Architecture and Facies Analysis of Allomember F, Upper Cretaceous Horseshoe Canyon Formation, Drumheller, Alberta

by

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Abstract

Mixed-influence, marginal-marine deposits are typified by complex heterogeneous architectures that are challenging to model in the subsurface. Utilization of modern and outcrop analogs can serve to mitigate these limitations. Marginal-marine successions of the Horseshoe Canyon Fm near Drumheller, Alberta are well exposed in laterally continuous outcrops for 15 km down depositional dip and 3.5 km along depositional strike. This study uses 30 outcrop sections from Allomember F along the Red Deer River and Willow Creek and 4 subsurface cores to classify the deposits in terms of facies and to identify element complexes (EC).

Depositional environments are interpreted to record a variety of marginal-marine, paralic, and coastal environments that include: wave-dominated, fluvial-influenced, tide-affected deltaic deposits (FA1); tidal-fluvial channels (FA2); wave-dominated, tide-influenced, fluvial-affected shoreface (FA3); and, delta plain/terrestrial deposits (FA4). The deposits are characterized using the WAVE Classification scheme. Using this process-based approach, FA1 is subdivided and categorized into two element complexes, namely a Fw (t) lobe complex and a Wf (t) mouthbar complex. FA2 is designated as a Ft channelized complex. FA3 is categorized as a Wtf beach complex. FA4 can be subdivided into multiple element complexes representing terrestrial deposits. Overall, the paleoshoreline forms a Wtf or Wft Element Complex Assemblage.

Keywords: Sedimentology; Ichnology; Horseshoe Canyon Formation; WAVE Consortium; WAVE Knowledgebase
For my Family.
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1. An Introduction to the Geology of the Upper Cretaceous, Horseshoe Canyon Formation, Alberta, Canada

1.1. Introduction

Mixed-influence, marginal-marine deposits are commonly typified by complex and heterogeneous architectures. The combined use of outcrop- and core-based studies helps to alleviate some of the difficulties associated with modelling intra-reservoir heterogeneities. To better understand these complex architectures as well as heterogeneities associated with potential reservoirs, it is critical to understand the sedimentological, ichnological, and stratigraphic character of the strata being studied.

The employment of classification systems to identify and categorize marginal-marine deposits is fraught with difficulty and simplifies the complexity present in these deposits. Existing classification systems typically force comparisons to end-member settings, such that sedimentary successions are described on the basis of the primary or most dominant depositional process affecting sedimentation (i.e., wave, tidal, fluvial). However, marginal-marine systems are dynamic and rarely have a single process acting on the system. Rather, multiple processes operating in conjunction serve to modify the coast and produce the resulting depositional architectures. Recently, the WAVE Consortium has developed a new process based classification system for marginal-marine deposits (e.g., Ainsworth and Vakarelov, 2013). The WAVE classification scheme enables a practitioner to classify deposits on the basis of relative percentages of wave, tide and fluvial processes responsible for the resulting depositional facies, instead of placing them under a broad field such as “wave dominated”, “tide dominated”, or “fluvial dominated”.

Figure 1.1  Location map of the study area located in Central Alberta, Canada. The outcrop belt used in this study is exposed roughly 8 kilometres southeast of Drumheller, Alberta, Canada. Figure modified from Ainsworth (1991).
The outcrops of the Horseshoe Canyon Formation are exposed for roughly 100 kilometres along the Red Deer River Valley and comprise deposits of terrestrial, marginal-marine, and fully marine environments. Owing to this exceptional, near continuous exposure, it is possible to evaluate and compare deposits of multiple depositional environments across and along depositional dip. This study was conducted using outcrop exposures approximately eight km southeast of Drumheller, Alberta, Canada, and are contained with a roughly 5 km² study area. In this area, sediments of the fully marine Bearpaw Formation intertongue with the marginal-marine deposits of the Horseshoe Canyon Formation. The outcrop belt along the Red Deer River valley is exposed and extends for almost 15 km in the oblique-to-depositional dip to dip-parallel direction. The valley in which Willow Creek is situated is normal to the Red Deer Valley (Fig. 1.2) and contains outcrops that extend for 3.5 km in the oblique to depositional strike to strike-parallel direction. The Red Deer River Valley and Willow Creek outcrops
allow for the detailed study of both vertical- and lateral-facies relationships in three dimensions. This enables the researcher to ‘walk out’ important contacts such as discontinuities and disconformities.

The focus of this study is the characterization, depositional interpretation, and stratigraphic assessment of a single parasequence, informally named Allomember F (Ainsworth, 1991), of the Horseshoe Canyon Formation. Allomember F underlies the laterally continuous and widespread Coal 2 marker bed (Allan and Sanderson, 1945; Gibson, 1977).

This thesis is presented in the following order. Chapter 1 describes the objectives of the study, the regional geology and stratigraphy, and previous work undertaken on the Horseshoe Canyon Formation. Chapter 2 is devoted to the conceptual underpinning of the thesis, which includes an explanation of the WAVE Classification system (Ainsworth and Vakarelov, 2012) as well as models used in previous studies to describe and interpret these deposits. Chapter 3 describes the physical sedimentology and ichnology of facies that occur in allomember F in order to produce an integrated facies scheme with process-response models. Chapter 4 focuses on identifying and interpreting the facies associations and element complexes, as well as the regional cross sections through the study area. The results in Chapter 4 are directly derived from the observations presented in Chapter 3. Finally, Chapter 5 comprises the discussion and conclusions of the thesis.

1.2. Objectives

The primary objectives of this thesis are to:

- Characterize and interpret the depositional environments of Allomember F, a single parasequence (transgressive-regressive cycle) within the lower Horseshoe Canyon Formation.
- Construct and correlate stratigraphic cross-sections that incorporate measured sections, wireline logs, and cored intervals, in order to produce a 3D characterization of the deposits.

- Test the relatively newly developed WAVE Classification and its applications to the characterization and modeling of potential petroleum reservoirs. By using the WAVE Classification, I attempt to evaluate the intra-reservoir heterogeneities and try to predict these heterogeneities based on dominant depositional processes that have affected sedimentation.

### 1.3. Methodology and Dataset

This study incorporates a large and diverse dataset. The primary data set incorporates 30 outcrop measured sections and gamma-ray profiles for five of those sections. The second data set is derived from four cored locations in the study area. Finally, a collection of panoramic photos taken from across the valley have been compiled to aid in the correlation of units. This data set has been invaluable in this study, as it permitted more accurate correlations of the depositional bodies between measured sections.

Fieldwork was the essential and the key component of the research. During the summers of 2012 and 2013, a total of two months were spent collecting data. Thirty outcrop sections were logged, with 23 from the Red Deer River Valley and 7 from Willow Creek. These sections started from the laterally continuous Coal 1 marker bed and ended at the first major coal encountered above Coal 1. These sections ranged from 7 metres to nearly 30 metres in thickness. Before measuring the sections, the outcrops were vigorously cleaned and prepared by extensive shovelling, scraping, brushing, and breaking or chipping the rock away to reveal primary physical and biogenic structures that were otherwise obscured by the bentonitic clays and “popcorn veneers” that are widespread on the outcrops. The resulting data is a high-resolution amalgamation of both physical sedimentology and ichnology observed in the outcrop sections. These
were then compiled and drafted into lithologs, the primary source of displaying the data for this thesis.

One feature of this study is the relatively close proximity of the measured outcrop sections and the subsurface wireline log data. This is important, since the architecture of these units can be resolved in detail and identified at the scale of individual flow. In conventional subsurface studies, data points (wireline logs or cores) are commonly spaced kilometres apart, and correlations are largely done by inference or based on general trends. With sections positioned very closely, more accurate correlations can be achieved, and heterogeneities identified and predicted within the different facies.

1.4. Regional Setting and Stratigraphy

During the late Campanian to early Maastrichtian, late-stage accretion of the Insular Superterrane with the Intermontane Superterrane resulted in thrust belts that formed on the western margin of North America (Cant and Stockmal, 1989; Price, 1994; Hamblin, 2004). With continued thrusting, the resultant flexure and subsidence of the Western Canadian Sedimentary Basin lead to the creation of a foreland basin. This resulted in both increased accommodation and elevated sediment volumes being delivered to the coastline through fluvial systems associated with the orogenic events. The interplay between mountain building from accreted terrains and the subsequent deepening of Western Canadian Sedimentary Basin resulted in the deposition of a thick, progradational, and easterly thinning clastic wedges (see Figure 1.3). This depositional body has been named the Edmonton Group (Tyrell, 1887). The Edmonton Group comprises four formations, of which the Horseshoe Canyon Formation constitutes the basal unit (Irish, 1970). The Horseshoe Canyon Formation is progressively overlain by the Whitemud Formation, Battle Formation, and Scollard Formation.

The Horseshoe Canyon Formation lies at what is interpreted to be the head of a northeast-southwest oriented embayment along the western margin of the epicontinental Bearpaw Sea (Williams and Stelck, 1975; Rahmani, 1983; Ainsworth, 1991, 1992,
The main outcrop belt along the modern-day Red Deer River Valley runs roughly perpendicular to the inferred paleo-shoreline-strike orientation (northeast to southwest), allowing for observations of lateral facies transitions from coal-bearing, alluvial deposits through intracoastal and marginal-marine deposits, and into fully marine deposits.

Figure 1.3 The six first-order clastic wedges shed into the Western Interior Seaway shown as a function of time. The succession that is studied in this thesis is in the fifth clastic wedge (red circle) known as the Edmonton Group (Modified from Stockmal et al., 1992).

The Horseshoe Canyon Formation is roughly subdivided into a lower and an upper unit. The lower unit is interpreted as a series of stacked parasequences of terrestrial to marginal-marine strata, deposited in multiple overall regressive sequences (e.g., Shepheard and Hills, 1970; Rahmani et al., 1983, 1988, 1989; Saunders, 1986, 1989; Ainsworth, 1991, 1992, 1994; Ainsworth and Walker, 1994; Lavigne, 1999; Ainsworth et al., 2010). The outcrops of the lower Horseshoe Canyon Formation are further subdivided into seven informal allomembers (A-G), all of which are separated by
laterally continuous coals. The exception to this is the boundary between Allomember A and Allomember B (Ainsworth, 1991, 1992, 1994; Ainsworth and Walker, 1994), where the allomembers are interpreted to represent periods of sustained regression and shoreline progradation (Ainsworth, 1991, 1992, 1994; Ainsworth and Walker, 1994; Smith, 1994). The upper Horseshoe Canyon Formation has been interpreted as predominantly fluvial and lacustrine in origin (Waheed, 1983; Dawson et al., 1994). The Horseshoe Canyon Formation averages about 230 metres in thickness (Irish, 1970). The Whitemud, Battle, and Scollard formations overlie the Horseshoe Canyon Formation, all of which have been interpreted to represent fully continental deposits following full regression of the Western Interior Seaway. In the Bow River to Red Deer River region (see Figure 1.4), the predominantly Maastrichtian-aged Horseshoe Canyon Formation comprises the basal formation of the Edmonton Group (Irish, 1970) and directly overlies the Campanian-aged Bearpaw Formation. The intertonguing relationship of Bearpaw Formation and Horseshoe Canyon Formation deposits has been described and named as the “Bearpaw-Horseshoe Canyon Transition Zone” (see Figure 1.4)(Shepheard and Hills, 1970; Rahmani, 1983, 1988, 1989, Ainsworth, 1991, 1992, 1994; Ainsworth and Walker, 1994, Lavigne, 1999). This transition zone consists of a series of paralic, sandy tongues that are capped by coals, which interfinger with the marine shales of the Bearpaw Formation (Ainsworth, 1994). The diachronous contact between these formations youngs towards the east, and is largely conformable along the contact (Gibson, 1977).

Lithostratigraphically, where the contact between the two formations is sharp, it is placed at the first appearance of the grey weathering sandstone typical of the Horseshoe Canyon Formation. However, where the contact is gradational, it is placed immediately below the horizon at which the light grey weathering sandstone of the Horseshoe Canyon Formation forms the predominant lithology (Gibson, 1977). Following the stratigraphic scheme of Allan and Sanderson (1945), Gibson (1977) has numbered and correlated 15 major coal-bearing intervals. Coals 0–2 occur within this particular study area, with Coal 2 capping Allomember F. Two other thin, discontinuous coal seams (called 1a and 1b by Ainsworth, 1991) are also present within the study area, but are not regionally extensive. Coals 1a and 1b are used as the allostratigraphic boundaries
separating Allomember D from E, and Allomember E from F, respectively (Ainsworth, 1991). All coals have been interpreted to represent maximum regression for their respective depositional package.

Biostratigraphically, the marine shales that make up the Bearpaw Formation have been assigned to the *Baculites compressus* Zone of the Pierre succession (Williams and Stelck, 1975). Maximum flooding of the Bearpaw Sea occurred in the latest Campanian during the time of *Baculites reesidei* (Williams and Stelck, 1975). However, some speculate that the Campanian-Maastrichtian boundary may lie as low as the base of the *Baculites reesidei* Zone (e.g., Obradovich and Cobban, 1975). Lerbekmo and Coulter (1985) disagree with Obradovich and Cobban (1975), however, and by using magnetostratigraphic correlation techniques, argue that the Campanian-Maastrichtian boundary should be placed at the same stratigraphic level as Coal 5. Coal 5 corresponds magnetostratigraphically with the base of the *Baculites baculus* Zone (absolute age of 71 Ma), indicating that the sediments that comprise the lower succession of the Horseshoe Canyon Formation are exclusively Campanian in age. Lerbekmo and Coulter (1985) results are further corroborated by the addition of palynological data that was collected by Srivastava (1970). The palynomorphs identified in his study demonstrate that the first occurrence of the genus *Wodehouseia* is slightly lower stratigraphically than the Coal 5 marker bed. The first appearance of this genus is regarded as the boundary between the Campanian and Maastrichtian (Lerbekmo and Coulter, 1985; Wiggins, 1976). Eberth and Braman (2012) published a summary of the Horseshoe Canyon Formation’s regional stratigraphy that suggests the Campanian-Maastrichtian boundary lies stratigraphically higher than Coal 5, and is equivalent to the Coal 10 marker bed. Based on Eberth and Braman (2012) and Lerbekmo and Coulter (1985), the sediments that comprise Allomember F reside exclusively within the Campanian.
Figure 1.4  A) A schematic diagram showing the diachronous contact between the Horseshoe Canyon Formation and the Bearpaw Formation. Although the study area is near the Campanian-Maastrichtian boundary, there remains debate as to the age of the strata. B) A more detailed diagram showing the informally named allomembers, their progradational limits, and the regressive coal that caps each of the deposits. The approximate 1 million year time period is derived from K/Ar dating of recovered ammonites. Modified from Ainsworth (1994).
Figure 1.5  The arcuate band of sediment that makes up the Edmonton Group. The Horseshoe Canyon Formation comprises the basal unit of the Edmonton Group. The lower Horseshoe Canyon Formation and St. Mary River Formation (lower part now regarded as the Blood Reserve Formation) are considered stratigraphic equivalents (Tozer, 1956). Modified from Irish (1970).
Figure 1.6  Stratigraphic column of the Horseshoe Canyon Formation, divided into members. The study area is in the basal Drumheller Member. The marginal marine portion of the Horseshoe Canyon Formation is located between 0—2 cz (coal zone). Modified from Eberth and Braman, 2012.
Figure 1.7  Paleogeographic map of the Western Interior Seaway during the Late Campanian to Early Maastrichtian (Modified from Williams and Stelck, 1975). Red square is the approximate study area.
1.5. Sedimentological Studies

1.5.1. Irish (1970):

The Horseshoe Canyon Formation was formally named by Irish (1970) and is used to identify the deltaic packages and non-marine sediments separating the Bearpaw Formation and Whitemud Formation. The Edmonton Formation was elevated to group status and the Horseshoe Canyon Formation erected as a mappable lithostratigraphic unit. The Horseshoe Canyon Formation includes the lower Edmonton Fm and most of the middle Edmonton Fm from Allan and Sanderson (1945), members A, B, and C of Ower (1960), and the lower six members of Srivastava (1968) from the earlier stratigraphic frameworks (Irish, 1970).

Since there is no complete outcrop section through the Horseshoe Canyon Formation, Irish (1970) used a composite type section that encompassed outcrop logs from the mouth of Willow Creek (Sec. 7, Tp. 28, Rge. 18W4), to the east bank of the Red Deer River Valley (Sec. 7, Tp. 34, Rge. 21W4) where the Whitemud Formation is well exposed along the side of the valley, thus forming a "continuous" litholog and the type section for the Horseshoe Canyon Formation.

The name "Horseshoe Canyon" is that of a prominent erosional feature, in which well-exposed strata of the formation is evident. Horseshoe Canyon is located west of Drumheller in parts of Tps. 28 and 29, Rge. 21W4 (Irish, 1970).

1.5.2. Shepheard and Hills (1970):

Shepheard and Hills (1970) completed the first detailed sedimentological-stratigraphic study of the Willow Creek and Red Deer River Valley, more specifically on outcrops that are found adjacent to the township of East Coulee. Their research established a general depositional framework of an easterly prograding deltaic complex believed at the time to be most akin to the Mississippi River Delta, or a large river-
dominated delta (Shepheard and Hills, 1970). A critical part of the Shepheard and Hills (1970) study was applying a stratigraphic framework to the lower succession of the Horseshoe Canyon Formation, which effectively divided the formation into five units (E1-E5, with the lowest unit being included in the Bearpaw Formation). Figure 1.8, shows the correlations between the stratigraphic frameworks of the various authors.

**1.5.3. Waheed (1983):**

In the areas surrounding the township of Drumheller, Waheed (1983) focused primarily on a lithofacies analysis of the Horseshoe Canyon Formation. His primary goal was to attempt to interpret the depositional environments that had allowed for accumulation of the abundant coals in the succession (Waheed, 1983). The study area focused on an outcrop belt that was 20 kilometres in length, running from 10 kilometres south of Drumheller to 10 kilometres north. Conclusions of his study were that there was a lateral transition from marginal-marine facies to the southeast of the study area through to delta-plain facies and finally into fluvial deposits that dominate in the northwest. Meandering river channel deposits were regarded to have formed the bulk of the deposits in the northwestern portion of the study area, with coal genesis directly related to swamp environments that formed around the channel margins.

**1.5.4. Rahmani (1981, 1983, 1988):**

Rahmani (1981; 1983; 1988) interpreted the lower Horseshoe Canyon Formation succession as estuarine and barrier-island deposits, which he believed were associated with an embayed shoreline. Analogs used to describe this depositional setting were taken from mesotidal estuaries that occur along the Georgia Coast, estuaries of the Rhone Delta of southwestern Netherlands, and the Willapa Bay estuary on the Pacific Washington Coast.

In addition to developing these depositional analogs, Rahmani (1983) was able to trace general trends within the paleoshoreline, and pick out both regressive and
transgressive packages. Rahmani (1983) subdivided the lower Horseshoe Canyon Formation into five genetically related units, each bearing both transgressive and regressive components (units 1-5) (Figure 1.8).

1.5.5. **Saunders (1986; 1989):**

The focal point of Saunders (1986, 1989) was on the informally named Appaloosa Sandstone, which is the down-dip (to the southeast) equivalent of Allomember F. He used an integrated ichnologic and sedimentologic approach to evaluate the unit. His study showed that the Appaloosa Sandstone can be effectively subdivided into a “Lower Zone”, “Middle Zone”, and “Upper Zone”, with each corresponding to specific shoreface subenvironments. The Lower Zone of the Appaloosa Sandstone was interpreted by Saunders (1986, 1989) as a storm-dominated lower shoreface deposit. The Middle Zone was interpreted as an upper shoreface deposit, and the Upper Zone was assigned to foreshore deposits. Saunders (1986, 1989) regarded the Appaloosa Sandstone as a prograding barrier-island shoreline similar to the model proposed by Rahmani (1983).


Ainsworth (1991, 1992, and 1994) and Ainsworth and Walker (1994) introduced an allostratigraphic framework for the lower Horseshoe Canyon Formation, dividing the exposed strata into 7 recurring and mappable allomembers (A-G). The allomembers are separated using laterally extensive coal seams. Ainsworth (1991) conducted a detailed sedimentological assessment of all the allomembers, providing descriptions of the sedimentology and ichnology in order to characterize the parasequence succession.
1.5.7. **Lavigne (1999):**

Lavigne (1999) completed an integrated sedimentological and ichnological study of Allomember B at the Willow Creek outcrop belt. Allomember B had widely been considered to be a likely incised valley complex or possible distributary channel complex, by previous workers who have worked on the lower portions of the Horseshoe Canyon Formation (e.g., Rahmani, 1983; Ainsworth, 1991, 1992, and 1994; Ainsworth and Walker, 1994). Lavigne (1999) concluded that the suspected incised-channel deposits were, in fact, representative of delta distributaries. As such, he regarded these units as autogenic channel systems actively feeding the shoreline, rather than allogenic incised valleys recording relative sea level fall.

1.5.8. **Ainsworth et al. (2010) and the WAVE Consortium:**

More recently, the WAVE Consortium has studied the lower Horseshoe Canyon Formation outcrops in the attempt to build a depositional model that accurately characterizes the observed heterogeneities within the succession. The model relies on the relative importance of different depositional processes that influence sedimentation. Ainsworth et al. (2010) subdivided each allomember into discrete architectural elements, assigning primary, secondary, and tertiary depositional processes responsible for their observed characteristics, and classifying the strata using a process-based classification scheme (Ainsworth et al., 2010). Currently, the majority of work has been conducted on Allomember C. This thesis is focused on using their process-based classification scheme to describe and interpret the origin of Allomember F.

1.5.9. **Eberth and Braman (2012):**

Eberth and Braman (2012) subdivided the Horseshoe Canyon Formation into seven members (From oldest to youngest – Strathmore, Drumheller, Horsethief, Morrin, Tolman, Carbon, and Whitemud members). This subdivision is based off subsurface and outcrop studies, lithostratigraphic variations from changes in sea level, as well as climate, volcanism, and orogenesis. Allomember F falls within the Drumheller Member,
and is interpreted to reflect both stable climate and tectonic regimes, characterized by vertical aggradation and moderate rates of progradation (Eberth and Braman, 2012).

Figure 1.8  The relative stratigraphic correlations suggested by previous workers within the lower Horseshoe Canyon Formation. All correlations are based on the appearance of various coal units throughout the study area. Modified from Ainsworth (1991)
Figure 1.9  Schematic diagram showing the allostratigraphic division of the Red Deer River valley, modified from Ainsworth (1991). The coals are used as boundaries for each of the allostratigraphic units. Modified from Ainsworth et al., 2010
2. Classification of Marginal-Marine, Mixed-Influence Systems and Interpretations of Allomember F, Horseshoe Canyon Formation, Drumheller, Alberta

2.1. An Introduction to the WAVE Classification System: A Process-Based Classification of Marginal-Marine, Mixed-Influence Deposits

2.1.1. Introduction

Historically, approaches to classifying most clastic shorelines include the use of models that forcibly categorize depositional processes onto a ternary plot with, wave, tidal, and fluvial processes serving as its apices (see Figure 2.1). These plots commonly consist of depositional end members, and rarely take into account or express poorly those settings characterized by mixed influence (Ainsworth et al., 2010). It is apparent that most paralic depositional environments are more likely to show combinations of processes and that wholesale dominance by a single process is rare. The dynamic interplay of depositional processes is commonly recognized to contribute to increasingly complex architectures within the subsurface. The aim of this chapter is to present the details of a relatively new classification scheme known as the WAVE Classification (Ainsworth et al., 2010). This chapter lays the groundwork for the theoretical as well as the practical aspects in which this classification scheme is used.
2.1.2. The WAVE Classification – New Terms and Hierarchy

The WAVE Classification was presented by Ainsworth et al. (2010) as a tool to determine geobody architecture through the recognition of physical depositional
processes. The processes that act on a shoreline ultimately determine the geometry and architecture of both sandbodies in the depositional environment and the potential heterogeneities encountered in the rock record (Ainsworth et al., 2010). The WAVE classification scheme uses a simple alphabetical notation to describe the depositional processes involved. Wave, fluvial, and tidal depositional process are abbreviated to W, F, and T, respectively. The dominant process is expressed by the primary term, which is capitalized and bold faced. The secondary process follows as a lower case bold faced letter and the tertiary process is expressed by a third italicized letter. For example, if the controlling factors are, in descending order: wave-dominated, tidal-influenced and fluvial-affected, the alphabetical notation would be Wtf (Ainsworth et al., 2010). Major process dominance is determined by identifying the various physical factors of the facies, assigning them to the process and calculating the percentage they constitute, based on the preservation of strata. In cases where sedimentary structures can be produced by multiple processes (e.g., trough cross bedding – which can be produced by all depositional processes), prevailing paleocurrent directions, ichnology and associated facies within a succession must be incorporated in order to identify the true depositional process (Ainsworth et al., 2010).

The classification hierarchy (Figure 2.4) for the WAVE Classification begins with the smallest unit used to characterize a deposit, identified as the “element” (E). As defined by Ainsworth et al. (2010), elements constitute the basic building blocks of a depositional environment, and can be described by some volumetric measurement (width and length). Elements can be arranged into “element sets” (ES), which constitute groups of elements that share common characteristics (Ainsworth et al., 2010). Elements are primarily used to characterize bed-scale observations.

The second level of the classification hierarchy is occupied by the element complex (EC) and element complex sets (ECS). Element complexes are broadly equivalent to the facies association scale of observation. The element complex is defined as a three-dimensional package of sedimentary rocks consisting of both elements and element sets deposited under similar coastal processes (Ainsworth et al., 2010). If the element complex comprises a potential reservoir, the regional extent and mappability is constrained by the element complex. However, the internal heterogeneities would be influenced by the elements and element sets of which the unit
is built (Ainsworth et al., 2010). Element complex sets (ECS) represent groupings of genetically related element complexes, and are also affected by the similar combinations of depositional processes that actively reworked the shoreline.

Element Complex Assemblages (ECAs) constitute the third tier in the classification's hierarchy and comprise genetically related element complexes (see Figure 2.3; Ainsworth et al., 2010). Element complex sets and element complex assemblages hierarchies are recognized by changes in the dominant processes in adjacent and vertically stacked depositional bodies (Ainsworth et al., 2010). Where the dominant depositional processes change laterally, there is a hierarchal change from element complex sets to the element complex assemblage.

Element complex assemblages also can be grouped together to form Element Complex Assemblage Sets (ECAS), constituting the fourth hierarchical tier in the WAVE Classification scheme. The ECAS represents groupings of element complex assemblages that are formed on a coastline during a single pulse of progradation or transgression (Ainsworth et al., 2010). These then can be aligned into either the Transgressive Element Complex Assemblage Set (TECAS) or Regressive Element Complex Assemblage Set (RECAS). The Regressive Element Complex Assemblage Set follows the same stratigraphic nomenclature of a parasequence (cf. Neal and Ardeu, 2009), wherein the TECAS is comparable to the Transgressive Systems Tract as defined by Embry and Johannessen (1992).

A T-R sequence, as described by Embry and Johannessen (1992), occupies the uppermost tier of the WAVE Classification hierarchy (Ainsworth et al., 2010). In an idealized case, a T-R sequence is made up of both the TECAS and RECAS, comprising a complete parasequence. If the upper surface of the RECAS is a subariel unconformity, this would form a complete depositional sequence (Ainsworth et al., 2010). The parasequences within the marginal-marine section of the Horseshoe Canyon Formation are effectively high order T-R sequences. The RECAS are effectively in between thin, rarely preserved, TECAS. The RECAS constitutes the parasequence and the TECAS is equivalent to the Transgressive Systems Tract, as defined by Embry and Johannessen (1992). The T-R sequence provides a direct link between the WAVE Classification and the existing sequence stratigraphic nomenclature (Ainsworth et al., 2010).
Figure 2.2  WAVE Classification (modified from Ainsworth et al., 2010). Coastlines that do not have fluvial systems are represented along the base of triangles A and B. Triangle A shows 15 possible classification categories. Triangle B depicts how percentages of sedimentary structures are used to characterize each category. F = Fluvial-dominated; W = Wave-dominated; T = Tide-dominated; Fw = Fluvial-dominated, wave-influenced; Ft = Fluvial-dominated, tide-influenced; Tf = Tide-dominated, wave-influenced; Ftw = Fluvial-dominated, tide-affected, wave-affected; Tw = Tide-dominated, wave-influenced; Wt = Wave-dominated, tide-influenced; Wf = Wave-dominated, fluvial-influenced; Fwt = Fluvial-dominated, wave-influenced, tide-affected; Ft = Fluvial-dominated, tide-influenced, wave-affected; Tfw = Tide-dominated, fluvial-influenced, wave-affected; Wtf = Wave-dominated, tide-influenced, fluvial-affected; Wft = Wave-dominated, fluvial-influenced, tide-affected.
2.1.3. Criteria for Identification of Depositional Processes

In order to apply the WAVE classification to Allomember F of the lower Horseshoe Canyon Formation, a depositional-process designation must be assigned to each facies association (equivalent to element complexes (EC)). Each category is based on the relative proportions of sedimentological features assigned to wave-, fluvial and tidal-generated processes. The sedimentary structures must be attributed to a specific process in order to accurately plot the system within the ternary diagram (see Figure 2.2). Therefore, it is paramount to assign the preserved sedimentary structures to their proper formative process.

The following groupings of physical sedimentary structures are commonly assigned to either wave, tidal, and fluvial processes. Structures that are typically ascribed to wave-generated processes include: hummocky cross-stratification (HCS); swaley cross-stratification (SCS); low-angle planar parallel lamination; wave-ripples, low-angle curvilinear lamination and some planar tabular and trough cross-stratification; (cf. Clifton et al., 1971; Leckie, 1988; Bhattacharya and Walker, 1991; Walker and Plint, 1992; Bann et al., 2008; Plint, 2010). Some diagnostic sedimentological features employed for recognizing tidal influence include: tidal bundles (Visser, 1980; Allen, 1981; Smith, 1988; Middleton, 1991); current-generated flaser, wavy and lenticular bedding (Reineck and Wunderlich, 1968); cross-bedding with evidence of current reversals (Kreisa and Moiola, 1986 and Middleton, 1991); reactivation surfaces (de Mowbray and Visser, 1984) and sigmoidal bedding (Kreisa and Moiola, 1986; Shanley et al., 1992). Fluvial-generated structures include: current-ripples; aggradational current ripples; some planar tabular and trough cross-stratification; drapes of inferred fluid mud origin; carbonaceous-rich beds; normal and inverse grading; synaeresis cracks; and soft-sediment deformation features (e.g., Bhattacharya and Walker, 1991; MacEachern et al., 2005; Hansen, 2007; Bhattacharya and MacEachern, 2009). Numerous structures, however, can be produced by various depositional processes (e.g., trough cross-stratification and planar parallel lamination), and are therefore not diagnostic to any single process. Additional information must be employed to accurately assign a probable process.
The role of ichnology can be critical when attempting to distinguish the probable depositional processes acting on a deposit. By incorporating ichnological analysis, one can begin to identify potential stresses that are imposed on the system and to use that information to aid in the identification of the depositional processes. Ichnology typically plays a subordinate role in assessing the physical sedimentology; however, it is a tremendously useful subordinate dataset to employ when attempting to identify depositional processes.

The WAVE Classification provides an expanded framework, allowing users to semi-quantify and thereby compare the subtle differences expressed by various mixed-influence, marginal-marine environments. A key assumption that is used when applying the WAVE Classification to the rock record is that the dominant depositional process that controlled sedimentation is responsible for the majority of the preserved sedimentary structures (Ainsworth et al., 2010). The WAVE Classification is predicated on the principle that sedimentary successions can only be characterized using the preserved features, and that these features must be employed to deduce the most reasonable formative processes affecting sedimentation.
Figure 2.3 A schematic diagram showing 15 discrete, idealized coastline configurations reflecting the Element Complex Assemblages (ECA). ECAs correspond to the 3rd hierarchical level in the WAVE Classification scheme. Figure modified from Ainsworth et al. (2011).
Figure 2.4  A schematic diagram that expresses the nested hierarchy of the WAVE Classification system, as well as the associated geometries that accompany each tier. The levels of architecture cover the complete range of scales, from elements (related to individual lithofacies), through to depositional sequences. Figure modified after Ainsworth et al., (2010).
2.2. Depositional Model Used to Interpret Allomember F, Horseshoe Canyon Formation, Drumheller, Alberta, Canada

2.2.1. Introduction

Over the last few decades, a great deal of time, effort, and money has been put into studies that revolve around the integration of sedimentology and ichnology to further our understanding and ability to accurately identify ancient depositional environments. The outcrop belt of the Horseshoe Canyon Formation offers an opportunity to evaluate the merits of various depositional models. Through a high-resolution study, we can accurately identify the depositional environment of Allomember F, and under what hydrodynamic conditions were present at times of deposition.

The deposits of Allomember F have been commonly associated with barrier-island complexes (Saunders, 1989; 1990; Ainsworth, 1991). The deposits of Allomember F have many characteristics, both sedimentologically and ichnologically, which support the barrier island interpretation.

2.2.2. Barrier-Island Complex Model

The facies model for a barrier-island complex revolves around three main environments: barrier beach, tidal channel-and-delta complex, and the lagoon (Figure 2.7; Reinson, 1992). The barrier-beach complex is sedimentologically and ichnologically identical to a classic shoreface succession. There are three major subaqueous environments associated with a shoreface succession, the lower shoreface, middle shoreface, and upper shoreface. Although the intertidal foreshore is not historically incorporated into a shoreface succession, I have included it into the description due to diagnostic features observed within Allomember F.

The lower shoreface typically consists of muddy sandstones that reflect wave agitation of the substrate, and are intercalated with tempestites. The middle shoreface
represent a higher energy environment, where the substrates are sandier and composed mainly of swaley cross stratification and local hummocky cross stratification. The upper shoreface is where the waves begin to break, and oscillatory motion gives way to current generated motion. Wave-forced currents in the upper shoreface produce trough-cross bedding. The foreshore occurs when waves break and thin sheets of water wash up and down and produce wedge shaped upper flow regime plane beds.

Since most shorefaces form on the margins of marine basins, salinity of the seawater is typically close to that of seawater (30-35 psu). Consequently the expected ichnological character would exhibit high density (high BI), comprising a diverse trace-fossil assemblage. In muddier substrates, the trace assemblage would correspond to the *Cruziana* Ichnofacies, and in shallow, sandier, and more mobile substrates the *Skolithos* Ichnofacies would occur (Seilacher, 1967). At the base of the foreshore, there is the potential to develop a “toe-of-the-beach” assemblage, composed of a dense network of *Macaronichnus segregatus* (Saunders *et al.*, 1994; MacEachern *et al.*, 1999; Pemberton *et al.*, 2001).

Along strike, barrier islands are often truncated by tidal channel-and-delta complexes; therefore, barrier island complexes are not laterally continuous. The tidal delta complexes are typically oriented perpendicular or oblique to the barrier complexes, and can extend into the lagoon (flood tidal delta) or into the open basin (ebb tidal delta). The transition between the barrier, channel and delta deposits occurs in the overlapping subenvironments of the back-barrier tidal flats, marsh, washover fans, and flood tidal deltas (Reinson, 1992).
To distinguish barrier-island complexes from regressive shoreface successions it is necessary to look at sediments deposited landward of the beach-shoreface. Instead of passing into continental deposits, a barrier-island succession will pass into back barrier lagoonal deposits. The dominant lithology within the lagoon would be consistent with muddy substrates and small washover sand deposits, the latter which would typically be wave rippled and current rippled. Muddy lagoon and sandy washover-fan deposits pass along strike into flood tidal delta complexes, where tidal energy erodes through the barrier producing small tidal deltas in the lagoon. Lagoon, washover fan and flood-tide delta deposits consistute back-barrier lagoon deposits, and the back-barrier lagoon is
typically a stressful environment for organisms to live in. This could lead to stressed suites of the *Cruziana* Ichnofacies (MacEachern *et al.*, 2005).
3. Facies Descriptions

3.1. Introduction

Thirty outcrop sections and 4 subsurface cores, totalling over 190 m of interval through Allomember F were analyzed on the basis of the sedimentologic and ichnologic character of the strata. From these data, eleven discrete and recurring facies were recognized. The facies are systematically described using three categories: (i) sedimentology, (ii) ichnology, and (iii) inferred process response models. Primary descriptions of the sedimentology encompass textures (including rounding and sorting), sediment calibre (grain size), physical sedimentary structures, bed thicknesses, bedding contacts, paleocurrent directions, and lithologic accessories. Characterization of the ichnology includes bioturbation intensities, trace-fossil distributions, ichnogenera identifications, and trace-fossil diversities. Process response models are constructed based on the implications of the dominant facies characteristics as indicated by the sedimentology and ichnology observed within the deposit.

Bioturbation intensities are assessed using Bioturbation Index (BI) (cf. Taylor and Goldring, 1993), with zero being defined as the sediment being devoid of bioturbation and six reflecting complete biogenic homogenization of the sediment. BI values are assigned grades of bioturbation intensity that have been deemed to be discernible to the human eye, and are derived from the original neoichnological work of Reineck (1963). Ichnological descriptions identify the relative abundances of individual traces as: very rare; rare; moderate; common; and abundant. Photo plates are also constructed to fully illustrate the typical appearance of the facies in core and in outcrop, as well as to demonstrate the differences between the individual facies.
3.1.1. **Facies 1: Mudstones with Interstratified Sandstones**

Facies 1 comprises mudstones and organic-rich mudstones, which are commonly heterolithic at the cm and lamina scale with interstratified sandstones. Mudstones commonly contain interlaminated bentonitic clay. Deposits vary from the more typical mud-dominated expressions to nearly subequal proportions of mudstone and sandstone (Figure 3.1). Sandstone interbeds occur largely as lenticular bedding of ripples encased in mudstone. Sandstone ripples are typically centimetre-scale in thickness and oscillation or current generated. Siltstone and mudstone beds are typically centimetre-scale in thickness, and are either normally or inversely graded. Organic-rich mudstone layers are sporadically distributed and contain isolated syneresis cracks. Facies 1 has been subdivided into two subfacies, based on discrete sedimentologic and ichnologic features.

**Facies 1a: Organic-Rich Mudstone**

*Sedimentology:*

Facies 1a is characterized by dark-brown to black, organic-rich fissile mudstone. Physical sedimentary structures are rare, consisting of localized millimetre- to centimetre-scale sandstone lenses. These lenses are moderately sorted, comprising coarse silt to lower very fine-grained sand, and commonly display current, combined flow and rare oscillation ripple lamination. Facies 1a is commonly fissile. Syneresis cracks are uncommon and only observed where there is sufficient lithologic contrast with the surrounding sediment (see Figure 3.1). Lithological accessories include common coalified plant fragments, wood fragments and macerated plant material. Centimetre-scale bentonitic layers are commonly interbedded within Facies 1a. The basal contact of Facies 1a is sharp.
**Ichnology:**

Bioturbation intensities of Facies 1a range from BI 0-4, with the ichnogenera consisting of rare occurrences of *Planolites*, navichnia and *Chondrites*. Facies 1a is generally almost completely devoid of bioturbation (BI 0), with exception of sporadically distributed, isolated intervals where bioturbation reaches BI 4. The trace fossils are commonly diminutive, and the overall trace fossil suite shows low diversity.

**Process Response:**

The sand lenses contain starved current ripples, combined flow ripples, and oscillation ripples, which suggest both quasi-steady currents and overriding oscillatory flow. Syneresis cracks are present throughout the facies, and reflect short-lived salinity fluctuations immediately above the sea floor (cf. Burst, 1965; Plummer and Gostin, 1981). The abundant coal fragments, wood fragments, and macerated plant material suggest a nearby fluvial source, wherein terrestrial organics were transported to the depositional site. The abundant organic detritus further supports the hypothesis of increased fluvial influence in the marine realm (e.g., Leckie et al., 1989).

Low diversity trace-fossil suites and reduced sizes of the ichnogenera are common characteristics of salinity-stressed settings (cf. Beynon et al., 1988; Beynon and Pemberton, 1992; Pemberton and Wightman, 1992; MacEachern and Gingras, 2007; Gingras et al., 2011). The presence of navichnia (sediment-swimming structures; cf. Gingras et al., 2007), otherwise referred to as “mantle-and-swirl structures” (Lobza and Schieber, 1999) within organic-rich mudstone laminae supports a fluid-mud interpretation, and indicates the presence, at least intermittently, of soupground conditions at the sea floor. Deposits of Facies 1a reflect stressed depositional conditions, which most likely are the result of salinity fluctuations and rapid emplacement of fluid muds.
Figure 3.1  **Facies 1a: Organic-Rich Mudstone.** (A) Organic-rich mudstone admixed with bentonite clays. Unit shows a low BI (0-1), with navichnia (na) (sediment-swimming structure or “mantle-and-swirl”). Photo is from the outcrop of RDV-B.  (B) Shows a sand lens encased in organic-rich mudstone, with sharp-based mudstones locally present. A syneresis crack (sy) is observed within the sharp-based mudstone. Photo from RDV-B.  (C) Lenticular bedded mudstone with isolated wave rippled (wr) sandstone lens. Photo from WC-4.  (D) Close-up photo of a sharp-based mudstone, interpreted to represent fluid mud deposition. Navichnia (na) and syneresis cracks (sy) are both present within the photo. Photo taken from RDV-B.  (E) Cored interval of Facies 1a. The photo shows a lenticular bedded, organic-rich mudstone with a BI 0-1 and rare Planolites (P) and Chondrites (Ch). Photo location is from ARC 19-79, 84.8m depth. The red dashed line is the interpreted contact between Allomember E and F.
**Facies 1b: Lenticular Bedded Mudstone**

*Sedimentology:*

Facies 1b consists of blocky to fissile, lenticular-bedded mudstone. The sandstone lenses consist of coarse silt to lower very fine-grained sand, and contain rare current ripples, oscillation ripples and combined flow ripples. Syneresis cracks are sporadically distributed, but generally confined to sharp-based, organic-rich mudstone beds. Convolute bedding and associated micro-faults are common. Common centimetre-to decimetre-scale intercalated sandstones showing low-angle undulatory parallel laminations and oscillation ripples are more common passing upwards in the facies. Lithological accessories occur as rare to uncommon sideritized horizons that are laterally continuous over metres to 10s of metres in outcrop. Disseminated organic material, carbonaceous lenses and macerated plant material are sporadically distributed throughout the facies. The basal contact of Facies 1b varies from sharp to gradational.

*Ichnology:*

No ichnological data were identified from the outcrop study of Allomember F. In the ARC 19-79 well, however, Facies 1b shows BI 0-4 with rare occurrences of *Planolites, Palaeophycus, Asterosoma, Teichichnus, Diplocraterion, Chondrites, Cylindrichnus, Arenicolites, Skolithos, Ophiomorpha* and navichnia (see Figure 3.2). All traces are diminutive, with a moderate diversity suite.
**Figure 3.2** Facies 1b: Lenticular Bedded Mudstone. (A) Lenticular bedded mudstone, which comprises 30% sand and 70% mud. Physical sedimentary structures are predominantly oscillation ripples (wr). Soft-sediment deformation (ssd) is visible at the bottom of the photo. BI is 3-4 with ichnogenera identified as Diplocraterion (Di), Chondrites (Ch) and Palaeophycus (Pa). Photo taken from ARC 19-79, 79.4m. (B) A muddier expression of Facies 1b. Physical sedimentary structures consist of isolated oscillation ripples. Organic-rich mudstone interbeds are interpreted as fluid muds (fm). This section of core shows BI 2-3. Ichnogenera include: Teichichnus (Te), Planolites (P), Asterosoma (As), Chondrites (Ch) and navichnia. Photo from ARC 19-79, 83.8m (C) Outcrop photo with an isolated oscillation ripple (wr) encased in brown mudstone. (D) Typical outcrop shot from a weathered example of the facies.

*Process Response:*

The intercalated oscillation and current ripples show that both waves and currents operated within the environment. Syneresis cracks present within the measured sections are indicative of salinity variations. The common convolute bedding suggests rapid emplacement of sediment followed by synsedimentary failure, probably reflecting the inability of the heterolithic units to dewater during burial. The wavy parallel laminations are interpreted to reflect storm processes. Lithological accessories show increased amounts of organic debris, suggesting enhanced fluvial processes (e.g., Leckie et al., 1989). Finally, the ichnological data suggests a stressed environment, based on the style of bioturbation: moderate-diversity trace fossil suite dominated by diminutive ichnogenera.
3.1.2. **Facies 2: Micro-Hummocky Cross-Stratified to Oscillation Rippled Silty Sandstone**

*Sedimentology:*

Facies 2 is characterized by moderately sorted, well-rounded, coarse silt to lower very fine-grained silty sandstone. Physical sedimentary structures are centimetre-scale oscillation ripples and centimetre- to decimetre-scale, low-angle undulatory parallel laminae, commonly referred to as “micro-HCS” (cf. Dott and Bourgeois, 1982). Sharp-based mudstones are commonly intercalated near the basal contact of the facies, and decrease in abundance upwards. These mudstone interbeds commonly drape micro-HCS and oscillation ripples. Syneresis cracks are commonly associated with the mudstone interbeds. Lithological accessories consist of disseminated carbonaceous debris and localized carbonaceous lenses. Basal contacts of the facies are sharp and commonly irregular, with loading and soft-sediment deformation present.

*Ichnology:*

Bioturbation in Facies 2 is absent to rare, showing BI 0-1. The trace fossil assemblage is low diversity, and consists of diminutive ichnogenera. Trace fossils comprise rare *Arenicolites, Skolithos, Ophiomorpha, Palaeophycus*, and *Planolites*, and well as common fugichnia. *Planolites* are isolated, and only observed within the sharp-based mudstone interbeds. The dominant ethology represented within the suite is permanent dwelling, and the assemblage can be regarded as a stressed expression of the *Skolithos* Ichnofacies.
Figure 3.3  Facies 2: Micro-Hummocky Cross-Stratified to Oscillation Rippled Silty Sandstone. (A) A well-cemented example of coarse silt to very fine-grained sandstone with combined flow ripples (cfr). (B) Coarse silt to very fine-grained sandstone consisting entirely of amalgamated oscillation ripples (wr). Mud interbeds, interpreted to be of fluid mud origin, are present throughout the lower 5 centimetres of the light-coloured sandstone unit, and mantle the crests of the ripples. BI 0–1 with rare Planolites (P) is present within the photo. (C) Coarse silt to very fine-grained sandstone with obvious, sharp-based mudstones that are interpreted to represent fluid-mud deposition. The physical sedimentary structures are wave ripples to micro-HCS. Numerous syneresis cracks (sy) are present throughout the centimetre-scale mudstone interbeds. (D) An expression of Facies 2 as seen in core. Interlaminated sandstone with sharp-based mudstone interbeds. The physical sedimentary structures are oscillation ripples (wr), and combined flow ripples (cfr). Syneresis cracks (sy) are present throughout the mudstone interbeds. BI is 0-1, with burrowed confined to the mudstone interbeds. Ichnogenera include Arenicolites (Ar), Planolites (P), and fugichnia. Core photos from ARC 19-79.

Process Response:

The abundance of oscillation ripples indicates active reworking of the substrate by wave processes. The low-angle undulatory parallel lamination is interpreted to form in response to storms. Fluvial input into the system is indicated by the common carbonaceous detritus and by the presence of syneresis cracks, which are attributed to salinity fluctuations (cf. Burst, 1965; Plummer and Gostin, 1981). Localized zones of rhythmic laminae occur in the intercalated mudstone interbeds, and could suggest that tidal processes were responsible for remobilizing and depositing the fluid mud. The low bioturbation index, reduced diversity, and diminutive ichnogenera characteristic of the facies suggest that the environment was physico-chemically stressed. Fugichnia are commonly associated with episodic deposition, wherein organisms are rapidly buried. Loading structures along the basal contacts indicate that the sands were emplaced onto a less dense, water-saturated mud, resulting in differential loading.
3.1.3. **Facies 3: Trough Cross-Stratified and Current-, Combined Flow-, and Oscillation-Rippled Sandstone**

*Sedimentology:*

Facies 3 is characterized by well sorted, moderately rounded, upper fine-grained to lower medium-grained sandstone. The sedimentary structures comprise common decimetre-scale trough cross stratification, planar tabular cross stratification, and low-angle planar parallel lamination, as well as centimetre-scale aggradational current ripples, current ripples, combined flow ripples and oscillation ripples. Organic debris is commonly disseminated throughout the lower one to two metres of the facies. Decimetre-scale, organic-rich mudstones are intercalated and separate metre-scale, sandstone-rich portions of the facies. Paleocurrent measurements indicate a dominant flow in a southeasterly oriented direction (see Figure. 3.5). Facies 3 sharply overlies other facies.

*Ichnology:*

The bioturbation index of Facies 3 is 0-2, and the suite consists of a monogeneric association of *Ophiomorpha*. Trace fossils are sporadically distributed throughout the facies and are commonly diminutive. The biogenic structures are typically isolated to parts of Facies 3 that are made up of centimetre-scale sedimentary structures (e.g., current ripple cross lamination). Where Facies 3 consists of large-scale sedimentary structures (e.g., trough cross stratification), it is typically devoid of bioturbation.
Figure 3.4  Facies 3: Trough Cross-Stratified and Current-, Combined Flow-, and Oscillation-Rippled Sandstone. (A) An outcrop expression of Ophiomorpha. (B) Outcrop photo of well-cemented aggradational current ripples (ccr). (C) Core photo of Facies 3, with organic detritus demarcating the foresets of current-generated sedimentary structures. Physical structures seen in the core are aggradational current ripples (ccr) and current ripples (cr). Photo from ARC 19-79.
Figure 3.5  Rose diagram of the dominant paleocurrent directions that are associated with Facies 3. The structures measured were larger scale (greater than 10 centimetres) to increase accurate paleocurrent directions. Measurements were taken from trough cross stratification and planar tabular cross stratification. Note that the dominant trend is to the southeast.
Process Response:

Facies 3 reflects environments that were subjected to multiple hydrodynamic processes that operated in concert. The dominant sedimentary structures are current-generated decimetre-scale dunes, and centimetre- to millimetre-scale current ripples and aggradational current ripples. These structures indicate traction transport by quasi-steady currents. Wave influence is apparent by the presence of minor oscillation ripples and combined-flow ripples. The organic debris (both disseminated throughout the facies and demarcating stratification) suggests a nearby fluvial input (e.g., Leckie et al., 1989). The paucity of bioturbation suggests a physico-chemically stressful environment. The decimetre-scale, sharp-based, organic-rich interbedded mudstones are interpreted to record fluid mud deposition. This is supported by their sharp-based character, the abundant organic debris and wood fragments, and the paucity of bioturbation. The dominant paleocurrents show current flow oriented in a south-southeasterly direction (see Figure. 3.5).

3.1.4. Facies 4: Organic-Rich, Trough-Cross Stratified to Current Rippled Sandstone

Sedimentology:

Facies 4 is characterized by a fining-upward succession of moderately sorted, moderate to well rounded, lower very fine- to lower medium-grained sandstone. The physical sedimentology comprises common decimetre-scale beds of trough and planar-tabular cross stratification, current ripple lamination, and rare aggradational current ripple lamination. Mudstone interbeds with syneresis cracks are rare though persistent throughout the facies and more prevalent upwards. Mudstone layers are commonly discontinuous and contain internal scour horizons (see Figure. 3.6). At the base of Facies 4, well-cemented, decimetre-scale trough and planar tabular cross stratification are common. Passing upwards, trough and planar-tabular cross stratification become rare and current ripple lamination dominates. Facies 4 produces a fining-upward trend as well as a “muddying” upward trend (e.g., more abundant mudstone layers upwards).
Disseminated organic debris, wood fragments, and carboneous lenses are abundant throughout the facies. Paleocurrents dominantly trend toward the northeast (see Figure 3.7). The basal contact of the facies is erosional, manifests either by a sandstone-on-sandstone contact, or locally incises into underlying mudstones of Facies 1b.

**Ichnology:**

Bioturbation is exceedingly rare within Facies 4, and most beds display BI 0-1. Trace fossils present include very rare *Skolithos* and rare *Planolites*. Trace fossils are isolated and typically associated with the sharp-based mudstone interbeds. Ichnogenera are diminutive and form very low diversity suites.

**Process Response:**

The hydrodynamic conditions reflected by Facies 4 indicate that these deposits were produced from a quasi-steady current flow that produced dune-scale bedforms (e.g., trough and planar-tabular cross stratification) as well as ripple-scale bedforms (e.g., current ripples and aggradational current ripples). The aggradational current ripples are indicative of high sedimentation rates during flow. The abundant organic debris distributed throughout Facies 4 suggests a close proximity to fluvial sources. The sharp-based mudstones coupled with associated syneresis cracks and organic debris can be used to infer fluid mud deposition (Lobza and Schieber, 1999). The internal scour horizons within the mud beds suggest possible episodic fluctuations in energy, possibly during bedload transport of mud. The transition from trough and planar-tabular cross stratification to current ripple lamination supports an upward decrease in flow strength. The degree of sorting and rounding suggest relatively immature sediment that was reworked and transported short distances. The sporadic distribution of bioturbation, overall low intensity of burrowing, and diminutive sizes of ichnogenera indicate physico-chemical stresses imposed on the fauna occupying the depositional environment.
Figure 3.6 Facies 4: Organic-Rich, Trough Cross Stratified to Current Rippled Sandstone and Facies 5: Blocky, Siderite-Cemented Mudstone. (A) Shows interbedded, sharp-based mudstones of Facies 4 that are interpreted to be from fluid mud deposition. Local syneresis cracks (sy) are present in the mudstone interbeds. The physical sedimentary structures are dominantly current ripple lamination. (B) Outcrop occurrence of Facies 5; a facies not intersected by cored intervals. (C) Current ripple lamination (cr) and internal scour horizons of mudstone at the top of the Facies 4 succession. (D) Well-indurated outcrop that shows current ripple lamination (cr). (E) Outcrop photo that shows a fining-upward succession, interpreted to reflect a decrease in flow velocity. Trough cross-stratification (txb) at the bottom of the photo passes upward into current ripple lamination (cr). Grain sizes decrease from lower medium to lower fine. Organic material commonly demarcates the tops and foresets of the sedimentary structures.
Figure 3.7  Rose diagram of the dominant paleocurrent directions associated with Facies 4. The structures measured were from beds greater than 10 centimetres thick to increase accurate paleocurrent measurements. Note the dominant trend to northeast, approximately 90° different than Facies 3.
3.1.5. **Facies 5: Blocky, Siderite-Cemented Mudstone**

*Sedimentology:*

Facies 5 is characterized by very well consolidated, blocky weathering, siderite-cemented mudstone. Sand content throughout the facies ranges from approximately 0-10%, with sand grains being lower very fine in size. Siderite horizons are widespread and typically form continuous centimetre- to decimetre-scale resistively weathered bands throughout the outcrops. Abundant organic debris in the form of wood fragments, carboneous lenses, and disseminated organic detritus are common throughout the facies. Rhizoliths (root traces) are also common and are sporadically distributed throughout Facies 5. Facies 5 is not widespread throughout the study area, and is isolated to four outcrop sections. The basal contact of Facies 5 is sharp to gradational, and always overlies the deposits of Facies 4.

*Ichnology:*

No trace fossils were identified within Facies 5.

*Process Response:*

The deposits of Facies 5 reflect environments that are closely associated with the terrestrial realm. Root traces indicate subaerial exposure of sediment and its subsequent colonization by plants. The abundant organic detritus and wood fragments suggest relatively close proximity to fluvial sources. The localized distribution of the facies suggests it could be closely related to channelized intervals. Bioturbation is absent, possibly indicating the potential for physico-chemical stresses in the depositional environment.
3.1.6. **Facies 6: Trough Cross-Stratified Sandstone**

*Sedimentology:*

Facies 6 is characterized by a coarsening-upward succession, consisting of stacked beds of well-sorted, well-rounded, upper fine- to lower medium-grained sandstone. Sedimentary structures include common decimetre-scale beds of trough and planar-tabular cross stratification, rare current ripples, low-angle planar parallel lamination, and localized low-angle undulatory parallel laminations. Low-angle undulatory parallel lamination is interpreted to represent hummocky cross stratification. At the base of the succession, centimetre-scale, discontinuous, organic-rich mudstone layers are commonly intercalated. Rare carbonaceous debris and wood fragments are sporadically distributed throughout the facies and commonly drape the foresets of the trough and planar-tabular cross stratification. Paleocurrent data derived from Facies 6 show a dominant flow direction to the southeast (see Figure 3.9). The basal contact of Facies 6 is erosional, and cuts into underlying sandstones or mudstones of Allomember E.

*Ichnology:*

Bioturbation associated with Facies 6 is rare and sporadically distributed. Bioturbation index ranges from 0-4, but commonly resides between BI 0-2. Trace fossils include very rare *Ophiomorpha* and *Schaubcylindrichnus coronus*, with rare *Skolithos*, *Thalassinoides*, *Palaeophycus*, *Rosselia*, *Cylindrichnus*, *Teichichnus*, and *Rhizocorallium* (see Figure 3.8). The ichnological assemblage is dominated by dwelling structures and can be attributed to the *Skolithos* Ichnofacies. Ichnogenera are robust and form a relatively high-diversity suite. Bioturbation intensities are generally absent where associated with large-scale sedimentary structures such as trough and planar tabular cross stratification. Higher bioturbation intensities (typically 2-3) are sporadically distributed but predominantly associated with the interstratified organic-rich mudstones.
Firmground *Thalassinoides*, passively infilled from above, commonly marks the basal contact.

*Process Response:*

The deposits of Facies 6 reflect conditions consistent with environments prone to quasi-steady current flow. Current-generated structures (e.g., trough and planar tabular cross stratification) dominate the facies. The low-angle undulatory laminae, which are confined to the lower parts of the facies, are typically associated with storm waves. The transition from rare oscillatory generated structures (low-angle undulatory parallel lamination) to current-generated structures (trough cross stratification) is interpreted to reflect shallowing and the shift from orbital wave flow to the development of translatory waves. The carbonaceous debris and wood fragments concentrated in the lower part of the facies suggests potential fluvial input into the system. The sharp-based, intercalated organic-rich mudstones are possibly sourced from fluvial systems. The coarsening-upward trend of the facies suggests a progradational setting. The progressive increase in sand:mud ratios (e.g., “sandying”-upward trend) is used to indicate increased energy conditions. The sporadically distributed and generally reduced bioturbation intensities, coupled with robust and relatively diverse suites of trace fossils suggests that physico-chemical stresses were probably related to episodic energy fluctuations.
Figure 3.8  Facies 6: Trough Cross-Stratified Sandstone. A--D show core expressions of Facies 6. The physical sedimentary structures are low-angle planar parallel lamination and localized trough cross-stratification. BI is 0-4, with the muddier portions being more thoroughly burrowed. Ichnogenera include Planolites (P), Thalassinoides (Th), Palaeophycus (Pa), Teichichnus (Te), Rhizocorallium (Rh), and Cylindrichnus (Cy). Photos from Core ARC 20-79 (E) Outcrop photo with an ice axe for scale (red circle). Large-scale trough cross stratification is the dominant sedimentary structure visible in the outcrop. The colour change at the ice axe marks the boundary between Allomember E and Allomember F.
Figure 3.9  Rose diagram of the dominant paleocurrent directions associated with Facies 6. The structures measured were from beds greater than 10 centimetres in thickness in order to increase the accuracy of paleocurrent directions acquired. Note the dominant trend to the southeast. Facies 3 and Facies 6 have similar paleocurrent trends, whereas Facies 4 show flow 90° to them.
3.1.7. Facies 7: Low-Angle Planar-Parallel Laminated Sandstone

Sedimentology:

Facies 7 is typified by a fining-upward succession that consists of well-sorted, well-rounded, lower to upper fine-grained sandstone. Sedimentary structures include low-angle planar-parallel laminations and very rare decimetre-scale planar tabular cross stratification and low-angle undulatory parallel lamination (See Figure 3.10, C). Low-angle undulatory parallel lamination is confined to a single location, appears to have been vertically accreted, and is not laterally continuous. The low-angle planar-parallel lamination commonly forms distinctive wedge-shaped morphologies (See Figure 3.10, B). Facies 7 sharply overlies Facies 6, demarcated by the sudden and abundant presence of dense concentrations of *Macaronichnus segregatis*.

Ichnology:

Ichnological characteristics of Facies 7 are expressed by a broad range of bioturbation intensities (BI 0-5). The bulk of the facies is unburrowed, with very rare (BI 1) *Skolithos* but locally abundant (BI 3-5) *Macaronichnus segregatis*. The *Macaronichnus segregatis* occurs near the basal contact of Facies 7, grading from lower abundances (BI 3), through to intensely burrowed beds (BI 5), but rapidly disappearing from the facies across a thickness of 0.1m to 0.5m. Bioturbation is absent to very rare above the *M. segregatis* occurrences.
Figure 3.10  Facies 7: Low Angle Planar-Parallel Laminated Sandstone. (A) Intensely bioturbated (BI 4-5) network of Macaronichnus segregatis (Ma). (B) Upper fine- to lower medium-grained sandstone consisting of upper flow regime, low-angle planar-parallel lamination (ufr). This is consistent with what is called swash zone cross-stratification (Clifton et al., 1975). (C) Shows an example of low-angle undulatory lamination (hcs) from Facies 7.
**Process Response:**

The low-angle planar-parallel laminations are interpreted to have been produced from current-driven, upper flow regime sheet-flow conditions. Wedge-shaped, low-angle planar-parallel lamination is commonly associated with swash zone deposits. Planar tabular cross stratification is produced from quasi-steady current flow. The localized occurrence of low-angle undulatory parallel laminations can be formed by storm events or potential high-energy combined flow events to produce “quasi-planar-laminations” or QPL (Arnott, 1993). *Macaronichnus segregatis* is typically associated with sandy, high-energy marine environments (cf. Saunders, 1990; Saunders et al., 1994).

### 3.1.8. Facies 8: Trough Cross-Stratified Sandstones with Stacked Current Ripples

**Sedimentology:**

Facies 8 is characterized by very well-sorted, well-rounded, lower to upper fine-grained sandstone. The physical sedimentary structures consist of stacked, decimetre-scale trough cross stratification with amalgamated current ripples infilling the troughs. Grains are locally abraded and locally show frosting, however these constitute a relatively small percentage (<10%). The plan view morphology of Facies 8 is suggestive of elongate mounds of sediment that trend toward the northwest, containing both topographic highs and lows. Between these elongate mounds of sediment, there are large intervening depressions filled with accumulated organic-rich detritus. The basal contact of the unit is sharp to gradational, producing a sand-on-sand contact with the deposits of Facies 7.

**Ichnology:**

No trace fossils were identified within Facies 8.
Process Response:

The deposits of Facies 8 reflect conditions of quasi-steady current flow as indicated by trough cross stratification and the amalgamated current ripples. Petrographic analysis indicates that the deposit is mature, as suggested by the high of quartz content and the high degree of sorting. Localized grain frosting observed through a petrographic microscope suggests the sand grains may have been entrained by eolian processes at some time during the sand’s transport history.
Figure 3.11  Rose diagram of the dominate paleocurrent current measurements from Facies 8. Measurements are from structures greater than 10 cm.
Figure 3.12  Facies 8: Trough Cross-Stratified Sandstones with Stacked Current Ripples. (A) Outcrop photo of fine-grained sandstone that consisting of trough cross stratification and amalgamated current ripple lamination (cr). (B) Close-up view of a decimetre-scale trough cross-stratified bed (txb). (C) Picture showing the facies transition from planar parallel lamination (ufr) of Facies 7 into amalgamated current ripple lamination (cr) that dominates Facies 8.
3.1.9. **Facies 9: Organic-Rich Rippled Sandstone**

*Sedimentology:*

Facies 9 is characterized by moderately sorted, well-rounded, upper very fine- to upper fine-grained sandstone. Sedimentary structures comprise locally abundant current ripples and combined flow ripples. Facies 9 is typified by abundant organic debris, wood fragments and carbonaceous lenses. Root traces are common, as are sporadically distributed pedogenic slickensides. Facies 9 is always situated below the Coal 2 horizon. The basal contact varies from sharp to gradational.

*Ichnology:*

No trace fossils were identified within Facies 9.

*Process Response:*

The combined-flow ripples indicate that there was an associated oscillatory component as well as current generated flow affecting deposition. Roots and pedogenic modification indicate subaerial exposure of sediment and its subsequent colonization by plants. The abundant organic debris is also indicative of terrestrial environments where plant material is readily deposited and incorporated into the sediment. The apparent lack of bioturbation could be attributed to pedogenic modification obscuring the traces, or to physico-chemical stresses.
3.1.10. **Facies 10: Organic-Rich Sandy Mudstone**

*Sedimentology:*

Facies 10 is characterized by organic-rich sandy mudstones. Mudstone-to-sandstone ratios are commonly 80:20, but can be as high as 50:50 in some locations. Lower fine-grained sand is either disseminated throughout or forms discontinuous sandstone lenses. These lenses show rare, centimetre-scale oscillation ripples sporadically distributed throughout the facies. Organic debris, wood fragments, and carbonaceous lenses are abundant. Roots are very common and pedogenic slickensides are sporadically distributed. Facies 10 contains discrete horizons that are completely sideritized and continuous throughout the outcrop sections. The deposits of Facies 10 are widespread and commonly underlie coal horizons. Where coal has been removed or was not deposited, Facies 10 forms the top of Allomember F, and characterized by a centimetre- to decimetre-scale siderite horizon. This capping siderite horizon is composed of abundant wood fragments and disseminated organic debris. The basal contact is sharp to gradational with the underlying unit.

*Ichnotology:*

No trace fossils were identified within Facies 10.

*Process Response:*

The deposits of Facies 10 reflect depositional conditions consistent with environments that are subjected to subaerial exposure and periodic inundation by water. The rare oscillation ripples are formed from small-scale waves. The abundant roots and sporadically distributed pedogenic slickensides also are evidence for subaerial exposure and indicate incipient paleosol development. The abundant organic debris, wood fragments, and disseminated organic debris throughout the deposit is suggestive of a
terrestrial environment. The absence of bioturbation could be due to traces being obscured by the pedogenic modification.
Figure 3.13  Facies 9 Organic-Rich, Rippled Sandstone and Facies 10 Organic-Rich Sandy Mudstone. (A) An organic-rich, current rippled sandstone that makes up Facies 9. Organic detritus mantles the current ripple (cr). (B) Photo of Facies 10 showing a large-scale oscillation ripple (wr) encased in organic-rich mudstone. (C) Photo of Facies 10 showing abundant wood fragments (wd) and plant material that are the primary lithological characteristics of the unit.
3.1.11. Facies 11: Coal

Sedimentology:

The coal observed in the study area varies from centimetre-scale to metre-scale seams. The coal is commonly bright, possesses a vitreous appearance, and breaks with concoidal fracture. The coal is well cleated at some locations. There is no pyrite intercalated within the coal; however a sulphur powder is locally present on the outside of the coal. Little to no clastic detritus is intercalated. Locally, *in situ* stumps are incorporated in the coal. The basal contact is dominantly sharp with localized gradational contacts where it grades out of Facies 9 or Facies 10 grade.

Ichnology:

There are no trace fossils directly associated with the coal units. At one location (RDV-8), possible rare (BI 0-1) *Bergaueria* or *Teredolites* are bored into the upper contact of the coal (see Figure. 3.13).

Process Response:

Facies 11 is widespread across much of the southeasterly portion of the study area and is a key stratigraphic marker bed (designated Coal 2) throughout the area. The paucity of pyrite intercalated within the coals suggests that the coal formed during regression in a fully terrestrial setting. The coal lacks any appreciable clastic detritus, suggesting that there was a limited amount of sediment transportation into the coal-forming area. The marine traces of *Bergaueria* or *Teredolites* suggest that there was a marine incursion into the area after the coal accumulated. The upper contact is therefore interpreted to be a marine flooding surface and forms the allostratigraphic boundary between Allomember F and Allomember E.
Figure 3.14  Facies 11: Coal. (A) Outcrop section of Facies 11 (Coal 2) as seen from outcrop at RDV-8. Coal 2 is commonly well cleated and lacks any appreciable clastic detritus or pyrite. Rarely, Coal 2 has borings into its upper contact. These disc-shaped borings have been identified as either Teredolites (T) or Bergaueria. (B) Coal 2 marker bed, as seen in core ARC 20-79 70.9m.
4. Facies Associations, Element Complex Designations, and Stratigraphic Architecture of Allomember F

4.1. Introduction

Facies associations are recurring vertical successions and lateral transitions of genetically related rocks, and are considered to be the foundation of facies analysis and environmental interpretation (cf. Reading and Levell, 1996). The facies observed within Allomember F occur as four broad facies associations (FA1-FA4). FA1 comprises sandy deposits interpreted to represent a delta lobe complex, FA2 is interpreted as channelized deposits that are fluvial-tidal in origin, FA3 corresponds to coarsening-upwards successions interpreted to represent deposition in a shoreface setting, and FA4 consists of mixed sandstone, mudstone, and coal deposits, interpreted to range from paralic to terrestrial in origin.

The previous chapter focused on the description and hydrodynamic process-response interpretation of the individual facies and their physical and biogenic structures. Facies associations, are the interpretation of the facies, based both on the process-response assessment of the facies as well as the context of the process-response interpretations of adjacent, overlying and underlying facies. Using these facies associations, element complex designations have been assigned that correspond to the WAVE Classification criteria (Ainsworth et al. 2010) presented in Chapter 2.
<table>
<thead>
<tr>
<th>Facies</th>
<th>Sedimentology</th>
<th>Ichnology/Ike</th>
<th>Process Response Model</th>
<th>Depositional Environments</th>
<th>Facies Association</th>
<th>Element Complex</th>
<th>Occurrence</th>
<th>Sedimentary Environments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a Organics-Rich Mudstone</td>
<td>- Dark-brown to black, organic-rich fine mudstone</td>
<td>- Rhizoliths indicate subaerial exposure</td>
<td>- Local lenses contain current ripples, oscillation ripples, and combined flow ripples which suggest current flow with a oscillatory component</td>
<td>Facies 1a is interpreted as a prodelta</td>
<td>FA1</td>
<td>Fw(t)-Loeb Element Complex</td>
<td>Northwest margin of the study area, occurs at the base of the Dredge Frons</td>
<td>RIV J-6</td>
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<tr>
<td>1b Laminated Bedded Mudstone</td>
<td>- Very rare sandstones which are thin to very thin</td>
<td>- Organic debris</td>
<td>- The abundance of oscillatory generated structures suggest deposition above fair weather wave base</td>
<td>Facies 1b is interpreted as a prodelta</td>
<td>FA1</td>
<td>Fw(t)-Loeb Element Complex</td>
<td>Northwest margin of the study area, occurs at the base of Facies 2</td>
<td>RIV J-7</td>
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<td></td>
<td>Bedded, current, trough-cross bedded</td>
<td>- Rare intercalated c 0.5 to 1.0 sandstone beds with low angle oscillatory laminations and oscillation ripples</td>
<td>- The abundance of oscillatory generated structures suggest deposition above fair weather wave base</td>
<td>Northwest margin of the study area, occurs at the base of Facies 2</td>
<td>FA1</td>
<td>Fw(t)-Loeb Element Complex</td>
<td>Northwest margin of the study area, occurs at the base of Facies 2 and Facies 3</td>
<td>RIV L, RIV 3-4</td>
</tr>
<tr>
<td>Micro-RECs and Oscillation Ripples Sandstones</td>
<td>- C. 0.5 to 1.0 sandstone</td>
<td>- Common sharp-based mudstones are indicative of fluid deposition</td>
<td>- Low angle undulatory laminations suggest large wave length oscillatory processes</td>
<td>Northwest margin of the study area, occurs at the base of Facies 2 and Facies 3</td>
<td>FA1</td>
<td>WC(t)-Mishub Element Complex</td>
<td>Northwest margin of the study area, occurs at the base of Facies 2 and Facies 3</td>
<td>RIV A- RIV A, WC 1-4</td>
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<tr>
<td></td>
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<td>- Small-scale trough cross bedding, planar-surface cross stratifications, low angle planar parallel laminations, climbing current ripples, current ripples, and oscillatory ripples</td>
<td>- The climbing ripples are indicative of high sedimentation rates</td>
<td>Northwest margin of the study area, occurs at the base of Facies 2 and Facies 3</td>
<td>FA1</td>
<td>WC(t)-Mishub Element Complex</td>
<td>Northwest margin of the study area, occurs at the base of Facies 2 and Facies 3</td>
<td>RIV A- RIV A, WC 1-4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Common organic debris is disseminated throughout the lower 1 to 2 m</td>
<td>- Organic-rich dm-scale trough cross-bedded organic-rich mudstone interbeds suggest potential fluid mud deposits or periods of dewatering</td>
<td>Northwest margin of the study area, occurs at the base of Facies 2 and Facies 3</td>
<td>FA1</td>
<td>WC(t)-Mishub Element Complex</td>
<td>Northwest margin of the study area, occurs at the base of Facies 2 and Facies 3</td>
<td>RIV A- RIV A, WC 1-4</td>
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<tr>
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<td>- Common dm-scale scale organic-rich mudstone interbeds</td>
<td>- The low BI observed suggest environment stresses</td>
<td>Northwest margin of the study area, occurs at the base of Facies 2 and Facies 3</td>
<td>FA1</td>
<td>WC(t)-Mishub Element Complex</td>
<td>Northwest margin of the study area, occurs at the base of Facies 2 and Facies 3</td>
<td>RIV A- RIV A, WC 1-4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Very rare mudstone</td>
<td>- The climbing ripples are indicative of high sedimentation rates</td>
<td>Northwest margin of the study area, occurs at the base of Facies 2 and Facies 3</td>
<td>FA1</td>
<td>WC(t)-Mishub Element Complex</td>
<td>Northwest margin of the study area, occurs at the base of Facies 2 and Facies 3</td>
<td>RIV A- RIV A, WC 1-4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Common trough cross-bedded and finscale current ripples</td>
<td>- The climbing ripples are indicative of high sedimentation rates</td>
<td>Northwest margin of the study area, occurs at the base of Facies 2 and Facies 3</td>
<td>FA1</td>
<td>WC(t)-Mishub Element Complex</td>
<td>Northwest margin of the study area, occurs at the base of Facies 2 and Facies 3</td>
<td>RIV A- RIV A, WC 1-4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- The basal contact of the 1b is sharp to gradational</td>
<td>- The abundance of oscillatory generated structures suggest deposition above fair weather wave base</td>
<td>Northwest margin of the study area, occurs at the base of Facies 2 and Facies 3</td>
<td>FA1</td>
<td>WC(t)-Mishub Element Complex</td>
<td>Northwest margin of the study area, occurs at the base of Facies 2 and Facies 3</td>
<td>RIV A- RIV A, WC 1-4</td>
</tr>
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<tr>
<td>5 Blackly, Sulfidated Mudstone</td>
<td>- Emulously hard, blocky mudstone</td>
<td>- Rhizoliths indicate subaerial exposure</td>
<td>- Basal contact is sharp</td>
<td>Channel morphology was from outcrop photos</td>
<td>FA2</td>
<td>Ft-Channelled</td>
<td>Northwest margin of the study area, occurs at the base of Willow Creek</td>
<td>RIV 5 and Between RIV 1 and 4 in outcrop photos</td>
</tr>
<tr>
<td>Facies Number</td>
<td>Sedimentology</td>
<td>Ichnology/I</td>
<td>Process Response Model</td>
<td>Depositional Environment</td>
<td>Depositional Facies Association</td>
<td>Element Complex</td>
<td>Occurrence</td>
<td>Sections Present</td>
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</tbody>
</table>
| 6 | Trough-Cross Bedded Sandstones | • Fl. to sl. sandstone  
• Well sorted, well rounded  
• Rare carbonaceous debris, sparsely distributed  
• Sedimentary structures include dm trough cross bedding, dm planar tabular cross bedding, current ripples, low angle planar parallel laminations, and low angle undulatory laminations  
• Rare wood fragments and layers of carbonaceous debris  
• The basal contact is sharp and erosional | • Rare Arthroichnus  
• Rare Palaeophycus  
• Rare Pedumichnus  
• Rare Planolites  
• Very rare Rosselia  
• Very rare Schaubcylindrichnus | • Quasi-steady currents produced the dm-scale trough cross bedding, planar tabular cross bedding, current ripples, and low angle planar parallel laminations  
• Localized low angle undulatory laminations were produced by oscillatory processes  
• The carbonaceous debris that is distributed throughout the facies suggests fluvial input  
• Low bioturbation index suggests environmental stresses | Facies 6 is interpreted as a upper shoreface deposit | FA3 | WE Beach Element Complex | Southern coast section of the study area Marks the base of Allomember F on sections observed | RGD 6,7,8,9,10,11,12,13 |
| 7 | Low Angle Planar-Parallel Laminitated Sandstone | • Fl. to sl. sandstone  
• Well sorted, well rounded  
• Cmv scale, wedge shaped, low angle planar parallel laminations  
• Basal contact is sharp and marked by intense bioturbation of Macaronichnus segregatus | • III D-I  
• Well developed "Tree-on-the-Beach" assemblage of Macaronichnus segregatus  
• Very rare Skolithos | • Low angle planar parallel laminations are produced by upper flow regime currents  
• The intensity of bioturbation is indicative of high energy, fully marine environments | Facies 7 is interpreted as Foreshore | FA3 | WE Beach Element Complex | Okolossa trough-cross bedded sandstone of Facies 7 | RGD 9,10,11,12,13 |
| 8 | Trough-Low Angle Planar Parallel Laminitated Sandstone | • Fl. to sl. sandstone  
• Dm-scale trough cross beds with amalgamated current ripples  
• Basal contact is sharp | • III B | • Quasi-steady current flow as indicated by trough-cross bed and amalgamated current ripples  
• The relatively high angle trough-cross beds possibly suggests sediment transport in wind  
• Sedimentary structures include dm trough cross bedding, planar tabular cross bedding, current ripples, and oscillatory ripples | Facies 8 maybe a potential back shore/bathymorphic | FA4 | Onshore Zone Element Complex | Located above the low angle planar parallel laminated sandstone of Facies 6 | RGD 12 and RGD 11 |
| 9 | Organic-Rich Current-Ripple Sandstone | • Abundant organic debris, wood fragments and masticated plant material  
• Local pedogenic modification  
• Local cm-scale current ripples, combined flow ripples, and oscillatory ripples  
• Poorly sorted, moderate rounding  
• Basal contact is gradational | • III B | • The current ripples which are locally abundant suggest a current flow  
• The combined flow ripples indicate oscillatory processes and current generated flow  
• The abundant bioturbation is also suggestive of sediment deposition near the terrestrial realm  
• The carbonaceous debris that is distributed throughout the facies suggests marine influence | Facies 9 and 10 are interpreted as backshore deposits transitioning into coastal plain deposits | FA4 | Onshore Zone Element Complex | All sites except for RGD 12 and RGD 13 where Coal 2 is not present | |
| 10 | Organic-Rich Admixed Sand Shales | • Admixed  
• Mudstone to sandstone ratio is typically 80-20, can be close to 50:50  
• Local wave ripples  
• Basal contact is gradational  
• The abundant bioturbation is also suggestive of sediment deposition near the terrestrial realm | • III F | • The abundant bioturbation is also suggestive of sediment deposition near the terrestrial realm  
• The carbonaceous debris and masticated plant material disseminated throughout the deposit is indicative of terrestrial sediments | Facies 9 and 10 are interpreted as backshore deposits transitioning into coastal plain deposits | FA4 | Onshore Zone Element Complex | Locally directly below Coal 2 or the equivalent horizon of Coal 2 | |
| 11 | Coal | • Bright  
• Vitreous  
• Well cleaned in locations  
• No clastic detritus present  
• No pyrite observed within the coal  
• Localized sulphur staining  
• Thin stumps observed at multiple locations | • III B-I  
• Very rare Burgessia  
• Trichichnus lineatus | • The paucity of pyrite and marine traces suggests coal that were formed during regression without influence of salt water  
• The coal lacks any appreciable clastic detritus suggesting coal produced away from fluvial input  
• Local tree stumps suggest the coal is derived from forested areas  
• The marine traces of Burgessia from the Trichichnus lineatus indicate a marine flooding surface that is above the coal | Facies 11 is interpreted as regressively coal deposits formed in a wooded area close to the coastal plain | FA4 | Coal-Onshore Zone Element Complex | The top of the coal signifies the top of Allomember F | RGD 2-11, WC 2-7 |
Figure 4.2  Legend of symbols used in the facies association lithologs. *(Physical structures and accessories symbols courtesy of the WAVE Consortium; trace fossil symbols from Dashtgard, pers. comm.)*
4.1.1. Facies Association 1 (FA1): Wave-Dominated, Fluvial-Influenced, Tide-Affected Delta

FA1 occurs in the northwestern portion of the Red Deer River Valley and at Willow Creek, and consists of four recurring facies. The facies that comprise FA1 are (in stratigraphic order from bottom to top): Facies 1a (Organic-Rich Mudstone); Facies 1b (Lenticular Bedded Mudstone); Facies 2 (Micro-Hummocky Cross-Stratified to Oscillation Rippled Silty Sandstone); and Facies 3 (Trough Cross-Stratified and Current-, Combined Flow-, and Oscillation-Rippled Sandstone). All facies contacts within FA1 are sharp or irregular. FA1 forms a coarsening-upwards succession varying between 3.5 metres and 7 metres in thickness. Facies 3 commonly marks the top of FA1, however at three locations (RDV-5, RDV-6, and RDV-6'), Facies 3 was not present. FA1 is interpreted to represent the deposits of a wave-dominated, fluvial-influenced, tide-affected lobe complex (i.e., a mixed influence delta).

Discussion and Interpretation of FA1:

Facies 1a and 1b reflect deposition of muds in the prodelta with thin interbedded sandy horizons interpreted to represent periodic higher energy storm events and sediment gravity flows. Passing upward through facies 1a and 1b, there is a gradual increase in the proportion of sand. This increase in sand content is interpreted to record upward shallowing of sediment deposition in the paleo-environment, wherein the overall effectiveness of the wave regime in reworking sediment increases. The coarsening-upward trend and increased sand content, coupled with locally abundant sandstone interbeds suggest the succession is progradational. The cm- to dm-scale intercalated sandstones also thicken upwards within the facies, and show both wave ripples and low-angle undulatory parallel laminations, which are interpreted to represent tempestites and waning flow deposits (cf. Dott and Bourgeois, 1982). The physical sedimentology is consistent with an environment that has an active nearby fluvial source that supplied sediment to the area. Enhanced fluvial input is indicated by the abundance of terrestrial-derived organic material, synaeresis cracks, starved current and combined-flow ripples, fluid mud accumulation, and soft-sediment deformation (see Figure. 3.1).
lenses that form the lenticular bedding show oscillatory, current, and combined flow ripples, which indicate quasi-steady current flow and oscillatory flow operating in conjunction within the environment.

The facies commonly displays BI values that range from 0--4, and comprises an impoverished ichnological suite. The trace fossils are commonly diminutive, consisting of rare *Planolites, Palaeophycus, Asterosoma, Teichichnus, Diplocraterion, Chondrites, Cylindrichnus, Arenicolites, Skolithos, Ophiomorpha* and navichnia. The dominant ethology present within facies 1a and 1b are deposit-feeding structures, however very rare dwelling structures, escape structures, and sediment swimming structures are present locally. Within the intercalated sandstone beds, the absence of biogenic structures supports rapid emplacement under high-energy conditions (e.g., Howard and Frey, 1984; Vossler and Pemberton, 1989; Pemberton and MacEachern, 1997; MacEachern and Bann, 2008). Potential stresses that can be inferred from the infaunal community are brackish-water conditions, salinity fluctuations, and episodic sedimentation, particularly interpreted to be the result of fluid mud deposition. The ichnological assemblage reflects a stressed expression of the archetypal *Cruziana* Ichnofacies (*cf.*, MacEachern and Bann, 2008).

The units of Facies 2 are interpreted to represent delta-front deposits. Facies 2 comprises coarse silt to lower very fine-grained sandstone with interbedded sharp-based mudstone layers. The sandstone to mudstone ratio is approximately 7:3. The basal contact separating Facies 2 from the underlying Facies 1a and 1b is sharp and commonly irregular, with loading at the contact. This is interpreted to be the result of a density contrast between the sands of the delta front (Facies 2) and the water-saturated muds of the prodelta (Facies 1a and 1b) (see Figure 4.3). The physical sedimentary structures consist of oscillatory ripples and micro-HCS (see Figure 3.3; Dott and Bourgeois, 1982) and indicate deposition above fair-weather wave base and under higher energy conditions than indicated by Facies 1a and 1b. This increase in energy conditions is interpreted to reflect an upward shallowing of the succession. The intercalated, cm-scale, organic-rich, sharp-based mudstones are interpreted to represent fluid mud deposition (e.g., Lobza and Schieber, 1999; Schieber, 2003; Hovikoski et al.,
2008), are commonly observed in the lower one metre of Facies 2. Upwards through the facies, a marked decrease in preserved mudstones of fluid mud origin is observed; this is attributed to increased energy conditions. A strong fluvial component is inferred from the deposits of Facies 2. Abundant carboneous debris, localized wood fragments, interbeds of inferred fluid mud origin, and syneresis cracks are distributed throughout the facies, and are consistent with fluvial influence. Syneresis cracks are commonly interspersed throughout the fluid mud beds, and are infilled with silt and very fine-grained sand. This is consistent with short-lived salinity changes immediately above the sea floor (Plummer and Gostin, 1981; Gingras et al., 1998; MacEachern et al., 2005; 2007).

The ichnological suite observed within Facies 2 is consistent with an impoverished suite and shows a strong departure from the archetypal Skolithos Ichnofacies. The trace-fossil assemblage is of low diversity, and consists of diminutive ichnogenera; mainly recording permanent dwelling or mobile deposit-feeding behaviours (cf. Gingras et al., 2007). Trace fossils include rare Arenicolites, Skolithos, Ophiomorpha, Palaeophycus, and Planolites, and well as common fugichnia. The increase in dwelling structures of inferred filter feeders suggests deposition occurred in shallower water with increased water turbidity. This is because the organisms occupying the dwelling structures do not actively search for food, but rely on currents to bring food to them. Mobile deposit feeding structures such as Planolites are isolated and limited to the sharp-base mudstone interbeds.

Passing upwards in the succession (and capping an idealized succession for FA 1), Facies 2 is sharply overlain by the deposits of Facies 3. Facies 3 is interpreted to represent the deposits of a distributary mouthbar complex. Facies 3 comprises upper fine- to lower medium-grained sandstone with interstratified, dm-scale, organic-rich mudstone beds. The facies show evidence of fluvial as well as marine-generated processes (waves and tides). Current-generated structures are indicated by trough cross stratification, planar tabular cross stratification, low-angle planar parallel lamination, aggradational current ripples, and current ripples. These are interstratified with oscillation-generated structures such as oscillation ripples and combined-flow ripples.
Facies 3 forms the uppermost unit of the coarsening-upward succession, corroborating the interpretation of a progradational setting subject to upward shallowing and increasing energy conditions. The trough-cross stratification that makes up the bulk of the mouthbar complex is interpreted to have been produced by wave processes (i.e., wave-forced currents in the nearshore), rather than by fluvial processes. The interpretation of wave dominance over fluvial dominance is based on the paleocurrent measurements taken from Facies 3. The paleocurrent trend suggests active reworking of the sediment parallel to the inferred paleoshoreline (approximately 130/310 degrees). If the dune-scale bedforms (e.g., trough-cross stratification) are produced from fluvial deposition, one would expect that the dominant paleocurrent trend would be perpendicular to the paleoshoreline (approximately 40 degrees). Wave dominance is further corroborated by the addition of oscillation ripples and combined-flow ripples in the interval. The predominance of oscillation-generated structures in Facies 2 (delta front) shows that the study area had a wave/storm climate able to produce event beds consisting of amalgamated oscillatory ripples and Micro-HCS (cf. Dott and Bourgeois, 1982; see Facies 2, Figure 3.3).

The deposits of Facies 3 are inferred to be associated with stressful environmental conditions. These environmental stresses are manifest by low bioturbation intensities (BI 0-2), consisting of diminutive, monospecific suites of *Ophiomorpha*. The integration of the ichnological data with physical sedimentological features suggests that prevailing environmental stresses were salinity fluctuations (e.g., syaeresis cracks), water turbidity, and high sedimentation rates (e.g., aggradational current ripples). Marine traces, though very rare throughout Facies 3; do indicate the presence of marine influence in the environment.
Figure 4.3  A litholog from measured section RDV-4. Facies that make up FA 1 at this location are Facies 1a (Organic-Rich Mudstone), Facies 2 (Micro-HCS and Oscillation Ripple Sandstone), and Facies 3 (Trough-Cross Bedded, Current, Combined-Flow, and Oscillation Rippled Sandstone). Legend for the litholog is Figure 4.2.
4.1.2. **Facies Association 2: Channelized facies association (FA2)**

FA2 consists of two discrete facies, which in stratigraphic order constitute Facies 4 (Organic-Rich Trough-Cross Stratified to Current Rippled Sandstone) either sharply or gradationally overlain by Facies 5 (Blocky, Siderite-Cemented Mudstone). FA2 is sporadically distributed throughout the study area and locally cross-cuts deposits of FA1. The Willow Creek outcrops contain most of the examples of FA2 (Fig. 4.4). The facies association forms a fining-upward succession in all localities, with a thickness that varies between 1 and 4 metres. The deposits of Facies 4 are interpreted to represent active sedimentation within a channel complex and Facies 5 reflects channel abandonment or laterally migrating overbank complexes.

**Discussion and Interpretation of FA2:**

The base of the facies association overlies a sharp, erosional contact. Facies 4 comprises lower very fine- to lower medium-grained sandstone. The sand grains are commonly moderately sorted and rounded, suggestive of relatively immature sediments. The common dune-scale bedforms reflected by planar tabular and trough cross-stratification supports deposition through traction transport processes, induced by turbulent quasi-steady currents, rather than rapid emplacement by sediment-gravity flows (cf. Miall, 1996). Dune-scale bedforms are common in the basal one metre of the succession. Passing upward, the trough and planar tabular cross-stratification give way to current ripple lamination. Current ripple lamination constitutes the dominant sedimentary structure preserved in the upper part of Facies 4. The fining-upwards profile, combined with a switch from dune- to ripple-scale bedforms indicates decreasing or waning energy conditions over time, typical of many channel deposits (cf. Miall, 1996, 2010). Aggradational current ripples also are incorporated, and are indicative of high sedimentation rates. Abundant organic debris, carbonaceous lenses, and wood fragments are disseminated throughout the facies, reflecting conditions of enhanced fluvial input (Leckie *et al.*, 1989). The rare organic-rich, sharp-based mudstones with syneresis cracks intercalated throughout the deposit are interpreted to reflect fluid mud
deposition, and attributed to tidal flow and subsequent flocculation of mud within the channel.

The ichnological character of Facies 4 indicates a stressed environment. This is inferred by the low bioturbation intensities (BI 0-1), the diminutive burrow sizes, and the low diversity. The trace fossils are sporadically distributed and largely confined to the fluid mud interbeds. The ichnogenera identified comprise only diminutive *Planolites* and *Skolithos*. Inferred environmental stresses include enhanced fluvial input, salinity variations (synaeresis cracks), high sedimentation rates (aggradational current ripples), and elevated water turbidity (decimetre-scale bedforms and internal scour horizons within the facies).

The base of Facies 5 is either a gradational or sharp contact. Facies 5 comprises a blocky, sideritized-cemented mudstone lacking sedimentary or biogenic structures. Abundant organic debris was observed in the outcrops, indicating that the deposits are most likely related to a nearby terrestrial source. Root traces present throughout the facies demonstrate that the sediment was subaerially exposed and that terrestrial plants were able to colonize the substrate. No trace fossils were observed in Facies 5. Facies 5 has been interpreted to represent overbank complexes deposited on the margins of a channel as it migrated laterally, or the abandonment of an active channel and its subsequent infill with fine-grained sediments.
Figure 4.4  Representative litholog of WC-6, showing the transition from FA1, erosionally overlain by the channelized complexes of FA2. FA2 comprises two distinct facies: Facies 4 (Organic-Rich Trough-Cross Bedded and Current Rippled Sandstone) and Facies 5 (Blocky, Sideritized Mudstone). FA 2 is gradationally overlain by coastal plain and coal deposits of FA4.
4.1.3. Facies Association 3: Shoreface facies association (FA3)

FA 3 is observed in the southeastern portion of the study area and only present in the Red Deer River Valley and in one cored interval. FA3 consists of two discrete facies which are used to define this particular facies association. The facies that comprise FA3 are Facies 6 (Trough Cross-Stratified Sandstone) and passes upward through a sharp contact into Facies 7 (Low Angle Planar-Parallel Laminated Sandstone). FA3 forms a coarsening upward succession and has a variable thickness, measured between 3.5 and 11 metres. The facies association is interpreted to represent the permanently subaqueous upper shoreface (Facies 6) environment, passing upward into the intertidal foreshore (Facies 7) deposits. An idealized succession has Facies 6 at the base, passing upward into Facies 7.

Discussion and Interpretation of FA3:

The basal contact of Facies 6 is erosional within the underlying unit and is expressed as either a sandstone-on-sandstone or sandstone-on-mudstone contact with the underlying deposits of Allomember E. This contact marks the top of Allomember E and the stratigraphic bottom of Allomember F in the southeastern portion of the study area. Facies 6 is composed of upper fine- to lower medium-grained sandstone and
forms a coarsening-upward succession. The sedimentary structures observed reflect environmental conditions prone to current-generated flow resulting in the formation of dune-scale bedforms (e.g., trough cross bedding and planar tabular cross bedding), current ripples, and low angle planar parallel laminations. Rare low angle undulatory laminations are interpreted to represent swaley cross stratification (SCS), and are generated by storm waves (Dott and Bourgeois, 1982). SCS is recognized as a more energetic expression of storm wave produced bedforms, which suggests shallower water depth where the sedimentary structure is more erosional (Dumas and Arnott, 2006). The SCS is very rare within Facies 6, and observed near the base of the succession. The change in energy conditions from local wave-generated bedforms to current generated bedforms is interpreted to represent a shallowing of the facies. Evidence of fluvial input is manifested as carboneous debris and wood fragments. Carbonaceous detritus demarcates the foresets trough-cross stratification and, locally, mudstone interbeds (Figure 3.8). Paleocurrents taken from Facies 6 (Figure 3.9) indicate the trough-cross stratification is produced by breaking waves that run parallel to the inferred paleoshoreline (longshore drift). The direction of flow taken from paleocurrent measures shows a dominant trend towards the southeast.

The ichnological character of the deposit indicates fully marine conditions, with BI 0-4 and a trace fossil suite that is attributed to the Skolithos Ichnofacies. Trace fossils include very rare Ophiomorpha and Schaubcylindrichnus coronus, and rare Skolithos, Thalassinoides, Palaeophycus, Rosselia, Cylindrichnus, Teichichnus, and Rhizocorallium. Stresses imposed on the environment have been interpreted to be water turbidity (evidenced by current-generated structures), episodic deposition rates, and short-lived salinity variations (localized evidence for fluid mud deposition) from enhanced fluvial input near the deposit.

Facies 6 passes upward through a sharp contact, which is signified by a change in physical sedimentary structures and a marked increased bioturbation. This change in sedimentologic and ichnologic character demarcates the base of Facies 7. The deposits of Facies 7 reflect deposition in an environment where high-energy sheet flow conditions characterize the depositional setting. The primary sedimentary structures present in
Facies 8 are common low angle planar parallel laminations (see Figure. 3.10), very rare trough cross bedding, rare planar tabular cross bedding, and one occurrence of ambiguous low angle undulatory lamination (Figure. 3.10C). The sedimentary structures are produced by current generated flow, which is ascribed to sheet flow conditions. This is consistent with the interpretation of deposition in a foreshore environment, where breaking waves drive thin sheets of water up the foreshore producing wedge-shaped low angle planar parallel laminations.

The ichnological data supports and also strengthens the foreshore environment interpretation. Intense bioturbation (Bl 4-5) of *Macaronichnus s egregatus* marks the contact and lower 50 centimetres between Facies 6 (Upper Shoreface) and Facies 7 (Foreshore). This is often described as the “Toe-of-the-beach” assemblage and is indicative of foreshore settings (cf. Saunders et al., 1994; MacEachern et al., 1999; Pemberton et al., 2001).
Figure 4.5  Litholog from RDV-13, showing the different facies that comprise FA 3, as well as representative photos. The red dashed line in the bottom left picture shows the sand on sand contact that separates Allomember E from the overlying deposits of Allomember F. Note the distinct colour change between Allomember E and Allomember F. FA 3 passes upward into the terrestrial deposits that comprise FA 4.
4.1.4. Facies Association 4: Onshore and terrestrial facies association (FA4)

Facies association 4 (FA 4) comprises four facies. The facies that make up FA 4 are: Facies 8 (Trough Cross-Bedded Sandstones with Stacked Current Ripples), Facies 9 (Organic-Rich Rippled Sandstone), Facies 10 (Organic-Rich Sandy Mudstone) and Facies 11 (Coal). FA 4 has a variable thickness throughout the study area, ranging between decimetre-scale to a maximum thickness of 2.5 metres. The base of the succession locally displays a sharp or gradational contact with the underlying units. FA4 marks the most landward facies within the succession, and represent paralic and fully terrestrial environments. In the northwestern section of the study, Facies 11 (Coal) has been removed, however a sideritized horizon that is made up of wood fragments and carboneous debris are interpreted to be an equivalent stratigraphic surface. The sideritized horizon, along with coal deposits which make up Facies 11 mark the top of the Allomember F parasequence in the study area.

Discussion and Interpretation of FA4:

In two locations (RDV-12 and RDV-13) the top of the section facies association is marked by the presence of Facies 8. The deposits of Facies 7 pass upwards into Facies 8 through a sharp contact (Figure 3.10A). The description of the Facies 8 is non-unique to any particular depositional environment, however based on detailed sedimentology and ichnology, stratigraphic relationships, and geomorphological features, the deposits have been interpreted to represent aeolian deposits. The sediments of Facies 8 were deposited by current generated processes, which produced both the trough cross stratification and amalgamated current ripples which infill the troughs. Facies 8 is completely devoid of bioturbation. Stratigraphically, Facies 8 is higher in the succession and overlies Facies 7, which has been interpreted as foreshore deposits. The succession has been interpreted as being progradational in nature, and likely represents permanently subaerial sand dunes located on the beach. Geomorphologically, Facies 8 deposits are characterized as topographic highs and elongate mounds of sediment that trend approximately parallel to the interpreted paleoshoreline.
Facies 7 passes gradationally upward into Facies 9 at two locations and is present in one cored interval of FA4 (RDV-10, RDV-11, and ARC 20-79). Facies 9 is interpreted to reflect the deposition associated with backshore and delta plain environments. Facies 9 is comprised of poorly sorted sandstones with current ripples, oscillation ripples, combined flow ripples, abundant organic debris, wood fragments, and root traces. The current and combined flow ripples indicate a quasi-steady current flow with oscillatory processes operating in the environment. The abundant organic-debris and wood fragments suggest a nearby terrestrial source with plant material readily available to be incorporated into the deposits. Root traces are common throughout, indicating colonization of land plants into the substrate. There is local pedogenic modification of the substrate demonstrating subaerial exposure of the deposit. The physical sedimentology associated with Facies 9 suggests the deposit was exposed after deposition with possible wash over to produce current ripples and wave ripples in times of elevated sea level or high-energy events. Colonization of the sediment is evident through root traces and close to the terrestrial realm through the incorporation of wood and organics.

Facies 10 typically forms the base of FA4 in the northwestern portion of the study area and consists of an admixed sandy mudstone with abundant organic detritus disseminated throughout the deposit. Local oscillation ripples are present in sandier portions of the facies. Abundant root traces are present throughout the facies, and pedogenic modification indicating both subaerial exposure of the facies and subsequent formation of soils. No bioturbation was observed from this facies.

Facies 9 (Organic-Rich, Current Ripple Sandstone) and Facies 10 both pass upwards through a sharp contact with Facies 11. Facies 11 consists of bright, vitreous, and well cleated coal that is easily recognizable throughout the study area. Facies 11 Contains features that correspond to coals formed during regression, instead of transgressive coals. There is no clastic detritus present within Facies 11, along with no sulphur present. Tree stumps are sporadically distributed in large coal horizons. The *Teredolites* Ichnofacies is present and marks a marine flooding surface and the bounding discontinuity to signify the end of Allomember F and the start of Allomember G.
This flooding surface has marine traces identified as either *Teredolites* or *Bergaueria*. *Teredolites* is a boring, and *Bergaueria* is a sea anemone resting trace, both of which indicate marine incursion over top of the terrestrial derived coal deposits of Facies 11 (see Figure 3.13).

### 4.2. Element Complexes

#### 4.2.1. Introduction

Element complexes and their internal features are the products of depositional environments and formed under a given range of wave, tide and fluvial process conditions (Ainsworth et al., 2010). Correspondingly, as the depositional processes acting on a shoreline vary, the resulting element complexes likewise change. As outlined in Chapter 2, element complexes are most closely related to the facies associations scale of observation; however, different methods are used to describe and characterize them in order to meet the criteria of the WAVE Classification system. The purpose of the element complex designation is to semi-quantitatively describe the dominant, secondary, and tertiary depositional processes responsible for the facies association’s character and depositional architecture. Once properly analysed, these element complexes can be placed into element complex assemblages, an architectural unit composed of genetically related element complexes formed under similar combinations of processes (Ainsworth *et al.*, 2010; Ainsworth *et al.*, 2011; Vakarelov and Ainsworth, 2013). The dominant, secondary, and tertiary processes that make up the element complexes and element complex assemblages then can be used to predict internal heterogeneities, depositional architectures of reservoirs, and shoreline morphologies and configurations.

**Workflow - Bridging the Gap between Facies Analysis and Element Complexes**

Within Allomember F, the facies as well as facies associations were defined (see Chapter 2). When a transition from one facies association to another was recognized,
either in a vertical or lateral transition, a boundary was placed. This boundary also
defined the element complexes within the study area. Element Complexes correspond to
facies associations with the inter-related depositional process used to define the
resulting geobody (Ainsworth et al., 2010; Vakarelov and Ainsworth, 2013). Each
element complex was then scrutinized in terms of the formative depositional processes
that were responsible for the generation of the sedimentary structures and influenced
animal responses that led to the biogenic structures observed. The element complex is
correspondingly ascribed a process classification set forth by the WAVE Classification
(see Chapter 2).

Once the depositional processes have been ascribed to the element complexes,
a zonation is then assigned to the element complex. The zonation is the relative
interpreted position of the element complex in a depositional environment (Ainsworth et
al., 2010; Ainsworth et al., 2012). There are three basic zones observed within
Allomember F: onshore, shoreline to offshore, and channelized.

The next step in the evaluative process was to assign an element complex
architecture to the element complexes defined within the study area. This was
accomplished by using the element complex chart of the WAVE classification scheme.
Once the formative processes and the zonation are assigned, the possible architectural
categories are derived from a chart call the WAVE Knowledgebase. Once the
architecture categories have been assigned to the element complexes, the appropriate
element complex assemblages (ECA) can be defined. ECAs are assemblages of ECs
that are genetically linked and / or a series of ECs that have the same process
interactions (Ainsworth et al., 2010).

The WAVE Classification provides a more structured terminology that must be
followed when classifying the different depositional deposits. An example of this
structured approach is exemplified when looking at deltaic deposits. Deltaic
sedimentation has been divided into updrift lobes, downdrift lobes, and mouthbar
complexes, all of which are defined on the basis of their differing processes controlling
deposition. To meet these criteria, many deposits that could otherwise be “lumped together” in terms of facies associations, necessitate being subdivided into different constituent parts of a coastline.

The element complex designation for Facies Association 1 can be subdivided into two discrete element complexes. Based on the WAVE Classification scheme, two element complexes are required to accurately categorize the geobody of Facies Association 1, namely: Element Complex 1 – $\text{Fw}(t)$ Lobe Complex and Element Complex 2 – $\text{Wf}(t)$ Mouthbar Complex.

### 4.2.2. **Element Complex 1- $\text{Fw}(t)$-Lobe Complex**

Element Complex 1 comprises Facies 1a (Organic-Rich Mudstone), Facies 1b (Lenticular Bedded Mudstone), and Facies 2 (Micro-HCS and Oscillation Rippled Sandstone). Fluvial and wave processes constitute the dominant depositional processes that have been identified. No diagnostic features indicating tidal processes were observed. Enhanced fluvial conditions are interpreted through multiple mudstone beds of inferred fluid mud origin, presence of soft-sediment deformation, abundant organic debris, synaeresis cracks, starved current ripples, and a stressed (low abundance and low diversity) ichnological suite, attributed to salinity fluctuations (cf. Beynon et al., 1988; Pemberton and Wightman, 1992; Buatois et al., 2005; MacEachern and Gingras, 2008). Wave-generated features include: oscillatory ripples and centimetre- to decimetre-scale, truncation bound low-angle undulatory parallel laminations. Processes that can be attributed to tidal deposition could be the possible remobilization of fluid muds and organic debris as bedload, as well as localized rhythmic laminae observed within the deposit (see Chapter 3). There are no diagnostic sedimentary structures (tidal rhythmites, mud couplets, or triplets) which reflect deposition influenced by tides, however the uncertainty remains and must be accounted for in potential environmental models.
Summary Characterization:

Process Dominance: $F_w(t)$

Zonation: Shoreline to Offshore

Element Complex Classification: $F_w(t)$ - Lobe

Element Complex Assemblage: $W_f t$ – Assemblage
Figure 4.6  A representative litholog from ARC 19-79 (01-24-28-19w4). The diagram shows the individual facies, formative processes assigned, and the interpreted element complexes. EC 1 is characterized as follows: dominant process - fluvial (70%), secondary process - wave (29%), and tertiary process - tide (1%). The resultant combination is a Fw(t)-Lobe Complex. Passing upward from EC 1, EC 2 is encountered and contains dominantly wave-generated structures with subordinate fluvial influence resulting in a Wf(t) designation.
WAVE Classification Scheme

**BOLD UPPER CASE** = Dominant process
**bold lower case** = Secondary process
**italic lower case** = Tertiary process

- Combined average of all EC 1 outcrop sections
- Potential range in variation

- **F, f, f** = Fluvial
- **W, w, w** = Wave
- **T, t, t** = Tidal
Figure 4.7  WAVE Process Classification plot for Element Complex 1. The white circle labeled EC 1 represents the combined average of depositional processes encountered in outcrop and cored sections of Element Complex 1. The red and yellow dashed lines are used to represent the range in variability in depositional processes between outcrop sections. Interpretations of dominant depositional processes based on sedimentary structures range from nearly completely fluvial generated to almost 70% of the element complex being attributed to wave generated. EC 1 is classified as Fw(t) – Lobe Complex, with tidal influence being an uncertainty within the system. Figure modified from Ainsworth et al., (2010).
4.2.3. *Element Complex 2 – Wf(t) - Mouthbar Complex*

The second element complex to be identified from Facies Association 1 consists of a single facies: Facies 3 (Trough Cross-Stratified and Current-, Combined Flow-, and Oscillation-Rippled Sandstone). The dominant depositional processes are wave and fluvial, with the degree of tidal influence being uncertain. The sedimentary structures in this element complex ascribed to wave processes are: trough-cross bedding (wave-forced currents), oscillatory ripples, and combined flow ripples. Fluvial processes are interpreted from abundant organic debris, fluid mud deposition, current ripples, local trough-cross stratification, and aggradational current ripples (high sedimentation rates are inferred nearby fluvial sources). The ichnological character of the deposit also indicates stressful conditions, likely the result of elevated water turbidity, salinity fluctuations, and/or high sedimentation rates.

**Summary Characterization:**

**Process Dominance:** $Wf(t)$

**Zonation:** Shoreline to Offshore

**Element Complex Classification:** $Wf(t)$ - Mouthbar

**Element Complex Assemblage:** $Wft$ – Assemblage
Figure 4.8  WAVE Process Classification plot for Element Complex 2. The white circle, labeled EC 2, represents the combined average of depositional processes encountered in outcrop and cored sections of Element Complex 2. The red and yellow dashed lines are used to represent the range in variability in depositional processes between the different outcrop sections. The dominant depositional process indicated is wave, with some localized expressions showing a marked increase in fluvial-generated features. The resulting combination of processes leads to a WAVE Classification of Wf(t) – Mouthbar Complex, with the degree of tidal influence being uncertain. Figure modified from Ainsworth et al., (2010).
4.2.4. **Element Complex 3 - Ft Channelized Complex**

Element Complex 3 is made up of 2 discrete facies: Facies 4 (Organic-Rich, Trough-Cross-Bedded and Current Rippled Sandstone) and Facies 5 (Blocky, Siderite-Cemented Mudstone). The dominant depositional process affecting sedimentation is interpreted to be fluvial, with inferred tidal influence being subordinate. The dominance of current-generated sedimentary structures and abundant carboneous debris are assigned to fluvial processes. Syneresis cracks and deposition of fluid mud within the channel are interpreted to represent some degree of tidal input into the system.

**Summary Characterization:**

**Process Dominance:** Ft

**Zonation:** Channelized

**Element Complex Classification:** Ft - Channelized

**Element Complex Assemblage:** Wft - Assemblage
Figure 4.9  Representative litholog from WC-5. The diagram shows the breakdown of individual facies, formative processes, and element complexes. EC 3 is broken down as follows: dominant process - fluvial (90%) and secondary process - tide (10%). The resultant combination is a Ft – Channelized Complex.
WAVE Classification Scheme

(A) F

Fw t
F t
Ftw

W f t
W f
W tw

T fw
T f
T tw

W
W t
W t

T
T w
T w

BOLD UPPER CASE = Dominant process
bold lower case = Secondary process
italic lower case = Tertiary process

ECS = Combined average of all EC 3 outcrop sections

Potential range in variation

F, f, f = Fluvial
W, w, w = Wave
T, t, t = Tidal
Figure 4.10   WAVE Process Classification plot for Element Complex 3. The white circle, marked EC 3, represents the combined average of depositional processes of EC 3. The yellow dashed line is used to represent the range of variability in depositional processes. Dominant depositional processes are fluvial, with some inferred evidence of tidal influx. The resulting combination of processes leads to a WAVE Classification of Ft – Channelized Complex. Figure modified from Ainsworth et al., (2010).
4.2.5. **Element Complex 4 - Wtf Beach Complex**

Element Complex 4 includes two facies: Facies 6 (Trough Cross-Bedded Sandstones) and Facies 7 (Low-Angle Planar Parallel-Laminated Sandstone). Dominant depositional processes are waves, inferred tides, and subordinate fluvial input. Sedimentary structures in this element complex that are interpreted to be produced by waves are: trough cross-stratification and planar tabular cross-stratification (wave-forced currents), low-angle planar parallel lamination (swash-zone cross-stratification), and low-angle undulatory lamination (possible HCS). Evidence for tides is inferred by the relatively thick foreshore deposits of Facies 7. Fluvial influence is reflected by the presence of rare beds of fluid mud origin and abundant terrestrial organic debris.

**Summary Characterization:**

**Process Dominance:** Wtf

**Zonation:** Shoreline to Offshore

**Element Complex Classification:** Wtf – Beach, Shoreface

**Element Complex Assemblage:** Wtf - Assemblage
Figure 4.11  Representative litholog from RDV-11. The diagram shows the breakdown of individual facies, formative processes, and element complexes. EC 4 is expressed at this location as dominantly wave generated, with localized carbonaceous lenses and mud drapes, interpreted to be fluvially generated. The reason for the segregation of wave and tide processes in the upper section of EC 4 is because while waves produced the sedimentary structures, significant tidal ranges were required to generate a thick deposit (4m) of foreshore sandstone. This is viewed as evidence for tidal activity within the system, although how important of a factor it was in the system is not clear. EC 4 is classified as a Wtf – Beach Complex, in correspondence with the WAVE Classification.
WAVE Classification Scheme

(A) BOLD UPPER CASE = Dominant process
   bold lower case = Secondary process
   italic lower case = Tertiary process
   ECA = Combined average of all EC 4 outcrop sections
   Potential range in variation
   F, f, F = Fluvial
   W, w, W = Wave
   T, t, T = Tidal

(B)
Figure 4.12  WAVE Classification plots for EC 4. The white circle, marked EC 4, represents the combined average of depositional processes of EC 4. The red dashed line is used to represent the range in variability in depositional processes between the different outcrop sections. Dominant depositional processes are wave, with subordinate fluvial and tidal influence. EC 4 has been classified as a Wtf – Beach Complex. Figure modified from Ainsworth et al., (2010).
4.2.6. **Element Complexes 5, 6, and 7**

Element Complex 5 consists of Facies 8 (Trough Cross-Bedded Sandstones with Amalgamated Current Ripples) and Facies 9 (Organic-Rich, Current Rippled Sandstone). Element Complex 6 comprises a single facies – Facies 10 (Organic-Rich, Admixed Sandy Mudstone). Element Complex 7 is also characterized by a single facies – Facies 11 (Coal). All facies mentioned are components of the depositional environment that do not satisfy the requirements to be characterized using a process-based classification scheme such as the WAVE Classification.

**Summary Characterization:**

**Process Dominance:** N/A

**Zonation:** Onshore

**Element Complex Classification:** N/A

**Element Complex Assemblage:** N/A

4.3. **Element Complex Assemblage for Classifying Shoreline Morphology of Allomember F**

As previously mentioned, the element complex assemblage is the combination of the genetically related element complexes (Ainsworth *et al.*, 2010). To classify the element complex assemblage making up Allomember F, the dominant depositional processes affecting the entire coastline were identified through the sedimentological and ichnological features of the different element complexes.
Wave processes were overwhelming dominant, making up the majority of the measured sections across the study area, and constituting the main depositional process in two element complexes (EC 2 - \textbf{Wf}(t) and EC 4 - \textbf{Wf}t). In EC 1, fluvial processes are dominant; however, this could be the result of a preservational bias for fluvial and tidal features within the mudstone-prone deposits. EC 3 is a fluvial dominated channel deposit, with localized indications of tidal activity. The presence of tides acting within the depositional setting is evident (e.g., large foreshore deposits, evidence of salinity fluctuations within fluvial channels, potential redistribution of fluid muds and terrestrial organics), therefore the models used to interpret the element complex assemblage must accommodate tidal influences. The amount of tidal influence within the deposit is uncertain. Consequently, the shoreline must be classified as either a \textbf{Wf}t or \textbf{Wft} element complex assemblage (Figure 4.12). The switching of the secondary and tertiary processes is a result of the inability to accurately quantify the tidal processes, but provides multiple working hypotheses for assessing possible depositional relationships and depositional architectures in the allomember.
Figure 4.13 The possible element complex assemblages configurations for coastline morphologies met by the process classifications of the different ECs of Allomember F. Allomember F can be represented by either of these two schematic diagrams which have a red star and a red dashed boarded, namely Wtf or Wft. Although the figures are not drawn to scale, they provide a potential plan-view morphology and configuration of the deposits that potentially could be encountered within the subsurface. Figure is modified from Ainsworth et al., (2010).
4.4. Stratigraphic Framework

4.4.1. Introduction

For the better part of 40 years, workers have been trying to apply a working stratigraphic framework in order to better characterize and understand the distribution of the deposits making up the lower Horseshoe Canyon Formation (Shepheard and Hills, 1970; Rahmani, 1983; Ainsworth 1991). Shepheard and Hills (1970) proposed the first stratigraphic breakdown for the lower Horseshoe Canyon Formation, dividing the section into six stratigraphic units (BP, E1-E5). Rahmani (1983) revised this stratigraphy, placing five stratigraphic breaks throughout the units, numbered 1-5. Finally, Ainsworth (1991) applied an allostratigraphic framework to the lower Horseshoe Canyon Formation, and identified seven allostratigraphic breaks, each marked by laterally continuous coals separating allostratigraphic units A-G (see Figure 1.8 for a correlation between the different stratigraphic studies, modified from Ainsworth, 1991). This study uses the informal allostratigraphic framework that was put forth by Ainsworth (1991), and utilizes the laterally continuous coal seams as the bounding discontinuities or equivalent surfaces (flooding surfaces) where these coals are not present.

Bounding Surfaces of Allomember F

In the northwestern portion of the study area, the basal contact of Allomember F is expressed as a mudstone-on-mudstone contact in four measured sections (RDV-OB, RDV-I, RDV-H, and RDV-C). The contacts are readily identified on the basis of discrete sedimentological and ichnological characteristics of the over- and underlying mudstones coupled with a distinct colour change. Throughout most of the study area, the contact is expressed as a prodeltaic mudstone (see Facies 1a) that overlies sandstones making up the deposits of Allomember E (Ainsworth et al., 2010). In the southeastern sections (RDV-8, RDV-9, RDV-10, RDV-11, RDV-12, and RDV-13), the basal contact is erosional, wherein the sandstones of Allomember F have eroded down into the underlying mudstones, sandstones or the Coal 1b marker bed of Allomember E.
The top of Allomember F is represented by Coal 2 in the southeastern sections of the study area. Northwest of RDV-A and WC-1, Coal 2 has been removed and is no longer present in any of the measured sections. An equivalent surface has been identified as a centimetre- to decimetre-scale, organic-rich sideritized horizon that is continuous across the northwestern portion of the study area. Between RDV-12 and RDV-13, the Coal 2 marker bed is typified by a patchy distribution. However, beyond RDV-13, Coal 2 is continuous and persists for another 18 kilometres to the southeast of the study area (Ainsworth et al., 2010).

4.4.2. Stratigraphic Cross-Sections

Cross-Section RDV-OB – RDV-13

Cross section RDV-OB – RDV-13 outcrops along Red Deer River Valley outcrop belt, and is oriented in the NW-SE direction. The cross section is approximately 13.5 kilometres in length and oriented in an oblique-to-depositional strike direction of the inferred paleoshoreline. Cross-section RDV-OB – RDV-13 is constructed using outcrop measured sections that were collected during the 2012 field season. The section is produced from 23 measured sections, and the spacing between sections varies from 500 metres to 1 kilometre. This cross-section transects all facies associations and element complexes encountered in the study area.

In the northwest portion of the cross section, FA 1 passes upward through a gradational contact into FA 4. The base of FA 1 is expressed as a mudstone-on-mudstone contact or mudstone-on-sandstone contact. The mouthbar complexes made up of Facies 3 (Trough-Cross Bedded, Current, Combined-Flow, and Oscillation Rippled Sandstone) pass along strike into the channelized complexes reflected by FA 2 at RDV-B, RDV-3, and RDV 5. Both the mouthbar complexes and channelized complexes are typically observed as amalgamated sand bodies, with subtle sedimentological and ichnological differences. The deposits that make up FA 1 gradually thin towards the southeast of the section. Between RDV-6 and RDV-7, there is a lateral facies transition,
such that FA 1 underlies the shoreface complexes made up of FA 3. FA 3 has an erosional contact, and is expressed either as a sand-on-mud, a sand-on-sand, or a sand-on-coal contact. FA 3 persists well to the southeast, beyond the study area. FA 4 is prevalent across the entire cross section. All facies associations in the study area pass upwards into the terrestrial deposits of FA 4.

4.4.3. Cross-Section WC-1 to WC-7

Cross-section WC-1 – WC-7 (NE-SW) is oriented approximately in the depositional dip direction, and roughly 3.5 kilometres in length. This cross-section is constructed from 7 outcrop sections roughly 5 metres thick. The cross-section yields the best expressions of the channelized complexes, which are dominantly constrained to WC-5, WC-6, and WC-7. The measured section for WC-7 is taken from a coulee outcrop that is positioned 0.45km behind the section.

The basal contact of Allomember F at cross-section WC-1 – WC-7 shows a sharp contact, with the prodeltaic mudstones of Facies 1a (Organic-Rich Mudstones) overlying the deposits of Allomember E. The top of the succession is represented by the laterally continuous Coal 2 unit; however, at WC-1 Coal 2 is absent and an organic-rich sideritized horizon is employed as the equivalent horizon. The cross-section intersects three of the facies associations encountered in the study area – FA 1, FA 2, and FA 4. The cross-section shows a coarsening-upward succession seen throughout FA 1, with amalgamated channelized complexes seen in the mouthbar complex of FA 2. The channelized complexes trend roughly 30° to the northeast, which is interpreted to be perpendicular to the paleoshoreline. Both FA 1 and FA 2 pass upward into the terrestrial deposits of FA 4.

4.4.4. Fence Diagram showing 3D Distributions

The fence diagrams are constructed using the RDV-OB – RDV-13 and WC-1 – WC-7 cross-sections, with two additional cored intervals that intersect Allomember F.
The fence diagrams show the 3D distributions of the facies, facies associations, and element complexes, as well as the depositional relationships between the different environments of study area.
Figure 4.14  Schematic cross-section from RDV-OB to RDV-13
Figure 4.15  Schematic cross-section from WC-1 to WC-2
Figure 4.15  Schematic fence diagram showing the two different cross-sections. It is constructed from data collected from the outcrop belt as well as lithologs constructed from two cored wells (courtesy of J.A. MacEachern). The Red Deer River (RDV) section runs northwest to southeast, as is approximately 13.5 kilometres in length. The Willow Creek (WC) section intersects the RDV sections at right angles and is 3.5 kilometres in length. This particular figure illustrates the facies and facies relationships observed within the study area.
Figure 4.17  Schematic fence diagram built using the same data as Fig. 4.17. This particular figure illustrates the element complex (WAVE Classification equivalent to facies associations) relationships observed in the study area.
5. Discussion and Conclusion

5.1. Summary and Interpretation

Based on this study, which integrates physical sedimentological and ichnological characteristics, Allomember F of the lower Horseshoe Canyon Formation can be subdivided into 11 depositional facies. These sedimentary facies can be grouped into 4 recurring and mappable facies associations, each representing a distinct depositional setting. The depositional environments are interpreted to record a variety of marginal-marine, paralic, and coastal environments that include: wave-dominated, fluvial-influenced, tide-affected deltaic deposits (FA1); tidal-fluvial channels (FA2); wave-dominated, tide-influenced, fluvial-affected shoreface (FA3); and delta plain/terrestrial deposits (FA4). The Allomember F succession represents a single progradational parasequence within the Horseshoe Canyon Formation.

The deposits are characterized in correspondence with the WAVE Classification scheme (Ainsworth et al., 2011), allowing for the semi-quantification of subtle differences in fluvial, wave, and tidal processes reflected by depositional features in each mixed-influence element complex. Using this process-based approach, FA1 is subdivided and categorized into two element complexes, namely a $F_w (t)$ lobe complex and a $W_f (t)$ mouthbar complex. FA2 is designated as a $F_t$ channelized complex. FA3 is categorized as a $W_t f$ beach complex. FA4 can be subdivided into multiple element complexes representing terrestrial deposits. No process-based interpretation was assigned to the terrestrial deposits. Furthermore it was possible to characterize the paleoshoreline as a $W_t f$ or $W_f t$ Element Complex Assemblage, and using the WAVE Knowledgebase, produce models showing the lateral variability that potentially might be encountered within the subsurface (See Chapter 4).
5.2. Depositional Model: Lateral Facies Transitions

A major lateral facies transition occurs between sections RDV-6 and RDV-7. Due to the condition of the outcrop belt in this area, the transition zone was not directly observed. However, a reasonable working hypothesis is that an asymmetric delta could permit this abrupt lateral relationship (Bhattacharya and Giosan, 2003). This model would consist of the downdrift lobe, the dominant facies association in the northwestern portion of the study area, and the updrift lobe, which characterizes deposition in the southwest.

Paleocurrents from the study indicate that the direction of flow (interpreted to be from produced from longshore drift; cf. chapter 4) was to the southeast (see Figure. 5.4). This is consistent with Slingerland’s model of southerly oriented flow on the western coast of the Western Interior Seaway (Slingerland et al., 1996, Slingerland and Keen, 1999). It is suggested that the outcrop belt intersects the downdrift lobe-updrift lobe relationship through autogenic lobe switching an establishment of a new delta to the southwest (See Figure 5.1).

Rahmani (1981; 1983) observed what he interpreted as “tidal-inlet complexes” occurring approximately 400 metres southeast of RDV-13. This study ended at RDV-13, therefore the channels described by Rahmani (1981; 1983) were not directly observed in this study. The description of the channelized systems is highly generalized, and could be applied to numerous channel settings. Given the facies associations identified through this study, we would predict that these channelized complexes correspond to distributaries within a deltaic complex. The abundance of coal and organic material identified by the previous researchers suggests progressive development of terrestrial conditions, and could be considered as strong evidence for a potential deltaic distributary channel system operating south of the outcrop belt.
Figure 5.1  The asymmetric delta model (modified by Hansen, 2007 after Bhattacharya and Giosan, 2003). In their model, marked discharge from the fluvial system leads to a strong groyne effect generated at the distributary mouth, tending to block sediment being transported alongshore. As a result, greater proportions of fine-grained, heterolithic deposits are associated with downdrift and prodelta areas, whereas thicker, more mature sands are deposited in updrift areas.
Figure 5.2  A schematic diagram illustrating delta asymmetry with autogenic lobe switching to explain the facies relationship seen in Allomember F of the Horseshoe Canyon Formation. Locations outside of the red outcrop and core spots are based off of the facies models generated for mixed river and wave influenced deltaic complexes, as described by Bhattacharya and Giosan (2003). A) Is the original position of the delta as it prograded into the basin. WtF Beach Element Complex represents clean sandstones, most closely associated with strandplain deposits. The Fw(t) is identified as the downdrift more heterolithic deposits, which typically show more fluvial influence. B) Shows a lobe switch and a re-establishment of the delta to the south. C) Illustrates how the shoreline can be categorized using WAVE Classification nomenclature.
Unfortunately, there is limited access to the outcrops on the opposite valley wall, due to vegetation cover and limited exposure; this is an area of potential future study. Gamma ray logs produced from this study may prove useful when comparing downdrift vs. updrift lobe relations within Allomember F, and potentially extrapolate the findings to low accommodation settings. Preliminary work with well logs in the area showed a more heterolithic character.

5.3. Paleoshoreline Orientation

Historically, the paleoshoreline of the lower Horseshoe Canyon Formation has been interpreted to trend in a northeast/southwest direction (Williams and Stelck, 1975) (Figure 1.1). In the study area, however, Allomember F is interpreted to represent shoreline progradation to the northwest, with a shoreline that is oriented in a northwest/southeast direction. This interpretation of the shoreline orientation is nearly 90° to the published interpretations of the paleogeography. Data collected indicates that the paleoshoreline was oriented in a northwest/southeast direction is accurate at least during the deposition of Allomember F. If we infer that the fluvial channels observed entered the basin perpendicular or slightly oblique to perpendicular to the shoreline, the shoreline trend would have had an azimuth of approximately 125/305° (see Figure 3.7 for the paleocurrent measurements taken from Facies 4). The paleocurrent current data from the channels can be corroborated further with the addition of paleocurrent data from the shoreface and mouthbar successions. These latter deposits are interpreted as longshore drift deposits. Longshore paleocurrents would be nearly parallel with the shoreline. The averages of those two facies show a dominant trend of approximately 130/310° (Figure 5.04). The data suggests that in the study area, the Allomember F paleoshoreline lay approximately 90° to the historically interpreted shoreline orientation. This suggests that the RDV sections do not reflect down depositional dip relationships during Allomember F, but are approximately oblique to strike. By contrast, the WC sections represent an arrangement closer to depositional dip during the deposition Allomember F.
The interpretation of the paleoshoreline has a consistent pattern with recent observations from Ainsworth et al., 2014 (in press). Their interpretation is that Allomembers A and B had an approximate SW – NE orientation. The paleoshoreline rotated counter clockwise to an N – S orientation during the deposition of Allomembers C, D, and E. Finally, a continued counter clockwise rotation resulted in the orientation of Allomember F described within this study (NW – SE).

It appears that the previous interpretation of Allomember F of the Horseshoe Canyon Formation (barrier island complex and barred estuaries) may have been influenced by an erroneous paleoshoreline interpretation. Considering the historical interpretation of the paleocoastline trend, the heterolithic deposits of the downdrift $F_w(t)$ mouthbar were likely misinterpreted as lagoon deposits. Correspondingly the shoreface deposits to the southeast would have been misconstrued as a barrier island rather than the updrift delta lobe of a $W_f$ beach complex. Based on a presupposition of a northeast to southwest oriented shoreline, the interpretations of barrier islands (Saunders, 1989; Ainsworth, 1991) and barred estuaries (Rahmani, 1983; Rahmani, 1988; Rahmani, 1989) becomes a relevant interpretation for Allomember F.
Figure 5.3  Paleocurrents taken from the mouthbar complexes (Facies 3) and the shoreface deposits (Facies 6). The paleocurrents were the added together to show a general orientation for the paleoshoreline. Note the dominant trend towards the southeast. Paleocurrent measures were only obtained from cross-stratified beds greater than 10 centimetres in thickness.
5.4. Alternative Process Dominance and Interpretation

Dipmeter data is one of the most important datasets acquired in this study. Process dominance can strongly influence the direction of paleocurrent orientation (fluvial and tidal systems will have sandbodies oriented perpendicular to the shoreline and wave dominated sandbodies will be oriented parallel to the shoreline, See Figure 2.1). Based off this study, the interpreted $F_t$ Channelized complex and $W_f(t)$ Mouthbar complex are genetically related, and we see a 90 degree change in orientation suggesting the fluvial systems are perpendicular to the shoreline and the mouthbars run parallel. If the $F_t$ Channelized complex and $W_f(t)$ Mouthbar complex are genetically decoupled, then different interpretations can be made. The mouthbar could be interpreted to be a $F_w(t)$ Mouthbar complex, and this could have profound changes on shoreline orientation, architecture and heterogeneity.

If the mouthbars are in fact fluvially dominated, then the paleoshoreline orientations may be interpreted to be in SW-NE direction, as described by Williams and Stelck (1975, approximately parallel to the $W_t(t)$ Mouthbar complex orientations). Architecture of the potential reservoirs can also be interpreted differently. Fluvial-dominated systems commonly show digitate morphology, unlike the shore-parallel morphology of a wave-dominated system, as illustrated in Figure 2.1. Based off this study, heterogeneity of fluvial systems is typically greater than wave generated systems. This is due to the large amount of fluid mud depositions and large accumulations of organic detritus. If this scenario is correct, then the Element Complex Assemblage (ECA) would be $F_w(t)$ shoreline and have a different lateral facies transitions then what is described in this thesis.

Paleoenvironmental interpretations would be different then what has been previously described. The mouthbars could be interpreted as the $F_w(t)$ mouthbar complex of a bayhead delta, prograding in a southeasterly oriented direction, perpendicular to the shoreline (shoreline orientation would be SW-NE). The $W_t$ Beach complex could be interpreted as a barrier island complex.
5.5. Heterogeneity

One of the aspects of the WAVE Classification is to assist in the identification and quantification of intra-reservoir heterogeneities in a single flow unit (effectively a parasequence). Allomember F of the Horseshoe Canyon Formation serves as an ideal case example. Within Allomember F, two element complexes were identified that are fluvial dominated (EC1 and EC3), and one with enhanced fluvial influence (EC2). The fluvially dominated deposits are the most heterogeneous successions observed, and are typically compartmentalized by mudstone interbeds of probable fluid mud origin as well as abundant carboneous debris. By contrast, wave-dominated element complexes (EC2 and EC4) display the least amount of heterogeneity. EC2 is identified as being fluvially influenced, and this corresponds to localized internal heterogeneities such as mudstone interbeds of probable fluid mud origin and organic detritus demarcating the foresets of primary sedimentary structures. EC4 is interpreted to be wave dominated and is characterized by relatively homogeneous sandstones; such units constitute ideal reservoirs. At the base of EC4 there is an increase in inferred fluvial influence, corresponding to potential compartmentalization of the sands. This is typically the result of organic debris and localized fluid mud drapes. The more mixed influence the succession, specifically those prone to fluvial and tidal influence, the more heterogeneity one can expect.

5.6. Conclusions

1. Based on the integration of physical sedimentological and ichnological characteristics, Allomember F of the lower Horseshoe Canyon Formation can be subdivided into 11 depositional facies. These sedimentary facies are grouped into 4 recurring and mappable facies associations, each representing a distinct depositional setting. Depositional environments are interpreted to record a variety of marginal-marine, paralic, and coastal environments that include: Wave-dominated, river-influenced, tide-affected lobes or deltas (FA1); fluvial-dominated tide-influenced
channels (FA2); wave-dominated, tide-influenced, fluvial-affected shoreface (FA3); and onshore, delta plain/coastal plain deposits (FA4).

2. FA1, FA2, FA3, and FA4 can be characterized using the WAVE classification scheme, which facilitates the semi-quantification of subtle differences in fluvial, wave, and tidal influence on the facies within each element complex. Using this process-based approach, FA1 is subdivided into two element complexes, namely a $F_{w(t)}$ lobe complex, and a $W_{f(t)}$ mouthbar complex. FA2 is designated as a $F_{t}$ channelized complex. FA3 is categorized as a $W_{t(f)}$ beach complex. FA4 is subdivided into multiple element complexes representing onshore terrestrial deposits. No process-based interpretation was assigned to the terrestrial deposits. Furthermore, the paleoshoreline of Allomember F is designated as a $W_{t(f)}$ or $W_{f(t)}$ Element Complex Assemblage and utilizing the WAVE Knowledgebase, models showing the potential lateral variability that might be encountered within the subsurface.

3. Paleoshoreline orientations in the study area during the deposition of Allomember F are interpreted to be trending northwest/southeast in direction. This is 90° to previously held interpretations of the paleoshoreline orientation for the lower Horseshoe Canyon Formation. An extensive study should be carried out in order to produce more accurate maps of Allomember F paleogeography, as this study covers a relatively small area.

4. Previous models (most notably the barrier island models of Saunders, 1989) used to interpret the depositional setting of the lower Horseshoe Canyon Formation are not applicable when evaluating the depositional history of Allomember F. While these models may work for other parasequences preserved of the Horseshoe Canyon, based on the data from this study, the asymmetric delta model of Bhattacharya and Giosan (2003) could be used to explain the observed facies distributions.

5. The WAVE Classification system for categorizing sedimentary environments is a useful tool when working with the rock record. By assigning depositional processes
to primary structures within a deposit, one can start to predict along-strike depositional features. This is very important when attempting to characterize reservoirs and predict the type(s) and distribution of potential heterogeneities that might be encountered within the depositional successions.

6. Heterogeneities within the deposits could act as baffles and barriers when producing from subsurface reservoirs. Typically, the more depositional processes that act on a deposit, the more complex and heterogeneous the succession is likely to become. That being said, Allomember F deposits that exhibit fluvial domination or fluvial influence are typically characterized by the most heterogeneous deposits (see EC1 and EC3). These heterogeneities commonly include continuous and discontinuous mudstone interbeds of fluid mud origin and dense accumulations of carbonaceous debris. The “clean” deposits of EC2 and EC4 are wave-dominated and are considerably less heterogeneous than the other element complexes. However, EC2 shows some fluvial influence and contains fluid mud interbeds and carbonaceous debris, which could serve as potential baffles and barriers. EC4 is characterized as wave-dominated and only fluvial affected, and is typified by the lowest degree of heterogeneity.
References


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## Appendix A

### Supplementary Log Data

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Magnetic declination is approximately 14 degrees East.
Measured Sections

Physical Structures

- Planar / low-angle cross-stratification
- Scoured hummocky cross-stratification
- Planar tabular cross-stratification
- Planar tangential cross-stratification
- Trough cross-stratification
- Herringbone cross-stratification
- Inclined heterolithic stratification
- Climbing ripple
- Unidirectional ripple
- Wave ripple
- Combined-flow ripple
- Rhythmic stratification
- Lenticular bedding
- Carbonaceous drape / shale drape
- Double carbonaceous / shale drape
- Structureless
- Local scour
- Convolute bedding
- Carbonaceous lens
- Tree stump/log
- Synaesesis cracks
- Soft-sediment deformation

Trace Fossils

- arenicolites
- asterosoma
- chondrites
- cosmoraph
- cubichnium
- cylindrichnus
- diplacriton
- fugichnium
- helminthopsis
- locketa
- palaeophycus
- planolites
- phycosiphon
- rhizocarallium
- Rosselia
- Schaeb cylindrichnus
- Scolicia
- Skolithos
- Teichichnus
- Thalassinoides
- Zoophycos
- Ophiomorpha
- Psilonichnus
- Macaronichnus
- Root traces

Bioturbation Index

- R1
- R2
- R3
- R4
- R5

Legend of symbols used in the facies association lithologs.
WC-3