local, penecontemporaneous folding affected the rate of accommodation (e.g., McNamara 2006) cannot be ruled out, but the study was too limited in area to evaluate this hypothesis.

The rate of change of the 4th-order sea level fluctuations, which is an order of magnitude greater than in the original Wright and Marriott model, coupled with tectonic subsidence can explain all the distribution of the facies associations, systems tracts, and sequence boundaries. The incised valleys and associated interfluves (Facies Association 6) formed when the rate of eustatic sea level fall exceeded subsidence rates. The brackish water fauna within sequence 2 formed when tectonic subsidence was augmented by a eustatic sea level rise. Continued tectonic subsidence coupled with a decrease in eustatic sea level rise produced the accommodation necessary for the formation anastomosed fluvial deposits of Facies Association 4 during the early HST. The position of the MFS of sequence 3 within Association 1 was a result of a combination of a lower amplitude glacial-eustatic rise and a decrease in subsidence.

Ethridge et al. (1998) argued that systems tracts are only appropriate if a valley-fill succession formed within zones of sea level influence and when the key surfaces can be correlated basinward. Although erosion prevents tracing the surfaces into correlative marine units, the correspondence of the fluvial architecture with the model of Wright and Marriott (1993) shows that the study area was close enough to the marine realm for the systems tracts concepts to be applied. This study shows that application of the Wright and Marriott model is valid for the basal Monongahela Group and can be extended to facies patterns produced by 4th-order changes in relative sea level.
Chapter 7
Conclusions

The data collected in this study were sufficient to evaluate the five hypotheses proposed in Chapter 1. The first hypothesis concerned the fluvial styles of the siliciclastic portion of the section. The detailed facies descriptions and facies associations determined from the nine measured sections confirmed the speculations of fluvial style reported by Nadon et al. (1998) and the preliminary work of Edwards (2001).

Comparison of the vertical and lateral changes in fluvial styles and palustrine limestones within the study area suggests that the current anastomosing/carbonate lake models (hypothesis 2) are not the simplest explanation for the juxtaposition of the different facies associations. Instead, variations in accommodation related to relative sea level change explain the local architecture. The model constructed for 4th-order relative sea level change in this study area has similarities to and differences from the 3rd-order model for continental sequence stratigraphy (hypothesis 3) proposed by Wright and Marriott (1993). The fluvial architecture was broadly similar with the addition of the palustrine limestones in the TST. The presence of the anastomosed fluvial style in the HST is a significant difference attributable to changes in the rate of formation of accommodation by tectonic subsidence on a 4th-order scale.

The change in fluvial style within the measured sections is consistent with the change in base level generated by glacial-eustatic sea level changes (hypothesis 4). The rapid rise in base level that lead to the deposition of the palustrine limestones in particular, is typical of glacial-eustatic transgression and associated climate shifts (e.g., Rankey 1997). The thickness of the Pittsburgh Limestone and overlying anastomosed fluvial deposits partially confirm hypothesis 5.
Tectonic subsidence, which generated rapid accommodation, was the greatest influence on fluvial architecture at the base of the study interval.
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Appendix A

Measured Sections
GRAIN SIZE

N = 1
Vector Mean = 302.0

N = 1
Vector Mean = 350.0

N = 6
Vector Mean = 249.7

N = 1
Vector Mean = 148.0

RK05

RK05

130
GRAIN SIZE

N = 1
Vector Mean = 10.0

N = 2
Vector Mean = 118.5

N = 5
Vector Mean = 218.4

N = 2
Vector Mean = 316.0
N = 3
Vector Mean = 74.3

N = 2
Vector Mean = 62.5

N = 2
Vector Mean = 7.0

N = 2
Vector Mean = 84.0

N = 2
Vector Mean = 344.0

N = 1
Vector Mean = 62.0

N = 1
Vector Mean = 63.0

N = 1
Vector Mean = 271.0

N = 1
Vector Mean = 146.0

N = 10
Vector Mean = 309.6