FLUVIAL-DELTAIC DEPOSITION IN HIGH ACCOMMODATION FLOODPLAIN LAKES, PENNSYLVANIAN APPALACHIAN BASIN, EASTERN KENTUCKY

by

Shea Atkins

Bachelor of Science, 2012

Middle Tennessee State University

Murfreesboro, Tennessee

Submitted to the Graduate Faculty of the

College of Science and Engineering

Texas Christian University

in partial fulfillment of the requirements for the

Degree of Master of Science in Geology

May 2016

Acknowledgements

I would like to thank Dr. John Holbrook for the opportunity to complete my graduate studies under his guidance. I would also like to thank Dr. Clay Harris who played a strategic role in developing my interest in geology at the undergraduate level, encouraged me to attend graduate school, and laid the frame work for pursuing my career in oil and gas. Also, Tom Duncan and Finley Resources Inc. for giving me the opportunity to be part of an outstanding company, mentoring me into a functioning petroleum geologist, and leading by example while showing support and encouragement as I continued working through my education. For this, I will always be indebted. Finally I would like to thank my loving wife Julie for everything she has done to help me through this while showing unwavering trust in my abilities. I could not have done it without you darlin.

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CHAPTER 1

Introduction

The objective of this investigation is to provide a detailed architectural analysis of high accommodation fluvial deposits as well as an understanding of the depositional relationship and geometry of thin flood basin sand units. Special emphasis is here given to definition and delineation of units consistent with deposits of modern tie channels and assessment of their role in connecting other sandstone units as potential fluid migration pathways.

The limited body of work on tie channels primarily focuses on modern systems without recognizing them in the rock record. The worldwide occurrence of modern tie channels, as noted by Rowland (2007), suggests the possibility of similarly common occurrences of tie channels in the ancient. When developed in high accommodation floodplain environments, deposits from these channels may provide a link for petroleum migration from floodplain source rock to higher quality reservoir rock deposited in belts of major river channels. This would be important for reservoir modeling in the oil and gas industry as tie channel deposits may not only be fluid conduits but may also mean floodplain lakes may not model well as a continuous seal (Stoner & Holbrook, 2008). Tie channels also tend to be associated with thin overbank sand sheets that may provide additional reservoir sand and reservoir connectors within otherwise muddy floodbasin strata (Tomanka, 2013). Delineation of tie channel sand body geometries and their relationship to subaqueous sheet sands in a high accommodation fluvial environment could provide insight to their potential as reservoirs and as connecters, and potentially yielding a significant increase in gross petroleum reservoir volume.

Tie Channels

Linear fluvial-deltaic channels, similar to what are commonly referred to as tie channels, occur in modern, high accommodation fluvial settings around the world. The term "tie channel" was first applied on the Fly River in Papua New Guinea by Blake and Ollier (1971) to channels with bi-directional flow that typically connect a river with a shallow water-filled basin such as an oxbow lake or other floodplain lake. Sixty-five percent of floodplain lakes along the Middle Fly River receive water and sediment through tie channels and a similar percentage of lakes along the Lower Mississippi possessed tie channels prior to levee construction and other river modifications that hydrodynamically separated the river from the floodplain (Rowland, et al., 2005).

Work after Blake and Ollier (1971) focused on examples found near Birch Creek, Alaska, on the Raccourci Old Oxbow Lake, Louisiana (Rowland et al., 2006) and in the Grijalva and Usumacinta River Basins, Tabasco State, Mexico (Hull and Holbrook, 2013). Tie channels occur in lowland floodplains as a unique type of channel connecting mainstream rivers to floodplain lakes or other bodies of water (Rowland, 2007). They generally exhibit bi-directional flow relative to the main channel that allows them to fill floodplain lakes with raises in stage level or drain lakes when stage level falls (Rowland, 2007). Other forms of floodplain channels such as side and back channels as well as sloughs (Mertes et al., 1996; Dunne et al., 1998), generally occupy abandoned sections of the main river channel (Mertes et al., 1996; Bridge, 2003).

Tie channels form in standing water through deposition along the margins of a sediment-laden jet as it enters open water (Figure 1.1.) and develop in conjunction with the formation of off-river water bodies such as oxbow lakes (Rowland, 2007). Tollmien (1926) first established Jet Theory as a process of sediment delivery. Jet Theory describes the transfer of energy of a radially symmetric turbulent jet of fluid from a source point as it enters a still body of fluid (Bates, 1953). This theory was expanded to include factors such

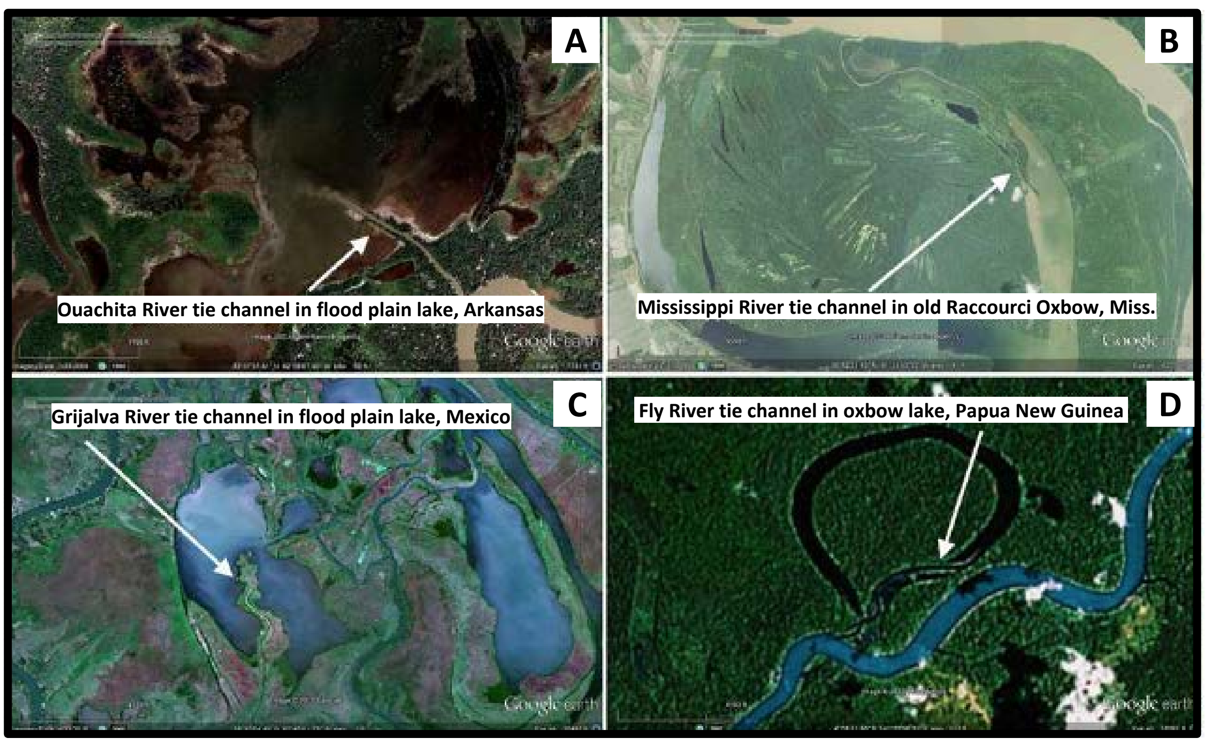

Figure 1.1. Four images of naturally occurring tie channels (A-D), Frames A, B, C, and D are images of tie channels off the Ouachita River, Mississippi River, Grijalva River, and the Fly River respectively. Images A and C show tie channels building into floodplain lakes; images B and D show tie channels building into oxbow lakes. Satellite images sources: Upper left: Google Earth™, USDA Farm Service Agency. Upper right: Google Earth™, USDA Farm Service Agency. Bottom right: Google Earth™, © 2013 TerraMetrics. Bottom right: Google Earth™, © 2013 GeoEye.

as, 1) hydraulic head where the jet enters the basin, 2) hypopycnal flow (inflow less dense than basin fluid), 3) hyperpycnal flow (inflow more dense than basin fluid), and 4) homopycnal flow (inflow and basin with equal densities), and the resulting depositional geometries that each flow type exhibits (Bates, 1953). This resulted in three fundamental geometric delta models predicting levee growth, bar mouth growth, and distributary bifurcation (Wright, 1977). Only one of Wright's models, the buoyant effluent model, addressed long non-bifurcating linear channel deltas; however, this model applied to fresh water entering a saltwater basin where the hypopycnal jet is supported by a density contrast between the lower-density jet and the higher-density basin fluids (Figure 1.2.). Falcini and Jerolmack (2010) since document that elongate non-bifurcating channels also occur in freshwater lakes where hypopycnal flow does not exist.

Tie channels propagate across floodplain lakes as deltas (Tomanka 2013; Hull and Holbrook, 2013; Huling, 2014). As suspended sediments move along the length of the tie channel, the coarse fraction of sediment load progressively settles out along the margins of the channel into newly forming subaqueous levees at the channel outlet. The finer fraction of suspended sediment settles to form a clay rich pro-delta deposit and/or blankets the subaqueous channel levees. Inter-bedding of mud with layers of coarser sediment in the levees and establishment of vegetation strengthens the levees and contributes to the narrow width of the prograding channel. This causes the channel to rapidly prograde basin-ward, with low sinuosity and without bifurcating, forming a V-shaped geometry as it erodes into the cohesive clay rich pro-delta (Rowland, 2007).

Tie channels also play a significant role in the filling of floodplain lakes (Rowland et al., 2005; Hull and Holbrook, 2013). Once the tie channel reaches the other side, the lake is then bisected by the narrow levees emplaced by the process of channel propagation, creating two smaller lakes (Rowland, 2007). Bisection of the lake by the tie channel creates a barrier for sediment transport resulting in asymmetrical deposition of splay deposits from the main river channel (Hull and Holbrook, 2013). Asymmetry in sediment input leads to filling of the floodplain lake as compartments rather than overall aggradation as a whole (Hull and Holbrook, 2013). As one compartment is filled and becomes a vegetated glade or marshy area (Rowland, 2007) (Hull and Holbrook, 2013) this permits the opportunity for overland bypass of sediment into the remaining compartment (Hull and Holbrook, 2013).

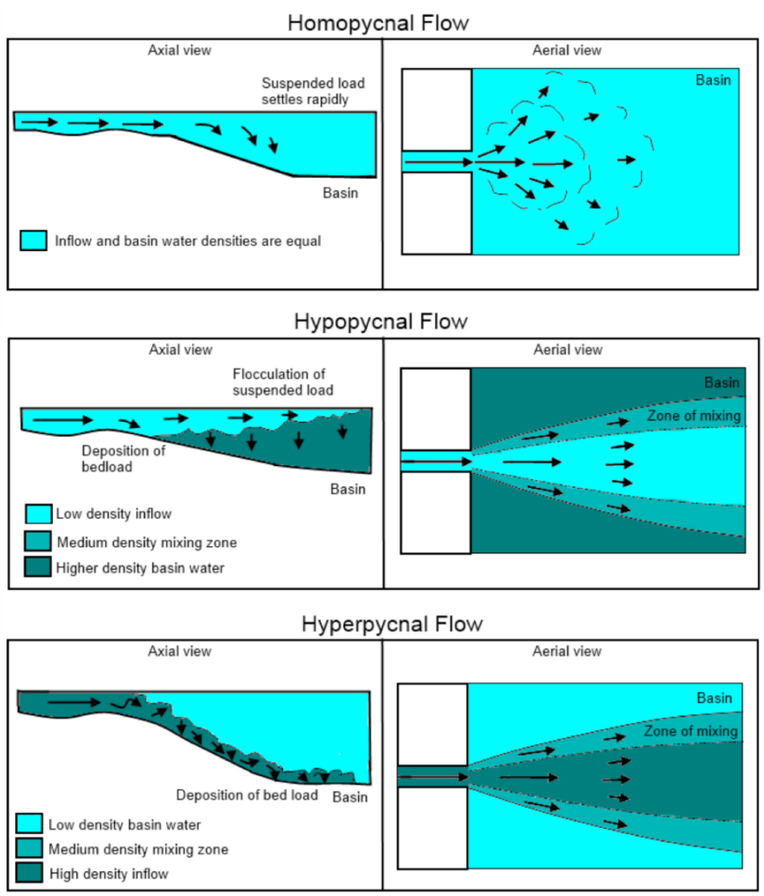

Figure 1.2. Diagramatic flows and spreading patterns based on relative fluid densities for homopycnal, hypopycnal, and hyperpycnal flows (Modified from Bates 1953 and Boggs 1995).

Fluvial Sequence Stratigraphy

Traditional system tract nomenclature for sequence stratigraphy is dependent on marine base level and reconstruction of depositional shoreline shifts (reviewed in Catuneanu, 2006). In cases where non-marine surface processes dominate a sedimentary basin or only the non-marine sediments are preserved, usage of traditional systems tract nomenclature is inappropriate (Catuneanu, 2006). High and low accommodation systems tracts are used as an alternative to marine–based systems tracts in order to extend the concepts of sequence stratigraphy into fluvial settings (Dahle et al., 1997; Martinson et al, 1999; Catuneanu, 2006). These system tracts are defined on the basis of fluvial architectural elements such as the ratio of channel fills to floodplain deposits independent of marine base level (Allen, 1978; Bridge and Leeder, 1979; Legarreta et al., 1993; Shanley and McCabe, 1994; Dahle, et al., 1997; Blakey and Gubitosa, 1984). This in turn allows for inference of the amount of fluvial accommodation (low vs. high) available at the time of deposition without reference to marine base level (Catuneanu, 2006).

The low-accommodation system tract is characterized by a relatively low base level rise compared to rate of deposition and comprises the coarsest sediment fraction of a fluvial depositional sequence (see Catuneanu, 2006). These conditions result in incised valley fill architecture with multi-story channel fills and a relative lack of floodplain deposits (Miall, 1988; Wright and Mariott, 1993; Legarreta and Uliana, 1998; Martinsen et al., 1999; Boyd et al., 1999; Bridge and Tye, 2000). Channel erosion and amalgamation explains the general lack of floodplain facies in low-accommodation systems tracts however, floodplain sediments that do exist are generally well drained and commonly form well developed paleosols (Bown and Kraus, 1987; Kraus, 1996; Aslan and Autin, 1999).

The high-accommodation system tract is characterized by a relatively high water table, lower sedimentation rate and preservation of an overall higher percentage of finer grained overbank deposits (Allen, 1978; Wright and Marriott, 1993; Shanley and McCabe, 1994; Boyd et al., 1999). As base level rises, increasing the rate of creation of fluvial accommodation, the overall depositional style becomes more aggradational resulting in channel fills isolated within floodplain facies that compose a majority of the sediment pile (e.g., Catuneanu, 2006; Stoner and Holbrook, 2008). A high water table results in the formation of floodplain lakes due to the poorly drained floodplain conditions (Aslan and Autin, 1999). Thus, tie channel development, associated with the formation of floodplain lakes between river channels (Blake and Ollier, 1971), should be commonly associated with high-accommodation fluvial system tracts. Table 1.1 outlines the defining features of the low and high-accommodation systems tracts.

Colombera et al., (2015) suggests that identifying low and high-accommodation systems tracts based solely on channel body architecture and stacking density (Leckie and Boyd, 2003; Catuneanu, 2006; Catuneanu et al., 2009) is not justified. They noted that most high-accommodation system tracts do not aggrade fast enough to make high-accommodation deposits and that the high mud preservation reflects phases of short and rapid aggradation within a longer term pattern(Colombera et al., 2015). For the purpose of this study, low- and high-accommodation system tracts are identified by the features in Table 1.1 as a whole without bias to aggradation rate. This distinction includes attention to the ratio of sand to mud deposits, development of coal seams and paleosols, and the abundance of floodplain facies in the vertical succession at each outcrop location. High and low-accommodation are used solely as a mapping convention to delineate deposits preserving significant floodbasin deposits.

System Tract Features	Low-accommodation systems tract	High-accommodation systems tract
Depositional Trend	**Early progradational [1]**	**Aggradational**
Depositional energy	**Early increase, then decline**	**Decline through time**
Grading	**Coarsening-upward at base [1]**	**Fining upward**
Grain Size	**Coarser**	**Finer**
Geometry	**Irregular, discontinuous [2]**	**Tabular or wedge-shaped [3]**
Sand : mud ratio	**High**	**Low [4]**
Reservoir architecture	**Amalgamated channel fills**	**Isolated ribbon sandstones [4]**
Floodplain facies	**Sparse**	**Abundant [4]**
Thickness	**Tends to be thinner [5]**	**Tends to be thicker [5]**
Coal seams	**Minor or absent [6]**	**Well developed [7]**
Paleosols	**Well developed [8]**	**Poorly developed [9]**

Table 1.1. Defining features of the low- and high-accommodation system tracts Notes: [1] – the progradational and associated coarsening-upward trend as the base of a fluvial sequence are attributed to the gradual spill over of coarse terrigenous sediment into the basin, on top of finer-grained floodplain or lacustrine facies. Once fluvial sedimentation is re-established across the basin, the rest of the overall profile is fining-upward. The basal coarsening-upward portion of the sequence thickens in a distal direction, and its facies contact with the rest of the sequence is diachronous with the rate of coarse sediment progradation; [2] – this depends on the landscape morphology at the onset of creation of fluvial accommodation, which is a function of the magnitude of fluvial incision processes during the previous stage of negative fluvial accommodation. Irregular and discontinuous geometries form where fluvial deposits prograde and infill an immature landscape; [3] – this depends on the mechanism that generates accommodation, i.e., sea-level rise or differential subsidence, respectively; [4] – this is valid for Phanerozoic successions, where vegetation is well established and helps to confine the fluvial systems. The fluvial systems of the vegetationless Precambrian are dominated by unconfined braided and sheetwash facies, which tend to replace the vegetated overbank deposits of Phanerozoic meandering systems; [5] – this depends on the rates of creation of fluvial accommodation, and the relative duration of systems tracts; [6] – where present, they commonly compound coals; [7] – simpler (fewer hiatuses), more numerous, and thicker; [8] – commonly multiple and compound; [9] – thinner, widely spaced, and organic rich. (modified from Catuneanu, 2003)

Location

Pennsylvanian aged rocks of the Appalachian Basin cover an area from New York to Alabama. This study will focus specifically on the Upper Pennsylvanian Breathitt Group and lower Conemaugh Group (Figure 1.3.) at five outcrop locations along Highway 23 near the town of Louisa, Kentucky (Figure 1.4.A.). Outcrops of the Breathitt Group offer good exposure in Eastern Kentucky and have resulted in a somewhat extensive volume of work owing to the economic significance of local coal production and the utility of the excellent exposures as a natural laboratory for the advanced study of fluvio-deltaic strata. Five outcrop locations shown in figure 1.4.A. are all located in the Adams quadrangle near Louisa, KY. Outcrop 1A, 1B and 1C are located at MP 17.6 on US-23 with an average elevation above sea level at 224 m and contains the bottom section of the Glenshaw Formation. Outcrops 2A and 2B are at MP 16.7 on US-23 with an average elevation above sea level of 208 m with the base of the outcrop containing the upper Princess Formation (Upper Breathitt Group) and the contact between Princess Formation and the Lower Conemaugh Group.

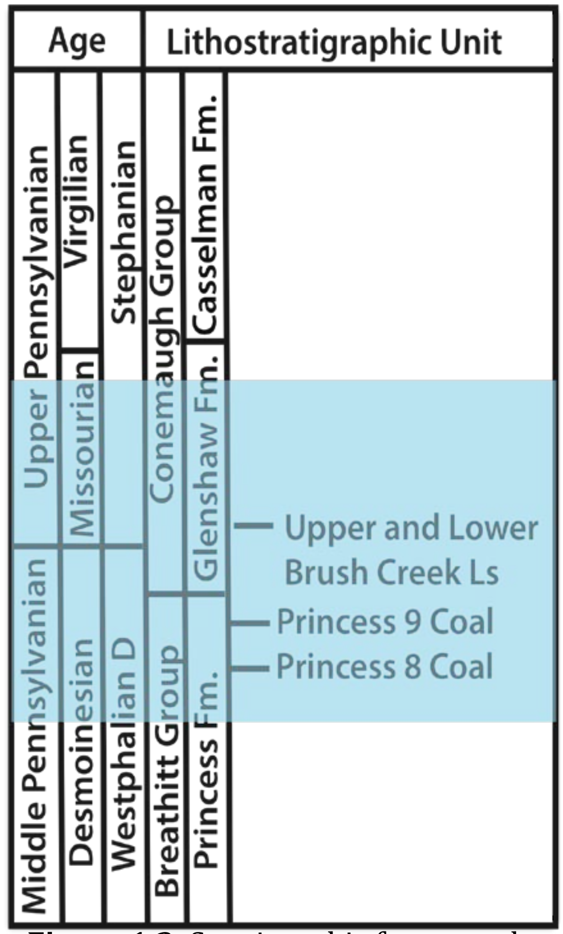

Figure 1.3. Stratigraphic framework for the middle to upper Pennsylvanian aged rocks in Eastern Kentucky and western West Virginia. (modified from Martino, 2004)

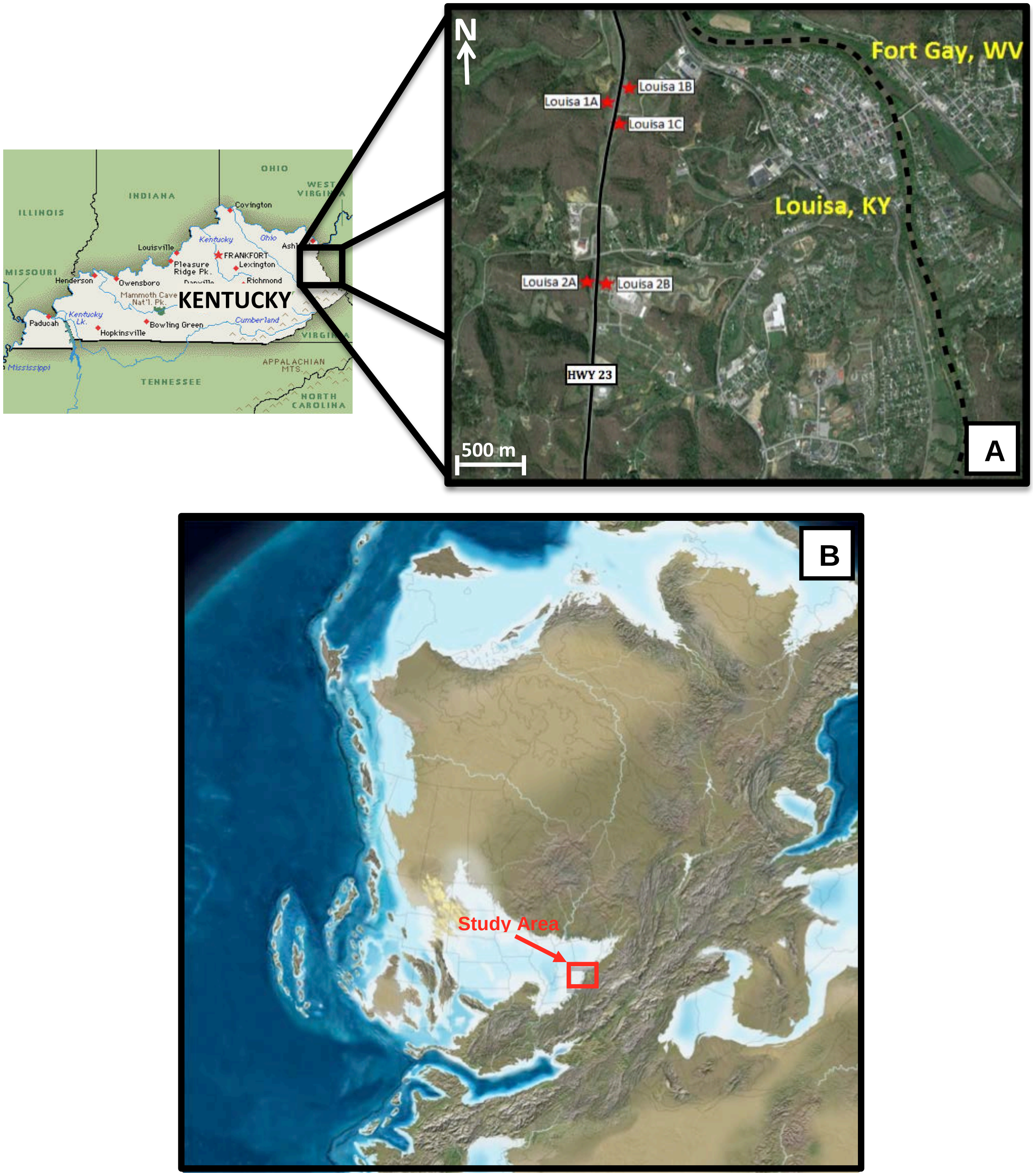

Figure 1.4. A. Outcrop locations along US 23 used in this study. Stratigraphic sections were measured and described at each location along with high resolution panoramic photographs of the entire outcrop. **B.** Pennsylvanian paleogeographic map of North America (Blakey, 2011).

Previous Work on the Breathitt and Conemaugh Groups

The Breathitt Group is a commonly applied analogue for constraining fluvial reservoir compartmentalization and modeling for producing oil and gas fields (e.g., the Cretaceous Hibernia Formation of the Hibernia oil field in offshore Newfoundland [Bidgood, 2003; Sinclair et al., 2005]; the Lower Ness Formation of the Tern Field in the Northern North Sea [Noad, 2004], etc.). Prior studies focus on middle Pennsylvanian Pikeville, Hyden and Four Corners formations of the Breathitt Group in an area interpreted as fluvial dominated, shallow water deltaic successions punctuated by marine shale deposits (Baganz et al., 1975; Ferm, 1970; Ferm and Horne, 1979; Horne et al., 1978; Chestnut, 1991, 1992, 1996; Greb and Chestnut, 1992, 1994, 1996; Greb et al., 2008; Aitken and Flint, 1995). Other works that focus on the Breathitt Group as a fluvial system primarily focus on sequence stratigraphy (Aitken and Flint, 1994, 1995) and fluvial-deltaic architecture (Bangz et al. 1975; Ferm, 1970; Ferm and Horn, 1979; Chestnut, 1991, 1992, 1993). Later authors apply sequence stratigraphic models (e.g. Vail et al., 1977a; Wilgus et al., 1988; Van Wagoner et al., 1990), which are conceptually designed for shallow and marginal marine application, to these predominantly fluvial to paralic successions (e.g., Aitken and Flint, 1995, 1996b). The focus area of these previous studies is primarily the southeastern Kentucky Appalachian Basin, near Pikeville and Hazard Kentucky, in a region proximal to marine influence, while there is comparatively little research on the up-dip fluvial pile which this study will target.

Aitken and Flint (1995, 1996b.) extended their work in primarily coastal strata north along Highway 23 to dominantly terrestrial strata in outcrop at the southern end of this study. Their primary focus was applying sequence stratigraphic concepts to predominately fluvial successions and identifying inter-fluvial sequence boundaries. Laterally extensive marker beds, including marine shales, coals, and paleosols, were identified and used to extend the stratigraphic framework northward toward the field area of this study. Aitkin and Flint (1996b) identified interfluves between valley fills of the Breathitt Group to trace subaerial unconformities and establish their application of sequence boundaries. Gleysols are recognized as the most common type of paleosol, indicating that interfluve deposition is dominated by poorly drained floodplains as is common in high accommodation fluvial settings (Bown and Kraus, 1987; Kraus and Aslan, 1993; Kraus, 1996; Aslan and Autin, 1999).

Martino (2004) presented a sequence stratigraphic framework for the Glenshaw Formation of the lower Conemaugh Group and Princess Formation of the Upper Breathitt Group in the southwest Dunkard Basin along the intersection of Ohio, West Virginia, and Kentucky (Figure 1.5). Well-developed paleosols and marine units were used to identify nine paleosol-bounded allocycles across the field area that correlate to their K-20 outcrop along Highway 23 (Figure 1.5). Martino describes paleosols markers for fifth-order sequence boundaries but, unlike Aitken and Flint (1996b.), they are described as having features indicative of well-drained floodplain conditions. The southern-most outcrop location of Martino (2004), named K-20 (Figure 1.5), is equal to the northern-most outcrop location of this study (Louisa 1A; Figure 1.4.A.). Martino (2004) offered a stratigraphic interpretation at this location but did not elaborate on flood basin architecture or depositional systems. The current study includes outcrops of both the Aitken and Flint (1994, 1995) and Martino (2004) work and bridges with outcrops in between.

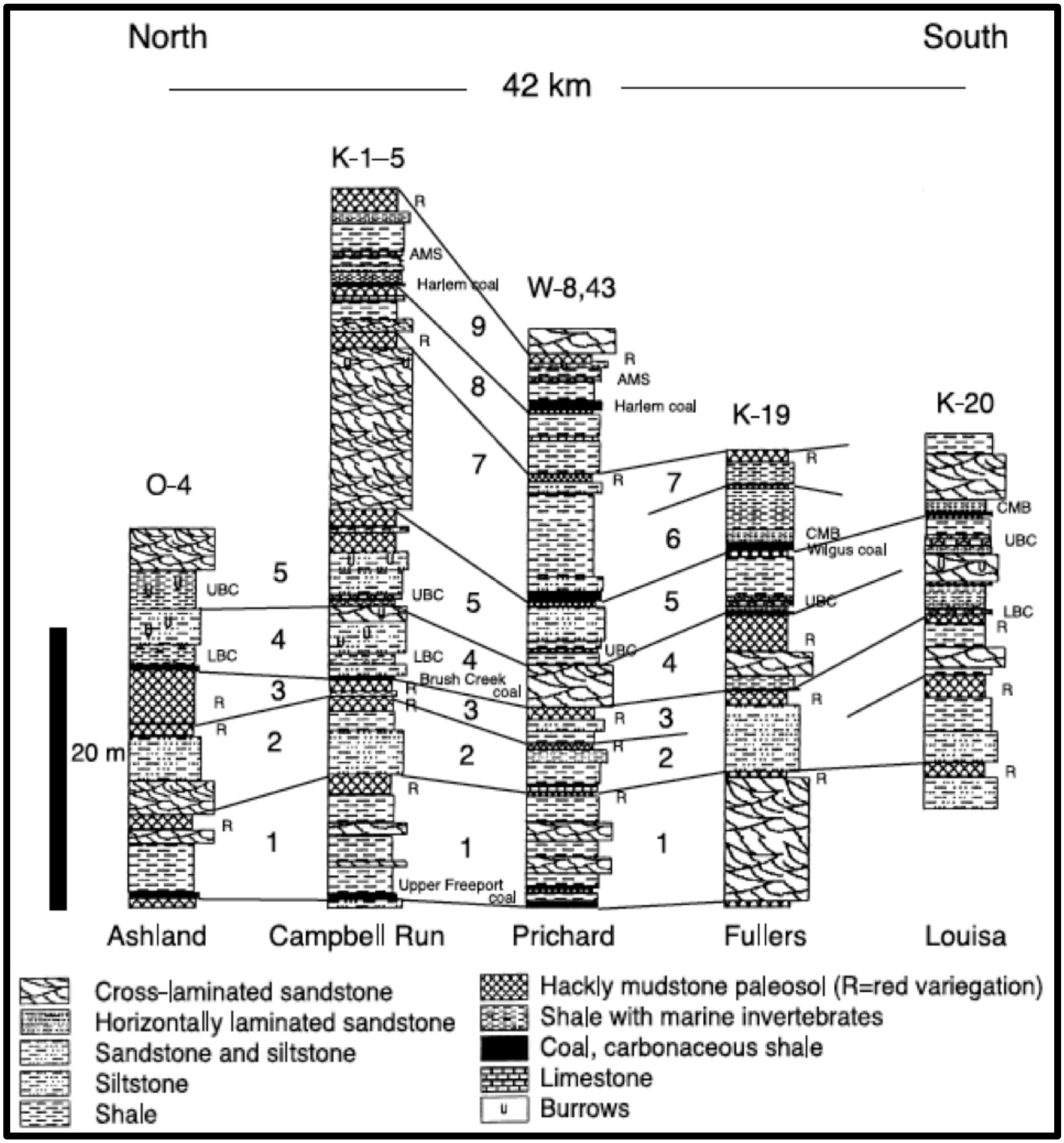

Figure 1.5. Correlation of Glenshaw sections from north to south through the northern portion of the study area using tops of paleosols. Nine paleosol bounded alocycles are labeled. Marine units: LBC = lower Brush Creek, UBC = upper Brush Creek, CMB = Cambridge limestone, AMS = Ames limestone. K-20 corresponds to Louisa 1A of this study (modified from Martino, 2004).

CHAPTER 2

Methods

Field mapping is the primary method to describe and delineate depositional setting and architecture of Pennsylvanian-aged sediments. Five road cuts were selected along Highway 23 near Louisa, Kentucky and labeled for the purpose of this study: Louisa 1A, Louisa 1B, Louisa 1C, Louisa 2A, and Louisa 2B. Outcrops 1B and 1C lie on the east side of Highway 23 directly across from the Louisa 1A location. Louisa 2B is also in a similar orientation to Louisa 2A which yields the opportunity to visualize deposition in three dimensions as well as to examine changes in architecture across short distances.

The main objective of this project is constructing a detailed architectural analysis of high-accommodation fluvial deposits with a focus on floodplain shales along with gaining an understanding of the depositional relationship and geometry of thin sand units that potentially record tie channels within these fine-grained sediments. A series of high-resolution photos were taken along the entirety of each outcrop location and stitched together using Adobe Photoshop to form one panoramic image per outcrop. Lithofacies descriptions were recorded and lateral facies changes were walked out and described in detail along the transverse of each outcrop.

Vertical sections were measured for each outcrop to identify vertical changes in lithofacies and correlate to previous works, such as Martino (2004), for a local sequence stratigraphic framework. A more accurate stratigraphic position was determined with the assistance of Dr. Steven Greb PhD. and Dr. Cortland Eble PhD. of the Kentucky Geological

Survey who conducted a petrographic analysis of two coal beds present in the Louisa 2A and 2B outcrops. By utilizing the petrographic analysis results, the Princess #8 and Princess #9 coals were identified with a high degree of confidence and shed light on the stratigraphic position at this location. Paleosols were identified and applied to understanding the sequence stratigraphic framework based on methods and descriptions outlined by Martino (2004).

Relationships of fluvial bounding surfaces were analyzed using the techniques of architectural-element analysis detailed by Miall (1985). Bounding surfaces of fluvial strata were identified with field mapping and extended by tracing bedding surfaces on photographs utilizing a set of assumptions described by Miall (1988, 1996) and outlined in Holbrook (2001) which follow the principles of superposition and cross-cutting relationships that apply to primary/depositional bedding (Figure 2.1). First, each surface is considered to be laterally continuous and unique until truncated or indiscernible. Second, surfaces may truncate each other but they cannot cross. Third, surfaces may be diachronous but all points along a surface must be older than the materials or surfaces it locally binds and must be younger than the material or surfaces it locally cuts. Fourth, surfaces can only be truncated by surfaces of equal or higher order (Holbrook, 2001).

Architectural analysis was used to discern relative water depth and energy level of the system, channel bodies and surrounding floodplain facies, and the hierarchy of depositional processes. Close up, bed scale, photos were used to understand architectural elements on a finer scale. Measurements from stratigraphic sections were used as a scale for quantitatively estimating aspect ratios of various elements on the panoramic photos. Ultimately, this contributed to the qualitative interpretation of fluvial depositional processes with an emphasis on fine-grained deposits and their spatial relationship channel bodies.

Grp	Time scale of processes (a)	Examples of processes	Instan-taneous sedimentation rate (m/ka)	Fluvial, deltaic depositional units	Rank and characteristics of bounding surfaces
1	10^{-6}	Burst-sweep cycle		Lamina	0th-order lamination surface
2	10^{-5} - 10^{-4}	Bedform migration	10^{5}	Ripple (microform)	1st-order, set bounding surface
3	10^{-3}	Bedform migration	10^{5}	Diurnal dune increment, reactivation	1st-order, set bounding surface
4	10^{-2} - 10^{-1}	Bedform migration	10^{4}	Dune (mesoform)	2nd-order, coset bounding surface
5	10^{0} - 10^{1}	Seasonal events, 10-year flood	10^{2-3}	Macroform growth increment	3rd-order, dipping 5-20^{0} in direction of accretion
6	10^{2} - 10^{3}	100-year flood, channel and bar migration	10^{2-3}	Macroform, e.g. point bar, levee, splay, immature paleosol	4th-order, convex-up macroform top, minor channel scour, flat surface bounding floodplain
7	10^{3} - 10^{4}	Long-term geomorphic processes, e.g. channel	10^{0-1}	Channel, delta lobe, mature paleosol	5th-order, flat to concave-up channel base
8	10^{4} - 10^{5}	5th-order (Milankovitch) cycles, response to fault pulse	10^{-1}	Channel belt, alluvial fan, minor sequence	6th-order, flat, regionally extensive, or base of incised valley
9	10^{5} - 10^{6}	4th-order (Milankovitch cycles, response to fault pulse	10^{-1}- 10^{-2}	Major dep. System, fan tract, sequence	7th-order, sequence boundary, flat, regionally extensive, or base of incised valley
10	10^{6} - 10^{7}	3rd-order cycles. Tectonic and eustatic processes	10^{-1} - 10^{-2}	Basin-fill complex	8th-order, regional disconformity

Figure 2.1. Hierarchies of fluvial architectural units (Miall, 1996).

CHAPTER 3

Results

Lithofacies Associations

Eight lithofacies assemblages are identified in the Princess and Glenshaw Formations along State Highway 23 near Louisa, Kentucky. Laminated shale and interbedded silt lithofacies of lacustrine origin is the most abundant at these lithofacies and encase all other described lithofacies. Table 3.1 summarizes each facies assemblage based on lithologic characteristics and depositional environment.

Facies	Lithology	Characteristics	Fossils	Deposition
Cross laminated sandstone (CLS)	Very fine to medium grained sandstone	Cross laminated, trough cross bedded, channel form, vertical and lateral accretion surfaces, rip up clasts	Few plant fragments	Bar and amalgamated bar in incised valley fill
Ripple laminated sandstone (RLS)	Silt to fine grained sandstone, interbedded shale and siltstone	Light to dark gray, small ripples and climbing ripples, parallel laminated, herringbone cross lamination, clay drapes, ribbon – sheet to tabular sandstone beds discontinuous	None	Blowout wings, medium to small channels, distal fluvial splay

Massive sandstone (MS)	Very fine to fine grained sandstone	Bioturbated, sheet to wedge shaped, sharp contact with underlying floodplain strata	Siderized roots	Crevasse splay in a sub-aerial floodplain
Laminated shale and interbedded silt (LSS)	Clay shale, mud shale, silty mud shale, siltstone; siderite nodules	Parallel laminated, laterally continuous, easily weathered, slope forming	In situ flooded tree stumps, calamites	Floodplain lake to lacustrine delta front
Composite paleosol (CP)	Clay shale, mud shale	Mottle, blocky to poorly laminated, grey to purple to yellow color	Rooting/ burrowing, fully to partly bioturbated	Alternating well drained and poorly drained floodplain
Well drained paleosol (WP)	Clay shale, mud shale	Mottled, blocky, reddish color, non-laminated	Plant fragments	Stable subaerial floodplain with long term soil development
Coal (C)	Coal, carbonaceous shale	Laminated, pods, sheets, thicken and thin over irregular surfaces	Plant fragments	Mire, peat swamp
Limestone (L)	Wackestone to Packstone	Thin-bedded, tabular	Brachiopods, bivalves, gastropods	Marine shelf

Table 3.1 Lithofacies associations

Lithofacies Descriptions

<u>Cross Laminated Sandstone</u>

Characteristics: Very fine to medium grained channel-form sandstone bodies ranging from 2 to 12 meters thick that are moderately well sorted with cross lamina, parallel lamina, and trough cross lamina sets only a few centimeters tall. Basal contacts with lake and coal facies are sharp with local mud rip-up clasts. Channels and bars are multilateral and multistory with vertical- and lateral-accretion elements separated by erosional bounding surfaces with local siltstone partings. Sandstone is organized into fining upward sequences that become increasingly heterolithic toward the top. These units form pronounced cliffs and ledges.

Interpretation: These sandstone bodies represent channel fill and bar deposition as a result of high energy flow. Channel deposits commonly are amalgamated into incised valley fills. Channel stories averages 2 meters thick. Channel bodies scour into lake muds as well as ripple laminated sandstone facies and are generally completely encased in lake sediments. Incised valley fills average 7 to 12 meters thick and represent the largest sand bodies in the area. They represent multiple down cutting events during a period of low base level followed by vertical accretion. Internal lateral accretion architecture shows an average bar height of 2 meters. Basal contact is abrupt as the channel cut into underlying floodplain sediments and mud rip-up clasts are preserved in the thalweg. These channel fill and bar deposits together represent incised valley deposition of a high energy axial or low-sinuosity stream.

<u>Ripple Laminated Sandstone</u>

Characteristics: Silt to fine grained ribbon- and channel-form sand bodies encased in lake sediments. Ribbon deposits are silt to very fine-grained sand with centimeter-size ripple to climbing-ripple laminations and local clay drapes. They extend laterally into and are interbedded with lake sediments before conformably pinching out into these mud facies or truncated by channel incision. Individual ribbon sands reach a maximum thickness of 0.5 meters but commonly form in clusters of various thicknesses with interbedded laminated shale facies (Figure 3.1). Channel form sand bodies are very-fine-to-fine grained with ripple and/or herringbone laminations and scour into underlying lake sediments but lack the rip-up clasts of the cross-laminated sandstone facies. They form as isolated channel bodies encased in lake sediments or as a channel belt with lateral accretion elements. Thicknesses average 1.5 to 2 meters with some visible internal architecture although they are typically heavily weathered. Channel bodies connect to their own ribbon features that extend into lake sediments as described above.

Figure 3.1. Ripple laminated sandstone facies with multiple stacked wings interbedded with lake deposits.

Interpretation: These strata record small individual channel bodies and channel belt elements. This facies also records linear prograding tie channels and attached wing deposits. Tie channel facies resemble isolated channel bodies but are encased in lake sediments and may have small faint herringbone cross laminations indicating local wave influence. Wings can be seen extending laterally from isolated channels, channel belts, and tie channel deposits. Wings are deposited from pulses of sediment during the process of levee building as channels prograde basinward (Tomanka, 2013).

Massive Sandstone

Characteristics: These strata constitute very fine to fine grained gray sandstone units with sheet geometry and with sharp contact into the underlying strata. Two of these units are seen in outcrop together, adjacent to an abandoned channel, with 40 cm of rooted mud shale separating them vertically. The lower unit is approximately 18 cm thick and has siderized root traces (Figure 3.2) penetrating the uppermost 3-5 cm of the sandstone body. The upper sand unit is 6 cm thick and does not have visible root traces preserved.

Interpretation: These sandstone sheets are interpreted as crevasse splays deposited on a subaerial floodplain. Rooting in the lower unit and overlying shale facies indicates

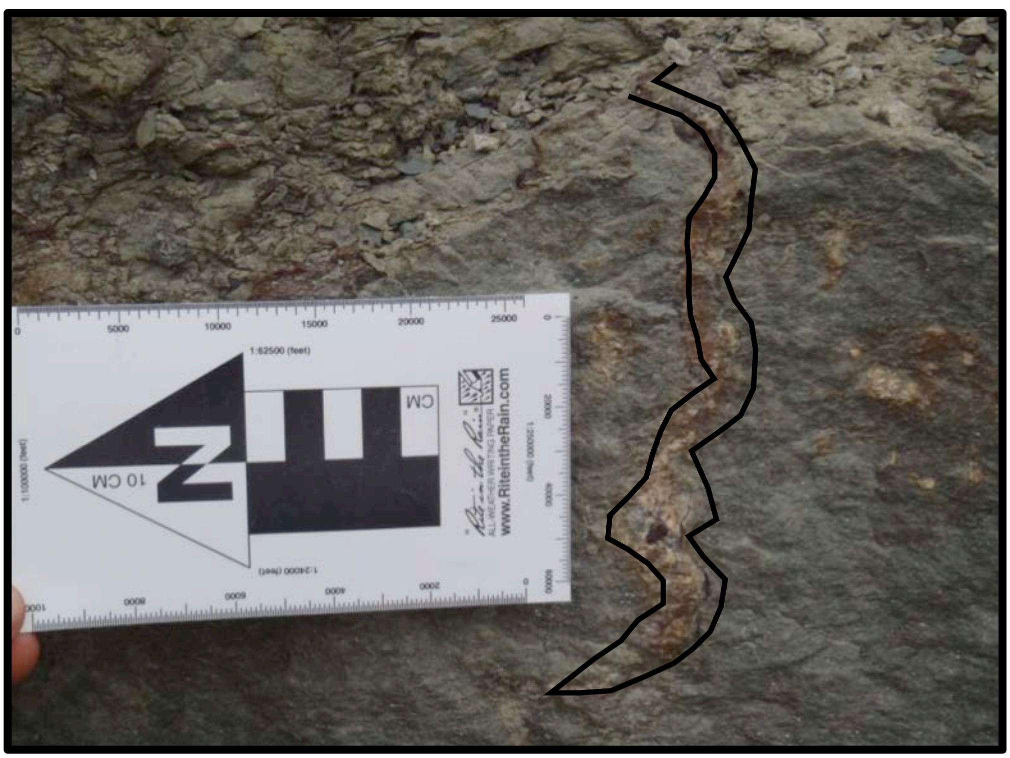

Figure 3.2. Close up of massive sandstone facies with siderized root trace outlined.

subaerial exposure long enough for plant growth and although root structure is not preserved in the upper unit, the lack of sedimentary structures is attributed to bioturbation. Both units form a wedge shape, thinning further from the channel as depositional energy decreased away from the levee breach.

Laminated Shale and Interbedded Silt

Characteristics: The dominant facies throughout the formation is parallel laminated mud shale and clay shale with variable amounts of interbedded silt content. Laminations are very thin (mm-cm) and are not consistently visible, possibly due to weathering, commonly giving a blocky appearance. These shale sections are laterally extensive but can be bisected by channel scours or grade laterally into wings of the ripple laminated sandstone facies. Changes in silt content appear irregularly in vertical section and can become more frequent near the interface with sandstone facies. Shale facies generally occur above and below cross-laminated and ripple laminated sandstone facies with a sharp contact. Soil facies also occur adjacent to laminated shale facies however these boundaries are abrupt and no rooting is seen extending from shale into soil facies. Shale intervals are the primary slope forming facies at each location (Figure 3.3).

Interpretation: Depositional environment for this shale facies is interpreted as low energy floodplain lake due to the lateral continuity of mudstone and relationship to fluvial channel bodies. The lack of bioturbation and preservation of sedimentary structures are indicative of a standing water environment due to a relatively high paleo-water table (Hasiotis, 1993; Hasiotis and Mitchell, 1993; Hasiotis and Honey, 2000). Covered sections are predominantly overlain by these lacustrine lithofacies and it is likely that rocks beneath the covered slopes are also lacustrine facies but could not be positively identified.

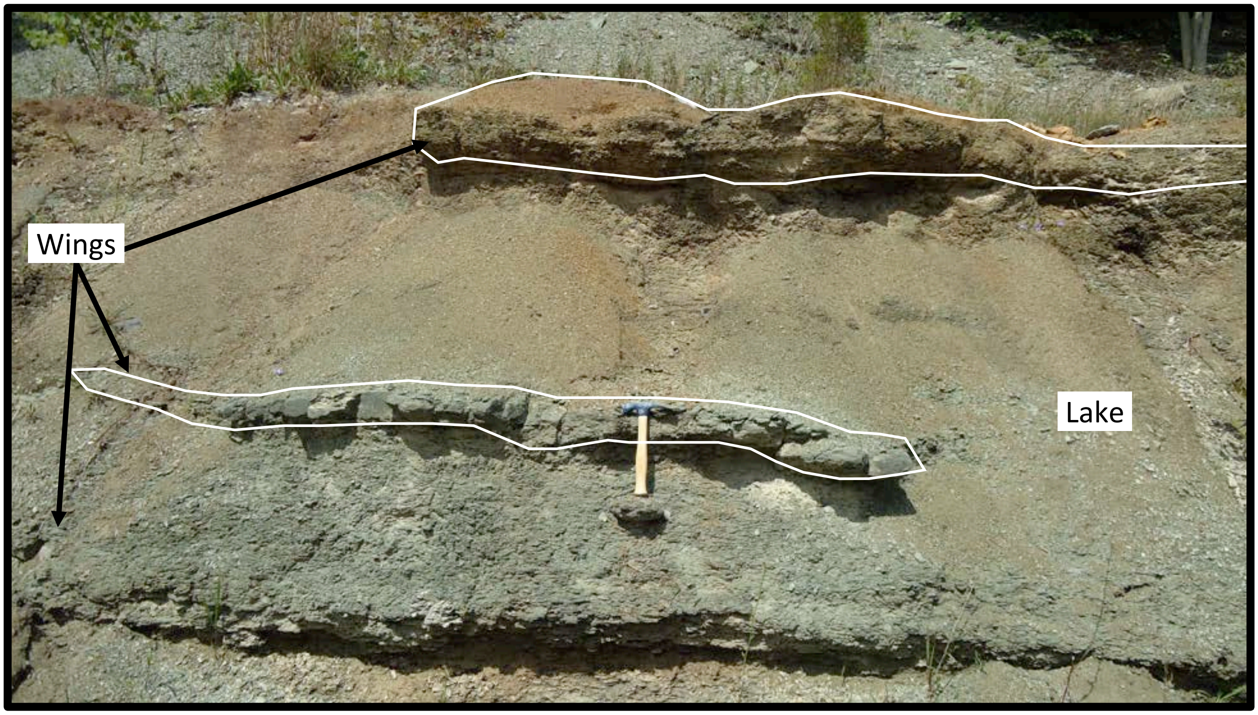

Figure 3.3. Example of lake deposits with interbedded wings.

Paleosol

This facies is found in manifestation distinctive of the Princess and Conemaugh Formations, respectively.

Paleosol Facies 1: Compound Paleosol

Characteristics: Identified in the Princess Formation as brown to purple to dark gray colored mud shale with local very fine laminations in an otherwise hackly, mottled mudstone. Rooting is abundant but small diameter. Some leaching is noted as well as oxidation resulting in iron concretions.

Interpretation: These strata represent compound paleosols deposited in an ephemeral floodplain lake environment. Increased mottling and bioturbation are a result of temporary emergence and the darker, slightly laminated soil horizons represent a subsequent re-drowning of the lacustrine system. This cycle is evident through multiple levels of rooting as plant life, possibly stygmaria, tried to keep pace with fluctuations of lake level and sedimentation rate.

Paleosol Facies 2: Well Drained Paleosol

Characteristics: Mudstone ranging from deep red to olive green with a weathered, hackly appearance (Figure 3.4). Slightly laminated with no visible rooting preserved. Identified in the Conemaugh Formation and forms distinct, laterally continuous horizons across the Louisa 1A, 1B and 1C outcrops.

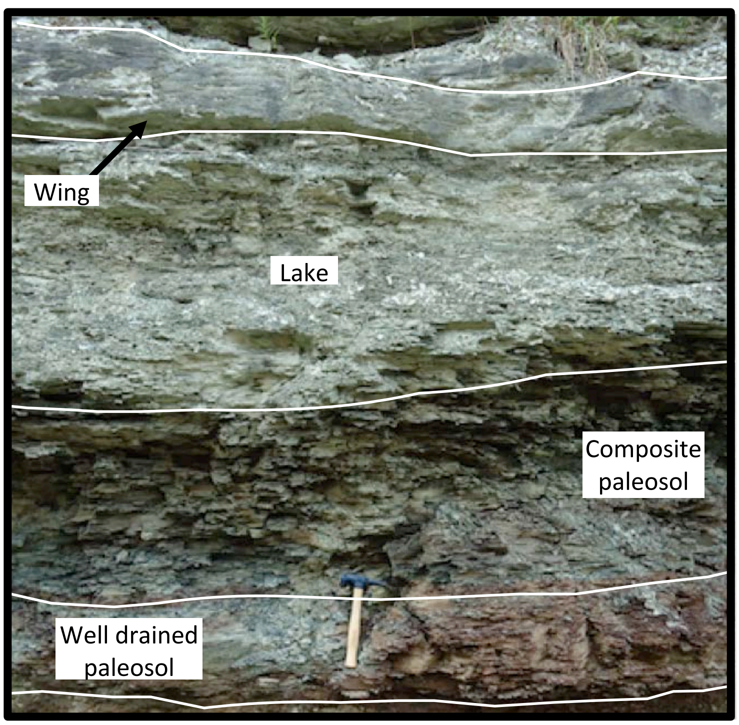

Figure 3.4. Example of well-drained paleosol and composite paleosol with overlying lake and wing sediments.

Interpretation: These represent weak to medium soil development on a well-drained floodplain with more consistently low water table than the compound paleosols. However, minor preservation of primary sedimentary structure, lack of developed soil horizons, and proximity to lacustrine facies argue that soils are poorly developed and periods of emergence were relatively short.

<u>Coal</u>

Characteristics: This facies consists of two distinct coal beds known as the Princess #8 and Princess #9. The Princess #8 is double benched at this location with a 43 cm (17 inches) thick lower bench and total thickness of 61 cm (24 inches). It is laterally extensive and mined locally due to its low ash content. The Princess #9 coal is thinner, with a maximum thickness of 10 cm (4 inches), and has higher ash content than the Princess #8 coal. The Princess #9 coal has a much higher shale component than the Princess #8 coal.

Interpretation: The Princess #8 coal is the result of an really extensive and long lived peat mire during a stable period of high base level and limited sediment input (Aitken and Flint, 1994). The Princess #9 coal is classified as a carbonaceous or "coaly" shale at this location due to the higher ash content compared to the Princess #8 (Eble, 2003). The Princess #9 was deposited in a back-swamp area with less isolation from the active fluvial system than the Princess #8 resulting in a higher sediment input (Aitken and Flint, 1994).

Architectural Analysis

The upper Breathitt and lower Conemaugh Formations in the Louisa field area represent two architectural assemblages, floodplain and channel belts. Floodplain elements comprise a significant portion of the Louisa outcrops containing well-drained and poorly drained packages that represent changes in paleo base level. This assemblage is made up of lake, coal, splay, and paleosol elements that are primarily defined by specific facies of which the boundaries are not consistently sharp. Therefore, this assemblage is more generally defined by the lithosomes that define which elements tend to be clustered. Relationships of the channel-belt assemblage comprise four elements; bars, isolated channels, and wings, and are locally amalgamated to form valley fills. Wings extend laterally from channel bodies. Channel-belt assemblages are commonly amalgamated with each other but also form as isolated channels and both are encased in the floodplain assemblage.

Floodplain Assemblage

<u>Poorly drained</u>

Characteristics: The poorly drained floodplain lithosome is dominated by laminated shale with interbedded silt facies but also contains composite paleosol and coal facies. Laminated shale is laterally extensive across the length of each outcrop but also grades to ripple laminated sandstone facies and is locally crosscut by the cross laminated sandstone as well as ripple laminated sandstone facies, forming a sharp contact. Channel-belt assemblage deposits can have a sharp vertical and/or lateral contact with the floodplain facies but some gradational contacts are also observed. Composite paleosol and coal facies are generally observed near the top or bottom of the poorly drained floodplain assemblage. *Interpretation*: This assemblage represents a diverse poorly drained floodplain environment that frequently developed into ephemeral lakes. Changes in water level and drainage conditions are evident by the composite paleosols alternating with well-laminated lacustrine muds. Interbedded silt and fine-grained sandstone of the ripple laminated sandstone facies can often be traced to the channel assemblage from which they were sourced but are also recorded where their associated channel body is not seen in the outcrop orientation. Laminations between thin sand units are slightly less developed because of a short time period between flooding events. However, fine laminations are more developed where floodplain lakes experienced low sediment input for a longer period of time.

Well drained

Characteristics: The well-drained floodplain lithosome is generally represented by well-drained paleosol facies but also contains the massive sandstone facies. Massive sandstone facies form a sharp contact to surrounding floodplain sediments and are stratigraphically equivalent to low-accommodation channel bodies. Elements of the channel-belt assemblage form sharp vertical and lateral contacts with well drained floodplain.

Interpretation: This assemblage represents deposition on a sub-aerially exposed floodplain that allowed pedogenesis to occur as well as plant growth. Massive sandstone facies represents crevasse splay deposits during flood events from an adjacent channel body. Well-drained floodplain facies are seen near the top and base of the Louisa 1 outcrops representing the boundaries of a high-accommodation sequence.

Channel Assemblage

The channel assemblage comprises three primary elements: bars, channels, and wings. These assemblages are encased in floodplain elements and are generally laterally and vertically amalgamated with wings extending laterally from the tops of channels.

Element 1: Bars

Characteristics: This assemblage is composed of cross-laminated and ripple-laminated sandstone facies. Bars scour into underlying channels, laterally cut into preceding bars, and some stack on top of one another to form bar sets. Bar thickness ranges from 0.3-2 meters. Scours form the basal boundary of bars while flooding surfaces, represented by mud drapes or preserved levee deposits, form the upper boundaries.

Interpretation: Bars are formed from bedload dunes, predominately as mid-channel and side-attached bars, based on the accretion macroforms and internal laminae. As bedload sheets and ripples migrate downstream they produced parallel laminations during low energy flow and anti-dunes during high-energy flow. Individual bars were smeared into compound bars as a result of high-flow flooding events indicated by cross-laminations along the bar face.

Element 2: Isolated channels

Characteristics: Isolated channels are composed of the ripple laminated sandstone facies and occur as lens shaped bodies with scour base encased in floodplain lake facies. Scours are concave up to flat and cut into floodplain lake sediments with a sharp contact while the upper bounding surface can be sharp or gradational from fine-grained sandstone to silt to laminated shale. Sedimentary structures are not readily identifiable in most channel fills giving them a massive appearance but this is probably a result of weathering and not reflecting the absence of sedimentary structures. Channel bodies range from 0.5 to 2 meters thick and occur either isolated or in clusters. Discontinuous ribbons of the ripple laminated sandstone facies extend laterally from lens shaped channel bodies and pinch out into floodplain lake sediments unless cross-cut by other channel bodies. Ribbons are generally thicker near the channel body from which they extend and taper away, resembling the cross sectional profile of a wing.

Interpretation: This element records small distributary channels and linear prograding channels deposited in conjunction with the poorly drained floodplain assemblage in a high-accommodation fluvial setting. Distributary and linear prograding channels generally range from very fine to fine grained sandstone, can have faint ripple laminations, and gradational upper bounding surfaces as decreases in depositional energy give way to surrounding lake sediments. Linear prograding channel bodies differ in that they do not only have ripple laminations but also herringbone cross laminations indicating wave influence flow between the primary fluvial channel and floodplain lake (Rowland, 2007; Tomanka, 2013). Shale partings are more common representing low-energy between pulses of deposition as the channel progrades into the basin. Lake and levee sediments surrounding the linear prograding channel exhibit a coarsening upward sequence from laminated pro-delta muds at the base with increasing ripple laminated sandstone facies near the top and are consistent with sediments described in modern examples of tie channels (Rowland, 2007; Rowland et. al., 2009; Tomanka, 2013).

<u>Incised Valleys</u>

Characteristics: Incised valleys include the architectural elements of bars and isolated channels and adds the bounding valley scour surface as defined by Holbrook (2001). Basal scour surfaces are sharp, flat or concave up, penetrate the underlying Princess #8 or 9 coal or floodplain lake deposits, and commonly exhibit mud rip-up clasts. The upper bounding surface is gradational with an increase in silt or shale partings near the top. Channel fill sediments are fine to medium grained sandstone of the cross-laminated sandstone facies. Channel fills are intensively amalgamated both laterally and vertically within the confined valley with up to 5 vertically stacked channel stories and greater than 10 lateral channel fills. Individual channel scours cut into bars deposited by previous channels as well as other channel fills. Bars average .75 to 2 meters thick and the total valley thickness ranges from 7 to 12 meters.

Interpretation: Incised valley units record filling and avulsing of multiple channels within the boundaries of a valley scour. Variations in channel belt elements within valley fills reflect not only changes in paleo base level but also changes in depositional energy. Bars and channel fill elements combine to form stories in complete or parts of channel belts (Bridge, 2004) resulting in multi-storied channel belts deposited by a low sinuosity river that incised and aggraded within a bounding valley scour.

Element 4: Wings

Characteristics: Wings are composed of ripple laminated facies and extend laterally from channels up to several hundred meters before pinching out unless truncated by other channel scours. Wings are generally encased in lake deposits and the boundary between the two is often difficult to distinguish due to weathering effects on depositional structures, such as laminations, as well as minor changes in grain size from sandy siltstone to muddy siltstone. Wings reach a maximum thickness of .5m but can also be much thinner depending on proximity to the channel deposit from which they were sourced. Multiple wings can be stacked or inter fingered with on one another separated only by thin shale layers.

Interpretation: As linear channels prograde into floodplain lakes, the finer fraction of suspended sediment settles to form a clay rich pro-delta deposit and/or blankets the subaqueous channel levees while coarser sediment is deposited along the flanks of the channel and tapers away from the channel axis resembling the cross sectional profile of a wing (Tomanka, 2013; Huling, 2014). Flood events cause pulses of high-energy deposition resulting in layers of coarser sediment flushed over mud-dominated levees. This high flow deposition forms the wing deposits that extend along the length of the channel (Huling, 2014).

Outcrop Architecture

Figures 3.5 through 3.7 illustrate uninterpreted and interpreted examples of the previously described facies and architecture at Louisa 1B, Louisa 1C, and Louisa 2A outcrop locations.

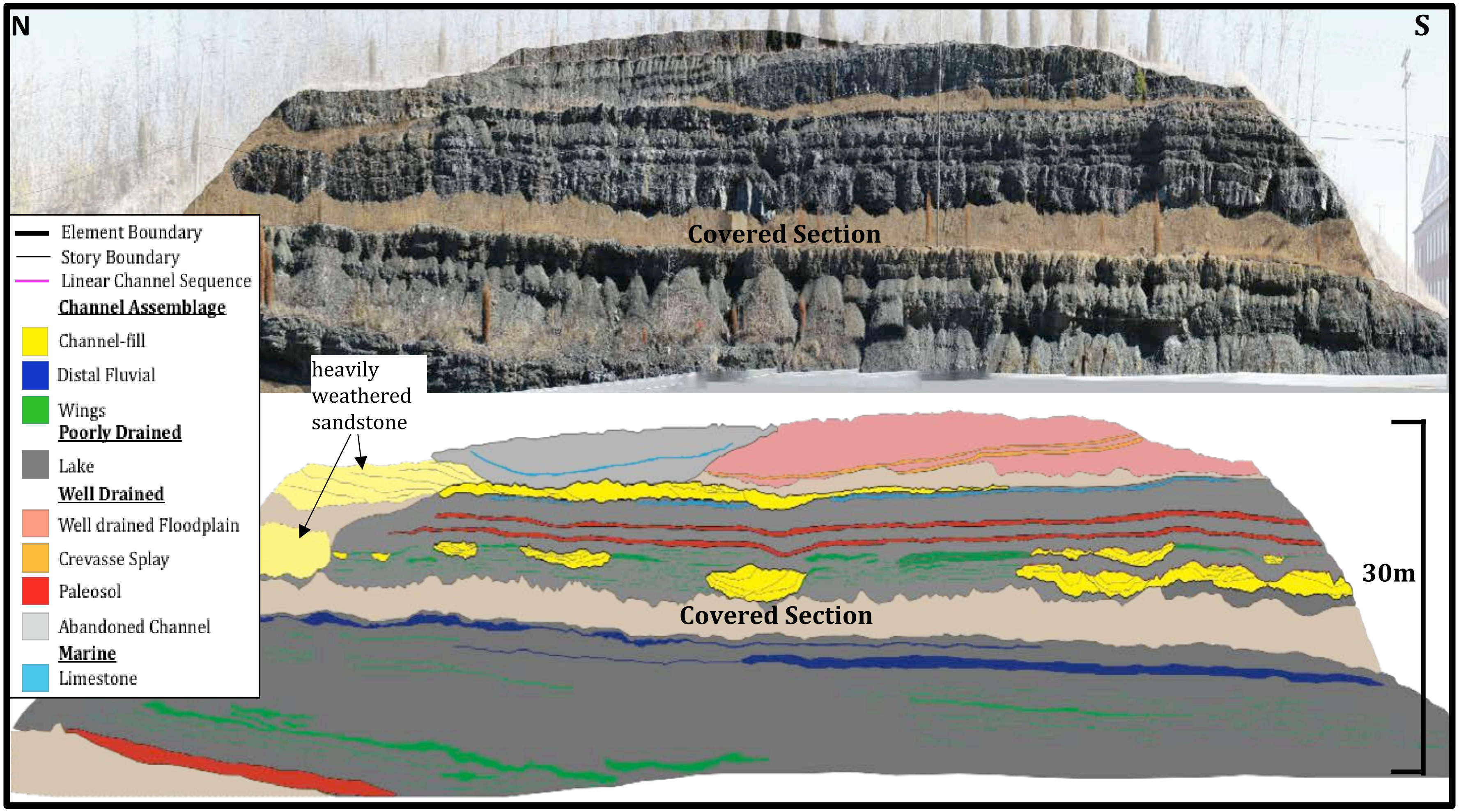

Figure 3.5. Uninterpreted and interpreted photo panels of Louisa 1B outcrop illustrating the architecture of each facies association recorded at this location.

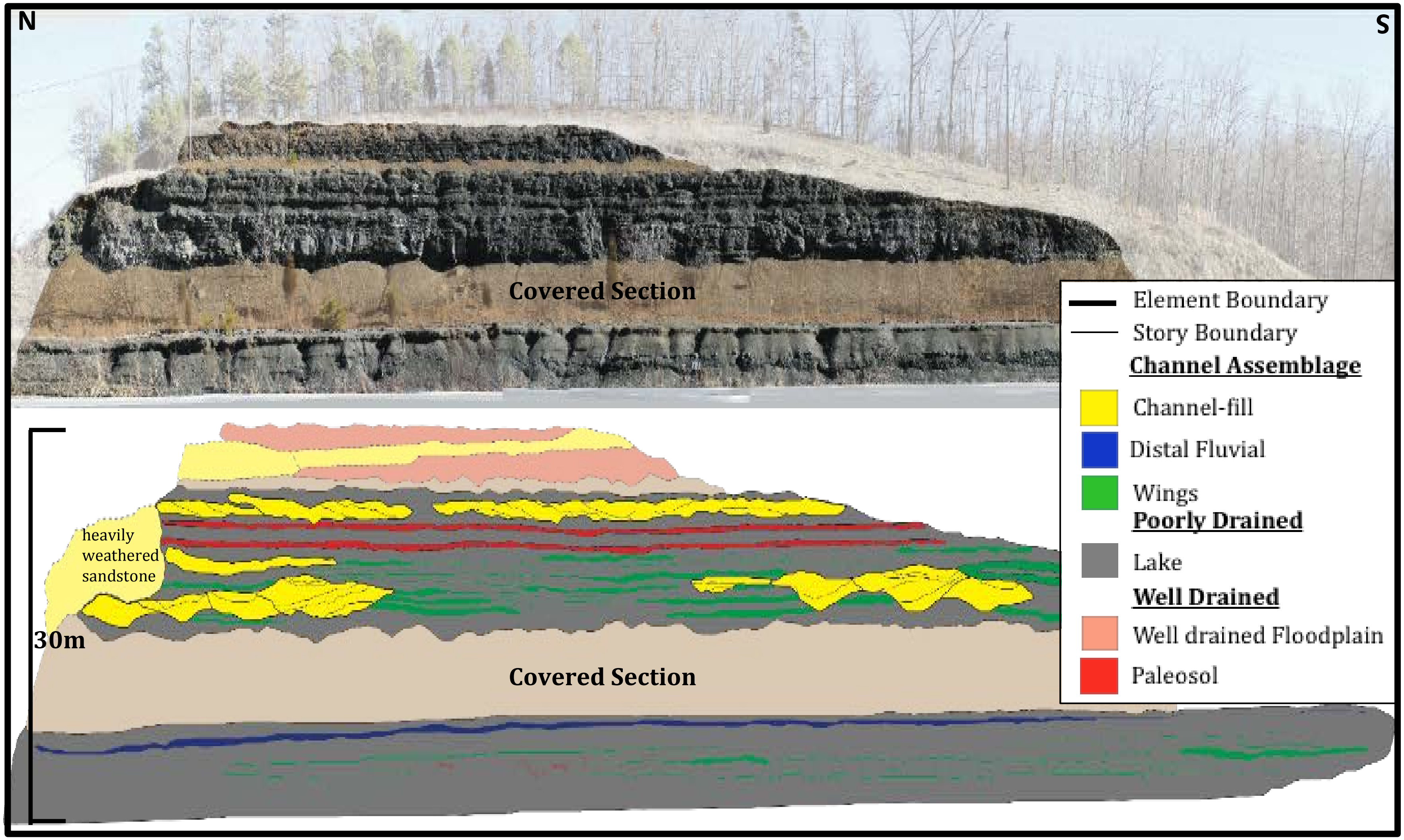

Figure 3.6. Uninterpreted and interpreted photo panels of Louisa 1C outcrop illustrating the architecture of each facies association recorded at this location.

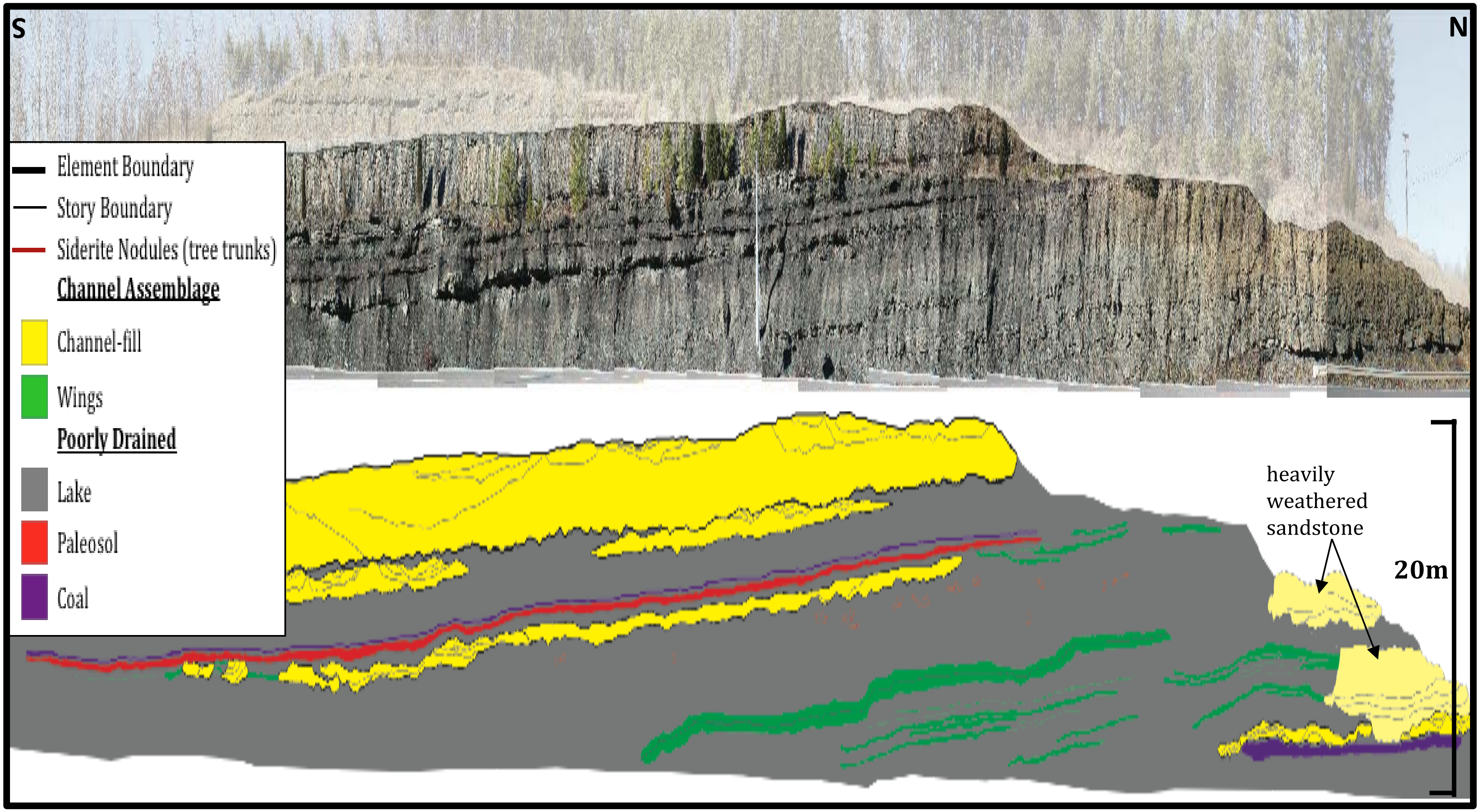

Figure 3.7. Uninterpreted and **i**nterpreted photo panels of Louisa 2A outcrop illustrating the architecture of each facies association recorded at this location.

CHAPTER 4

Discussion

The Princess Formation of Upper Breathitt Group and the Lower Conemaugh Group near Louisa, Kentucky are interpreted to record a dominantly fluvio-lacustrine setting during periods of relative high and low paleo-base level based on the above observations. The well-drained floodplain assemblage with rooted sandstone and paleosol layers along with incised valley channel elements record periods of relatively stable base level. In contrast, laminated mud and silt of the poorly drained floodplain architectural assemblage records a floodplain lake environment adjacent to fluvial channel deposition that dominates the periods of rising paleo-base level. Isolated channels bisect the floodplain lake deposits with wings extending laterally from their respective source channel as well as cross cut by other isolated channels.

A composite vertical section of all outcrops illustrates the combined sequence stratigraphy of the Louisa outcrops (Figure 4.1). Interpretations are applied to the composite vertical section with periods of relative stable paleo-base level corresponding to the low-accommodation system tract and relative rising paleo-base level corresponding to the high-accommodation systems tract (Catuneanu, 2006). This illustrates two sequences of high and low-accommodation with incised valley channel elements at the top of each trend.

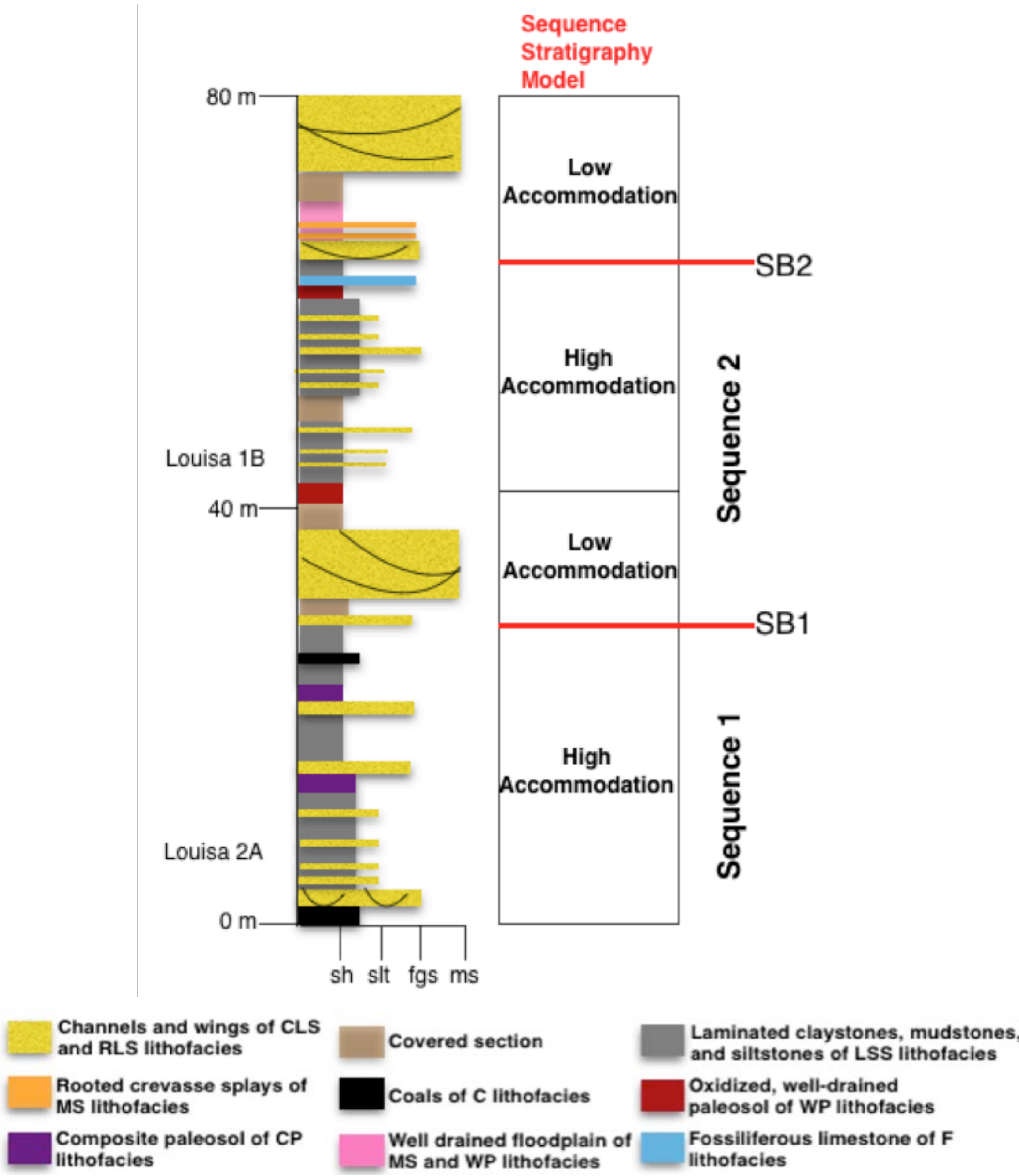

Figure 4.1. Composite vertical section for the Louisa outcrops outlining the interpreted sequence stratigraphic intervals.

Significance of Tie Channels and Lakes in the Ancient Floodplain Record

High-accommodation intervals of the Louisa outcrops produce evidence for preservation of linear propagating channels, similar to those described as tie channels, building into floodplain lakes. Lobate geometry due to channel bifurcation is typically associated with deltaic sedimentation (Miall, 1996); however, non-lobate lacustrine deltas building into freshwater lake environments appear to be common in the modern yet relatively unreported in the rock record (Huling, 2014). Rowland (2007) describes modern examples of tie channels extending from active rivers to adjacent water-filled basins. Likewise, Tomanka (2013) describes a non-bifurcating deltaic channel prograding into a manmade reservoir and suggests it as an analogue to the formation of tie channels due to the strong geomorphic similarities.

Fluvio-lacustrine channels debouching into lakes form subaqueous levees that decrease in maximum height away from the channel outlet into the lake (Rowland, 2007). They rapidly prograde basinward and are not substantially reworked by waves or tides. They build to emergence as the channel propagates and tend not to migrate laterally and show little tendency to develop point bars thereafter (Rowland, 2007).

Tomanka (2013) described a two-phase self-propagating process for tie channels of eroding prodelta clay while simultaneously constructing sandy levees behind the channel mouth. Channels pouring into standing water bodies produce a turbulent jet at the channel mouth that carries prodelta clays basinward while entrained sands are contemporaneously deposited along channel margins to form levees. Over time, the mouth of the turbulent jet gradually moves downstream causing deposition along the margin to coincidently migrate downstream forming a linear zone of deposition on both sides of the channel. This creates a self-sustaining process where levees extend down dip relevant to the channel mouth while sustained deposition along channel margins allows levee height to continue building up dip of the mouth (Tomanka, 2013). The result is a muddy propagating channel with a downstream decrease in grain size and a majority of sand deposited on channel margins (c.f. Dietrich et al., 1999). During high flow events, sand is washed over channel levees and deposited in the floodplain as sheets (Tomanka, 2013). This could be the process responsible for creating wings seen throughout high accommodation sections of the Louisa outcrops. These observations are consistent with previous descriptions of tie channel levee morphology (Rowland & Dietrich, 2005; Rowland, 2007).

Tie channels and non-bifurcating channels in man-made reservoirs both exhibit continuous progradation and a basinward decrease in levee height (Rowland, 2007; Tomanka, 2013). Sedimentation at jet margins is long recognized as a mechanism for levee growth (Bates, 1953; Axelsson, 1967; Wright, 1977; Edmonds & Slingerland, 2010) and recent studies on tie channels further the understanding of this process (Rowland and Dietrich, 2005; Rowland, 2007; Rowland, et al., 2009; Rowland et al., 2010). Through flume experiments, Rowland (2007) was able to produce levee channels similar to tie channels. This showed that jet margin sedimentation results in longitudinal sediment deposits on the flanks of the channel that taper away from the channel axis at an acute angle in the downstream direction. Sediment accumulation is thickest near the channel and thins away from the channel axis resembling the cross sectional profile of a wing (Figure 4.2.).

Figure 4.2. Flume experiment with 1.9 cm/s settling velocity particles. Oblique view with 20 cm grid show experimental levee sedimentation. (Rowland, 2007)

Tomanka (2013) describes levee composition of a non-bifurcating channel through the analysis of gouge cores taken across Denton Creek where it enters the Grapevine Reservoir, (Tarrant Co., Texas). Facies described in cross section show that levees on both sides of the channel were topped with sandy and loamy deposits overriding prodelta clay. Sand thickness on the levee tops reached a maximum over one half meter (two feet) with approximately 5.3 meters (17 feet) of underlying prodelta and pre-impoundment floodplain clay. Leaf and woody debris are abundant in the upper portions of levee clays in some cores, but visible organics diminished with core depth. Tomanka also described the typical levee facies progression as seen in Denton Creek (Figure 4.3.). Levee deposits

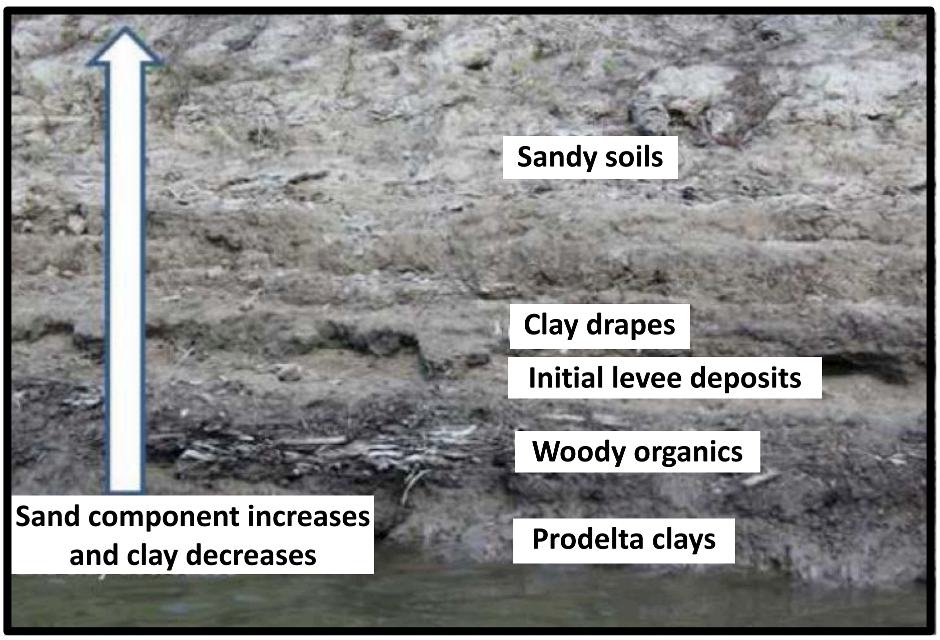

Figure 4.3. Typical progression of levee facies observed at Denton Creek, Grapevine Reservoir, Texas. Arrow shows direction of decreasing clay and increasing sand components. (from Tomanka, 2013)

contain less clay and more sand vertically and progress from prodelta clays at the base, to clays or loams with woody debris, to loams or loamy sands, and finally to sands at the top. This vertical progression of decreasing clay sediments and increasing sand, coarsening upward, is also seen in the Louisa outcrops adjacent to isolated channels (Figure 4.4).

Levees build vertically as sand was deposited along the margins of the channel (Rowland, 2007) with ribbon sands extending laterally from channels as a result of over levee flow during high flow events (Tomanka, 2013).

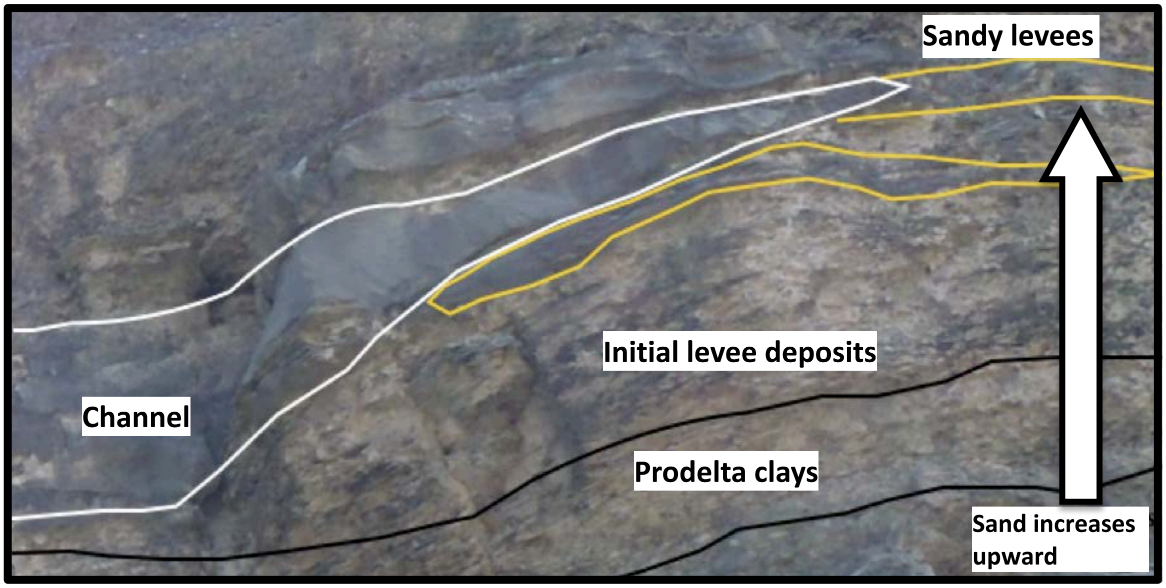

Figure 4.4. Typical progression of levee facies adjacent to isolated channels observed in the Louisa outcrops. Arrow indicates increasing sand and decreasing clay content vertically.

Martino (2004) identifies flood basin facies at the Louisa 1B location along with a description of crevasse splay deposits as wedge shaped sandstone-shale bodies adjacent to channel deposits and exhibiting ripple to parallel laminations. They thin away from the channel grading laterally to grey lacustrine shales that also lie above and below. This description closely resembles that of wing sediments; however, wings are associated with sub-aqueous deposition as part of the mechanism for levee construction (Rowland, 2007; Rowland et. al., 2010; Tomanka, 2013; Huling, 2014) in a high-accommodation setting. In contrast, crevasse splays are typically deposited as lobate sediment bodies on a sub-aerial floodplain through levee breach in a low-accommodation setting. Although both may exhibit tabular or wedge geometry in cross section, rooting and other indications of bioturbation are more common in crevasse splays due to the well-drained nature of the floodplain. Examples of wings (ripple laminated sandstone facies) and crevasse splays (massive sandstone facies) can be seen in the Louisa 1B outcrop yet they occur at different stages in paleo-base level. Based on the lack of bioturbation, well-developed paleosols or other indicators of subaerial exposure, laminated shales deposited in the high-accommodation settings are here interpreted as floodplain lakes. Given that lake sediments encase wing deposits and the above distinctions between sub-aerially exposed crevasse splays, wings are interpreted as sub-aqueous deposits in the Louisa outcrops.

Floodplain lakes with no evidence of vegetative growth make up roughly 80 percent of high-accommodation floodbasin sediments in the Louisa outcrops. The remaining floodplain is composed of compound paleosol and coal recording periods of slightly lower water table that allowed for dense aquatic vegetation growth. Wing sediments are only observed in lake deposits and do not inter-finger with compound paleosols or coals therefore supporting fully sub-aqueous deposition limited to the areal extent of the lake. Discrete intervals of lake sediments in the Louisa outcrops extend across the length of each location but wings within lake sediments do not consistently exceed outcrop width. Wings range from 0.1 to 0.5 meters thick depending on proximity to the source channel and extend up to 300 meters wide, locally across the entire outcrop. Wing facies are moderately to well-sorted ripple laminated sandstone similar to that described by Huling (2014). Wing density increases when proximity to visible channel bodies; however, it is suspected that sections with lower densities of wing deposits would exhibit an increased wing density moving toward the source channel in three dimensions. Increased wing density can also occur when channel reactivation or incision occur along a previously active channel pathway resulting in a more densely stacked pattern due to active wing deposition on top of prior levees with remnant wing sediments from original levee buildup (Huling, 2014).

Wing architecture is described in relation to linear prograding channels as terminal fluvio-deltaic systems building into large lakes (Tomanka, 2013; Huling, 2014) as well as tie channels building into floodplain lakes (Rowland and Dietrich, 2005; Rowland et al., 2006; Rowland, 2007) with strong similarity to isolated channels encased in floodplain lake deposits seen in the Louisa outcrops. According to Slingerland and Smith (2004), linear prograding channels require “standing bodies of water, favored by slow runoff promoted by low floodplain slopes; dense vegetation; and high water tables that encourage ponding, slow drainage, and settling of fine sediment.” All of these hold true for the high-accommodation floodbasin sediments in the Louisa outcrops and suggests that isolated channels encased in lake sediments are linear prograding channels building into floodplain lakes.

Isolated channels are surrounded by lake sediments and underlain by finely laminated pro-delta clay shale. Adjacent to the channel body, wings increase in thickness from 1 cm near the base of the channel to .25 meters at the top of the preserved levee. Wings also show a vertical increase in occurrence with a coinciding decrease in clay content which combines to form a coarsening upward sequence of levee sediments adjacent to the channel (Figure 4.5). This vertical progression resembles that described for non-bifurcating deltas building into a modern lake environment by Tomanka (2013).

Isolated channel bodies in the Louisa outcrops differ from linear prograding channels building into a large lake system as described by Huling (2014) in that not only do they have ripple laminations but also herringbone cross laminations indicating bi-directional flow between the primary fluvial channel and floodplain lake (Rowland et al., 2006; Rowland, 2007). Bi-directional flow is related to stage level in the main channel and allows them to fill or drain floodplain lakes as stage fluctuates. Herringbone cross laminations were observed in only one isolated channel in the Louisa outcrops however sedimentary structures reflecting bi-directional flow are often not preserved in the rock record (Ainsworth et al., 2011).

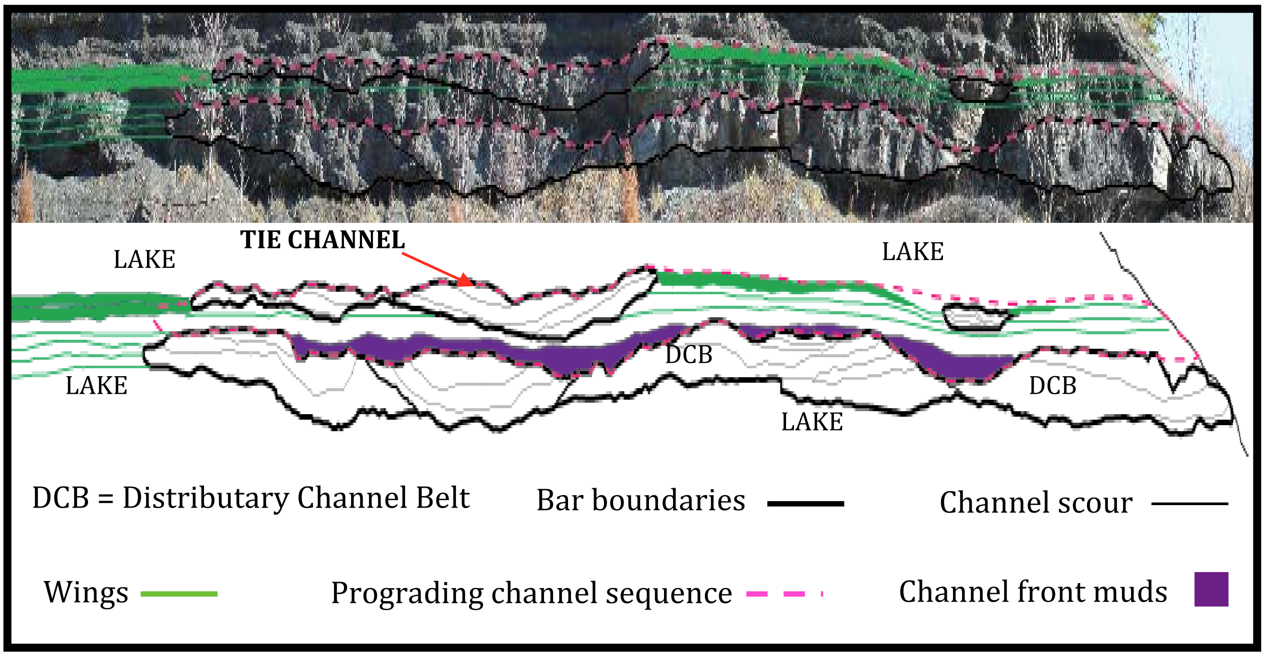

Figure 4.5. Architecture of a linear prograding channel moving basinward over a previously active channel belt that has been covered by a floodplain lake. Channel front muds are at the base of the sequence with an increasing density of wing deposits toward the top. This coarsening upward sequence represents channel growth in a linear direction while building subaqueous levees through blowout wing deposition.

Shale partings are present in Louisa channel fills representing pulses of deposition separated by low energy deposition as the channel progrades into the floodplain (Rowland and Dietrich, 2005; Rowland, 2007). It should also be noted that these pulses of high energy deposition, followed by periods of low energy, reflect the mechanism by which wings are deposited as over levee flow during high flow events and support variable flow energy in isolated channels. A combination of the prograding delta sequence with levees building adjacent to and wings extending laterally from the channel body, indications of bi-directional flow along with shale partings representing highly variable flow within the channel, and the relationship with surrounding high-accommodation lake and fluvial sediments suggests that isolated channels exhibiting these features are non-bifurcating deltas prograding into floodplain lakes adjacent to larger fluvial channels. More specifically, these features closely resemble that of tie channels and are here interpreted as such.

Connectivity

Connectivity of channel bodies in the study area occurs through the cross cutting of wing sediments deposited as part of the levee building process of prograding channels. Wings extend perpendicular to channel bodies from distal reaches of the channel mouth to more proximal settings where bars and lateral migration occur (Figure 4.6).

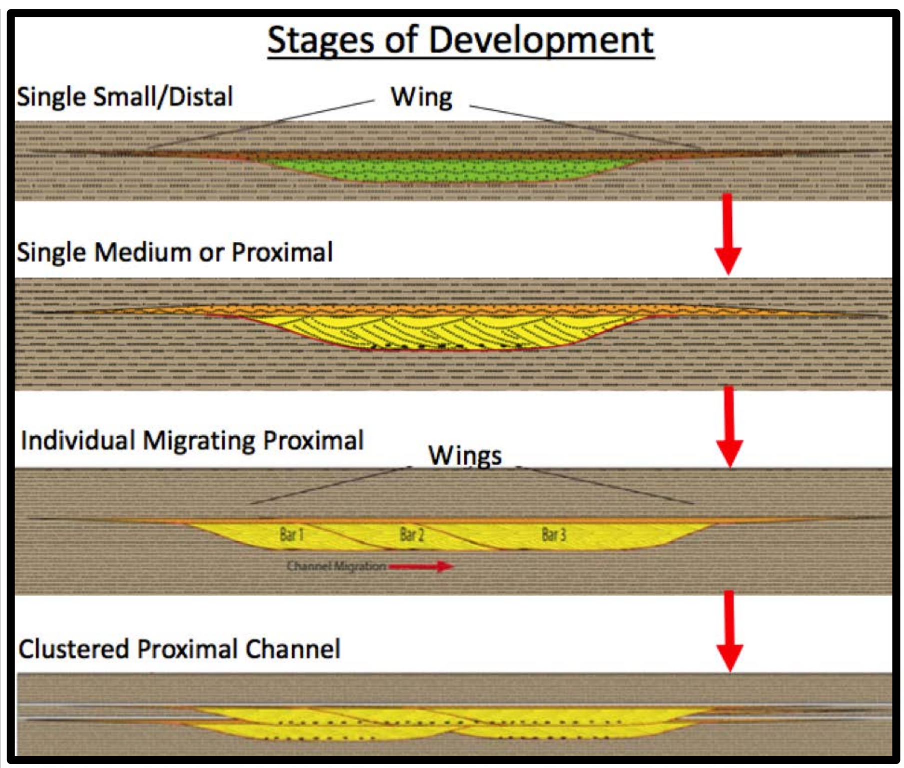

Figure 4.6. Illustrates multiple stages of fluvio-lacustrine development and highlights that wings are deposited in each stage of channel development (from Huling, 2014).

Lateral connection of isolated channel bodies typically happens with wings extending horizontally into adjacent channels while vertical connection occurs where later-generation channels scour into wings deposited by a previous channel. This joins channels and offers a pathway for fluid flow between the two sand bodies that otherwise appear to be isolated reservoirs (Figure 4.7).

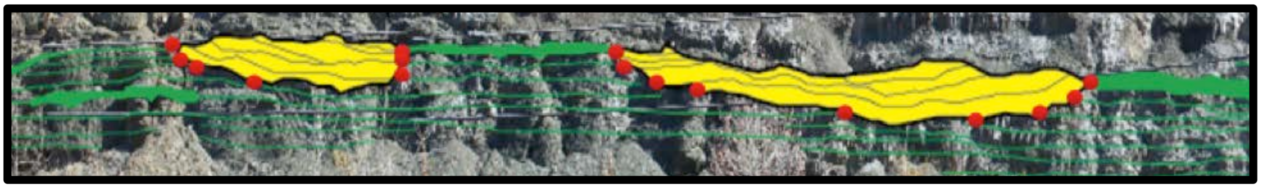

Figure 4.7. Connectivity of isolated channels through wing sediments. Channels are 1-1.5 meters thick and illustrated in yellow while wings are centimeters to .3 meters thick and illustrated in green. Red dots indicate the locations of connectivity between wings and channels.

Wings are laterally extensive throughout the Louisa 1A, 1B, and 1C outcrops and the termination of some could be established by walking them out while others extend beyond the exposure. Facies are composed of ripple laminated sandstone similar to that of the channel bodies from which they are sourced and their contact with surrounding sediments is generally sharp owing to scour. They are relatively well sorted and lack bioturbation due to subaqueous deposition and limited plant growth in this environment. Mud drapes or other obvious restrictions to fluid flow were not observed, indicating the potential for similar permeability in wings and the channels they connect to. Further work in a laboratory setting will better define the preserved permeability of wings.

Within high-accommodation sediments of the Louisa 1B and 1C outcrops, all channel bodies are connected to at least one other channel or channel belt through wing sediments as detailed below (Table 4.1). Thirteen individual channel bodies make up the connections listed with an average of eight wing connections per channel body across these 2D exposures. Given that all channel bodies at this location are connected to an average of eight wings, there is a high probability of 3D connections for wings not seen connecting in 2D.

Type of connection	Valley-valley	Valley-channel	Channel-channel	*Wing-wing
Number of connections	2	2	7	2-5

Table 4.1. Type and number of potential reservoir body connections through wings in the Louisa 1B and 1C outcrops. *Isolated wings also exist.

Industry Applications

Oil and gas reservoirs in fluvial depositional systems are located around the globe (Halbouty et al., 1970; Bidgood, 2003). Due to the variation in sand distribution and lithologic changes over short distances, fluvial reservoir patterns can be difficult to predict. Numerous studies are aimed at determining the “net sand” from channel-belt reservoirs (Miall, 1988; Martin, 1993; Bridge and Tye, 2000), yet floodplain lake deposits typically constitute the majority of the “gross” section in wet high-accommodation settings (Catuneanu, 2003; Stoner, 2010). The presence of linear fluvial-deltaic channels, such as tie channels, and wing deposits may serve as conduits for hydrocarbon migration from organic source rocks in non-reservoir lacustrine settings to larger channel belt reservoirs and provide potintial reservoir facies within otherwise non-reservoir floodbasin mud (Stoner, 2010; Huling, 2014).

The exploitation of fluvial reservoirs by industry is enhanced by improving production and well economics with efficient recovery of available reserves. This is accomplished through a greater understanding of depositional setting and the associated rock characteristics to determine recoverable hydrocarbons. Due to the difficult predictability of fluvial channels and lithologic changes over short distances, a drill hole can penetrate through floodplain deposits and completely miss the targeted channel reservoir (Figure 4.8.). These strata are generally assigned a low reservoir potential because of a low net-to-gross ratio (Stoner, 2010). However, this assumption can leave a large depositional volume poorly modeled, which could potentially contain a significant amount of recoverable hydrocarbon reserves.

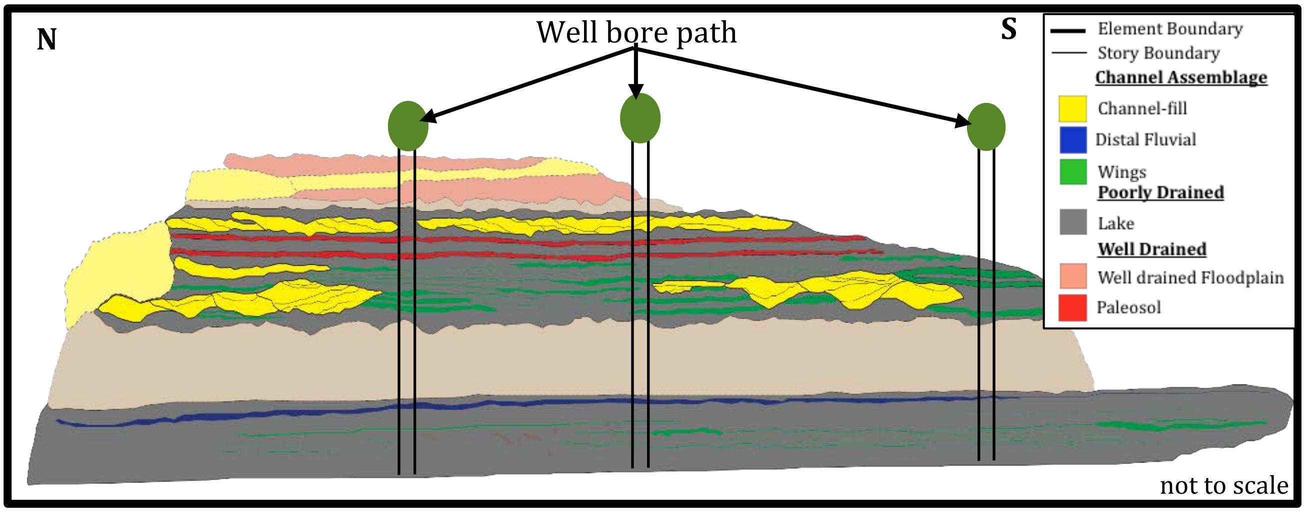

Figure 4.8. This figure illustrates potential well bore pathways in the Louisa 1C outcrop that can miss channel fill sands but still drain these reservoirs through connectivity of channel wings.

Reservoir connectivity, the percentage of a reservoir connected to wells, represents one of the primary controls on recovery in low net to gross environments (Larue and Hovadik, 2006). Previous studies tested channel connectivity in two-dimensional cross section using simulations of channel geometry. This resulted in significant decay in connectivity between 60-70% net-to-gross ratio (King, 1990; Allard & HERESIM Group, 1993). Larue and Hovadik (2006) extend these studies of fluvial reservoir connectivity using three-dimensional geostatistical modeling resulting in 90% connectivity when net to gross ratio is greater than 30%. In high-accommodation sections of the Louisa outcrops, net to gross ratios for channel bodies are estimated to range from 10-20%. However, estimated net to gross ratios for channel bodies and wings combined range from 30-40% in these two-dimensional exposures. It can be reasonably expected that these estimates hold true in three dimensions, yielding a 90% chance of reservoir connectivity; even when larger channel bodies aren't directly penetrated by a well bore (Larue and Hovadik, 2006).

High-accommodation fluvial systems with linear propagating channels and wings extending into the surrounding floodplain could have increased pressure communication and enhanced fluid flow between isolated channel bodies than previously thought (Slingerland and Smith, 2004). Floodplain sediments adjacent to fluvial channels may not act as an impermeable boundary for containment of oil and gas reserves in higher quality reservoir rock (Stoner and Holbrook, 2008). Wings and tie channels could also be significant in the management of groundwater or waste disposal should they have sufficient permeability to act as aquifers or flow conduits (Huling, 2014). Further study on the permeability of wings and tie channels preserved in the rock record, similar to those seen in the study area, will continue to shed light on their role as flow conduits within the floodplain.

CHAPTER 5

Conclusions

1. Two sequences of high to low-accommodation systems tracts are observed in the upper Princess and lower Glenshaw Formations near Louisa, Kentucky representing broad variation in paleo base level. Poorly drained floodplains represent periods of relatively high base level rise compared to sedimentation and indicate more accommodation space available for sediment accumulation. These high-accommodation intervals are composed of floodplain lakes, coals, isolated channels, tie channels, and wings. Well-drained floodplains exhibit rooted crevasse splays and paleosol development associated with lower base level and sub-aerial exposure during periods of slower accommodation relative to sediment supply.

2. Floodplain lakes dominate the high-accommodation intervals and are bisected by linear non-bifurcating deltaic channels. Delta front sediments are composed of laminated mud with sub-aqueous levees forming along the length of channels owing to jet margin sedimentation. Levees continue building up stream of the channel mouth as the channel progrades. Wings extend laterally from channels into the floodbasin as a result of high-flow events that forced bedload sediment over the top of submerged levees. Although they have been described in modern systems, this represents the first documentation of tie channels in the rock record.

3. Development of tie channels with associated wing increases connectivity and reservoir potential for floodbasin strata. This study illustrates the value of understanding non-

bifurcating deltas as they relate to floodplain sedimentation and their potential role in reservoir characterization. However, continued study of Central Appalachian Basin outcrops could further define the distribution of wings and tie channels in the area. More data could lead to increased predictability of fluid migration characteristics through floodplain sediments.

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VITA

Shea Atkins was born in Franklin, Tennessee on June 9, 1987. He moved to Hallsville, Texas at age five then returned to Franklin, Tennessee at age sixteen where he graduated from Fred J. Page High School.

He attended Columbia State Community College in Columbia, Tennessee for two years before transferring to Middle Tennessee State University (MTSU) in Murfreesboro, Tennessee where he graduated with a Bachelor of Science in Geology in May, 2012. While attending MTSU he met his wife, Julie Wingate, and they were married October 13, 2015. Shea worked full time as an environmental technician for W.Z. Baumgartner and Associates while pursuing his undergraduate degree where he gained experience in hydrogeology and the environmental industry in general.

In August, 2012, he enrolled in graduate school at Texas Christian University. Shea also worked as an intern for Finley Resources Inc., an oil and gas company in Fort Worth, Texas, beginning November 2012. Shea accepted a full time position with Finley beginning September 1, 2013 where he worked while completing his Master's Degree.

ABSTRACT

FLUVIAL-DELTAIC DEPOSITION IN HIGH ACCOMMODATION FLOODPLAIN LAKES, PENNSYLVANIAN APPALACHIAN BASIN, EASTERN KENTUCKY

Shea Atkins, MS Geology, 2016

School of Geology, Energy, and the Environment

Texas Christian University

John M. Holbrook, Thesis Advisor, Professor of Geology

Arthur Busbey, Associate Professor of Geology

Xiangyang, Xie, Assistant Professor of Geology

Middle to Upper Pennsylvanian sedimentary rocks in the central Appalachian Basin of Eastern Kentucky contain a significant fluvial component that has been extensively studied in some areas. However, most of the previous work focused on coastal plain sequence stratigraphic analysis and fluvial architecture with little focus on the up-dip fluvial pile.

Low energy regime fine-grained sediment dominates the high-accommodation fluvial setting along Highway 23 near Louisa, Kentucky. Relatively high water tables resulted in poorly drained floodplains and the formation of floodplain lakes adjacent to main fluvial channel bodies. Very fine grain sediments, interpreted as floodplain lakes, surround isolated tie channels connecting to the main channels. Thin, discontinuous, fine to very fine grain sand sheets connected to isolated channels represent pulses of subaqueous

deposition from tie channel propagation across the lake as a delta. The formation of tie channels from the main channel to floodplain lake deposits creates potential connectivity of otherwise isolated sand bodies. Bisection of the lake by tie channels creates a barrier for sediment transport and resulted in asymmetrical deposition of splay deposits from the main river channel. Examination of these outcrops revealed ancient examples of tie channel deposition into floodplain lakes that can be related to processes seen in modern environments.