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Fluvial Architecture and Sequence Stratigraphy of the Upper Williams Fork Formation, Plateau Creek Canyon, Piceance Basin, Colorado

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FLUVIAL ARCHITECTURE AND SEQUENCE STRATIGRAPHY OF THE
UPPER WILLIAMS FORK FORMATION, PLATEAU CREEK CANYON,
PICEANCE BASIN, COLORADO

by

RYAN JAMES SHARMA
B.S., University of Wisconsin – Madison, 2007

A thesis submitted to the
Faculty of the Graduate School of the
University of Colorado in partial fulfillment
of the requirement for the degree of
Master of Science
Department of Geological Sciences
2013
This thesis entitled:
Fluvial Architecture and Sequence Stratigraphy of the Upper Williams Fork Formation,
Plateau Creek Canyon, Piceance Basin, Colorado
written by Ryan James Sharma
has been approved for the Department of Geological Sciences

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Date _____________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.
Abstract

Ryan J. Sharma (M.S. Geology [Department of Geological Sciences])

Fluvial Architecture and Sequence Stratigraphy of the Upper Williams Fork Formation, Plateau Creek Canyon, Piceance Basin, Colorado

Thesis directed by Associate Professor Matthew J. Pranter

The upper Williams Fork Formation (Upper Cretaceous) of the Piceance Basin is a relatively high net-to-gross (>50% sandstone) low-sinuosity fluvial sequence deposited during the regression of the Western Interior Seaway. Six stratigraphic sections (total footage=1300 ft; 400 m) from exceptionally well exposed outcrops in Plateau Creek Canyon, 10 mi (16 km) northeast of Palisade, Colorado, were measured and described to evaluate the sedimentology and stratigraphy of the 500 ft (150 m) study interval. In addition, high-resolution photo-panoramas were acquired from the opposing cliffs to enable description and quantification of the external and internal architecture of the large-scale amalgamated channel complexes. The dimensions of reservoir-scale channel complexes in the lower and middle Williams Fork Formation have been well documented. This study is one of the first to describe these features in the upper Williams Fork Formation.

The study interval consists of three informal members: a lower, low net-to-gross (41%) interval containing areally restricted channel-complex deposits embedded in overbank mudstones and thinly bedded sandstones; a middle, intermediate net-to-gross (63%) interval dominated by sandstone-rich, laterally and vertically amalgamated channel complexes that form
laterally extensive sheet-like units with apparent widths of almost 1 mi (1.6 km) and thicknesses averaging 20-40 ft (6-12 m); and an upper, high net-to-gross (~80%) interval containing highly amalgamated bar sets and channel-fill elements. The two lower members are interpreted as the non-amalgamated and semi-amalgamated sequence sets of a basin-scale composite sequence, reflecting a transition from low- to high-accommodation conditions. The upper member is interpreted as the amalgamated sequence set of a second composite sequence, reflecting low-accommodation conditions subsequent to a major erosional event. The channel complexes in all three members are characterized by sharp erosional bases, stacked fining-upward bar and bar-set successions, a predominance of trough-crossbedding, extensive internal erosion, and sparse accretionary bedding. The sedimentological characteristics suggest that the fluvial style remained relatively constant across the study interval and that the increase in sandstone content and amalgamation of channel complexes toward the top of the study interval reflects changes in accommodation rather than a change in the depositional environment.
Dedication

This thesis is dedicated to my parents, Linda and Brahma, for their constant support and encouragement.
Acknowledgements

I would like to thank my advisor, Dr. Matthew Pranter, and my committee members, Dr. Penny Patterson (ExxonMobil), Dr. Gus Gustason, (Enerplus) and Rex Cole (Colorado Mesa University) for their guidance, knowledge, and encouragement. I am also grateful to all of those involved in the Williams Fork Consortium who provided valuable feedback along the way. Thanks to Brian Spitzmiller for his excellent work as my field assistant, and to Dr. Russell Stands-Over-Bull for providing the handheld spectral gamma-ray tool.

Special thanks to Bob and Sue Cluff, Keith Shanley, Daniel Hallau, and The Discovery Group for their flexibility and understanding as well as their technical and financial support.
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Introduction

Late Cretaceous-age fluvial deposits of the Williams Fork Formation form significant tight-gas reservoirs in the Piceance Basin of northwestern Colorado. A thorough understanding of the size, shape, and connectivity of these reservoirs is crucial to the effective development and production of this hydrocarbon resource because this information affects well spacing and completion practices. Reservoirs associated with fluvial settings, like those in the Williams Fork Formation, appear highly discontinuous and their dimensions may be difficult to determine and predict in the subsurface. Outcrop studies can be instrumental in reducing this uncertainty and can provide valuable information regarding the geometry, heterogeneity, and stratal-stacking patterns of a given interval that cannot be determined from subsurface data alone.

Prior studies have addressed the basin-scale sequence stratigraphy and geologic history of the Mesaverde Group and equivalent deposits (Tyler and McMurry, 1995; Hettinger and Kirschbaum, 2002; Johnson and Flores, 2003; Patterson et al., 2003; Kirschbaum and Hettinger, 2004; Hood and Yurewicz, 2008; Foster, 2010; Leibovitz, 2010; Aschoff and Steel, 2011; Hlava, 2011). A number of outcrop-based studies, including Cole and Cumella (2005), German (2006), Panjaitan (2006), Pranter et al. (2009), Harper (2011), and Pranter and Sommer (2011) have documented the sedimentology, fluvial architecture, and dimensional characteristics at several locations within the Piceance Basin, however they were primarily focused on the lower and middle Williams Fork Formation. Only a few studies (Cole et al., 2002; Patterson et al., 2003; Leibovitz, 2010; Keeton, 2012) have addressed the upper Williams Fork Formation.

The intent of this study was to fill this “data-gap” by examining outcrop exposures of the upper Williams Fork Formation in and above Plateau Creek Canyon in the southwestern portion of the Piceance Basin (Figure 1). The study interval is approximately 500 ft (150 m) thick and
Figure 1. A: The study area is located in Plateau Creek Canyon, approximately 20 mi (32 km) northeast of Grand Junction, CO (image from USGS DDS-69-B). B: The study outcrops (shaded orange) are exposed along the north side of Highway 65 and within Shire Gulch. The locations of the photo-panoramas shown in Figures 8, 11, and 12 are shaded blue.
begins directly on top of the highly amalgamated sandstone-rich middle Williams Fork Formation described by German (2006) and extends upward to the Cretaceous-Tertiary unconformity separating the Cretaceous Williams Fork Formation from the overlying Paleocene Ohio Creek Formation. The lower portion of the study interval is characterized by an abundance of mudstone and a scarcity of fluvial sandstone bodies while the upper portion is characterized by an abundance of highly amalgamated fluvial sandstone bodies. These two informal members were termed the “Flaco” and the “Ges,” respectively, by Keeton (2012) who described one complete stratigraphic section in the study area. This study proposes a subdivision of the Ges member into an upper, extremely sandstone-rich interval referred to as the A member, and a lower less sandstone-rich interval referred to as the B member. The underlying Flaco member is herein referred to as the C member (Figure 2).

The four primary objectives of this study were to 1) determine the depositional environment of the upper Williams Fork Formation at Plateau Creek Canyon, 2) determine the dimensions and spatial distribution of the reservoir-scale fluvial architectural elements, 3) address the cause of the dramatic change in sandstone content within the study interval, and 4) place the outcrop observations in a regional stratigraphic context. These objectives increase our understanding of the geologic history of the study interval and may improve modeling, production, and completion of the Williams Fork Formation and analogous fluvial reservoirs.
Figure 2. Terminology used in this report, type log (see Figure 1B for location) and relevant prior studies.
Geologic Setting

The Piceance Basin is located in northwestern Colorado and is bounded to the east by the White River Uplift, to the west by the Douglas Creek Arch, to the south by the Uncompahgre and Sawatch uplifts, and to the north by the eastern reaches of the Uinta Mountains (Cole et al., 2002; Patterson et al., 2003). By late Cretaceous time, the Piceance Basin region was situated on the western margin of the Western Interior Seaway (Figure 3). The seaway reached its maximum extent within the Rocky Mountain Foreland Basin during the Turonian, extending from northern Canada to the Gulf of Mexico and from central Utah to Minnesota (Roberts and Kirschbaum, 1995; Hettinger and Kirschbaum, 2002; Patterson et al., 2003; DeCelles, 2004). During the subsequent eastward retreat, the shoreline migrated back and forth across the Piceance Basin region before retreating completely by the Maastrichtian (Hettinger and Kirschbaum, 2002). During the entire transgression and regression of the seaway, fluvial systems transported large volumes of sediment from the Sevier orogenic belt in the west to coastal areas in the east resulting in the deposition of thousands of feet of clastic strata, including the Mancos Shale and overlying Mesaverde Group (Figure 4).

The retreat of the Western Interior Seaway is well preserved within the Cretaceous-Tertiary (Paleocene) deposits of the Piceance Basin. In the vicinity of the study area, the vertical succession shallows upward from the marine Mancos Shale to the fluvial Williams Fork Formation (Hettinger and Kirschbaum, 2002). Overlying and interfingering with the Mancos Shale are the Corcoran, Cozzette, and Rollins Members of the Iles (Mt. Garfield) Formation (Young, 1955; Erdmann, 1934) which represent three eastwardly progradational shoreline successions (Patterson et al., 2003). The basal portion of the overlying Williams Fork Formation contains the Cameo coal zone which was deposited in low-lying coastal plain settings landward
Figure 3. A: Paleogeographic setting of North America during the Late Cretaceous (~75 Ma). B: The present-day location of the Piceance Basin (outlined) was located on the coastal plain adjacent to the Western Interior Seaway during this time. Modified from Blakey (2008), Sloan (2012).
Figure 4. Cretaceous stratigraphy from eastern Utah to central Colorado. Red bar approximates the study interval. Modified from Cole and Pranter (2010); modified from Molenaar and Rice (1988).
of the shoreline. The remainder of the Williams Fork Formation can be subdivided into three informal members: lower, middle, and upper. The lower Williams Fork Formation is interpreted as meandering fluvial deposits while the middle and upper members are interpreted to contain both meandering and low-sinuosity to braided fluvial deposits.

The stratigraphic interval between the late Cretaceous Williams Fork Formation and the Eocene Wasatch Formation is occupied by a complicated and somewhat poorly understood succession containing fluvial sandstone and quartz-pebble conglomerate which has been referred to as the Ohio Creek Conglomerate, the Ohio Creek Member (of the Mesaverde Group), and the Ohio Creek Formation in the Piceance Basin. Both the relationship to the underlying Williams Fork Formation (conformable vs. unconformable) and the age of the sediments (Cretaceous vs. Tertiary) has been debated and revised for almost one hundred years (see Johnson and May, 1980). By the 1980’s, analysis of palynomorph assemblages suggested a late-Cretaceous age for the Ohio Creek Member and placed the Cretaceous-Tertiary boundary within the regional unconformity at the base of the overlying Wasatch Formation. However, new palynomorph analyses presented by Patterson et al. (2003) and fossil vertebrate fauna described by Burger (2007) suggest that not only is the Ohio Creek Member of Tertiary age, but the upper portion of the Williams Fork Formation may be as well.

The final regression of the Western Interior Seaway and formation of the Piceance Basin was associated with deep-seated Laramide tectonics that subdivided the Rocky Mountain Foreland Basin into numerous sub-basins (Dickinson et al., 1988; Hettinger and Kirschbaum, 2002; Patterson et al., 2003; DeCelles, 2004). The basin axis trends roughly NNW-SSE and is asymmetrical in profile, with the eastern margin dipping steeply against the White River Uplift and the western margin dipping more gently across the Douglas Creek Arch, which is a north-
south trending structural high separating the Uinta and Piceance basins. This structural configuration has resulted in a ring of Mesaverde Group outcrops around the edges of the basin that allow for examination of strata analogous to the tight-gas sandstone targets currently producing gas in the deeper portions of the basin.
Methodology

Six stratigraphic sections (measured sections MS-1 to MS-6) covering approximately 1,300 ft (400 m) were measured and described along Plateau Creek Canyon and within Shire Gulch (Figure 5). Two of the measured sections were located within the C member (MS-1, MS-4), three were located in the A and B members (MS-2, MS-5, MS-6), and one was located in the Ohio Creek interval (MS-3). Lithology, grain size, sedimentary structures, ichnofossils, paleocurrent direction and bounding surfaces were observed and recorded in all measured sections. The total gamma-ray signature of the outcrop was measured at 1-ft (0.3 m) intervals with a Super-Spec RS-125 scintillometer (Radiation Solutions, Inc.) (Appendix A).

High-resolution photo-panoramas acquired from the cliffs opposing the outcrops of interest provide photographic documentation of the entire 3.5 mi- (5.6 km-) long outcrop exposure on the north side of Plateau Creek, as well as the 0.5 mi- (0.8 km-) long exposure on the west side of Shire Gulch. These photo-panoramas allowed for the description and quantification of the large-scale amalgamated channel complexes that are difficult to access on foot. Width and thickness measurements of the channel complexes were estimated from the photo-panoramas and GPS field measurements. To validate the estimated values, the estimates were compared to a number of outcrop measurements made with a tape measure. The estimates vary from the true values by less than 15% (Appendix A). No attempt to correct for paleoflow direction was made because the outcrops utilized are oriented approximately normal to the paleoflow direction.

A Petra project containing 2,886 wells with digital gamma-ray logs was assembled to facilitate regional subsurface correlation within the Piceance Basin. The gamma-ray logs from 65 wells between the study area and Rifle Gap were normalized to representative type-wells
Figure 5. Measured sections (MS) described in this study. Left track = handheld gamma-ray, right track = sedimentological description. Both gamma-ray and grain size increase to the right. The blue line indicates the location of the cross section displayed.
(Appendix A). This subset of wells allowed for correlation and comparison to other Williams Fork Formation studies within the Piceance Basin. Log-derived net-to-gross ratios were calculated within the vicinity of the study area for comparison to outcrop observations. It should be noted that in this study, “net-to-gross” refers to the proportion of sandstone relative to the gross thickness of the interval. “Net” refers only to sandstone lithologies, and should not be confused with “pay” or “net pay” which implies other criteria such as minimum porosity or resistivity.
Hierarchy of Fluvial Deposits

This study utilizes the hierarchical framework established by Patterson et al. (1995) and Sprague et al. (2002) which is based on the physical characteristics of fluvial stratigraphic elements and their associated bounding surfaces. Fluvial deposits contain a hierarchy of depositional elements that range in scale from individual lamina to basin-scale composite sequences. Eleven such hierarchical elements are recognized in this model, however analysis of fluvial architecture primarily relies on the seven largest elements. A full discussion of these hierarchical elements is provided in Patterson et al. (2010), and is summarized in Table 1 and Figure 6. The concept of hierarchical order within fluvial strata is not new (e.g. McKee and Weir, 1953; Allen, 1966, 1983; Miall, 1974, 1988); however, the hierarchical approach utilized in this study is advantageous in that the larger hierarchical elements are directly related to stratal units defined using modern sequence stratigraphy which allows direct comparison to sequences and related units observed in shallow-marine settings (Sprague et al., 2002).

The small- to intermediate-scale hierarchical elements (beds, bars, and channel-fills) are thought to respond primarily to autogenic factors such as channel avulsion, local hydrodynamic conditions, and local base-level change while large-scale elements (sequence sets and composite sequences) are thought to reflect basin-scale changes related to allogenic factors such as tectonism, climate, and sediment supply (Shanley and McCabe, 1994; Patterson et al., 2012). Depositional sequences are intermediate-scale elements that are probably influenced by both autogenic and allogenic mechanisms, to varying degrees, depending on the unique circumstances of a given depositional setting at a given time. The various mechanisms may interfere constructively or destructively, potentially resulting in ambiguity regarding the interpretation of causal mechanisms within continental strata.
Figure 6. Schematic diagram of alluvial hierarchical elements. Fluvial sandstones are shown in yellow, floodplain mudstones are shown in green, levee sandstones are shown in brown, and crevasse splays are shown in pink. Red lines represent sequence boundaries. The colored triangles associated with each hierarchical element are consistent throughout this report. From Patterson et al. 2010, modified from Sprague et al., 2002.
<table>
<thead>
<tr>
<th>Alluvial Hierarchical Element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar</td>
<td>The aggregate of genetically related beds and bedsets deposited within a confined channel. May form by lateral- or downstream-accretion, or as vertically aggrading fields of migrating bedforms.</td>
</tr>
<tr>
<td>Bar Set</td>
<td>A relatively conformable succession of genetically related bars that amalgamate vertically and/or laterally within the channel. Typically exhibit a fining-upward grain-size trend.</td>
</tr>
<tr>
<td>Channel-Fill</td>
<td>A relatively conformable succession of genetically related bar or bar-set elements that are deposited and preserved within a river channel that is defined by bankful discharge. Typically exhibit a fining-upward grain-size trend which reflects scouring, filling, and abandonment of the channel.</td>
</tr>
<tr>
<td>Channel Complex</td>
<td>Two or more channel-fill elements of similar fill type and their coeval floodplain deposits. Stratal stacking patterns may be described as amalgamated, semi-amalgamated, or non-amalgamated.</td>
</tr>
<tr>
<td>Depositional Sequence</td>
<td>A relatively conformable succession of genetically related channel-complex elements and their coeval floodplain strata bounded by regional surfaces of erosion or their correlative conformities (“sequence boundaries”). Typically composed of an amalgamated sand-rich channel complex element that is conformably overlain by a non-amalgamated mud-rich channel complex element.</td>
</tr>
<tr>
<td>Sequence Set</td>
<td>Two or more sequences that possess a similar stratal stacking pattern, bounded above and below by regional erosional surfaces or their correlative conformities. Three types are recognized: amalgamated, semi-amalgamated, and non-amalgamated. Allogenic mechanisms, such tectonism or climate, are the primary influences on sequence set accumulation.</td>
</tr>
<tr>
<td>Composite Sequence</td>
<td>A succession of sequence sets recording a basin-scale cycle of decreasing and increasing accommodation relative to sedimentation. Rapidly decreasing accommodation results in regional surfaces of erosion which are overlain by amalgamated or semi-amalgamated sequence sets reflecting a return to positive accommodation. These deposits are overlain by non-amalgamated sequence sets which reflect a pronounced increase in accommodation. The non-amalgamated sequence set may be succeeded by a semi-amalgamated sequence set resulting from a decrease in accommodation prior to development of the overlying regional surface of erosion.</td>
</tr>
</tbody>
</table>

Table 1. Summary of alluvial hierarchical elements (*sensu* Patterson et al., 2010).
All hierarchical elements outlined in Figure 6 can be readily observed within the outcrops of Plateau Creek Canyon. As will be discussed in following sections, the study area contains amalgamated and non-amalgamated channel complexes that comprise a number of depositional sequences, which in turn comprise amalgamated, non-amalgamated and semi-amalgamated sequence sets that can be correlated via well logs throughout the Piceance Basin. Smaller-scale elements such as channel fills, channel complexes, and depositional sequences can also be identified in well logs, however due to their limited lateral extent, well-to-well correlations are often impossible unless the wells are closely spaced.
**Lithofacies and Facies Associations**

Eleven unique lithofacies were identified in the Plateau Creek Canyon outcrops (Table 2). There is a strong bias toward sandstone lithofacies, both in the total amount observed and in the level of detail recorded, because the thick sandstone-rich channel-fills tend to be resistant cliff-formers and are therefore well exposed in outcrop. The intervening floodplain-related intervals tend to be slope-forming and are typically covered by colluvium and vegetation, making direct observation difficult or impossible in all but a couple of isolated locations. One such location revealed that while the covered intervals are generally considered to be mudstone-dominated, the dominant lithology may in fact be fine- to very fine-grained sandstone (Figure A1). The slope-forming nature of these intervals is due to the relatively high mudstone content and the thinly-bedded nature of the sandstone bodies, which are seldom thicker than 2 ft (0.6 m).

Trough cross-bedded sandstone and structureless sandstone are the dominant lithofacies observed, comprising roughly 70% of the non-covered intervals (Figure A2). With the exception of more abundant bioturbated sandstone in the C member, the relative proportions of the remaining lithofacies are remarkably consistent in both the B and C members, suggesting little significant change in hydrodynamic conditions across those intervals. The bioturbated sandstone observed primarily in the C member contained numerous ichnofossil types including pelleted burrows (*Ophiomorpha*), *Skolithos, Arenicolites, Teredolites*, and dinosaur tracks (Figure A3). The sandstone-rich A member is comprised of approximately 85% trough cross-bedded and structureless sandstone reflecting a lack of preservation of low-energy sedimentary features.

The lithofacies observed in outcrop occur as three distinct facies associations: sandy bars, crevasse splays, and floodplain-fines. Sandy bars are the primary constituents of depositional
<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Symbol</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trough cross-bedded sandstone</td>
<td>St</td>
<td>sinuous-crested or linguoid (3-D) dunes</td>
</tr>
<tr>
<td>Planar cross-bedded sandstone</td>
<td>Sp</td>
<td>straight-crested (2-D) dunes</td>
</tr>
<tr>
<td>Structureless sandstone</td>
<td>Ss</td>
<td>sediment gravity-flow deposits or highly bioturbated</td>
</tr>
<tr>
<td>Contorted sandstone</td>
<td>Sc</td>
<td>rapid deposition resulting in soft-sediment deformation or fluid escape</td>
</tr>
<tr>
<td>Bioturbated sandstone</td>
<td>Sb</td>
<td>sedimentary structures destroyed by burrowing organisms, preserved dwelling/feeding structures or root traces</td>
</tr>
<tr>
<td>Ripple cross-laminated sandstone</td>
<td>Sr</td>
<td>ripples</td>
</tr>
<tr>
<td>Low-angle to horizontally laminated sandstone</td>
<td>Slh</td>
<td>upper plane bed</td>
</tr>
<tr>
<td>Laminated mudstone</td>
<td>Ml</td>
<td>settlement from suspension</td>
</tr>
<tr>
<td>Structureless mudstone</td>
<td>Ms</td>
<td>sedimentary structures destroyed by burrowing/rooted organisms, pedogenic modification, or outcrop weathering</td>
</tr>
<tr>
<td>Structureless conglomerate</td>
<td>Cs</td>
<td>bedload transport; sediment gravity flow or unrecognizable structure/grading (Ohio Creek only)</td>
</tr>
<tr>
<td>Planar bedded conglomerate</td>
<td>Cp</td>
<td>bedload transport (Ohio Creek only)</td>
</tr>
</tbody>
</table>

**Table 2.** Summary of lithofacies observed in Plateau Creek Canyon outcrops.
elements that form under confined flow conditions (e.g., channel fill and crevasse-channel elements). Crevasse splays and floodplain-fines are associated with unconfined flow on the floodplain. This three-component system is based on the classification scheme of Patterson et al. (2012) who described ten unique facies associations in similar late-Cretaceous fluvial deposits from the Doba Basin, Chad. Those ten facies associations were divided into three groups: 1) sandstone lithofacies associations (coarse sandy bar, sandy bar, and mixed sand and mud bar), 2) sandstone and mudstone lithofacies association (crevasse channel, crevasse splay, floodplain couplet, and terminal splay), and 3) mudstone lithofacies association (abandoned channel, floodplain mudstone, lacustrine mudstone). Poor outcrop exposure of mud-rich and thinly bedded sediments prevented conclusive identification of any of the mudstone lithofacies so these, along with floodplain couplets, have been consolidated into the floodplain-fines facies association in this study. No coarse sandy bar or terminal splay facies associations were observed in the study area.

Sandy Bar Facies Association

Sandy bars are characterized by fining-upward packages (beds and bed sets) that range from medium- to very coarse-grained sand at the base to fine- or very fine-grained sand at the top (where preserved). From bottom up, an idealized bar sequence contains an erosional base, a coarse lag deposit often containing mud chips, cosets of trough sets that tend to decrease in size, low-angle to horizontal planar lamination, and ripple cross-lamination at the top (Figure A4). The low-flow regime structures (planar lamination and ripple cross-lamination) are commonly bioturbated; however, tubular burrows have also been found in the higher-energy trough cross-bedded lithofacies. The average thickness of individual bar sequences is 5.2 ft (1.6 m, N = 20) in
the C member, 7.3 ft (2.2 m, N = 16) in the B member, and 3.9 ft (1.2 m, N = 13) in the A member (Figure A5). The sandy bar facies associations are interpreted to have formed within crevasse channels or as midstream and bank-attached bars within low-sinuosity braided river channels due to the abundance of trough and planar cross-bedding, multiple erosional surfaces, and lack of lateral accretion deposits. Mud-chip clasts found dispersed throughout the bar sequences are attributed to bank collapse and the reworking of mud and silt deposited in abandoned chutes and cross-bar channels.

*Crevasse Splay Facies Association*

Crevasse splays form adjacent to the margins of channels during a levee breach, resulting in the deposition of relatively coarse sediment on the otherwise fine-grained floodplain deposits (Miall, 1996). A typical crevasse splay succession coarsens-upward, reflecting lateral progradation of the splay deposits during one or more flood events. The top of the succession may exhibit a fining-upward trend formed as the flood wanes and energy levels decrease. The coarsening-upward trend was only very rarely observed in the outcrop measured sections (Figure A6). These “classic” crevasse-splay deposits are interpreted as relatively proximal to the levee breach. Far more common are the distal deposits, representing only the lower portion of a coarsening-up sequence, which tend to be less than 3 ft (0.9 m) thick and are characterized by low-flow regime lithofacies (Sr, Slh, Ml, Ms) and abundant bioturbation (Sb) (Figure A7). These distal deposits exhibit variable grain-size trends and are commonly interbedded with mudstone, suggesting episodic deposition. Unfortunately, the distinction between distal crevasse-splay deposits and other floodplain-fines (described in next section) is somewhat ambiguous and distinguishing one from the other is difficult, particularly when the overall geometry of the
sandstone body cannot be determined due to poor outcrop exposure. For example, the interval shown in Figure A7 is tentatively interpreted as distal crevasse-splay deposits, but may alternatively be interpreted as floodplain-fines akin to the floodplain couplet facies of Patterson et al. (2012). The average thickness of crevasse-splay deposits observed in the measured sections is 3.1 ft (0.9 m, n = 21).

*Floodplain-Fines Facies Association*

The lithofacies associated with the floodplain-fines facies association are poorly constrained because these deposits are rarely exposed in outcrop (Figure A1). Where visible, they are thinly bedded and lithologically diverse. The dominant lithofacies are Ss, Sr, Sb, Ms, and Ml. Floodplain-fines are likely to include deposits from floodplain lakes and swamps, flooding events, and interfluve soil development. As mentioned in the previous section, distal crevasse splay deposits potentially constitute a significant portion of the floodplain-fines because they are difficult to distinguish from larger-scale flooding events that also distribute relatively coarse sediment across the floodplain. During analysis and interpretation of the measured sections and photo-panoramas, all covered intervals were assumed to contain the floodplain-fines facies association.
Fluvial Architecture

Architectural Elements

The three main architectural elements identified at the outcrop scale in this study are 1) channel-fills, 2) crevasse-splays, and 3) floodplain-fines. This schema conforms loosely to many prior Williams Fork Formation studies (e.g., German, 2006; Pranter et al., 2009; Harper, 2011; Keeton, 2012), but primarily follows the hierarchy of fluvial strata and its constituent elements defined by Patterson et al. (2010) (Figure 6).

The channel-fill element, roughly analogous to the single-story or simple channel element of Friend et al., (1979), is defined as a relatively conformable succession of genetically related bar or bar-set elements that are deposited and preserved within a channel defined by bankful discharge (Patterson et al., 2010). It is bounded at its base by a concave-up erosional surface and at its top (when preserved) by a transition from sandstone-dominated channel lithofacies (sandy bar facies association) to mudstone-dominated overbank lithofacies (floodplain-fines facies association). Channel-fill elements amalgamate to form amalgamated channel complexes, which are in turn overlain by non-amalgamated channel complexes which consist of smaller, isolated channel fills embedded within floodplain-related sediments. Together, the amalgamated channel complex and the non-amalgamated channel complex form a depositional sequence which is bounded at its top and base by sequence boundaries (Figure 7).

The internal architecture of a channel-fill is diagnostic of the fluvial style of deposition (Allen, 1983). For example, channel-fills deposited in a highly sinuous, meandering river system will exhibit abundant lateral-accretion deposits as was observed in the lower Williams Fork Formation by Cole and Cumella (2005) who also described five unique sandstone body types observed in outcrop. Sandstone bodies exhibiting similar overall geometry to these five types are
Figure 7. Outcrop example of a complete depositional sequence. Bars and bar sets stack to form channel-fill elements that amalgamate both laterally and vertically to form a sandstone-rich amalgamated channel complex (A). The amalgamated channel complex is bounded at its base by an erosional sequence boundary and at its top by an abandonment surface (white line) delineated by a transition from sandy bar lithofacies (yellow) to floodplain-fines lithofacies. It is overlain by a non-amalgamated channel complex (N) which contains floodplain-fines, crevasse-splays, and small channel-fill elements. The entire sequence is bounded above and below by sequence boundaries.
observed in the upper Williams Fork Formation at Plateau Creek Canyon however the internal architecture is significantly different. As noted by Cole and Pranter (2008) channel-fill elements in the upper Williams Fork Formation rarely contain lateral-accretion deposits and instead are characterized by abundant internal scours at a variety of scales that are filled with complex cross-bedding. After adjusting for the variation in internal architecture, the “narrow,” “simple sinuous,” and “poorly channelized” sandstone bodies (Types A, B, and D) of Cole and Cumella (2005) are classified as channel-fill elements in this study, and the “compound sinuous” sandstone bodies (Type C) are classified as amalgamated channel complexes (Figure A8).

Crevasse-splay elements, formed under unconfined flow conditions, tend to be broadly lenticular to sheet-like in shape and often interfinger with fine-grained floodplain sediments at their margins due to episodic deposition (Miall, 1996; Cole and Cumella, 2005). They are identified in outcrop by their associated lithofacies, relatively non-erosional bounding surfaces, and lenticular geometry. Crevasse-splay elements tend to be relatively thin (~ 3ft [0.9 m]) and fine-grained which results in poor outcrop exposure. As such, apparent widths could not be determined. Crevasse-splays generally correspond to the “broadly lenticular” sand-body geometry (Type E) of Cole and Cumella (2005) (Figure A8).

The floodplain-fines architectural element encompasses all deposits not associated with channel-fill or crevasse-splay elements that are deposited on the floodplain. As described in the facies association section, floodplain-fines are typically covered by colluvium. Therefore, all covered intervals encountered in measured section or photographs are classified as floodplain-fines. As an architectural element floodplain-fines have no discrete boundaries, instead they exist as a fine-grained matrix into which channel-fill and crevasse-splay elements are embedded.
Fluvial Architecture

The C member is characterized by relatively abundant floodplain-fines and crevasse-splays, and relatively small amalgamated channel complexes (Figure 8). Outcrop observations suggest a net:gross ratio of 40-60%, which is somewhat higher than the net:gross ratio determined from normalized gamma-ray logs using a 90 API cutoff (Table 3, Figure 9). This discrepancy is explained by two factors: 1) outcrop work is biased toward the more sand-prone locations because they offer better exposure even though they may not be representative of the interval as a whole, and 2) thin sandstone units, which can be observed in outcrop, are not accurately measured by the gamma-ray tool when they are interbedded with radioactive mudstones, resulting in an underestimation of the total amount of sandstone present.

Amalgamated channel complexes embedded in the floodplain deposits of the C member are typically 20-35 ft (6-11 m) thick, with apparent widths ranging from several hundred feet to over 3000 ft (915 m) measured approximately perpendicular to the paleoflow direction (Figure 10). Based on these dimensions and their associated width-to-thickness ratios, the majority of these amalgamated channel complexes would be classified as narrow sheets according to Gibling (2006) (Table 4). Somewhat unique to this interval are a number of small, isolated sandstone bodies with channel-form or tabular geometry. They typically measure 3-9 ft (1-3 m) in thickness and 40-70 ft (12-21 m) in width and are interpreted as crevasse channels or small secondary channels cross-cutting the floodplain (Figure A9).

In contrast, the B member is characterized by a relative scarcity of floodplain-fines and crevasse-splays, though these floodplain-related sediments may be locally abundant as was observed in MS-5 (Figure A11). Elsewhere, the amalgamated channel complexes, which are typically separated from one another by slope-forming non-amalgamated channel complexes, are
Figure 8. The C member is characterized by relatively abundant floodplain-fines (un-shaded, covered by colluvium and vegetation) and crevasse-splays (shaded orange). In this view, amalgamated channel complexes (shaded yellow) and associated non-amalgamated channel complexes form five depositional sequences (orange triangles) bounded by sequence boundaries (red lines). The D member (middle Williams Fork Formation, not shown) is just below the exposed interval pictured here. See Figure 1 for location.
Table 3. Net: gross ratios were calculated from normalized gamma-ray logs using a 90 API cutoff (Figure 9). The calculated ratios are likely a reasonable approximation of the abundance of reservoir-scale amalgamated channel complexes, though they probably underestimate the true abundance of sandstone. The well-to-well variability observed primarily in the B member but also in the C member is consistent with outcrop observations.
Figure 9. The cross-section shown above contains six wells from Shire Gulch field which is adjacent to the study area. Track 1 displays color-filled normalized gamma-ray logs. Intervals colored green in track 2 indicate sandstone based on a 90 API cutoff. The average net:gross (N:G) ratio for each interval is listed to the right (A member N:G ratio estimated from outcrop observations and log data where available). Cross-section datum = abandonment surface at the top of the middle Williams Fork Formation (WFF).

The map at right shows the location of the cross section (blue line), the study area (yellow star), gas fields (pink), and the Mesaverde outcrop (green). All of the cross-section wells are within 3.5 miles (5.6 km) of the study area.
Figure 10. Width vs. thickness crossplot of 14 amalgamated channel complexes. Complexes in the B member are significantly wider however, with the exception of the two circled data points which are the result of localized incision, they are only slightly thicker than the complexes in the C member.
Table 4. Dimensions of the 14 selected amalgamated channel complexes, their associated width-to-thickness ratios, and classification according to Gibling, 2006. The apparent widths measured in the B member (*) do not represent the true lateral extent of the channel complexes and therefore the corresponding classification may be incorrect. Many of these channel complexes may actually be broad sheets.

<table>
<thead>
<tr>
<th>Member</th>
<th>Maximum thickness (ft)</th>
<th>Apparent width (ft)</th>
<th>W:T ratio</th>
<th>Classification</th>
</tr>
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<tbody>
<tr>
<td>B</td>
<td>32</td>
<td>1392*</td>
<td>44</td>
<td>Narrow Sheet</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>1629*</td>
<td>68</td>
<td>Narrow Sheet</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>1951*</td>
<td>108</td>
<td>Broad Sheet</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>2173*</td>
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<td>36</td>
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<td>50</td>
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<td></td>
<td>62</td>
<td>4805*</td>
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<td>10</td>
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<tr>
<td></td>
<td>22</td>
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<td></td>
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<td>78</td>
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<tr>
<td></td>
<td>27</td>
<td>3057</td>
<td>113</td>
<td>Broad Sheet</td>
</tr>
</tbody>
</table>
Figure 11. The B member is characterized by abundant amalgamated channel-complexes that exhibit more lateral amalgamation than those in the underlying C member. True apparent widths of the channel-complexes could not be determined in this interval since one or both ends are typically truncated due to modern erosion of the outcrops. The amalgamated channel-complexes typically exhibit a sheet-like geometry with little variation in thickness across their widths, however localized incision does occasionally occur which creates anomalously thick sandstone bodies that may be several times the average thickness (1). See Figure 1 for location.
stacked directly atop one another, resulting in a localized succession of nearly 90% sandstone (Figure 12). Outcrop observations suggest the amalgamated channel complexes constitute, on average, approximately 60% of the semi-amalgamated sequence set. This agrees well with the log-derived net:gross ratio of 63% (Table 3). From a purely lithological standpoint, however, the true net:gross ratio is probably closer to 80% because, as discussed previously (see Figure A1), the intervals between the amalgamated channel complexes may contain as much as 60% sandstone.

The amalgamated channel complexes in the B member exhibit more lateral amalgamation than those in the underlying C member, resulting in measured apparent widths of 1400 to 4800 ft (427 to 1460 m) (Figure 10). These values, however, represent minimum widths since in all cases one or both ends of the channel complexes have been truncated by modern erosion, thus making accurate measurement impossible. The true lateral extent of these channel complexes is therefore unknown. Maximum thicknesses typically range from 18 to 62 ft (5.5 m to 19 m), though values over ~40 ft (12 m) are likely to reflect relatively localized features. In some cases the maximum thickness approximates the average thickness, however where deep incision into the underlying sequence has occurred, the maximum thickness may be up to double that of the average thickness. This deep incision is generally only observed in the B member and is responsible for the two anomalously thick measurements highlighted in Figure 10. Without this effect, the average thickness of amalgamated channel complexes in the B member would be approximately 30 ft (9 m), only 5 ft (1.5 m) larger than the average value in the C member. Based on the dimensions listed in Table 4, most of the amalgamated channel complexes would be classified as narrow sheets, however if the true lateral extent could be determined it is likely that they would be re-classified as broad sheets (Gibling, 2006). Outcrop limitations prevented
Figure 12. An outcrop from the east side of the study area shows increased vertical amalgamation of amalgamated channel-complexes within the B member. Incision into underlying non-amalgamated channel-complexes is also more prevalent, resulting in localized successions of almost 90% sandstone (1). A well drilled at location (1) would encounter what appeared to be a single 130 ft thick sandstone interval. In contrast, a well drilled approximately 1800 ft to the west at location (2) would encounter several discrete sandstone bodies, each 20-40 ft thick. Marks indicating 660-ft intervals simulate 10-acre well spacing. See Figure 1 for location.
sufficient examination of amalgamated channel complexes in the downstream direction so the relationship between width and length could not be determined.

The A member, representing the uppermost portion of the Williams Fork Formation within the study area, contains a 60-90 ft (18-27 m) thick, regionally continuous amalgamated sandstone interval (Figures 11 & 12). This interval is dominated almost exclusively by the sandy bar lithofacies association and contains abundant scour surfaces separating amalgamated channel-fill elements. The high degree of amalgamation prevents identification of discrete amalgamated channel complexes, though the interval as a whole appears to have lateral extents of at least 10-20 mi² (26-52 km²). Spherical concretions often exceeding 3 ft (1 m) in diameter are common in this interval.

The top surface of the A member is extremely flat and was therefore used a datum within the study area. While this surface appears similar to the abandonment surfaces associated with amalgamated channel complexes in the underlying sequence sets, it is unique in that it is not overlain by the same floodplain-fines lithofacies. Instead, it is overlain by a variegated (purple, gray, and yellow) regionally extensive mudstone interval that is capped by a distinctly white, fine- to medium-grained sandstone interval (Figure A10). The mudstone interval, interpreted as the Ohio Creek paleosols described by Johnson and Flores (2003), contains abundant root traces, burrows, and carbonaceous material and exhibits a lack of sedimentary structures (Figure A11). Distinct color-bands suggest pedogenic alteration and the development of soil horizons (Figure A12). The overlying sandstone interval varies in thickness but typically ranges from 20-40 ft (6-12 m) depending on the amount of incision into the underlying paleosols, and probably represents amalgamated fluvial channel-complexes. This interval is succeeded by the “Ohio
Creek Conglomerate” or “unnamed basal conglomerate” of Johnson and Flores (2003) which is characterized by well-rounded chert pebbles and cobbles (Figure A13).
Depositional Environment

Multiple lines of evidence suggest the rivers during upper Williams Fork deposition were straight to braided with low-sinuosity. Paleocurrent measurements \((n=49)\) show a relatively consistent paleoflow direction to the northeast (Figure 13) which is in general agreement with the findings of Keeton, 2012. Sinuosity was calculated from Equation 1, sensu McLaurin and Steel, 2007:

\[
\text{sn} = \frac{4.84}{(4.84-\phi^2)}
\]  

(1)

where \(\text{sn}\) is sinuosity and \(\phi\) is the circular standard deviation in radians. The sinuosity of the C member, B member, and A member is 1.03 \((\phi = 0.34)\), 1.37 \((\phi = 1.15)\), and 1.17 \((\phi = 0.84)\), respectively. The sinuosity for the entire study interval is 1.19 \((\phi = 0.89)\). With the exception of the B member, all of these values indicate low-sinuosity, straight to braided rivers (Miall, 1996). The sinuosity of the B member would suggest rivers of intermediate sinuosity. These results are in conflict with those of Keeton, 2012 who calculated greater sinuosity in the C member \((1.9)\) than in the overlying units \((1.1)\). Two factors probably account for this discrepancy: first, the stratigraphic section described by Keeton contains one of the few amalgamated channel-complexes that contain lateral-accretion deposits indicative of a high-sinuosity river. No such deposits were encountered in any of channel-complexes examined in this study. Second, the sample size of paleocurrent measurements utilized in both studies may be too small to accurately describe paleoflow directions and sinuosity of the individual sequence sets within the study interval.
Figure 13. Paleocurrent orientations measured primarily from trough crossbed axes. All three intervals show relatively consistent paleoflow to the northeast with vector means (μ) ranging from approximately 45° to 63°. Circular standard deviation (φ) shown in radians.
Further evidence for a braided fluvial setting is found in the internal architecture of the amalgamated channel-complexes. In a meandering fluvial setting, point-bar deposits exhibiting lateral accretion are the dominant sedimentary feature within the amalgamated channel-complexes. Such features are commonly described in the lower Williams Fork Formation (e.g. Cole and Cumella, 2005; Pranter et al., 2009; Harper, 2011; Keeton, 2012; Sloan, 2012). The upper Williams Fork Formation at Plateau Creek Canyon, however, contains relatively few lateral accretion deposits. Instead, amalgamated channel-complexes are characterized by a high degree of internal complexity resulting from repeated scouring and filling of channels within a sandy braidplain (Figure 14). These deposits are consistent with the depositional processes associated with braided rivers and their internal structure closely resembles that of modern braided river deposits (e.g. Lunt et al., 2013).

Channel depth can be estimated through several methods. A number of authors (e.g. Leeder, 1973; Miall, 1996; Bridge and Tye, 2000) have demonstrated that fining-upward successions in meandering fluvial deposits can approximate the bankfull channel depth of the river during deposition. In braided fluvial systems, however, the relationship between fining-upward successions and channel depth is complicated by the presence of multiple channels within the braidplain, some of which may only be active during periods of high discharge. Fining-upward successions approximate the depth of the channel in which they are deposited but it is highly likely that each channel within the braided river will have a different depth (Bristow and Best, 1993). Additionally, the convergence of two channels may produce excessive scouring, or “hollows” that can be up to six times the mean channel depth, resulting in anomalously thick, localized channel-fill successions that would not accurately reflect the overall channel depth (Miall, 1996). Overall, the range in the thickness of fining-upward successions may reflect the
Figure 14. A portion of an amalgamated channel-complex from the B member illustrating internal architecture typical of bradied fluvial deposits. Colored polygons delineate individual bars and bar sets that record repeated scouring and filling of channels within the braidplain. Paleoflow direction is into the page. Vertical exaggeration = 2X.
range of channel sizes within the braidplain and the variety of bar forms associated with fluctuating discharge over time (Bristow and Best, 1993).

The fining-upward bar successions shown in Figure A5 represent individual bars and bedforms migrating within the channel. Together, these bars form bar sets which, in turn, form channel-fills which can approximate channel depth during deposition. Identifying individual channel-fills can be difficult in highly amalgamated channel-complexes where a significant portion of a channel-fill may be eroded by an overlying channel, thus giving the appearance of a single fining-upward channel-fill succession composed of stacked fining-upward bars and bar sets. Thus, only those channel-fills that could be identified with a reasonable degree of confidence were selected for the estimation of channel depth. The base of a channel-fill succession was identified by an erosional surface overlain by relatively coarse sandstone often containing mud-chip and/or quartz pebble clasts (interpreted as thalweg deposits). This is followed by relatively conformable bed sets, bars, and bar sets that exhibit an upward decrease in size, flow regime, and grain size until full abandonment of the channel and a transition to floodplain-fines deposition. In total, 10 channel-fills meeting these criteria were identified in the C member set and 13 were identified in the B member.

The average thickness of channel-fill successions in the C member and B member is 10.1 ft (3.1 m) and 13.6 ft (4.1 m), respectively, with maximum thicknesses of 18 ft (5.5 m) and 24 ft (7.3 m), respectively. Assuming these successions represent channel depth, this suggests average channel depths of approximately 10-15 ft (3-4.5 m) during the deposition of both members (McLaurin and Steel, 2007). It should be noted that these data come from the measured sections, the locations of which were selected for their quality of exposure and accessibility on the outcrop. Therefore they do not necessarily describe the thickest or most complete channel-fill.
successions within each amalgamated channel complex. As a result, the maximum thicknesses observed, which suggest channel depths exceeding 20 ft (6.1 m), may be more representative of the true bankfull flow depth during deposition. The smaller successions may represent the edges of larger channel-fills, barforms deposited in cross-bar channels during high stage, or legitimately shallower channel depths (Bridge and Tye, 2000).

Due to the excessive amalgamation in the A member, individual channel-fills could not be confidently identified. Stacked fining-upward successions, interpreted as bars and bar sets are smaller on average than in the underlying units at 3.9 ft (1.1 m) (Figure A5). In addition, the range is considerably restricted relative to the other two intervals. The mode for all three intervals is approximately 4 ft (1.2 m) however the A member lacks a significant number of fining-upward successions in excess of ~8 ft (2.4 m). While this may represent a shallowing of the channels, it is probably more likely that it reflects the greater degree of scouring and amalgamation in that interval which prevented thick successions from being preserved.

A second method for estimating flow depth correlates mean crossbed set thickness to mean dune height, which is then extrapolated to flow depth (Bridge and Tye, 2000; Leclair and Bridge, 2001). The mean set thickness for the C member, B member, and D member is 9.9 in (25 cm), 8.0 in (20 cm), and 9.9 in (25 cm), respectively (Figure A14). Equation 2, modified from Leclair and Bridge, 2001 (Equations 4 & 6) provides the mean dune height, $h_m$:

$$h_m = 5.3(sm/1.8) + 0.001(sm/1.8)^2$$  \hspace{1cm} (2)
where $s_m$ is mean set thickness. There is considerable scatter in the relationship between mean dune height and flow depth ($d$), however $d/h_m$ is typically between 6 and 10 which provides a range of probable flow depths of approximately 12 ft (3.6 m) to 24 ft (7.6 m) (Table 5).

The flow depths calculated from crossbed thickness agree well with those inferred from the thickness of channel-fill elements identified in outcrop, suggesting bankfull flow depths of approximately 10-25 ft (3.0-7.6 m) during deposition of the amalgamated channel-complexes without significant variation across the study interval.
<table>
<thead>
<tr>
<th>Interval</th>
<th>$s_m$ (in)</th>
<th>$h_m$ (ft)</th>
<th>$d$ (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A member</td>
<td>9.9</td>
<td>2.4</td>
<td>14.6 - 24.3</td>
</tr>
<tr>
<td>B member</td>
<td>8.0</td>
<td>1.9</td>
<td>11.8 - 19.6</td>
</tr>
<tr>
<td>C member</td>
<td>9.9</td>
<td>2.4</td>
<td>14.6 - 24.3</td>
</tr>
</tbody>
</table>

**Table 5.** Mean crossbed set thickness ($s_m$), mean dune height ($h_m$), and flow depth ranges ($d$) for each interval. The mean dune height calculated here is consistent with Keeton (2012) who calculated a mean dune height of 2.46 ft for the upper Williams Fork Formation.
Sequence Stratigraphy

The hierarchical framework of fluvial deposits developed by Patterson et al. (1995) and Sprague et al. (2002) is uniquely suited to sequence stratigraphic analysis of continental deposits because the largest hierarchical elements (depositional sequences, sequence sets, and composite sequences) are in many ways analogous to the parasequences and systems tracts defined in marginal marine settings. While it is well documented that only the most distal portion of a river system may be affected by relative sea-level change, the fundamental principles of sequence stratigraphy that were established in marginal marine settings also apply to continental deposits (Koss et al., 1990; Autin et al., 1991; Shanley and McCabe, 1994; Blum and Tornqvist, 2000). The primary difference in continental settings is the relative importance of allogenic factors, such as climate, tectonism, and sediment supply, that are generally considered to be of lesser consequence in marine settings which are primarily controlled by sea level fluctuations (Figure 15 & A15) (Catuneanu, 2006). Each of these factors, alone or in combination with others, has the ability to form depositional sequences that can be grouped into predictable composite sequences composed of amalgamated, non-amalgamated and semi-amalgamated sequence sets (Figure 6).

In marine settings where sea level is the main controlling factor and sediment supply is relatively constant, a sequence is defined by three basic phases: relative sea level fall (loss of accommodation space), relative sea level rise (creation of accommodation space), and relative sea level fall (loss of accommodation space). Under these idealized conditions, this cycle creates the regional unconformity that defines the base of the sequence, which is subsequently followed by the lowstand systems tract, the transgressive systems tract, the highstand systems tract, and a capping unconformity. A composite sequence in continental deposits is fundamentally similar in that it too represents a complete cycle of decreasing, increasing, and decreasing accommodation.
Figure 15. The relative role of eustasy diminishes with increasing distance from the shoreline while the relative role of “upstream” controls, such as climate and tectonism, increases. The landward limit of marine influence is typically on the order of 10’s of miles, though in low gradient settings it may exceed 100 mi (160 km). From Shanley and McCabe, 1994.
relative to sediment supply on a regional scale (Shanley and McCabe, 1994; Patterson et al., 2012). Figure 16 demonstrates the expected relationship between fluvial and shoreface architecture as a response to changes in accommodation. The base of a composite sequence is delineated by a regional unconformity representing a period of negative accommodation which results in widespread incision. When accommodation gradually regains a positive trend, deposition occurs on the regional erosional surface. The creation of accommodation is slow at this time, leading to highly amalgamated, sandstone-rich fluvial deposits which constitute an amalgamated sequence set. As the rate of accommodation creation increases, less reworking of the floodplains occurs allowing for greater preservation of floodplain deposits and less amalgamation of fluvial channel complexes. These deposits, characterized by isolated, areally restricted channel complexes, constitute a non-amalgamated sequence set. When the rate of accommodation creation begins to slow, channel complexes will exhibit greater amalgamation, creating a semi-amalgamated sequence set. Finally, accommodation creation may cease and regain a negative trend, resulting in widespread erosion. This erosional surface marks the top of one composite sequence and the base of another. If in close proximity to coeval shorelines, these accommodation-cycles in continental deposits may be controlled by relative sea-level change, however they may instead reflect long-term climate fluctuations or tectonic events, especially with increasing distance from potential marine influences (Figure 15). The distal portion of a river system affected by relative sea-level change can be said to be under the influence of “downstream controls,” while the more proximal portion that is not affected by relative sea-level change is said to be under the influence of “upstream controls” (Catuneanu, 2006).

Application of the hierarchical approach to the upper Williams Fork Formation outcrops in Plateau Creek Canyon reveals fluvial stratal stacking patterns and changes in net:gross ratios
**Figure 16.** Idealized stacking patterns of fluvial and shoreface deposits as a function of accommodation relative to sediment supply. In marine settings, accommodation is controlled primarily by relative sea-level fluctuations that cause landward and basinward shoreline shifts. In continental settings, stacking patterns may reflect long-term fluctuations in other allogenic factors such as tectonism, climate, and sediment supply. When this occurs, continental sequences may become decoupled from those in the coeval marine setting. In the example pictured above, both the alluvial deposits and the marginal marine sequences are in-phase because the alluvial setting is influenced by the same relative sea-level changes affecting the shoreface deposits. Figure modified from Cumella and Scheevel, 2008. Based on concepts from Shanley and McCabe, 1994 and Patterson et al., 2012.
that fit those predicted by models that relate fluvial architecture to fluctuating accommodation relative to sediment supply (e.g., Wright and Marriot, 1993; Shanley and McCabe, 1994; Miall, 2002; Patterson et al., 2003, 2010; Catuneanu, 2006). A regional sequence boundary, recognized by a number of authors (Patterson et al., 2003; German, 2006; Foster, 2010), is located approximately 200 ft (60 m) below the base of the study interval, representing the base of a composite sequence (Figure 17). The amalgamated, sandstone-rich middle Williams Fork Formation overlying the sequence boundary, referred to as the sandstone-rich portion of the upper Williams Fork Formation (German, 2006), the “middle Williams Fork 2” (Foster, 2010), and the “middle Williams Fork Formation” (Hewlett, 2010; Sloan, 2012), represents the amalgamated sequence set of a composite sequence which can be correlated across much of the Piceance Basin (Figure 18). It corresponds to the WF400 amalgamated sequence set of Patterson et al. (2003) and is interpreted to have formed in response to low accommodation relative to sediment supply.

The base of the C member coincides with the top of the middle Williams Fork Formation amalgamated sequence set. The C member is characterized by abundant floodplain deposits (low net: gross ratio) and isolated channel complexes that reflect deposition under relatively high-accommodation conditions. It is therefore interpreted as a non-amalgamated sequence set, corresponding to the lower portion of the WF500 of Patterson et al. (2003). Within the study area and immediate vicinity (e.g., Shire Gulch field), this non-amalgamated sequence set is approximately 300 ft (90 m) thick, though defining the top of the interval is somewhat subjective because the contact with the overlying semi-amalgamated sequence set is gradational.

The B member, averaging 200 ft (60 m) in thickness, is characterized by more areally extensive amalgamated channel complexes and a scarcity of floodplain deposits relative to the
Figure 17. Schematic diagram of the middle and upper Williams Fork Formation in the study area. The middle Williams Fork Formation (WFF) and the three members of the study interval have been interpreted as sequence sets (A = amalgamated, N = non-amalgamated, S = semi-amalgamated) comprising one complete and one partial composite sequence. The inferred accommodational setting is shown at right. Note the similarity of the overall architecture shown above to that of the idealized succession shown in Figure 16. Not to scale.
Figure 18 A

Patterson et al., 2003

WF800
WF700
WF600
WF500 (undifferentiated)
WF400

Ohio Creek
A member
B member
C member
middle WFF

Rollins
Cozzette

500 ft
Figure 18 A: (previous page) Regional SW-NE gamma-ray cross section showing the relationship between the study interval and the sequence stratigraphic framework of Patterson et al., 2003. The yellow star denotes a composite outcrop gamma-ray curve from this study. The red circles in both panels A and B denote locations interpreted by Patterson et al. (2003). The right-most location in the cross section is a grain-size log from Rifle Gap outcrops. Amalgamated (A), non-amalgamated (N), and semi-amalgamated (S) sequence sets are indicated by green triangles. Composite sequences are indicated by yellow triangles. B: the location of the cross section, Mesaverde outcrops (green), and Piceance Basin gas fields (pink).
underlying C member signifying the onset of reduced-accommodation conditions. It is not, however, as sandstone-rich as the overlying A member. The B member is therefore interpreted as a semi-amalgamated sequence set, corresponding to the upper portion of the WF500 of Patterson et al. (2003). In this study, the top of the semi-amalgamated sequence set (B member) is defined by the base of the highly amalgamated, sandstone-rich A member. Under this interpretation, this contact would also represent the top of the first composite sequence which is comprised of the middle Williams Fork Formation, the C member, and the B member. The overlying sandstone-rich A member is interpreted as the amalgamated sequence set of a second composite sequence, the remainder of which having been subsequently eroded or not deposited prior to Ohio Creek deposition. It is possible that the A member is part of the underlying semi-amalgamated sequence set and that it simply reflects a continuation of the reduction of accommodation before the onset of regional incision. However, given the dramatic increase in sandstone content, expansive lateral extent, and architectural similarities to the middle Williams Fork Formation (WF400 amalgamated sequence set), it is deemed more appropriate to consider this interval an amalgamated sequence set at the base of a new composite sequence. It is interpreted as the WF800 of Patterson et al. (2003) Under this interpretation, the first composite sequence is approximately 700 ft (215 m) thick. The thickness of the second composite sequence could not be determined because it is incomplete.

The study interval exhibits fluvial architecture that is in accordance with the models for increasing and decreasing accommodation in continental settings; however, it is not clear which factor or factors are responsible for the change in accommodation over time. During deposition, the study area was geographically within the range of sea-level influence observed in many modern settings (typically 10’s of miles) so it is at least possible that sea-level fluctuation
influenced stratal stacking patterns. Shanley and McCabe (1991) demonstrated how sequence boundaries identified in marine deposits could be traced landward into coeval fluvial deposits as a way to determine whether the fluvial stratigraphy was controlled by sea-level change. Unfortunately, the marine deposits required to undertake this exercise in the middle and upper Williams Fork Formation have not been preserved.

In lieu of coeval marine deposits, the recognition of tidal or marine influences within the fluvial succession may indicate the influence of downstream controls. In downstream-controlled fluvial settings the lower portion of the non-amalgamated sequence set may contain tidally influenced fluvial deposits which reflect coeval coastal transgression. These deposits may therefore represent the landward expression of a marine flooding event, thereby providing strong evidence that sea-level change could be an important influence on the fluvial stratigraphy (Shanley et al., 1992). The aforementioned authors list nine characteristics of tidally influenced fluvial deposits, none of which are individually conclusive but the occurrence of many of the characteristics in the same interval is highly indicative of tidal effects. The vast majority of the features observed, summarized in Table 6, occur within the non-amalgamated sequence set as would be expected if the fluvial and marine settings were in-phase.

The most abundant (or conspicuous, perhaps) evidence for tidal influence is the presence of ichnofossils attributed to the *Skolithos* ichnofacies, which is typically associated with high energy, sandy shallow-marine environments (Pemberton and MacEachern, 2005) (Figure A3). These include forms of *Skolithos, Ophiomorpha, Palaeophycus/Planolites* and *Arenicolites*. *Teredolites*-bored wood fragments also suggest brackish conditions. It should be noted that these ichnofossils do not necessarily imply tidal influence because many have been observed in purely
<table>
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<th>Tidal Feature</th>
<th>Occurrence</th>
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</thead>
<tbody>
<tr>
<td>Sigmoidal bedding</td>
<td>Rare</td>
</tr>
<tr>
<td>Paired mud/silt drapes</td>
<td>Rare</td>
</tr>
<tr>
<td>Wavy and lenticular bedding</td>
<td>Very Rare</td>
</tr>
<tr>
<td>Shrinkage cracks</td>
<td>Never</td>
</tr>
<tr>
<td>Multiple reactivation surfaces</td>
<td>Common</td>
</tr>
<tr>
<td>Inclined heterolithic strata</td>
<td>Never</td>
</tr>
<tr>
<td>Complex compound cross-beds</td>
<td>Common</td>
</tr>
<tr>
<td>Bidirectional cross-beds</td>
<td>Common</td>
</tr>
<tr>
<td>Trace fossils (e.g., Teredolites, Arenicolites, Skolithos)</td>
<td>Very Common</td>
</tr>
</tbody>
</table>

**Table 6.** The nine characteristics of tidally influenced fluvial deposits proposed by Shanley et al. (1992) and their frequency of occurrence within Plateau Creek Canyon outcrops.
fluvial settings (Fitzgerald and Barrett, 1986; Woolfe, 1990). It is only in conjunction with the other tidal features that they provide evidence of a downstream-influenced fluvial setting.

The fluvial architecture within the study interval depicted in Figure 17 and the presence of features that may indicate tidal influences within the non-amalgamated sequence set (C member) suggest that stratal stacking patterns during deposition of the upper Williams Fork Formation may have been at least partly controlled by changes in relative sea-level. If so, the observed sequence sets and composite sequences could theoretically be tied to sequences in the coeval marine deposits, as depicted in Figure 16. While fluvial settings under the influence of upstream controls are, by definition, affected by factors such as climate and tectonism, it is important to note that downstream-controlled fluvial settings are also subject to these factors, to varying degrees. Therefore it is likely that cyclical affects from relative sea-level change will be imprinted on other influential long-term cycles. For example, any downstream influences acting on the middle and upper Williams Fork Formation during the late Cretaceous and Paleocene did so in conjunction with Laramide partitioning of the Rocky Mountain foreland basin. This large-scale structural movement probably accounts for the extensive erosion at the base of the A member which completely removed the WF600 and WF700 identified by Patterson et al. (2003) in the east side of the Piceance Basin (Figure 18).

When discussing sequence stratigraphy in continental settings, many authors use systems-tracts terminology (lowstand, transgressive, highstand, etc.). This is appropriate when the deposits in question can be shown to have responded primarily to relative sea-level change, such that the continental and marine sequences are genetically related and in-phase. However, when the primary allogenic factor controlling stratal stacking patterns cannot be determined, systems-tracts terminology should not be utilized. While relative sea-level change has herein
been tentatively proposed as a significant allogenic mechanism influencing the upper Williams Fork Formation, further evidence is required to confirm this. Therefore, the interpreted sequence sets within the middle and upper Williams Fork Formation have not been assigned to potentially analogous marine systems tracts.
Conclusions

Fluvial amalgamated channel complexes of the upper and middle Williams Fork Formation exposed at Plateau Creek Canyon exhibit an abundance of trough cross bedding, stacked fining-upward bar deposits and internal scour surfaces, in addition to a lack of lateral-accretion deposits suggesting deposition in a northeasterly flowing, low-sinuosity to braided-fluvial setting where midstream and bank-attached bars underwent continuous re-working. In contrast, the lower Williams Fork Formation is characterized by an abundance of laterally accreting point-bar deposits and coal beds indicative of a high-sinuosity, meandering-fluvial system in a paludal, coastal-plain environment. This transition from distal to proximal alluvial deposits within the Williams Fork Formation records the recession of the Western Interior Seaway during the Late Cretaceous.

Amalgamated channel complexes form the primary gas-producing reservoirs in the Williams Fork Formation. The channel complexes in the C member are typically 500-1500 ft (150-460 m) wide (apparent), 20-35 ft (6-11 m) thick, and tend to be isolated within abundant floodplain deposits. The channel complexes in the B member form laterally amalgamated sheet-like units that comprise a greater proportion of the total interval than in the C member. They are often vertically separated by floodplain deposits; however, they occasionally stack directly on top of one another resulting in very high localized net-to-gross ratios. The true apparent width of these channel-complexes could not be determined due to modern outcrop erosion, but they are at least 1500-5000 ft (460-1525 m) wide (apparent). Localized incision may result in thicknesses in excess of 60 ft (18 m); however, the average thickness is 20-40 ft (6-12 m). The overlying A
member is a highly amalgamated, extremely sandstone-rich sheet-like unit with lateral extents of at least 10-20 mi² (26-52 km²) and a thickness of 60-90 ft (18-27 m).

The size and style of the fluvial system does not appear to have changed significantly within the study interval, thus these factors are not considered to have been responsible for the change in sandstone content. Instead, the study interval exhibits alluvial architecture that is in accordance with the models for increasing and decreasing rates of accommodation creation in continental settings. The C member was deposited under high-accommodation conditions which allowed for increased preservation of the floodplain deposits and isolation of the channel-complexes. The B member was deposited under decreased-accommodation settings which resulted in slightly greater amalgamation of channel-complexes. The A member reflects low-accommodation conditions resulting in erosion followed by extensive re-working of the floodplain deposits and amalgamation of channel-complexes.

A number of authors have interpreted the middle Williams Fork Formation below the study interval as low-accommodation deposits overlying a basin-wide sequence boundary and the overlying upper Williams Fork Formation as high-accommodation deposits. This study demonstrates that these deposits may be further subdivided into several smaller-scale sequence sets and composite sequences which can aid in predicting the distribution of sandstone reservoirs within the basin. The alluvial stratal-stacking patterns are shown to be consistent with regional fluctuations in accommodation relative to sediment supply in continental settings. Features that indicate marine influences in the fluvial deposits suggest relative sea-level change may have at least partly influenced deposition on the adjacent coastal plain, though it is likely that climate and Laramide tectonism were contributing factors as well.
References


Patterson, P. E., A. R. Sprague, R. E. Hill, and K. M. McDonald, 1995, Sequence Stratigraphy and Fluvial Facies Architecture, Farrer and Tuscher Formations (Campanian), Tusher Canyon, Utah (abs.): AAPG Abstracts with Program, p. 74A.


APPENDIX A

Expanded methodology
Outcrop gamma-ray measurements

A Radiation Solutions, Inc. Super-Spec RS-125 scintillometer was used to determine the total gamma-ray signature of the outcrops in Plateau Creek Canyon. Measurements were collected at 1-ft (0.3 m) intervals on all exposed rock with an assay time of 40 seconds. Additional measurements were taken at the base and top of sandstone bodies if those surfaces did not correspond to the 1-ft increments. No measurements of covered intervals were attempted. For display purposes in this report, a value of 4000 cps was assumed for the covered intervals as this was a typical reading for the fine-grained floodplain deposits.

Determination of the dimensions of channel complexes

Accurate analysis of the geometry, dimensions, and internal architecture of the large channel complexes was difficult in the field due to the size of the features and limited outcrop accessibility. High-resolution photo-panoramas taken from the cliffs opposing the study outcrops were therefore instrumental in determining this information. The internal architecture of channel complexes was revealed by carefully identifying and tracing individual scour surfaces, bar sets, and channel-fills observed in the photographs. Dimensional data (apparent width and height) was acquired from the photographs by using trees near the outcrop as a reference point. The height and width of 20 full grown juniper trees were measured in the field. They were found to be, on average, 12.5 ft tall and 13 ft wide with relatively little variation. Full grown trees in the photographs near the feature of interest could then be used to measure that feature. To test the accuracy of this method, 6 height and width measurements collected in the field with a tape measure and GPS unit were compared to measurements of the same features
determined from the photographs. The agreement between measurements was found to be quite good (see figure on following page) and the error in all cases was less than 15%.

Gamma-ray log normalization procedure

The gamma-ray logs from the 65 wells utilized in this study for net:gross calculations and subsurface correlations were normalized in order to remove the well-to-well variability caused by different types and vintages of gamma-ray tools. Six wells from the Piceance Basin deemed to be representative and of high quality were selected as type wells (API: 05045064130000, 05077081340000, 05045061780000, 05045062990000, 05045072820000, and 05077086690000). A composite histogram of the gamma-ray values from the type wells was created in the log-analysis software package LESA (Digital Formation). This type histogram defined the sandstone and shale values to which the non-type wells will were matched. The distribution of the gamma-ray values in the normalization interval of each non-type well were compared to the type histogram and the entire gamma-ray curve was shifted or stretched as necessary to create the set of normalized gamma-ray logs used in this study.
Crossplot of measurements estimated from photo-panoramas vs. measurements acquired in the field with a tape measure and GPS unit.
APPENDIX B

Supplementary figures
Figure A1. Outcrops within the study area are typified by well exposed fluvial sandstone bodies embedded within floodplain-fines that are usually covered by colluvium and vegetation (a). A rare exposure of floodplain-fines in Shire Gulch allowed for observation of these deposits (b). The floodplain deposits consist of approximately 60% fine- to very fine-grained sandstones with sheet-like or lenticular geometry interbedded with structureless and bioturbated mudstone. The dominant sandstone lithofacies are Ss, Sb (burrowed and rooted), and Sr (see Table 2 for abbreviations). Carbonaceous material and fossilized leaves are commonly found within the floodplain deposits. Yellow line indicates location of measured section.
Figure A2. Relative proportion of lithofacies observed in measured sections of the upper Williams Fork Formation outcrops. Charts (a), (b) and (c) show the proportions of lithofacies observed relative to the total footage measured. It is inferred that the covered intervals are composed of mudstone and thinly bedded sandstone lithofacies. Charts (d), (e) and (f) have been normalized to show only the relative abundance of lithofacies observed in the non-covered intervals. See Table 2 for abbreviations.
Figure A3. Examples of ichnofossils found within the C member of the Upper Williams Fork Formation. *Ophiomorpha* (*O*), *Skolithos* (*Sk*), *Arenicolites* (*Ar*) and dinosaur tracks. Jacob’s staff segments = 1 ft (0.3 m).
Figure A4. Outcrop example of the sandy bar facies association. The basal surface (1) is abrupt and shows incision into the underlying carbonaceous floodplain-fines. Several discrete layers of pebbles and cobbles composed of clay to very fine sand are present in the lower portion of the succession (2). These clasts are often associated with scour surfaces (3) however they may also be sparsely distributed within higher-energy lithofacies such as trough cross-bedding. This succession shows multiple fining-upward bar sequences (green triangles) that stack to form a single bar set (red triangle).
Figure A5. Thicknesses of fining-upward bar sequences in the A member (a), the B member (b) and the C member (c). It should be noted that some of the thickness values may be erroneously high since it can be difficult to distinguish a meaningful basal scour surface from a bed-set boundary when variations in grain size are subtle or channel lag is absent. This would explain the anomalously thick bar sequences observed in the B and C members.
Figure A6. This coarsening-upward crevasse splay succession was encountered in MS-1. Both the grain-size profile and lithofacies succession exhibit progressively increasing energy levels as the delta-like splay prograded away from the levee breach. Such successions were only rarely encountered in the measured sections.
Figure A7. This 1.5 ft (0.5 m) interval, comprised of interbedded fine- to very fine-grained ripple cross-laminated sandstone (Sr) is representative of the sandstone bodies deposited in unconfined conditions. This particular interval is tentatively interpreted as distal crevasse-splay deposits; however, due to poor outcrop exposure, the overall geometry of the sandstone body is unknown.
Figure A8. The types of fluvial sandstone bodies and their associated architectural element classification observed in the study area. Sandstone body outlines and nomenclature modified from Cole and Cumella (2005), internal geometry has been altered to represent the low-sinuosity to braided fluvial deposits of the upper Williams Fork Formation.
Figure A9. Stacked crevasse-splay deposits (shaded orange) and small, isolated channel-fill elements interpreted as crevasse-channels or small floodplain channels (circled).
Figure A10. The Ohio Creek interval consists of a variegated mudstone interval interpreted as paleosols, a distinctly white fluvial sandstone interval, and a chert-clast conglomerate. A second white sandstone is occasionally present beneath the paleosol interval (not pictured).
Figure A11. Left: root traces and mottled texture typical of the paleosol interval. Right: large branching burrow within the paleosol interval interpreted as a crayfish burrow as described by Johnson and Flores (2003).
Figure A12. Distinct coloration of the paleosol interval at the location of MS-03b
Figure A13. Multi-colored, well-rounded chert pebbles and cobbles of the Ohio Creek conglomerate.
Figure A14. Thicknesses of crossbed sets in the A member (a), the B member (b) and the C member (c).
Figure A15. The complex interaction of allogenic controls on fluvial sedimentation. From Catuneanu, 2006.
APPENDIX C

Outcrop measured sections
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<td>Planar Cross Bedding</td>
<td>= Crevasse Splay</td>
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<td>Branching/multidirectional burrows</td>
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<td>Root traces</td>
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<td>Wood debris</td>
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<td>Dinosaur track</td>
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Symbols used in the display of sedimentological descriptions in this report.
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<tr>
<th>Notes</th>
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</table>

- **Difficult to see structures, trough sets appear to increase in size**
- **As below, faint TCB?**
- **Abundant straight, tubular structures ~3 mm wide. All orientations. Insect burrows?**
- **Small TCB ~ 4" x 15"**
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**Total GR (cps)**

- 1000
- 2000
- 3000
- 4000

**A.E.**

- 88

**Notes**

- Root traces, coaly fragments
- Large trough: 2.25 ft x 16.5 ft
- Measured 3 distinct trough sets: 1 ft thick by 8 ft, 7 ft, and 7 ft wide.
- 2 distinct vertical burrow sizes: 5 mm x ~60 mm and 30 mm x ~120 mm
- Thin ripple beds between trough sets
- Wood fragments? Concretions?
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**Gravel**
- Pebble
- Granule
- V. Coarse
- Coarse
- Fine
- V. Fine
- Silt
- Clay

**Notes**
- Poorly preserved ripple x-lam, small trough sets
- Predominantly south dipping
- Mud clasts along bedding planes
- Reactivation surfaces, sigmoidal beds?
- Isolated ripple x-lam, finely laminated mud lenses
- Burrows: ~ 1 cm diameter
- Dip direction alternates
- Large, steep cross beds
- ~15 ft left of line: trough 1 ft x 13 ft
- Sand-filled scours
- Root traces
MS-01

Gravel | Sand | Mud | Covered |
--- | --- | --- | --- |
Pebble | Granule | V. Course | Coarse | Fine | V. Fine | Silt | Clay |

Height (ft)

115
120
125
130
135

Notes

- Massive, a few trough sets ~ 8-12" high
- Bioturbated (same as feet 3-16)
- Some TCB visible, up to 1.5 ft
- Low-angle cross beds
- Almost structureless, planar lamination? TCB?
- Wavy lamination? Ripple x-lam?
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</table>

**Total GR (cps)**

- **1500**: 10-13
- **2000**: 17-28
- **3000**: 36-44
- **4000**: 53-59

**A.E.**

- **Highly burrowed**
- **Burrow entrances on top surface**
- **Mud clast pebbles and coarse sand on many bedding planes**
- **Basal sand poorly cemented**
- **15' left of line: 8-12” TCB, wood fragments, horizontal and vertical burrows, mud clast pebbles**
- **Burrowed, primarily vertical**
- **Coarse sand at base of troughs with scattered small pebbles**

**Notes**

- Angles of some bedding planes
- Burrow entrances on top surface
- Mud clast pebbles and coarse sand on many bedding planes
- Basal sand poorly cemented
- Highly burrowed
- Angular pebbles on some bedding planes
<table>
<thead>
<tr>
<th>Height (ft)</th>
<th>Total GR (cps)</th>
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<th>Notes</th>
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<td>1000 2000 3000 4000</td>
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- Slightly distorted wavy/planar bedding
- Clasts up to 4"
- Sub-horizontal planar parallel laminations, possible RCB, weakly cemented
- TCB 2’ high by up to 10’ wide
- Scattered 0.5-1” clasts
- Friable, wavy laminted
- Log cast, Teredolites, 0.5’-1.5” mud clasts
- Silt pebbles and cobbles, up to 6” long
- 1-4” clasts weathered out along bedding planes
- Root traces in top 6” of siltstone
- Trace amounts organic/coaly material, very abundant in top 1’. Wood fragments up to 1” long
- 30’ left of line: TCB, RCB, log casts with teredolites, gravel channel lag, burrows
<table>
<thead>
<tr>
<th>Gravel</th>
<th>Pebble</th>
<th>V. Course</th>
<th>Coarse</th>
<th>Medium</th>
<th>Fine</th>
<th>V. Fine</th>
<th>Silt</th>
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**Notes**

- Alternating small TCB (8" high) and RCB
- Possibly burrowed
- Continuous layer of pebble clasts ~40' wide
- Thinly bedded alternating F + C sand
- Friable mudstone, possible root traces
Pebble clasts

Silt/clay clasts, mostly pebbles, up to 12"

Very finely laminated, occasional burrows, sparse woody material

183'-200' inaccessible, viewed with binoculars

Pebble clasts (GR data continues on sidetrack line, page 4b)
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<th>Mud</th>
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Abundant pebbles throughout
Lithic and mud pebbles
Quartz and mud pebbles
Mud chip clasts from underlying mudstone
Quartz and mud pebbles
Quartz pebbles
Mud pebbles
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**MS-02**

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Scattered pebbles

(No data)
(Continued from page 4)

Pebble clasts

Very thinly bedded, TCB?

Quartz and siltstone pebbles

Sparse small quartz/chert pebbles
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<th>Total GR (cps)</th>
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<th>Mud</th>
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**Possible TCB**
Slightly contorted sub-horizontal planar parallel bedding
Quartz and mud pebbles
### MS-03

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</table>

- **Gravel**: Pebble, Granule, V. Coarse, Coarse, Medium, Fine
- **Sand**: Fine, V. Fine, Clay
- **Mud**: Silt, Clay, (Covered)

**Notes**:%
- Vertical burrows, 0.5-1 cm x 10+ cm
- 2-3 mm burrow holes on top surface
- 1-3 mm vertical and horizontal burrows
- Highly bioturbated/poorly preserved sediment structures
3-4 cm chert pebbles in M-C sand

White, weathers into smooth, round “pillows”

Large logs found ~25 yds left of line

Mud drapes on ripples

Slightly curved parallel lam. hummocky?

0.5 cm mud clasts, mostly eroded

Root traces, friable siltstone
Better exposure of paleosol interval, roughly equivalent to 5-30' of MS-03

Color of fresh face
- Gray
- Red-brown
- Reddish brown
- Brown-purple
- Dark maroon
- White
- Purple
- Mottled green & purpled
- Gray-purple
- Dark purple
- Dark purple-gray
- Green-gray
- Yellow
- Olive-tan
- Dark gray-purple
- Blue-gray

Notes
- Some burrows pelletized
- Faint branching structures - roots?
- Heavily bioturbated
- Heavily bioturbated
- 2 mm tubular structures - burrows? roots?
- Crumbly, oxidation streaks, 1" wide sandstone clastic dikes
**MS-04**

**Gravel**
- Cobble
- Pebble
- Granule
- V. Coarse
- Coarse
- Medium
- Fine
- V. Fine
- Silt
- Clay
- Covered

**Sand**

**Mud**

**Height (ft)**
- 40
- 35
- 25
- 20
- 15
- 10
- 5
- 0

**Total GR (cps)**
- 1000
- 2000
- 3000
- 4000

**Notes**
- **0 ft**
  - Weathered and covered

- **5 ft**
  - Scattered, weathered out clasts along bedding planes

- **10 ft**
  - Highly bioturbated ~30 ft left of line
  - Weathered out clasts along bedding planes
  - Sparse green mudstone clasts ~ 1 cm

- **20 ft**
  - Very finely laminated, splitting along lamination planes
  - Distal crevasse-splay deposits?

- **30 ft**
  - Weathered out clasts along bedding planes

- **35 ft**
  - Weathered and covered
<table>
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<th>A.E.</th>
<th>Notes</th>
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<td></td>
<td>Deciduous leaves and twigs in top 2”, 3 mm vertical burrows</td>
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Notes:
- Deciduous leaves and twigs in top 2”, 3 mm vertical burrows
- Highly bioturbated
<table>
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<tr>
<th>Height (ft)</th>
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</table>

Gravel: Pebble, Granule, V. Coarse, Coarse, Medium, Fine, V. Fine, Silt, Clay (Covered)

Load casts and tool marks into underlying mudstone

Highly variable bedform types and directions
Round burrow entrances abundant on top surface, as large as 3.5 cm

Rib and furrow in float

Root traces, abundant leaves, sticks, palm fronds ~ 15 ft right of line

Pea-sized pebbles scattered throughout

0.5 - 10 cm mud clasts

Notes:
- Round burrow entrances abundant on top surface, as large as 3.5 cm
- Rib and furrow in float
- Root traces, abundant leaves, sticks, palm fronds ~ 15 ft right of line
- Pea-sized pebbles scattered throughout
- 0.5 - 10 cm mud clasts
<table>
<thead>
<tr>
<th>Gravel</th>
<th>Sand</th>
<th>Mud</th>
<th>Height (ft)</th>
<th>Total GR (cps)</th>
<th>A.E.</th>
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165

180
0.5-10 cm mud clasts, tool marks on basal surface

Dinosaur tracks, other traces on rippled surface

Slickenlines along some bedding planes

Coaly fragments, sticks

Notes
<table>
<thead>
<tr>
<th>Gravel</th>
<th>Sand</th>
<th>Mud</th>
<th>Covered</th>
<th>Height (ft)</th>
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</table>

Weathered out clasts throughout, along bedding planes
Pea-sized mudstone clasts along bedding planes

Deciduous leaves, twigs, bioturbated

Deciduous leaves, twigs, bioturbated
<table>
<thead>
<tr>
<th>Gravel</th>
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<td>172-197</td>
<td>Nearly flat, mostly covered top of outcrop. No suitable exposure for GR measurements.</td>
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Total GR (cps)
1000 2000 3000 4000
Gravel Sand Mud Cobble Pebble Granule V. Coarse Coarse Medium Fine V. Fine Silt Clay (Covered)
Height (ft)
A.E.
Notes
Dozens of stacked TCB sets
3-5 mm tubular burrows
Unusual dip - large piece of float?
Page 6
Flat top of outcrop, mostly covered, probably TCB
<table>
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<th>Height (ft)</th>
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Beds near vertical in places, mud clasts along bedding planes

2-8 cm mud chips

Bright orange/yellow siltstone
<table>
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<th>Height (ft)</th>
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</tbody>
</table>

**MS-05**
Clasts up to 4 cm scattered throughout

Planar beds of 3 cm pebbles
Large wood fragments

3 mm burrows, vertical and horizontal

Coal fragments, leaves, twigs
<table>
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<th>Mud (Covered)</th>
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</table>

**Total GR (cps)**

- 1000
- 2000
- 3000
- 4000

**A.E.**

**Notes**

- Highly bioturbated
- Clasts up to 5 cm
- Highly bioturbated

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**MS-06 Page 3**
Mud clasts up to 3 cm

Vertical 3 mm tubular burrows
Gravel | Pebble | Granule | V. Coarse | Course | Medium | Fine | V. Fine | Silt | Clay | (Covered)
---|---|---|---|---|---|---|---|---|---|---
1000 | 2000 | 3000 | 4000 | A.E. | Notes
---|---|---|---|---|---
160 | 170 | 175 | 180 | 185 | 190 | 195 | 200 | Mudstone clasts, up to 5”
Very poor sorting
Mudstone clasts, up to 6”
Mudstone clasts, up to 5”
(Inaccessible)
<table>
<thead>
<tr>
<th>Height (ft)</th>
<th>Total GR (cps)</th>
<th>A.E.</th>
<th>Notes</th>
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</table>

Inaccessible, observed with binoculars

Pea sized quartz pebbles

Pea sized quartz pebbles

(Inaccessible, observed with binoculars)
This interval was covered by several inches of loose gravel. Dug through it to access fresh rock at 1-ft intervals. Rock was generally well consolidated but could easily be broken into plates ~1 cm thick.