Ichnology, Sedimentology, and Regional Sandstone Body Correlations of the Peay Member (Frontier Formation), Northeast Bighorn Basin, Wyoming, U.S.A.

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Ichnology, Sedimentology, and Regional Sandstone Body Correlations of the Peay Member (Frontier Formation), Northeast Bighorn Basin, Wyoming, U.S.A.

By

Trevor J. Hurd

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Ichnology, Sedimentology, and Regional Sandstone Body Correlations of the Peay Member (Frontier Formation), Northeast Bighorn Basin, Wyoming, U.S.A.

Trevor J. Hurd, M.S.

University of Nebraska, 2012

Adviser: Christopher R. Fielding

A detailed outcrop and sub-surface analysis was completed on the Peay Member sandstone (Frontier Formation) in the northeast Bighorn Basin, Wyoming, building on previous work by Clark (2010) and Hutsky (2011). Regional correlations reveal the sandstone body to be digitate in planform geometry, elongate along depositional dip, and restricted across depositional strike. It is interpreted to be the product of southsoutheastward progradation from a fluvially-dominated delta lobe into the Cretaceous Western Interior Seaway (KWIS) Basin. This shore-parallel progradation direction suggests a southward-deflected delta lobe, facilitated by a counter-clockwise gyre circulation in the KWIS. Outcrop investigations concentrated on evaluating lateral variations in sedimentological and ichnological characteristics across a single river-dominated deltaic sandstone body. The Peay Member grades laterally from a thick, high-energy, fluvial mouth bar facies (axial core), to a tide- & wave-influenced proximal-medial delta flank facies, and finally to a thin, low-energy, storm- and wave-influenced prodelta-distal delta flank facies at the peripheries of the delta lobe. The axial core contains a vertical succession of prodelta-mouth bar facies displaying generally low and sporadic bioturbation intensities, reflecting depositional conditions that were stressful to bottom-dwelling organisms. Flankward, the medial delta flank facies reflects more tidal-,
wave-, and storm-influences resulting in an impoverished expression of the proximal *Cruziana* Ichnofacies with elements of distal *Skolithos* Ichnofacies; bioturbation intensities fluctuate within facies. At the delta lobe peripheries, the prodelta-distal delta flank facies contains an archetypal expression of the *Cruziana* Ichnofacies with abundant bioturbation. Similar cross-sectional and planform geometries reveal a relationship between specific geomorphic zones and recurring facies distribution patterns. This relationship is used to develop a three-dimensional model that could potentially predict sandstone body geometry, regional facies distribution, and sandstone body dispersal patterns in the Bighorn Basin in this and other sandstone bodies. This study emphasizes the point that most deltas are dynamic systems and depositional influences may fluctuate both temporally and spatially throughout their existence.
Acknowledgements

The successful completion of this thesis project would not have been feasible without the avid support of the following dedicated individuals and organizations to which I am forever indebted: First and foremost, I would like to express my most sincere gratitude toward my parents, Betty and Greg, and my closest friends from Florida and Nebraska for their precious moral support and extensive wisdom; my adviser Dr. Christopher Fielding for his infinite wisdom and counsel through the entirety of this project; the Department of Earth and Atmospheric Sciences at University of Nebraska-Lincoln for providing me financial support and the opportunity to complete graduate level research amongst a distinguished faculty; Mr. Mark Mathison and the Iowa State University Geology Field Station, Shell Wyoming for housing accommodations during field work; Dr. David Watkins and Dr. Matt Joeckel for serving on my committee.
Preface

This document is presented as two separate papers. Part I focuses on the detailed mapping and analysis of a depositional strike-oriented section across the sandstone-dominated Peay Member delta lobe of the Upper Cretaceous Frontier Formation in the northern Bighorn Basin, Wyoming. This outcrop-based study reveals notable variations in sedimentology and ichnology the axial zone (core) to the delta flank. Part II presents the regional mapping of the Peay Member delta lobe throughout much of the eastern Bighorn Basin. This study incorporates both outcrop and subsurface data to develop interpretations of overall lobe geometry and dispersal patterns for the Peay Member delta lobe.
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Part I
Introduction

Incorporating ichnological data into sedimentological and stratigraphic analyses of deltaic successions has the potential to add significant value to interpretations. Ichnologically informed facies models for deltaic settings have been in existence for a number of years, but most are based on data from vertical facies successions such as those encountered in drillcores (e.g., Moslow and Pemberton, 1988; Gingras et al, 1998; Bann & Fielding, 2004; Sadeque et al, 2007; Gani et al, 2007; Bann et al, 2004, among others). Few studies have documented trace fossil distributions across an entire ancient delta based upon three-dimensional exposure of the same sediment body. Thus, many extant models suffer from uncertainty due to lack of physical continuity in datasets. In this paper, I seek to provide an integrated example that documents variations in trace fossil distribution across a continuously exposed delta lobe deposit.

Early ichnological studies recognized key differences in trace fossil assemblages and bioturbation intensity between deltaic and non-deltaic facies in situations where sedimentary structures were insufficiently preserved or absent (Moslow & Pemberton, 1988; MacEachern & Pemberton, 1992; Gingras et al., 1999, among several others). Recent review articles on process-based ichnology have detailed characteristic departures from the archetypal or Seilacherian ichnofacies that are interpreted to represent stressed environments including deltas. These variations are manifested as impoverished expressions of Seilacher’s (1967) marine ichnofacies (cf. MacEachern et al., 2007; MacEachern & Bann, 2008; Gingras et al., 2011). The ichnology of deltas was originally classified in terms of the tripartite division of deltas (river-dominated, wave-dominated,
and tide-dominated: Galloway, 1975; Coleman & Wright, 1975) because each end-member shows diagnostic trace fossil responses to adverse physicochemical stress unique to the depositional conditions. More recent studies recognize that deltas are dynamic depositional systems and better described as mixed-energy depositional environments. Hansen & MacEachen (2005) and Dafoe & Pemberton (2010) studied the Basal Belly Formation and Viking Formation (respectively) in Central Alberta focusing on the sedimentological and ichnological variations between fluvial-influenced and wave-influenced deposits. These authors concluded that locations proximal to the distributary mouth contained a more stressed trace fossil assemblage than an inferred wave-influenced location. Additionally, Hansen and MacEachern (2005) provided one of the first ichnological studies along depositional strike in an asymmetric, wave-dominated delta. Sadeque et al (2007) completed a comprehensive core-based study in the Powder River Basin focusing on the Wall Creek Member of the Frontier Formation, which distinguished river-, wave- & storm-, and tide-influenced facies in deltaic successions according to physical sedimentary structures and trace fossil assemblages. Correlations from core descriptions into uncored but wireline-logged drillholes determined that different lobes in the Wall Creek delta system were dominated by different depositional influences (river, tidal, wave). Gani et al (2007) demonstrate how labeling deltaic deposits from the Wall Creek Member (Frontier Formation) according to the traditional tripartite classification of deltas could be misleading because most delta systems are mixed-energy in nature.
This paper presents an ichnological study of an ancient shore-detached, fluvially-dominated delta (Peay Member of the Frontier Formation in northern Wyoming, USA) in which the complete lateral relationships among trace fossil assemblages from the high-energy, fluvially-dominated core to a low-energy, wave- & tide-influenced flank of the digitate sandstone body are documented from three-dimensional mapping. In this manner, changes in the nature and distribution of traces can be directly linked to changes in depositional facies and paleogeographic context. This study is a rigorous test of ichnological facies models for fluvially-dominated deltas.

**Stratigraphy and Regional Geology**

The Upper Cretaceous Frontier Formation (Cenomanian-Turonian) is the northernmost of a series of prograding deltas sourced from the Sevier orogenic belt feeding eastward into the U.S. part of the Cretaceous Western Interior Seaway (KWIS) basin (Figure 1). It is bounded above and below by thick marine shales (Cody Shale and Mowry Shale respectively). Several isolated sandstone bodies, encased by marine mudrocks, occur within the Frontier Formation and represent coarsening-upward cycles deposited in coastal-shallow marine environments (cf. Bhattacharya & Willis, 2001; Kirschbaum et al., 2009). Many of these bodies are top-truncated and elongate in planform, and have been interpreted as deltaic progradational cycles in response to lowering of relative sea level at various times during the Cenomanian and Turonian stages of the Cretaceous (Bhattacharya & Willis, 2001; Clark, 2010; Hutsky, 2011).
Figure 1: A) Paleogeographic reconstruction of western North America during the Late Cretaceous (Cenomanian-Coniacian). The map shows several deltas sourced from the Sevier orogenic belt feeding eastward into the U.S. portion of the Cretaceous Western Interior Seaway (KWIS). Red box denotes study area within the Frontier delta system. B) Present-day Wyoming with Bighorn Basin highlighted in grey. The study area (Fig. 3) is denoted (red box) within the north-central Bighorn Basin. Modified after Clark (2010) & Hutsky (2011).

In the Powder River Basin, such sandstone bodies have been interpreted as a series of overlapping wave-, tide-, and river-dominated delta lobes separated by prodelta mudstones (Lee et al., 2005; Sadeque et al., 2007; Gani et al., 2007). The Peay Member forms the upper, sandstone-dominated part of the lowermost of several coarsening-upward cycles in the Frontier Formation of the northeast Bighorn Basin of Wyoming (Figure 2). Subsurface correlations show the Peay Member sandstone to have a thick, north-south elongate central core with abrupt lateral pinchouts over several km on both flanks. Clark (2010) & Hutsky (2011) provided mapping and facies analyses of the Peay Member sandstone in the northeast Bighorn Basin along a down-depositional dip.
transect, involving a number of measured sections located largely within the fluvially-dominated axial zone or core of the lobe. These studies established a southeast to southward progradation direction for the Peay Member delta.

**Data and Methodology**

A detailed sedimentologic and ichnologic analysis was completed over a ~20 by 15 km outcrop belt of the Frontier Formation in the northeast Bighorn Basin. Eleven measured vertical outcrop sections address issues of facies variability from the southeast-trending delta lobe core to its eastern flank (Fig. 3). These new data build upon previous work by Clark (2010) and Hutsky (2011) that followed the axial core down depositional dip. Physical sedimentary structures, bedding style and character, sandstone body thicknesses, trace fossils, and bioturbation intensity were logged in each section (Fig. 4). The Peay Member exhibits a vertical and lateral gradation in described features providing the foundation for defining distinct depositional facies. Depositional facies of the delta axial zone, initially documented by Clark (2010) and Hutsky (2011) are illustrated in Figure 5, and summarized below. Facies representative of the eastern flank of the delta, as defined in this work are then documented, and illustrated in Figure 4. Figure 3 shows the regional distribution of the depositional facies across the study area. Table 1 provides details of all ichnological and sedimentological data collected for each facies as summarized below.
Figure 2: Composite log of the Frontier Formation in the northeast Bighorn Basin. Thicknesses of individual members vary throughout the study area and this log does not accurately represent total thickness at any single location.
Figure 3: Map of the study area showing locations of 11 numbered sections (red; this study) around Greybull, Wyoming. Sections from previous studies (Clark, 2010; Hutsky, 2011) (yellow) are located within the axial zone (delta core) of the Peay delta lobe. Regional distribution of interpreted facies and ichnofacies (Fig. 4) derived from outcrop locations are denoted by color shading. Facies distribution is facilitated by correlations across a depositional strike-oriented cross-section (Fig. 4). Recorded paleocurrent data are plotted showing a southward flow direction within the delta core and an eastward direction along the eastern delta flank. Lower picture illustrates a net sand isolith map of
(Figure 3 continued) the Peay Member sandstone derived from 147 outcrop sections and geophysically logged boreholes from across the Bighorn Basin. Delta lobe geometry is elongate down depositional dip and slightly lobate across depositional strike (Fig. 4).

**Facies analysis of the delta axial zone**

Figure 5 illustrates the vertical succession of the Peay Member in the axial zone of the delta body. It shows a ~60 m thick progradational cycle recording the vertical transition from prodelta, through distal, medial, and proximal delta front settings to a mouth bar facies at the top of the sandstone body. The vertical trends in bioturbation style and sedimentary structures of conformable facies are used to interpret the changes in depositional environment experienced during the progradation of a fluvial dominated delta lobe. The following is a summary of the facies analysis, incorporating the work of Clark (2010) and Hutsky (2011).

**Figure 4:** (Next Page) Cross-Section 1 (see Fig. 3 for location), illustrates lateral changes in depositional facies in a direction perpendicular to depositional dip, i.e. from the delta axial core to its eastern flank. Physical data include lithology, sedimentary structures, body and trace fossils, and Bioturbation Index (BI) (See fig. 2 for key). The regional distribution of interpreted depositional facies and ichnofacies is displayed below the graphic logs. Vertical column displays interpreted facies for section 3 located within the fluvial-influenced core (Fig. 5) (M: Mowry, PD-DF: Prodelta-Distal Delta Front; MDF: Medial Delta Front; PDF: Proximal Delta Front; MB Mouth Bar).
Figure 4

<table>
<thead>
<tr>
<th>Facies</th>
<th>Mouth Bar</th>
<th>Proximal-Medial Delta Flank</th>
<th>Prodelta-Distal Delta Flank</th>
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<tbody>
<tr>
<td>Ichnofacies</td>
<td>Impoverished Skolithos</td>
<td>Mixed Cruziana &amp; Skolithos</td>
<td>Cruziana</td>
</tr>
</tbody>
</table>
Table 1

<table>
<thead>
<tr>
<th>Interpreted Depositional Environment</th>
<th>Lithology</th>
<th>Sedimentary Structures</th>
<th>Bioturbation Index, Ichnofacies Assemblage, Trace Fossil Assemblage</th>
<th>Primary Depositional Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prodelta-Distal Delta Front</td>
<td>Bioturbated, heterolithic laminated mudstone and very fine-grained sandstone</td>
<td>Lenticular-, wavy-, planar parallel-laminated, rhythmic normal and inverse interbedded mudstone and very fine-grained sandstone, carbonaceous mud drapes, current- &amp; wave-ripple laminations, soft sediment deformation, syneresis cracks, hummocky cross-lamination, thick siltstone beds</td>
<td>Sporadic; Isolated; BI 0-2; localized BI 3-5 (Rare); More frequent in sand-rich lithology</td>
<td>Primary: Fluvial- &amp; Storm-Influence</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Impoverished archetypal <em>Cruziana</em> Ichnofacies</td>
<td>Secondary: Tidal- &amp; Wave-Influence</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><em>Planolites, Thalassinoides, Diplocraterion, Lockeia, Cosmorhaphe, Zoophycos, Teichichnus, Asterosoma, Palaeophycus, Chondrites, Ophiomorpha, Rosselia,</em> navichnia (mantle and swirl structures</td>
<td></td>
</tr>
<tr>
<td>Medial Delta Front</td>
<td>Sand-dominated, thinly-medium bedded tabular fine-grained sandstone; with mudstone partings</td>
<td>Lenticular- &amp; flaser-bedded sandstones, current- &amp; wave-ripple cross laminations, carbonaceous mud drapes (single &amp; paired), syneresis cracks, wave-rippled bed tops, flat-low angle cross-stratification, tidal-bundle cross-stratification</td>
<td>Sparse and sporadic: Internal: BI 0-1 Bedding planes: 0-4; Average BI 1-2; occasional heavy bioturbation 3-4</td>
<td>Dominant: Fluvial- &amp; Storm-influence</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Impoverished proximal <em>Cruziana</em></td>
<td>Secondary: Tidal- &amp; Wave-influence</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><em>Planolites, Diplocraterion, Lockeia, Thalassinoides,Ophiomorpha, Taenidium, Palaeophycus, Undichnia, Chondrites</em></td>
<td></td>
</tr>
<tr>
<td>Proximal Delta Front</td>
<td>Medium-thickly bedded fine-grained sandstones (10-150 cm), rare-frequent mudstone partings (1-20cm) decreasing up-section, sharp bedding contacts often erosional, bedding character fluctuates between adjacent beds</td>
<td><strong>Internal</strong>: planar parallel-low angle cross-stratification, swaley &amp; hummocky cross-stratification, oscillatory-, current-, &amp; interference- ripple cross-stratification, climbing ripples, carbonaceous mud drapes soft sediment deformation (localized; small-large scale), top-truncated up-stream dipping trough cross-bedding antidune features</td>
<td>Bioturbation is sporadic with BI=0-4, dominantly 0-1, isolated BI 3-4 (rare). Proximal <em>Cruziana</em> with elements of distal <em>Skolithos</em></td>
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<td><strong>Bedding Surfaces</strong>: wave ripple tops (symmetrical, interference, and cuspate), syneresis cracks, load structures, scour marks, heterolithic wavy-bedded fine-grained sandstone &amp; carbonaceous shale, plant debris mudstone partings, well-rounded siltstone cobbles-granules, slump features, low-angle clinoform sets</td>
<td>Dominant: Fluvial Influence Minor: Wave &amp; Storm</td>
<td></td>
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<tr>
<td>Proximal Delta Front</td>
<td>Medium-thickly bedded fine-grained sandstones (10-150 cm), rare-frequent mudstone partings (1-20cm) decreasing up-section, sharp bedding contacts often erosional, bedding character fluctuates between adjacent beds</td>
<td>Rare BI 0, rare 1-2 on bedding planes; Impoverished <em>Skolithos</em> Ichnofacies</td>
<td>Dominant: Fluvial Influence Minor: Wave &amp; Storm</td>
<td></td>
</tr>
<tr>
<td>Mouth Bar</td>
<td>Massive, tabular, amalgamated fine-grained sandstones very few mudstone partings</td>
<td>Flat- to low-angle cross-stratification (dominant), hummocky cross-stratification, small cross-bed sets, wave &amp; interference rippled bed planes, scour marks, rounded siltstone pebbles-cobbles, plant debris, syneresis cracks</td>
<td>Dominant: Fluvial Influence Minor: Wave &amp; Storm</td>
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</table>
Table 1: Characteristics of Peay Member lithofacies. Described physical structures and trace fossils are listed in decreasing order of abundance.
Prodelta-Distal Delta Front

The basal facies of the progradational cycle comprises bioturbated, thinly interbedded siltstone and very fine- to fine-grained sandstones dominated by several types of ripple-scale current-, storm-, & wave-derived structures (Figure 5, Table 1). The bioturbation in this interval displays a sporadic distribution (BI 0-2 in most exposures; BI 3-5 uncommonly), focused within heterolithic sandstones and mudstones, but absent within thick mudstone intervals (Figure 6 C-E). The diverse trace fossil assemblage contains both complex, fully marine ichnogenera (e.g. Cosmorhaphe, Asterosoma, Zoophycos, Teichichnus) and abundant, simple traces of deposit-feeding trophic generalists (Table 1; Gingras et al, 2011). Traces record predominantly deposit- feeding behavior with minor filter-feeding structures in most intervals.

Interpretation

This facies represents the prodelta and distal delta front of a fluvial-influenced delta system that experienced episodic fluvial-, storm-, and wave-conditions with tidal-processes. The trace fossil assemblage has been interpreted (Clark, 2010; Hutsky, 2011) as an archetypal expression of the Cruziana Ichnofacies with mixed elements of impoverishment based on the high diversity and abundance of complex traces. The sporadic bioturbation distribution indicates episodic depositional conditions with strong fluctuations in stress levels; however, yielding different bioturbation suites. Thicker sand beds display low bioturbation intensity, and trace fossil diversity is restricted to facies-crossing trophic generalists. This pattern may reflect some combination of elevated bed
**Figure 5:** Graphic log of Section 3 (Figs. 3 & 4) representing a vertically continuous progradational cycle from within the fluvial-influenced, core annotated with interpreted depositional facies. Grain-size and fluvial-influence increase up-section, but Bioturbation Index (BI) decreases along the same trend.
Figure 6: (Previous Page) A) Thin (<5 m) sheet-like sandstone body of the prodelta-distal delta flank facies. Taken at Section 10 at 18 m above base level (Figs. 3, 4). B) Event bed displaying swaley cross-stratification (SCS) and hummicky cross-stratification (HCS) from the distal delta flank facies. Heavily bioturbated bed juxtaposed above event bed interpreted as quiescent, fair-weather conditions. Taken at Section 8 (Fig. 3). C) Rhythmic inverse and normal graded, interbedded sandstones and mudstones from the prodelta-distal delta front facies. Current- and wave-rippled structures are present (top) with isolated and sporadic bioturbation distribution (BI = 0-2). Planolites (P), Teichichnus (T), Zoophycos (Z), mantle and swirl structures (MS). Taken at Section 3 at 14 m above base level (Figs. 3, 5). D) Heavily bioturbated interval (BI = 2-4) from the prodelta-distal delta front facies. Planolites (P), Palaeophycus (Pa), Asterosoma (As), Teichichnus (T). Taken at Section 3 at 19 m above base level (Figs. 3, 5). E) Sporadic bioturbation distribution from the prodelta-distal delta front. Interval shows heavily bioturbated zone (BI = 5) amongst sparsely bioturbated intervals (BI = 0-2). Thalassinoides (Th), Cylindrichnus (Cy), Planolites (P), syneresis crack (Sy). Taken at Section 3 at 19 m above base level (Figs. 3, 5). F) Thoroughly bioturbated (BI = 4-5) muddy sandstone from the prodelta-distal delta flank facies. Gyrolithes (Gy). Taken at Section 8 (Fig. 3).

Shear stress and turbidity, fluctuating water salinity, fluidal substrate, and rapid deposition. Finer-grained lithologies, representative of quiescent, fully marine conditions, contain high bioturbation intensity and a diverse suite of complex traces; however, likely reflecting lower levels of physico-chemical stress. (Bann & Fielding, 2004; Hansen & MacEachern, 2005; MacEachern & Bann, 2008; Bhattacharya & MacEachern, 2009; Defoe & Pemberton, 2010; Gingras et al., 2011). The presence of navichnia (mantle and swirl structures, cf. Lobza & Schieber, 1999) within unbioturbated, structureless mudstones implies a thixotropic substrate, which hindered substrate colonization (Bhattacharya & MacEachern, 2009).
Medial Delta Front

The prodelta-distal delta Front facies coarsens upward gradually into the medial delta front facies (Fig. 5). This facies is a lenticular-flaser bedded sandstone displaying abundant rhythmic mudstone partings and syneresis cracks (Figure 7 C, F, Table 1). Bioturbation is mainly restricted to bedding planes (BI 1-2; locally BI 3-4) and internal bioturbation is sparse and isolated (BI 0-1) (Figure 7 D, E). The trace fossil assemblage is dominated by horizontal deposit feeders and simple trophic generalists (Table 1).

Interpretation

The medial delta front facies records deposition from fluvial outflow-, wave-, and storm-induced processes with notable elements of tidal forcing, resulting in a mixed energy depositional environment (Table 1). The trace fossil assemblage has been interpreted as an impoverished proximal expression of the *Cruziana* Ichnofacies because of the dominance of horizontal deposit-feeding structures (Clark, 2010; Hutsky, 2011). The bioturbation distribution and physical structures indicates a highly stressed depositional environment with high sedimentation rates, water turbidity, strong salinity fluctuations (large syneresis cracks), and high-energy storm events (*cf.* Bann & Fielding, 2004; MacEachern & Bann, 2008; Gingras et al., 2011). High fluvial outflow sedimentation rates limited extensive colonization of the substrate, resulting in minimal internal bioturbation. The predominance of traces along bedding planes is interpreted as organism colonization after the deposition of an ‘event bed’ to utilize newly deposited food resources. These traces often coincide with the presence of well-developed syneresis
cracks indicating brackish water conditions post-deposition; moreover, the salinity stressed conditions were advantageous for tolerant trophic generalists in search of food resources (Beynon et al., 1988; Bann & Fielding, 2004; MacEachern & Gingras, 2007; MacEachern et al., 2007; Gingras et al., 2011). The paucity of traces made by suspension-feeders, however, indicates turbid water conditions after deposition, which inhibited filter-feeding organisms but did not adversely affecting deposit-feeders (cf. Moslow & Pemberton, 1988; Coates & MacEachern, 1999; Bann & Fielding, 2004; MacEachern et al., 2005; MacEachern et al., 2007; MacEachern & Bann, 2008; Gingras et al., 2011). Several members of the Frontier Formation from the adjacent Powder River Basin preserve similar tidally-influenced intervals (Frewens sandstone: Willis et al., 1999; Bhattacharya & Willis, 2001; Wall Creek Member: Sudeque et al., 2009; Gani et al., 2007) and these units show similar trace assemblages.

**Proximal Delta Front**

The proximal delta front facies comprises sharply-based and thickly bedded sandstone beds (Figure 7 C). Individual beds contain several high-energy sedimentary structures with wave rippled tops, but the nature of internal stratification varies between adjacent beds (Table 1, Figure 5, Figure 8 G). Event beds are common in this facies and show a similar bioturbation style as in the medial delta front facies, but are consistently thicker. Fissile, flat-laminated mudstone partings between sandstone beds are largely unburrowed and progressively decrease in frequency and thickness up-section (Figure 8 F, G). Bioturbation is typically isolated and sporadic in distribution (BI=0-4; average BI=0-1), with most traces on or subtending from beds tops (Figure 8 B, C, E, F, G). Discrete
beds with high bioturbation intensities (BI= 3-4) occur locally and are dominated by one or two ichnogenera (Figure 8 B). The trace fossil assemblage is of moderate diversity (12 ichnogenera) and consists of simple, horizontal deposit-feeding traces from facies-crossing trophic generalists. Many beds display an abundance of domicnchia from suspension-feeders, however, seldom are more than two ichnogenera found together (Table 1; Figure 8 E). Some domicnchia occur as isolated, deeply penetrating burrows (Fig. 8 C).

**Interpretation:**

The proximal delta front facies presents several lines of evidence supporting episodic, high-energy fluvial outflow conditions in close proximity to a river mouth. The presence of several upper-flow regime physical structures supports the interpretation of episodic deposition during high-energy fluvial outflow (cf. Arnott & Southard, 1990; Southard et al., 1990; Dumas et al., 2005; Dumas & Arnott, 2006; Fielding, 2006).

**Figure 7:** (Next Page) **A)** Tidally- influenced Heterolithic Interval (H.I.) with Tabular Sandstone (T.S.) (event bed) from the proximal-medial delta flank facies. Taken at Section 4 at 24 m above base level (Figs. 3, 4). **B)** Rhythmic mudstone drapes interbedded with bi-modal wave-ripple cross-lamination from the proximal-medial delta flank facies. Taken at Section 4 at 24 m above base level (Figs. 3, 4). **C)** Boundary between proximal delta front and medial delta front facies from the delta core. Taken at Section 3 at 24 m above base level (Figs. 3, 5). **D)** Interference wave-rippled sandstone bed from the medial delta front facies. Bioturbation (BI = 2) is restricted to bedding planes. *Thalassinoides* (Th), *Diplocraterion* (D), *Planolites* (P), shell casts (S.C.). Taken at Section 3 (Figs. 3, 5). **E)** Intense bioturbation (BI = 3-4) of sandstone bed from trophic generalists with large syneresis cracks (Sy). *Planolites* (P), *Diplocraterion* (D). Taken at Section 3 (Figure 3). **F)** Lenticular-flaser bedded sandstone with abundant mudstone drapes from the medial delta front facies. Taken at Section 3 at 23 m above base level (Figs. 3, 5).
The trace fossil assemblage represents an impoverished expression of the proximal *Cruziana* Ichnofacies with elements of the distal *Skolithos* Ichnofacies, based on the presence of ichnogenera representing both deposit- & filter-feeding fauna. Episodic
depositional events created significant fluctuations in several physicochemical stresses including elevated bed shear stress, rapid sedimentation rates, salinity changes, high water turbidity, and substrate consistency (mud vs. sand) (MacEachern et al., 2007; MacEachern & Bann, 2008; Gingras et al., 2011; among others). Traces on or subtending from bed tops indicate an episodic depositional regime with organisms only able to exploit bed surfaces after a sedimentation event. The overlying fissile, flat-laminated mudstone partings resulted from suspension settling of fine-grained sediments during turbid water conditions following discharge events. Turbid conditions hindered colonization by most suspension-feeders, but discrete, highly bioturbated beds dominated by Diplocraterion also indicate occasional clear-water conditions (Fig. 8 B).

High sedimentation rates and fluctuating salinity levels are the most influential physicochemical stresses because of the energy requirements needed to colonize environments with rapidly shifting substrates and fluctuating salinity levels (MacEachern & Bann, 2008; Gingras et al., 2011). The occurrence of monogeneric or monospecific assemblages is substantive evidence for reduced salinity, particularly if such ichnogenera represent strongly facies-crossing behaviors and deeply penetrating burrows (trophic generalists) (Grassle & Grassle, 1974; Beynon et al, 1988; MacEachern et al., 2007; MacEachern & Gingras, 2007; Gingras et al., 2011). The consistently low bioturbation intensity resulted from prolonged stressful conditions, but occasional periods of favorable ambient conditions allowed for intensely bioturbated intervals (Figure 7 B). Gingras et al (2011) called this bioturbation style a sporadic homogeneous distribution, which is typical of locations proximal to high-energy environments such as distributary channels,
storm-dominated shelves, delta fronts, and flooding rivers. Sporadic distribution of trace fossils can be also be affected by the degree of storm influence (MacEachern & Gingras, 1992).

**Mouth Bar**

The mouth bar facies is the thickest (>30 m) and uppermost unit within the Peay progradational cycle. Deposits are dominated by cliff-forming, amalgamated sandstone beds containing few mudstone partings (Figs. 8 A, 9). Sedimentary structures are dominated by low-angle stratification and associated flat stratification and cross-bedding (Table 1). Bioturbation intensity and diversity are the lowest of all facies (BI = 0), but lenses of bioturbation are preserved locally (BI=1-2) (Table 1, Figure 5). Trace fossil diversity is restricted largely to simple vertical or inclined burrows subtending from bedding planes, but horizontal deposit-feeding traces locally occur (Figure 8 D, E).

**Interpretation**

The mouth bar facies preserves structures indicating consistently high depositional energy and represents the most proximal position within this deltaic progradational cycle. Sedimentary structures indicate persistent fluvial outflow processes consistent with the central location within the delta core. The extremely low bioturbation intensity and limited diversity of simple vertical and inclined traces are interpreted as an impoverished expression of the *Skolithos* Ichnofacies. This trace assemblage is typical of very stressed environments with consistently high depositional energy and sedimentation rates, punctuated by brief periods of slack-water conditions with short colonization
windows otherwise too stressful to support bottom-dwelling life (Bann & Fielding, 2004; MacEachern et al., 2005; MacEachern & Bann, 2008). Sedimentation rates were too rapid to support most deposit feeders, but select filter-feeding organisms were able to maintain contact with the sediment-water interface. The ichnogenus *Macaronichnus*, typical in some temperate zone shoreface environments, is not preserved in the Peay Member.

**Facies analysis of the delta core to flank transect**

This section describes the facies distribution from the fluvial-dominated axial core to the delta flank environment (Fig. 3). Cross-section 1 (Fig. 4) shows the Peay Member as a thick (> 40 m) sandstone body in the delta axial core, which thins and to a < 5 m thick, sheet-like body at the delta flanks.

**Figure 8:** (Next Page) **A)** Boundary between proximal delta front and mouth bar facies from the delta axial zone. Note decrease in mudstone partings up-section. Taken at Section 3 at 35 m above base level (Figs. 3, 5). **B)** Intensely bioturbated zone (BI = 4) between unbioturbated sandstones within the proximal delta front facies within the delta core. Interval exclusively burrowed by domicinia of filter-feeding organisms. *Diplocraterion* (D). Taken at Section 3 at 30 m above base level (Fig. 8 continued) base level (Figs. 3, 5). **C)** Isolated, deeply penetrating *Diplocraterion* burrow within the proximal delta front facies. (D). Taken at Section 3 at 28 m above base level (Figs. 3, 5). **D)** Bioturbated zone within the mouth bar facies. *Diplocraterion* (D), unnamed trace fossil (?). Taken at Section 3 at 45 m above base level (Figs. 3, 5). **E)** Isolated horizontal *Ophiomorpha* (O) from the proximal delta front facies. Taken at Section 3 at 32 m above base level (Figs 3, 5). **F)** Organic-rich lense with allochthonous *Teredolites* (Td) within wave-rippled sandstone unit with mudstone parting above. *Cylindrichnus* (Cy) traces originating from bedding surface to exploit lense. Taken at Section 3 at 32 m above base level (Figs. 3, 5). **G)** Top-truncated trough cross-beding below massive sandstone bed, separated by thin mudstone parting. Bioturbated (BI = 2) interval below trough cross-bedding unit. *Planolites* (P), *Diplocraterion* (D), possible resting trace (RT). Taken at Section 3 at 28 m above base level (Figs. 3, 5).
Figure 9: Outcrop photo showing vertically stacked conformable facies from the fluvially-dominated delta axial zone. Taken at Bighorn River outcrop exposure at Section 3 (Fig. 3).

**Mouth Bar**

The mouth bar and proximal delta front facies (described above) dominate the upper part of the Peay Member along the delta axial core and are here combined as the mouth bar facies along the lateral transect (Figs. 3, 4).

**Proximal-Medial Delta Flank**

The proximal-medial delta flank facies is a moderately thick (<20 m), heterolithic interval characteristic of the central part of the cross-delta transect between the prodelta/distal delta flank and mouth bar zones (Figs. 3, 4). Lithology and physical structures are similar to the medial delta front, but have more abundant mudstone partings.
and drapes (Table 1, Fig. 7 A, B). This facies is divided into 1. heterolithic- & mudstone-dominated intervals, and 2. tabular sandstone (event) beds based on the distinct differences in sedimentary structures and bioturbation character (Table 1). The heterolithic intervals display little or no bioturbation (BI = 0-1) and, where present, bioturbation occurs locally within mudstone drapes or along bedding planes. These event beds are similar to those in the proximal and medial delta front facies and often erosionally truncate the heterolithic intervals. Event beds show sporadic bioturbation intensities concentrated on bedding surfaces (BI = 0-4) with internal traces being sparse to absent (BI = 0-2) (Figure 7 D, E). The trace fossil assemblage for this facies has a moderate overall diversity (12 ichnogenera) of traces recording both deposit- and filter-feeding organisms, but most individual beds have a low diversity of traces (2-4 ichnogenera) (Table 1).

**Interpretation:**

The proximal-medial delta flank is here interpreted as a mixed tidal-, wave-, and storm-influenced depositional environment with a lesser fluvial influence. Depositional conditions fluctuated significantly at bed-scale, often representing periods of ambient conditions (tidally influenced), punctuated by event bed deposits. The heterolithic interval records strong tidal- and wave-influence with cyclic fluctuations in the dominant depositional agent. These deposits have low bioturbation intensities because high tidal sedimentation rates resulted in narrow colonization windows (Gani et al., 2007). It is important to note that the relative influence of tidal-influence to wave-influence varies,
possibly due to proximity to the river mouth or to fluctuations in the strength of tidal cycles.

The trace fossil assemblage of the proximal-medial delta flank facies is interpreted as an impoverished proximal expression of the *Cruziana* Ichnofacies with elements of distal *Skolithos* Ichnofacies (Table 1). This facies experienced many of the same stresses as the proximal to medial delta front, thus resulting in similar bioturbation distribution and trace assemblages. The strong imprint of fluvial outflow processes on the proximal and medial delta front facies is replaced by high tidal sedimentation rates and slight differences in bioturbation. Event beds and the more conspicuously wave-influenced intervals show an increase in trace fossil diversity (e.g. *Rhizocorallium, Chondrites, Conichnus, Palaeophycus*) compared to the medial delta front facies of the axial core. This increase in diversity is interpreted to be the result of persistent wave agitation effectively buffering high tidal sedimentation rates, which allowed for more faunal colonization opportunities. On the other hand, the proximal delta front shares a comparable trace assemblage and distribution to the wave-influenced lithologies, supporting evidence for proximity to the river mouth.

**Prodelta-Distal Delta Flank**

Figures 3 and 4 show the prodelta-distal delta flank as a thin (<5 m), sheet-like sandstone body located on the outermost delta peripheries. Physical structures occur at lamination-scale and are dominated by wave- & storm-derived structures, but also include subordinate elements of fluvial and tidal generated structures (Table 1, Figs. 4, 6
B). The bioturbation distribution fluctuates at bed-scale with homogenized zones (BI = 4-5) juxtaposed above low-moderately disrupted beds (BI = 0-3) showing remnants of the original wave- & storm structures (Figs. 4, 6 B, F). This facies contains the highest diversity (19 ichnogenera) and abundance of trace fossils from the delta succession. The trace fossil assemblage is similar to the prodelta-distal delta front showing the presence of both fully marine ichnogenera (i.e. Asterosoma, Cosmorhaphe, Schaubcyllndrichnus, Zoophycos, Conostichus) and abundant traces of trophic generalists (Table 1) (Gingras et al., 2011).

**Interpretation:**

The prodelta-distal delta flank facies is interpreted as the product of a wave-dominated subaqueous delta setting that experienced largely wave- & storm-influences with lesser elements of tidal and fluvial processes. Low-energy wave agitation created a more open marine environment where organisms experienced fairly uniform salinity conditions with low sedimentation rates, homogeneous food distribution, consistent salinity levels, and oxygenation at the sediment-water interface (MacEachern & Pemberton, 1992; Gingras et al., 1999; MacEachern et al., 2005; Gani et al., 2007). Well-preserved deposits displaying storm- & wave-generated structures with little to no internal bioturbation are interpreted as event beds. These event beds were highly favorable for post-deposition colonization because of the well oxygenated sediment-water interface, sandy substrate, and abundance of new food resources, but the low-salinity levels were intolerable for many sediment-disrupting fauna (MacEachern et al., 2005; MacEachern & Bann, 2008). The high preservation potential resulted from
relatively elevated sedimentation rates and stressful post-deposition conditions immediately after depositional events (MacEachern et al, 2007; MacEachern & Bann, 2008). Deposit-feeding trophic generalists were able to colonize surfaces of the event beds, but continued relatively high sedimentation rates prevented thorough bioturbation, resulting in lower bioturbation intensities (BI 0-3). Eventually, persistent wave agitation circulated the water column creating more desirable conditions at the sediment-water interface, which allowed more disruptive and fully marine fauna to effectively colonize the beds, resulting in high bioturbation intensities (BI 4-5).

The trace assemblage can be interpreted as a slightly impoverished expression of the archetypal *Cruziana* Ichnofacies, showing a high abundance and diversity of complex and fully marine trace fossils (Table 1, Figure 4). As such, it is close to representing “utopian” open marine shoreface conditions. The trace fossil assemblage slightly resembles the prodelta-distal delta front facies, but distinct differences in bioturbation distribution indicate different depositional conditions. Wave-dominated delta environments tend to show the lowest degrees of physicochemical stresses because persistent wave circulation reduces the diversity of possible environmental stresses (Bann & Fielding, 2004; MacEachern & Bann, 2008; Dafoe & Pemberton, 2010; Gani et al., 2007; Sadeque et al., 2007). The irregular sedimentation experienced in the prodelta-distal delta front resulted in sporadic intervals of higher bioturbation enveloped within uniformly low bioturbated lithologies. Sadeque et al (2007) and Gani et al (2007) found similar wave-dominated delta facies including the archetypal *Cruziana* Ichnofacies in the Wall Creek Member of the Frontier Formation.
Discussion

Wright (1977) and Coleman (1988) describe how hydraulic mixing dissipates fluvial transport energy away from river mouth settings, resulting in distinct depositional environments down the delta front. This concept is applied here to the Peay Member to establish how the fluvial influence in a river-dominated lobe is dissipated along depositional strike and replaced by other depositional processes along the flanks of the delta lobe. The central premise is a delta complex may show variation in degrees of fluvial, tidal, wave, and storm influence because the strength of each individual process may change across the full coastline of the delta (Bhattacharya & Giosan, 2003; Hansen & MacEachern, 2005; Gani et al., 2007; Sadeque et al., 2007; Dafoe & Pemberton, 2010; among others). The traditional method of simplistically classifying delta systems via the ternary process frameworks of Coleman & Wright (1975) and Galloway (1975) has proved impractical because of the heterogeneity inherent within most deltas in both space and time.

Figure 10 illustrates how the Peay Member delta lobe changes along depositional strike from a fluvial-dominated core, to a mixed tidal-, storm-, and wave-influenced proximal to medial delta flank, and finally to a wave- & storm-influenced distal delta flank to prodelta. Several lines of evidence including an increase in bioturbation intensity and diversity, the transition of bed-scale to ripple-scale structures, significant thinning of the sandstone body, and decrease in sediment caliber suggest the dominant fluvial influence was dissipated away from the delta core and succeeded by marine influences (tidal & wave) along the delta flank. Paleocurrent data supports a switch from a S-SE
current direction in the core to a E-NE direction along the delta flank (Fig. 3). This shift possibly occurred from increased sedimentation along the delta core, creating an elevated delta body and encouraging gravity-driven sedimentation down the delta flank slope. Storm deposits are described in all facies; however, the thickness and evidence for erosional energy consistently decrease away from the delta core. Trace fossil assemblages and bioturbation intensity notably differ from delta core to flank in response to shifting depositional processes and their associated stresses (Fig. 10). The proximal delta front and mouth bar facies experienced the highest degrees of physicochemical stresses because most benthic organisms were intolerant of the high depositional energy, rapid sedimentation rates, and fluctuating salinity levels (Bann & Fielding, 2004; Hansen & MacEachern, 2005; Gani et al., 2007; Sadeque et al., 2007; MacEachern & Bann, 2008; Dafoe & Pemberton, 2010; Gingras et al., 2011). As the fluvial energy was dissipated along the proximal-medial delta flank facies, marine processes (tidal & wave) dominated sedimentation. Bioturbation was still sparse because high tidal sedimentation rates hindered colonization. Periods of increased wave-influence, however, resulted in higher bioturbation intensity and diversity from the wave action buffering tidal sedimentation rates.
Figure 10: Depositional model of the delta axis to flank transition. Model illustrates the progressive change in depositional processes away from the fluvially-dominated delta core to the wave-influenced delta flank. Representative graphic logs depict generalized sandstone body thickness, physical structures, bioturbation intensity (BI), and trace fossil diversity. Interpreted ichnofacies, lithofacies, and dominant depositional processes annotated along the base. Lower picture illustrates the location of the core to flank transect along an idealized river-dominated delta lobe. Actual location is given in Figure 3.

Both the mouth bar and proximal-medial delta flank environments show evidence of episodic deposition with short colonization windows, resulting in most bioturbation on or subtending from bedding surfaces. The prodelta-distal delta front preserve features
indicative of the lowest levels of environmental stress (highest trace diversity and 
bioturbation intensity). The tidal influences became subordinate, and were replaced by 
wave-influenced sedimentary structures. The presence of fully marine ichnogenera also 
indicates more stable depositional environments with low sedimentation rates and wide 
faunal colonization windows.

The differences in ichnology and sedimentology of the fluvially-dominated delta 
front compared to the mixed-energy delta flank equivalents convey how different regions 
of a delta environment may experience varying depositional processes. The prodelta-
distal delta front and prodelta-distal delta flank facies have similar trace assemblages, 
suggesting both environments experienced periods of similar conditions; however, the 
more stressful conditions in the delta front setting resulted in a sporadic bioturbation 
distribution. Bioturbation distribution from the medial delta front is comparable to the 
medial-proximal delta flank, but the dominance of deposit-feeding traces in the delta 
front setting reflects impoverishment compared to the delta flank setting. This 
emphasizes how interpretations based on a single or localized rock succession may bias 
the perception of a mixed-energy delta system. Figure 5 displays a single coarsening 
upward cycle located along the axial core during the progradation of the Peay Member 
lobe. This progradational cycle experienced persistent fluvial-influence, resulting in 
consistently lower bioturbation intensity and distribution compared to the delta flank 
setting. The delta core shows a typical coarsening-upward cycle exposing a vertical 
succession of fluvial-dominated facies from prodelta to mouth bar, but clearly does not 
represent the entire mixed-energy delta lobe because it lacks delta flank facies. This
demonstrates how an analysis based on only part of a delta body could be interpreted as an end-member in the tripartite classification system, but in reality is merely a component of a mixed-influence depositional system with varying depositional conditions from core to flank. As a result, sedimentological and ichnological studies should always take into account the relative position data are collected from within a delta complex before making process, and thus planform interpretations.

**Conclusions**

The Peay Member is interpreted to transition laterally from a high-energy, fluvial mouth bar facies within the axial core, to a tide- & wave-influenced proximal-medial delta flank facies, and finally to a low-energy storm- and wave-influenced prodelta-distal delta flank facies at the peripheries of the delta lobe. Bioturbation intensity and trace fossil assemblages reflect a dissipation of stresses from core to flank. The trace assemblage in the core is interpreted as a highly stressed, impoverished expression of the *Skolithos* Ichnofacies, passing to a low-stress, archetypal expression of the *Cruziana* Ichnofacies along the delta flanks. Ichnology provides crucial information to delineate the relative influence of fluvial, tidal, wave, and storm processes, which could not be derived from sedimentology alone. This study integrates the use of ichnology with an analysis of the lateral transition of depositional facies in a fluvially-dominated delta lobe. The vertical and lateral transition of facies and ichnofacies emphasizes that most deltas are dynamic systems and depositional influences may fluctuate both temporally and spatial throughout its existence. In conclusion, isolated sedimentological and ichnological data may only reveal part of a complex delta environment, thus leading to biased
interpretation as an end-member in the tripartite classification unless the relative position within a delta is taken into account.
References


Part II
Introduction

The reliable correlation of sandstone and other sediment bodies in the subsurface is an essential prerequisite to developing stratigraphic models for exploration and for scientific purposes. Modern understanding of subsurface sedimentary successions has shown that the traditional view of horizontally stacked or “layer-cake” stratigraphy is unrealistic in many if not most cases, and this view has been supplanted by alternative models invoking diverse stratal geometries and the recognition that sandstone bodies are more often than not finite in cross-sectional dimensions. Several studies from the Cretaceous Western Interior Basin (KWIS) of North America have successfully utilized sub-surface geophysical data to aid in correlations of Upper Cretaceous shallow marine sandstone bodies (Bhattacharya & Willis, 2001; Vakarelov et al, 2006; Gomez-Veroiza & Steel, 2010; Kirschbaum & Roberts, 2010; among others). Finn (2010) and Finn et al (2010) provided a comprehensive subsurface mapping and hydrocarbon assessment for several Cretaceous and Tertiary formations spanning hundreds of kilometers across much of the Bighorn Basin in central Wyoming and southern Montana. Included in this analysis was the Frontier Formation, the subject of the present work. Several sandstone bodies (marine, marginal marine or coastal in origin) within the Frontier Formation were correlated north-south (depositional dip) and east-west (depositional strike) to provide general trends of several, laterally discontinuous bodies across the basin. These studies were carried out at a regional scale with borehole spacing typically on the order of 5-50
km; however, they did not integrate detailed mapping of individual formations or sandstone bodies. Kirschbaum & Roberts (2010) provided a more detailed sub-surface mapping study focusing on sandstone bodies and other important stratigraphic markers in the Frontier Formation of southwest Wyoming. This study incorporated both outcrop and sub-surface geophysical data to create several cross-sections and isolith maps showing the thickness distribution of the Frontier Formation.

Kirschbaum et al (2009) produced three cross-sections (two northwest-southeast, one east-west oriented) correlating the Frontier Formation tens of kilometers across the present study area (Fig. 1) of the northeastern Bighorn Basin, near Greybull, Wyoming. These authors correlated several key stratigraphic surfaces and sandstone bodies from outcrop sections to distinct geophysical responses in wireline logs, and developed a nomenclature system for identification. The offlapping sandstone body geometry predicted by these cross-sections has not yet been confirmed by utilizing more closely-spaced data. Hutsky (2011) provided the foundation for this study by mapping several sandstone bodies and key stratigraphic surfaces both north-south and east-west across much of the northeastern Bighorn Basin. This author made direct correlations from sandstone bodies mapped at outcrop (Fig. 2) to subsurface well log data, which allowed for a limited assessment of the distribution of sub-surface facies along depositional dip (northnorthwest to southsoutheast).

The purpose of this study is to build on Hutsky’s (2011) interpretation of the basal Peay Member sandstone (Fig. 2) by adding greater areal coverage of data points, particularly across depositional strike, and projecting the facies variability mapped at the
surface into the sub-surface. This will establish a three-dimensional model of sandstone body geometry and facilitate correlation across the basin. This model provides a means of predicting sandstone body geometry, lateral terminations of facies (stratigraphic pinchouts), and dispersal patterns within the Bighorn Basin while providing potential insights into other shallow marine sandstone bodies within the Cenomanian-Turonian of the KWIS. The study has significant potential to hydrocarbon exploration in predicting reservoir geometries and potential trapping mechanisms within the Bighorn Basin.

**Figure 1:** A) Paleogeographic reconstruction of western North America during the Late Cretaceous (Cenomanian-Coniacian). The map shows several deltas sourced from the Sevier Orogenic Belt feeding eastward into the Cretaceous Western Interior Seaway (KWIS). Red box denotes study area within the Frontier delta system. B) Present-day Wyoming with Bighorn Basin highlighted in gray. The study area (Fig. 3) is denoted (red box) within the north-central Bighorn Basin. Modified after Clark (2010) & Hutsky (2011).
Geologic Setting & Stratigraphy

The Upper Cretaceous (Cenomanian-Turonian) Frontier Formation developed as a series of prograding clastic wedges sourced from the Sevier Orogenic Belt into the KWIS (Fig. 1). Sediment accumulation occurred in the Western Cordilleran Foreland Basin (foredeep) on a gently eastward-sloping sea floor (Posamentier & Morris, 2000). Most recent studies have concluded that these bodies represent shallow marine and deltaic systems that were partly controlled by relative sea level fluctuations (Bhattacharya & Willis, 2001; Lee et al., 2007; Vakarelov & Bhattacharya, 2009). Many of these isolated bodies display top-truncation interpreted as transgressive ravinement following falling stage and low-stand sand accumulation, in an overall low accommodation context, which resulted in non-accumulation or removal of nearshore and fluvial deposits from most sandstone formations (Bhattacharya & Willis, 2001; Lee et al., 2007; among others).

In the northeast Bighorn Basin, the Frontier Formation consists of several discrete sandstone bodies encased in marine mudrock intervals with bentonite beds preserved at certain stratigraphic levels (Fig. 2). This study uses the stratigraphic nomenclature for the northeast Bighorn Basin established by Hutsky (2011), which provides several newly named members (Fig. 2). The Frontier Formation conformably overlies the marine Mowry Shale and is overlain by the marine Cody Shale. Previous studies have put the Mowry-Frontier boundary at the Clay Spur Bentonite (Hintze, 1914; Kirschbaum et al., 2009), but this bed is not pervasive across the region and is susceptible to misidentification amongst other bentonite beds within the Mowry Shale. Accordingly, this study defines the boundary at a distinct, laterally persistent upward change in
lithology from a light grey porcellaneous siltstone (Mowry Shale) to dark grey, fissile shale (Stucco Member of the Frontier Formation) (Clark, 2010; Hutsky, 2011). This change is also readily recognizable in subsurface wireline log data. The Peay Member sandstone is the lowest coarsening upward sandstone unit that overlies up to 40 m of fissile shale and thin sandstones of the Stucco Member (Fig. 2). The lower boundary of the Peay sandstone is a gradational boundary with the underlying Stucco Member. In outcrop, the upper boundary of the Peay Member is an abrupt contact between massive, cliff-forming sandstones and an overlying, thin, heavily bioturbated siltstone of the Potato Ridge Member that underlies the ‘X’ Bentonite (Hutsky, 2011).

Methods

A detailed sedimentologic analysis was performed along a ~25 km northwest-southeast trending outcrop belt of the Frontier Formation within the northeast Bighorn Basin. Eleven outcrop sections were measured south, east, and northeast of Greybull, Wyoming and southeast of areas mapped by Clark (2010) and Hutsky (2011) (Fig. 3). Vertical sections were measured at outcrop, incorporating data on lithology, body and trace fossils, sedimentary structures, sandstone body thickness, grain-size trends, paleocurrent data, and lithological bedding trends and contacts. This provided the basis for facies and depositional environment interpretations.
Figure 2: Composite log of the Frontier Formation in the northeast Bighorn Basin. Thicknesses of individual members vary throughout the study area and the log does not accurately represent total thickness at any one location. Key to sedimentary structures, trace fossils, and other features are also given.
Two outcrop-based cross-sections oriented northwest-southeast (depositional dip) (Hutsky, 2011) and southwest-northeast (depositional strike) were constructed to illustrate the three-dimensional geometry of sandstone and other bodies (D-D’ & E-E’ on Fig. 3, respectively). Well logs from drill holes located throughout the eastern Bighorn Basin (Bighorn, Park, and Washakie Counties) were acquired from the Wyoming Oil and Gas Conservation Commission and used to generate regional maps showing sandstone body distributions and correlations of key stratigraphic surfaces across the Bighorn Basin. Six cross-sections oriented down depositional dip (A-A’, F-F’ Fig. 3) and across depositional strike (A-A’, C-C’, E-E’, G’-G Fig. 3) were compiled in addition to the outcrop-based cross-sections to facilitate subsurface correlations. The boundary between the Peay Member sandstone and Potato Ridge Member was chosen as the cross-sectional datum because this contact best shows the Peay sandstone body geometry and is easily determined in outcrop and geophysical data (gamma ray, neutron porosity, and resistivity logs). A net sand isolith map (Fig. 4) of the Peay sandstone was created using PETRA computer software.

**Figure 3:** (Next Page) Map of the study area showing locations of measured outcrop sections and wells used in this study to correlate the Peay Member sandstone across the Bighorn Basin, Wyoming (Park, Bighorn, and Washakie Counties). Previously measured outcrop sections from Clark (2010) (purple) and Hutsky (2011) (yellow) located within the axial zone (delta core) were correlated along depositional dip (D-D’). Sections from this study (red) are oriented along depositional strike (E-E’) and depicted in higher resolution in the lower image. Well logs acquired from the Wyoming Oil and Gas Conservation Commission (green) were correlated east-west, across depositional strike (A-A’, C-C’, E-E’, G-G’) and northeast-southwest, along depositional dip (B-B’, F-F’). Well-outcrop calibration points (Fig. 5) are located at either end of the outcrop belt.
This isolith map was created by subtracting intervals displaying high gamma signatures from the total thickness of the sandstone interval, yielding the total thickness of the sandstone body at a given location.
**Figure 4**: Net sand isolith map of the Peay Member sandstone derived from 147 outcrop and well log data points from across the Bighorn Basin. Map shows a northwest-southeast elongate, southeast narrowing, digitate body showing abrupt (<25 km) lateral thinning from axial core (15-75 m) to the lobe flanks (0-10 m). Locations of cross-sections (Fig. 3) are illustrated on the map. Delta lobe geometry is elongate down depositional dip and somewhat lobate across depositional strike.
Outcrop Analysis

Figure 5 (D – D’; modified from Hutsky, 2011) illustrates a high-resolution northwest-southeast oriented cross-section displaying correlations of the Peay Member sandstone and other important stratigraphic markers from outcrop. This cross-section is located in the axial zone (core) of the delta lobe, parallel with depositional dip as established by Clark (2010) and Hutsky (2011). The Peay Member shows a consistently thick body (15-75 m range), but thickening and thinning trends occur along section; variations in sandstone body thickness may have originated from post-depositional tectonic activity (Hutsky, 2011). Physical structures and the digitate body geometry (Fig. 4) indicate a deltaic depositional environment that prograded under a strong fluvial influence, accumulating delta front and mouth bar facies (Hutsky, 2011). Paleocurrent data from small-scale sedimentary structures and gently dipping clinoforms surfaces indicate a south-southeast progradation direction, which was parallel to the regional paleoshoreline and thus somewhat anomalous (Fig. 1). Figure 6 (E – E’) displays a northeast-southwest oriented cross-section near Greybull, Wyoming composed of both outcrop and well log data. This cross-section is oriented across depositional strike and displays an abrupt (<20 km) lateral thinning (~40 m to <5 m) trend away from the core toward both flanks. Outcrop analysis details a transition from a strong fluvial-influence in the core to a mixed tidal, wave, and storm influences along the flanks. The thin flank deposits have been interpreted as a proximal-medial delta flank and prodelta-distal delta flank facies (part I)
**Figure 5**: Northwest-southeast oriented cross-section derived from several measured outcrop sections from the axial core (along depositional dip) of the Peay Member lobe (Figs. 3, 4). High-resolution (<1-6 km) cross-section shows a consistently thick (15-75 m) Peay Member sandstone body (highlighted in blue) with thickening and thinning trends internally. Modified from Hutsky (2011).
Figure 6: Northeast-southwest oriented cross-section composed of outcrop and well log oriented across depositional strike, near Greybull, Wyoming (Figs. 3, 4) showing the Peay Member sandstone (highlighted in blue) as a thick (>30 m) axial core body abruptly (<20 km) transitioning into a thin (<5 m), sheet-like bodies at the at both flanks. Peay displays contrasting thinning patterns on either flank.
Regional Subsurface Analysis

A regional subsurface analysis of the Peay Member was completed throughout much of the eastern Bighorn Basin, revealing vertical and lateral variations in the cross-sectional geometry of the sandstone body. Key stratigraphic surfaces were identified from the outcrop analysis and then correlated into the subsurface through distinctive geophysical responses to these lithology changes. The lateral and vertical changes observed in outcrop serve as a control for interpreting trends in subsurface gamma ray logs. Figure 7 shows two outcrop-well log correlation points where geophysical responses are compared to measured outcrop sections.

Kirschbaum et al. (2009) provided initial regional correlations of the Frontier Formation across much of the Bighorn Basin from widely-spaced well log data and presented naming conventions for several key stratigraphic surfaces. Hutsky (2011) expanded upon these sub-surface correlations by establishing high-resolution, outcrop-based interpretations down depositional dip and correlating through much of Bighorn and Washakie Counties. These studies provided the foundation and nomenclature for this study. The Clay Spur Bentonite is recognized in geophysical logs (Fig. 7 A, B) from an abrupt, large amplitude increase in gamma ray values and is interpreted to be the M100 surface of Kirschbaum et al. (2009; their Figure 7). This study does not employ the Clay Spur Bentonite as the Mowry/Frontier contact because it is not ubiquitous across the basin, however, it is a useful correlation point because of the distinctive wireline log response and its known age. The Mowry/Frontier contact is taken at the transition from grey silicified siltstone (Mowry) to dark, fissile shale (Stucco Member) at outcrop.
Figure 7: Two outcrop-well log correlation points providing calibration between outcrop and geophysical well log data (see Fig. 3 for site locations). Several key stratigraphic surfaces (e.g. Torchlight Member, Alkali Member sandstones, Potato Ridge Member, Peay Member, and Clay Spur Bentonite) were identified in outcrop and correlated into the subsurface through distinctive geophysical responses to lithology changes. Key correlation surfaces presented by Kirschbaum et al. (2009) are labeled between the subsurface and graphic logs. The Peay Member sandstone displays an upward declining, abruptly topped, ‘funnel-shaped’ character in gamma ray log profiles.
This contact is identified in some gamma ray logs as an abrupt increase in gamma ray values, but is not as marked a change in gamma values as the Clay Spur Bentonite (Fig. 7). Neutron porosity logs also show a distinct response at this contact, but many wells lack these logs. The contact is not discernible in many well logs, thus it is used only as a low confidence correlation point. The Stucco Member displays moderately high gamma ray readings that progressively decrease up-section, forming a partial funnel shape (Fig. 7). The thickness of this interval is typically around 30-40 m within the core of the axial lobe zone, decreasing in thickness to ~15 m along the delta flanks (Hutsky, 2011).

The Peay Member sandstone directly correlates to the F500 surface of Kirschbaum et al. (2009; their Figure 7). The Peay member consistently displays an upward declining, ‘funnel-shaped’ character in the gamma ray log profile. The lowest gamma ray responses within the ‘funnel-shaped’ log profile directly correspond to the massive sandstone units described in outcrop and interpreted as prograding delta front and distributary mouth bar deposits (Fig. 7). Cant (1992) suggested that such abruptly topped, progressive decreases in gamma ray response commonly represent a coarsening upward cycle from distributary mouth bar deposition. Thickness of the Peay Member significantly varies across most of the northeast Bighorn Basin (Fig. 4). Hutsky (2011) concluded that upward-declining, funnel-shaped gamma ray responses in the subsurface directly correlate to prograding delta front and mouth bar deposits from within the core of the Peay Member delta lobe, but lateral variations in facies distribution toward the flank remained largely uncertain.
Depositional Dip-Oriented Cross-Sections

The thickest sandstone accumulations of the Peay Member (55-70 m) occur near Greybull and extend north-northwest and south-southeast along depositional dip (Figure 4). Figures 5 (D-D’; outcrop data) and 8 (B-B’) are oriented parallel to the axial zone of the delta core (along depositional dip) and together indicate a consistently thick (>30 m) sandstone body over an extended distance (>120 km). Figure 9 (F-F’) shows a cross-section from the southeasternmost part of the study area, where the Peay sandstone displays a gradual southward thinning trend, passing from a thick (>30 m), massive body in the north into a thin (<10 m), sheet-like body in the south. This trend coincides with the primary paleoflow direction recorded in the axial core of the delta lobe.

Depositional Strike-Oriented Cross-Sections

The sandstone isolith map of Figure 4 shows the Peay Member sandstone to be laterally restricted, having abrupt regional thinning trends to both the northeast and southwest (depositional strike) of the main, southeast-trending delta lobe body. Figures 6 (E-E’), 10 (C-C’), 11 (G-G’), and 12 (A-A’) are oriented across depositional strike, perpendicular to the elongation direction. The Peay Member sandstone in Figures 6 and 10 displays an abrupt (<25 km) thinning and interfingering relationship passing from a thick (>30 m), massive core sandstone body into thin (2-10 m), sheet-like bodies along the flanks. Figure 6 illustrates the complete cross-sectional geometry of the Peay Member sandstone body across the delta lobe; this cross-section incorporates both outcrop-based interpretations (northeast) and subsurface data (southwest). The flanks of the sandstone
body reveal contrasting thinning geometries. The SW flank laterally thins and interfingers into several discrete bodies, whereas the NE flank thins into a single sandstone body. This disparity in flank geometry could develop from different depositional conditions along each flank. Figure 10 only contains the western flank of the delta lobe, but illustrates the same thinning and interfingering geometry described in Figure 6. Figure 11 (modified from Hutsky, 2011) shows the Peay Member sandstone to be a uniformly thin (<10 m), sheet-like sandstone body across the southern (distal) termination of the body. Figure 12 (A-A’), however, illustrates a fairly uniform sandstone thickness distribution (20-30 m) at the updip (farthest northwest) mapped extremity of the Peay Member, which is similar to the geometry seen along the axial core zone in the depositional dip direction. This conflicts with the other east-west oriented cross-sections because it does not display any substantial thinning trend, implying a possible change in sandstone body orientation in the northernmost region of the Bighorn Basin in Wyoming.
Figure 8: Northwest-southeast oriented cross-section located parallel with the Peay Member’s axial core body (along depositional dip) (Figs. 3, 4) showing a thick (>30 m), continuous sandstone body (highlighted in blue) along the northern length of the delta core.
**Figure 9**: Northwest-southeast oriented, depositional dip parallel cross-section in the southern region of the study area (Figs. 3, 4) showing the Peay Member thinning from a thick (>30 m), massive body (F) thinning and interfingering southward (F’) to a thin (<5 m) sheet-like sandstone body (highlighted in blue). Cross-section does not use Peay datum.
Figure 10: Northeast-southwest oriented cross-section located perpendicular to the Peay Member’s axial core body (across depositional strike) (Figs. 3, 4) showing a thick (~30 m), massive sandstone body (highlighted in blue) in the axial core (C) abruptly thinning and interfingering into a thin (<10 m) sheet-like body along the lobe flank (C’).
Figure 11: Northeast-west oriented, depositional strike parallel cross-section in the southern region of the study area, near Worland, Wyoming indicating the Peay as a thin (<5-10 m), sheet-line sandstone body across the cross-section (highlighted in blue). Cross-section does not use Peay datum. Modified from Hutsky (2011).
**Figure 12**: East-west oriented cross-section of the updip extremity of the Peay Member sandstone highlighted in blue (Figs. 3, 4) indicating a fairly uniform sandstone thickness (20-30 m) with a massive, blocky gamma ray log character.
Discussion

The Peay Member is a northwest-southeast elongate, southeastward-narrowing, digitate sandstone body with abrupt peripheral thinning from the axial core to the lobe flanks (Figure 4). Cross-sections parallel to depositional dip (Figs. 5, 8) indicate a thick (>30 m), continuous sandstone body within the fluvial-dominated core, which eventually thins and pinches out in the southern part of the Bighorn Basin (Fig. 9). On the other hand, depositional strike sections (Figs. 6, 10) display abrupt lateral thinning away from the axial core resulting in a slightly lobate geometry; however, Figure 6 displays the flanks to contain contrasting geometries. In the northernmost extent of the study area, the Peay does not display the same abrupt southwest-northeast thinning pattern evident further south. Figure 12 shows a cross-sectional geometry similar to that characteristic of depositional dip sections (Fig. 5, 8). The paleocurrent direction evident from outcrops of the axial core strongly suggests a southward progradational direction, which would have been parallel to the contemporary paleoshoreline to the west. This suggests a shift in delta progradation direction from initially eastward dispersal to southward with increasing distance from the contemporary shoreline.

Hutsky (2011) suggested that the southsoutheastward progradational pattern displayed by the Peay Member could result from longshore wave-driven and geostrophic currents associated with a counterclockwise gyre that existed within the Boreal Ocean waters and southern Tethyan Ocean waters of the KWIS during the Late Cretaceous (Slingerland et al., 1996). Sediments shedding eastward into the KWIS were deflected south-southeastward through a combination of the Coriolis Effect and differential
pressure gradients, which would produce a shore-parallel geostrophic depositional pattern. This current deflection pattern and the low-gradient seafloor could have resulted in sandstone bodies being elongate down depositional dip and laterally restricted across depositional strike (Hutsky, 2011). This is similar to a model invoked by Fielding (2010) to explain predominantly southsoutheastward paleoflow in delta front deposits of the Ferron Sandstone in south-central Utah. The Po River Delta, discharging into the northern Adriatic Sea, is a modern analog for such a downdrift-deflected delta planform (Cattaneo et al., 2003). Hutsky (2011) suggested that a similar model could explain the geometry and paleoflow patterns exhibited by the Peay Member.

The plan geometry of the Peay sandstone could be said to resemble that of a typical incised-valley fill on the basis of sub-surface data (e.g. Fig.4); however, outcrop analysis has established there is no evidence indicating that the Peay Member filled an incised valley. Though the sandstone body is thick, elongate, and laterally restricted, there is no evidence for a regionally extensive basal erosion surface denoting a sequence boundary. Sub-surface mapping reveals thicker accumulations of mudstone in the underlying Stucco Member along the axial core compared to the flanks (Figs. 6, 10). This argues against erosional downcutting, which would produce thicker underlying mudstone accumulations along the flanks of the body relative to beneath the axis. In addition, compensational stacking patterns are evident between the various sandstone units of the Frontier Formation wherein thick accumulations of stratigraphically younger units overlie thin accumulations of older units (Brown, 1979). This suggests that non-compactable accumulations of sand may have limited accommodation locally, forcing subsequent sand
deposition into residual topographic lows. The Peay Member is composed of one sandstone body deposited during a single progradational cycle; therefore, both properties conflict with the definition of an incised valley fill requiring multiple, erosionally-based, stacked fluvial channel deposits (Van Wagoner et al., 1990; Wroblewski, 2006). On the other hand, there is still the possibility that this body becomes more incised updp, in the northernmost regions of the Bighorn Basin where erosional capacity may have been greater. Figure 12 displays some evidence for an abrupt upward transition from a high uniform gamma ray response below to a sharp, lower response with a blocky log character above. This change in character results in a sharp-based, cylindrical-shaped gamma ray response, which elsewhere has been interpreted as a typical geophysical log indicator of an incised body and contrasts with funnel-shaped responses determined to be the product of prograding delta deposits.

Facies show a transition along depositional strike from a massive (>30 m thick), fluvial-dominated delta core to a thin (<5 m), sheet-like, tidal- and wave-influenced body along the northeastern delta flank (Part I). Figure 6, based on both outcrop and subsurface data, indicates a similar geometric thinning pattern across depositional strike on both sides of the axial core; however, the overall flank geometry suggests slightly different depositional conditions on either side of the delta lobe. The basinward flank (NE; Fig. 6) was exposed to constant long-shore wave activity, but the leeward flank (SW; Fig. 6) was likely a more restricted or protected environment. Nonetheless, a similar progression of facies is interpreted to occur from core to the opposite flank within the subsurface; although, the leeward flank would likely have a reduced wave-influence. A similar
comparison can be made from Figs. 5 and 8, both showing a continuous, massive (>30 m) sandstone body along the same depositional dip trend. Outcrop analysis (Fig. 5) reveals facies from the axial delta core to be persistently fluvially-influenced delta front/mouth bar deposits along the length of the outcrop belt. This trend can be projected as continuing into sub-surface deposits along the axial core, thus extending the facies distribution distally. It is interpreted that regions along the thick, elongate axial zone will likely contain fluvially-influenced facies along the entire length of the delta lobe. Thus, the recurring abrupt lateral pinch-outs along the delta body flanks have been interpreted to contain a transition of facies from fluvial-influenced facies (core) to tidal-, wave-, and storm-influence (flank). This association between recurring facies within specific, geometrically defined zones of the Peay Member sandstone suggests a predictable relationship between planform body geometry and the depositional facies distributions. This relationship can be used to develop a three-dimensional model to predict sandstone body geometry, depositional facies distributions, and dispersal patterns with the Peay Member sandstone.

**Conclusion**

In the northeast Bighorn Basin, the Peay Member sandstone has a digitate planform body geometry, which is elongate along depositional dip (northwest-southeast), southeastward-narrowing, and laterally restricted across depositional strike showing abrupt peripheral thinning from the axial core to the lobe flanks (Fig. 4). This delta lobe reflects a dominantly southward progradation direction derived from a shore-parallel, counter-clockwise gyre in the KWIS. Part I details how this deltaic sandstone body shows
a lateral transition in depositional facies from a thick, fluivally-dominated axial core body to a thin, sheet-like tidal-, wave-, and storm-influenced body along the delta flanks. The recurring pattern of facies associations within particular elements of planform body geometry suggests a predictable relationship between sandstone geometry and facies distribution. This facies relationship to planform geometry combined with regional sub-surface mapping can be used to develop a three-dimensional model that could potentially predict sandstone body geometry, regional distribution of depositional facies, and sandstone body dispersal patterns across the eastern Bighorn Basin. This model provides potential insights on sandstone body distribution patterns within the Bighorn Basin, which has significant application in hydrocarbon exploration in predicting reservoir geometries and potential trapping mechanisms. In conclusion, this study not only provides a detailed regional analysis of sandstone body and facies distribution patterns, but provides further insights on dispersal patterns, transport mechanisms, and body geometries for deltaic sandstone bodies within the KWIS.
References


