INTEGRATED ICHNOLOGY, SEDIMENTOLOGY AND STRATIGRAPHY OF THE LOWER CRETACEOUS GRAND RAPIDS FORMATION AND EQUIVALENTS, EAST-CENTRAL ALBERTA

by

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Bachelors of Science in Geology, Weber State University 2006

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

In the
Department of Earth Sciences

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Degree: Master of Science

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**Abstract**

Uppermost parasequences of the Grand Rapids Formation and Upper Mannville Group record progradation of open-coast wave/storm-dominated deltas in the west, passing eastward into brackish-water bay-head deltas. Distributary channel deposits occur in close proximity to both settings. Stratigraphic cross-sections indicate that autocyclic delta lobe switching occurred in both delta types.

Open-coast deltas contain low-diversity trace fossil suites consisting of slightly more robust ichnogenera, most of whom reflect opportunistic colonization of storm beds. Ichnogenera typical of more marine conditions are sporadically distributed, indicating that environments were not as persistently salinity stressed as in the east.

Bay-head deltas in brackish-water settings display the lowest trace fossil diversities and pronounced size reductions. Facies lack ichnogenera associated with more marine conditions. Brackish-bay deposits are the most intensely burrowed, attesting to low deposition rates. Ichnological diversities are slightly greater than in bay-head delta deposits, reflecting less marked salinity fluctuations in persistently brackish-water conditions.

**Keywords:** Grand Rapids Formation; Bay-Head Delta; Brackish-Water Bay; Distributary Channel

**Subject Terms:** Ichnology, Sedimentology, Stratigraphy, Geology
It doesn’t have to bioturbated to be beautiful.

-Dr Murray K. Gingras
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CHAPTER 1: INTRODUCTION

1.1 Introduction

The Lower Albian Grand Rapids Formation is largely located in northeastern Alberta, and comprises the upper part of the largely regressive Upper Mannville Group (Jackson, 1984). The succession consists of multiple stacked, sanding-upward parasequences that accumulated along the southeastern margin of the Boreal Seaway (Jackson, 1984). The most characteristic feature of the Grand Rapids Formation is the vertical repetition of facies and their corresponding depositional environments (cf. Beynon 1991). Within the Cold Lake area of Alberta, Beynon (1991) subdivided the Grand Rapids Formation into six flooding-surface-bounded lithosomes (parasequences), each interpreted to record deltaic sedimentation. Hobbs (2003) studied the integrated ichnological, sedimentological, petrophysical, and sequence stratigraphic characteristics of the roughly time-equivalent Lower Albian-aged upper Falher Member and basal Notikewan Member of the Spirit River Formation in NE British Columbia and NW Alberta. He characterized the upper part of the Falher Member as coarse-grained, wave- and storm-dominated strandplain shorefaces and associated wave- and storm-dominated deltaic successions, deposited during periods of pronounced shoreline progradation.

The Grand Rapids Formation is stratigraphically equivalent to the Upper Mannville Group and the Falher Member of the Spirit River Formation of central and western Alberta, respectively (Figure 1.1) (Hayes et al., 1994). As a result of this stratigraphic affinity, work by Beynon (1991) and Hobbs (2003) may be integrated, creating a coherent depositional framework that evaluates the along-strike variations in shoreline character along the southeastern margin of the Boreal Seaway, using core from the undifferentiated Upper Mannville Group and the Grand Rapids Formation. By integrating sedimentological and ichnological datasets, refinements in our understanding
of the mixed influences of storms, waves, and rivers on such shoreline successions can be attained, leading to more accurate paleoenvironmental models for the study interval.

Figure 1.1 Stratigraphic relationship of the Falher Member with the Upper Mannville Group and the Grand Rapids Formation (modified after Pemberton and MacEachern, 1995).

1.2 Objectives and Methodology

Objectives
The principal objective of this thesis is to characterize and interpret the depositional facies of the Grand Rapids Formation through the integration of ichnology and sedimentology. Additional objectives include the construction of a depositional model for the interval, evaluation of along-strike changes in depositional character of the facies, and construction of an ichnological model for bay-head delta complexes deposited within brackish-water basins.
Methodology
An initial scoping study was undertaken to locate cored wells using the Accumap database. Geophysical well logs were used to correlate cored intervals and for determining the position of the parasequences sets. Ichnological descriptions include trace fossil abundances, ichnogenera diversities, trace fossil types, trace fossil size, bioturbation intensities (Figure 1.3) and assessment of bioturbation distributions. Sedimentological descriptions include lithologies, grain-sizes, bedding types, bedding contacts, primary physical structures, and secondary physical features (e.g., bitumen saturation, clay alteration). Integration of these datasets results in a framework for the construction of depositional facies. An in-depth discussion about the facies concept is outlined in Chapter 3.

1.3 Study Area and Well Control

The Grand Rapids Formation extends from approximately Townships 50 to 90 and Ranges 21W3 to 4W5 (Figure 1.2). However, in order to concentrate on the analysis of the along-strike variations recorded in the southern margin of the Boreal Seaway, the study area has been constrained to Townships 59-69 and Ranges 2W4 to 25W5.

The intervals studied include the three uppermost parasequences of the Grand Rapids Formation and undifferentiated Upper Mannville Group. This data set, integrated with the frameworks of Beynon (1991) and Hobbs (2003), results in a detailed paleoenvironmental reconstruction of the southern margin of the Boreal Seaway.
Figure 1.2 Study location and well distribution within the study area.
1.4 Data Base

A total of 56 cored wells were evaluated (Table 1.1), for a total thickness of 962.4 m. Primary well selection criteria included: 1) their particular location within the study; 2) wells containing the two uppermost parasequences; 3) core with a minimum diameter of 5.1 cm (2 inches); and 4) exclusion of cored intervals dominated by rubble. Some wells contained extremely dark bitumen saturation, which masked many sedimentary and ichnological features.

1.5 Rationale For Research

The purpose of this research is to examine along-strike variations in the shoreline architectures of units along the southern margin of the Boreal Seaway, which is expected to provide an improved understanding of the paleogeography and paleoenvironments of central Alberta during the Lower Cretaceous. Although previous workers (cf. Beynon, 1991 and Hobbs, 2003) studied the western and central portions of the southern margin of the Boreal Seaway, no applied ichnological study has yet evaluated the along-strike variations of parasequences of the roughly time equivalent Falher Member, Upper Mannville Group and Grand Rapids Formation, correlating the same parasequences within the three stratigraphic units. Jackson (1984), Leckie and Smith (1992), and Cant and Abrahamson (1997), have studied specific intervals within these areas; however, none of these authors focused on integrating ichnology, rather they, concentrated for the most part, on the stratigraphy and regional paleogeography. Additionally, the scope of these authors’ studies did not permit evaluation of the subtle along-strike variations in storm-, river-, wave- and tidal-processes that operated on the shoreline systems. The evaluation of dominant processes that operate at the coast as shorelines become sheltered from (or open to) storm- and wave- influences is critical.
<table>
<thead>
<tr>
<th>Core Location</th>
<th>Core Interval (m)</th>
<th>Stratigraphic Unit</th>
<th>Core Location</th>
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Table 1.1 Well locations and cored intervals with corresponding stratigraphic units.
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<td>Sparse bioturbation, bedding distinct, few discrete traces</td>
</tr>
<tr>
<td>2</td>
<td><img src="image2" alt="Mudstone Facies" /></td>
<td>Rare bioturbation, bedding distinct, low trace density</td>
</tr>
<tr>
<td>3</td>
<td><img src="image3" alt="Mudstone Facies" /></td>
<td>Moderate bioturbation, bedding boundaries sharp, traces discrete with rare overlap</td>
</tr>
<tr>
<td>4</td>
<td><img src="image4" alt="Mudstone Facies" /></td>
<td>Common bioturbation, bedding boundaries indistinct, high trace density with common overlap</td>
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<td>5</td>
<td><img src="image5" alt="Mudstone Facies" /></td>
<td>Abundant bioturbation, bedding just visible, though completely disturbed</td>
</tr>
<tr>
<td>6</td>
<td><img src="image6" alt="Mudstone Facies" /></td>
<td>Complete bioturbation, total biogenic homogenization of sediment</td>
</tr>
</tbody>
</table>

Figure 1.3 Bioturbation Index (BI) values, related to mudstones and sandstones after (Reineck, 1962; Taylor and Goldring, 1993; Bann et al., 2008).
The role of shoreline and deltaic complex orientations may be important in understanding longshore drift and net sediment transport, in addition to a thorough understanding of the paleoenvironments.

Limited ichnological criterion exists for evaluating bay-head delta complexes that are deposited in brackish-water basins (MacEachern and Gingras, 2008). The ichnology of deltas in normal open-coast, marine settings has been evaluated by MacEachern et al. (2005). Previous workers have discussed the architecture of bay-head deltas as part of the estuary environment (e.g., Dalrymple et al., 1992). Identifying the differences and therefore separating the two environments ichnologically will allow accurate interpretations of paleoenvironment and paleogeography within the Boreal Seaway, in addition to similar environmental settings elsewhere. Correctly identifying the delta types allows accurate predictions of facies and their associated environments, both spatially and temporally.
CHAPTER 2: GEOLOGICAL FRAMEWORK

2.1 Regional Stratigraphy

The Albian-aged Grand Rapids Formation is the stratigraphically highest part of the Upper Mannville Group. It is unconformably overlain by the Joli Fou Formation. The underlying Clearwater Formation interfingers with the Grand Rapids Formation (Figure 1.1 and 2.1) (Singh, 1964; Kramers, 1974; Stelck and Kramers, 1980; Leckie and Smith, 1992; Cant and Abrahamson, 1997). All the Grand Rapids Formation sandstones terminate southward but permit correlation to the Lloydminster area by using minor coarsening-upward successions and shales (Cant, 1996; Cant and Abrahamson, 1997) (Figure 2.1). Subsidence rates were lower in the eastern part of the basin as a response to flexural loading in the west, resulting in off-lapping successions within the Grand Rapids Formation (Cant, 1996; Cant and Abrahamson, 1997). The basal Grand Rapids is correlative with the top of the Sparky Formation/base of the Waseca Formation in the Lloydminster area (Vigrass, 1977; Putnam, 1982; Cant, 1996; Cant and Abrahamson, 1997).

The Falher Member of the Spirit River Formation and the undifferentiated Upper Mannville Group are roughly time equivalent to the Grand Rapids Formation, and lay along depositional strike to the west.
2.2 Basin Evolution

The Western Canada foreland basin has been directly impacted by the evolution of the Western Canada Cordillera, which started in the Early to Middle Jurassic (Leckie and Smith, 1992; Stockmal et al., 1992). Compression from terrain accretion on the western margin of North America created a foreland basin toward a stable craton platform in the east (Monger and Price, 2002). The basins are asymmetric and deepest near the fold and thrust belt. Most sediment accumulated in the deepest portions of the basin and resulted in stacked, westward-thickening clastic wedges (Figure 2.2). The asymmetric subsidence also affected fluvial patterns creating a prevailing drainage system that was mostly parallel to the basin axis (Price, 1973; Jordan, 1981; Leckie and Walker, 1982; Taylor and Walker, 1984; Leckie and Smith, 1992).

Figure 2.1 The Grand Rapids Formation stratigraphy extending from the Lloydminster area (Cant and Abrahamson, 1997).
Figure 2.2 Idealized stratigraphic cross section of the Western Canada foreland basin during maximum transgression (Leckie and Smith, 1992).

Two prominent structural features are located within the study area: the regional dip of the Upper Mannville Group to the southwest, and the presence of an elongate syncline trending north-northeast (Beynon and Pemberton, 1992b).

Large and small-scale structural features are associated with the dissolution of Devonian salt beds in the eastern portion of the basin. Removal of Devonian salt prior to and penecontemporaneous with younger sedimentation has also influenced the sediment thicknesses and depositional patterns in various parts of the basin (Simpson et al., 1988). Heavy oil in northeastern Alberta is trapped in part, by massive structural up-dip salt removal from the Devonian Elk Point Group during the Cretaceous and Tertiary (Hayes et al., 1994).
2.3  Paleogeography

The paleogeography of the Grand Rapids Formation and Falher Member has been interpreted in two main ways. Cant and Abrahamson (1997) interpreted the transition of sandstone in the north to interbedded mudstones and sandstones in the south as a shoreface to back-barrier facies contact similar to the Falher Member sediments (Figure 2.3a). The uppermost parasequences were deposited during a period of sea level fall. The back-barrier area is interpreted by Cant and Abrahamson (1997) as a prograding system of thin channels and associated crevasse-splay sands into interdistributary muds, perhaps in the overall form of a low-energy fluvial-dominated delta. When the progradation reached a break in slope with deeper, higher energy open marine water, the major lowstand shoreface complex was formed. Masters (1984), Leckie and Smith (1992), and Smith et al (1994) interpreted the Grand Rapids Formation as thick barrier island complexes with a brackish-water embayment behind that extended as far south as northern Montana (Burden, 1982). The Falher Member was regarded as prograding deltaic successions (Figure 2.3b).

2.4  Previous Work

Several authors have studied the Grand Rapids Formation using both outcrop and subsurface data (Kramers, 1974; Keeler, 1978; Keeler, 1980; Stelck and Kramers, 1980; Kramers, 1982; Beynon, 1991; Beynon and Pemberton, 1992a; 1992b; Cant and Abrahamson, 1997). The oil reserves and description of reservoir properties have also been evaluated (Harrison, 1977; Kendall, 1977; Towson, 1977; Lennox and Lerand, 1980; Kramers, 1982; Flach, 1984; Beynon and Pemberton, 1992a; Cant and Abrahamson, 1997). Micro- and macrofloral studies established Albian age (Singh, 1964; Stelck and Kramers, 1980). There are several regional subsurface studies of the Mannville Group, which include the Grand Rapids Formation (Williams, 1963; Mellon, 1967; Jackson, 1984; Masters, 1984; Leckie and Smith, 1992; Smith et al., 1994; Cant, 1996; Cant and Abrahamson, 1997). The Grand Rapids Formation was cited as an example to characterize the ichnological characteristics of brackish-water deposits (Beynon and Pemberton, 1992b).
Figure 2.3a,b: (a) Paleogeography modified after Cant (1997); (b) Paleogeography modified after Masters (1984), Leckie and Smith (1992).

Red box indicates the study area, and logged cores.
CHAPTER 3: FACIES DESCRIPTIONS AND INTERPRETATIONS

3.0 The Facies Concept

The facies concept has been one of the most important methods for evaluating sedimentary rocks. “Facies” is derived from the Latin (“facies” or “facia”), meaning “appearance of” (Teichert, 1958; Walker, 1992). Nicholas Steno was the first to introduce the concept into a geological context, in 1669. Amand Gressly (1838) was the first to utilize facies in a stratigraphic context. Gressly’s original definition of a facies encompasses the sum total of lithological and paleontological aspects of a stratigraphic unit (Walker, 1992). Facies can be defined on several different scales, depending upon the scope of the study.

Facies successions refer to certain facies properties that change either laterally or vertically (Walker, 1992). These properties may include the proportion of sand, bioturbation intensity, grain size, and other lithological or paleontological properties. Recurring three-dimensional groups of facies that are genetically related and have some environmental significance constitute “facies associations” (Collinson, 1969; Walker, 1992).

Ichnofacies comprise recurring ethological groupings of biogenic structures regardless of suites (MacEachern et al., 2007b). Dolf Seilacher (1953; 1967) was the first to recognize that there are a limited number of ichnofacies. Seilacher’s original work focused on the application of trace fossils solely (and erroneously) as relative bathymetric indicators (Pemberton et al., 1992). More recently, ichnology has been recognized as a powerful tool in environmental reconstructions, with paleobathymetry as only one aspect of the ichnofacies concept (Frey et al., 1990; Pemberton et al., 1992). A total of 9 recurring facies were identified within the study area.
3.1 Facies 1: Fissile Mudstone Facies

Sedimentology:

Facies 1 consists of dark gray to light gray, fissile, laminated to massive (apparently structureless) mudstone beds (shale) (Figure 3.1). The lighter coloured mudstones are commonly smectitic and swell when wet, making them difficult to analyze. Siderite cement occurs sporadically throughout the facies, but is more commonly associated with the lighter and more heterolithic portions of the units.

Rare, normally graded siltstone to fine-grained sandstone laminae locally comprise up to 5% of the facies. Individual lamina-sets are typically mm-scale, although they may be up to 1cm thick. Rare oscillation-ripple cross-lamination is present. Facies 1 is locally massive, and generally coarsens upward into Facies 2a or Facies 2b.

Ichnology:

Facies 1 displays BI 0-1 and is sporadically bioturbated. Trace fossils include Planolites, navichnia (mantle and swirl structures), and rare fugichnia.

Interpretation:

Facies 1 indicates standing water where sediment is deposited from suspension or as flocculated clay. Thick laminae of structureless mud suggest that accumulation occurred at an elevated rate. Oscillation-ripple lamination indicates subaqueous deposition in response to wind generated surface waves. Rare, normally graded siltstone and very fine-grained sandstone layers reflect waning energy conditions. Navichnia (mantle-and-swirl structures) (Figure 3.1a) indicates sediment-swimming behaviour in soupy substrates (Lobza and Schieber, 1999). Low bioturbation intensities also may be the result of high sedimentation rates or other physico-chemical stresses. Smectite or other swelling clays may be the result of diagenesis (Kramers, 1979). This low-diversity assemblage cannot be attributed to any ichnofacies. Possible environments might include shallow brackish-water embayments, estuaries, and prodeltas.
Figure 3.1 Fissile Mudstone Facies

A) Mudstone with thin, normally graded siltstone laminae. Trace fossils include navichnia (na).

B) Fissile mudstone with centimeter-scale siderite-cemented zones and siltstone laminae. Note that individual siltstone laminae are commonly normally graded (black arrow).

C) Mudstone, becoming increasingly heterolithic with thin oscillation-ripple laminae and siderite cemented zones. Trace fossils include *Planolites* (P).
3.2 Facies 2: Mudstone-Prone Heterolithic Facies

Facies 2 constitutes mudstone-dominated heterolithic units possessing at least 70% mudstone; with the remaining components consisting of siltstone and sandstone layers. This facies has been subdivided into 3 sub-facies on the basis of subtle, but recurring sedimentological and ichnological features.

Sedimentology:

Mudstone layers are 0.1-0.5 cm thick, although siltstone and mudstone bedsets may reach 3 cm in thickness. Sandstones and siltstones are lenticular bedded and form composite bedsets. Contacts between bedsets may be sharp, scoured, and erosional. Convolute bedding is present locally. Mudstones are rarely fissile. Carbonaceous detritus is locally common and may demarcate laminae.

Facies 2a: Weakly Burrowed, Lenticular-Bedded Mudstone

Facies 2a is weakly burrowed, which distinguishes it from Facies 2b. It contains abundant oscillation-ripple lamination, differentiating it from Facies 2c (Figure 3.2). Mudstones are generally thinly bedded (less than 1 cm) and commonly interlaminated with siltstone. Mudstone and siltstone bedsets are typically 2-3 cm thick, although they may reach thicknesses up to 6 cm, and drape oscillation-rippled sandstones. The facies locally contains synaeresis cracks.

Facies 2a sandstones and siltstones are typically lenticular bedded with abundant and pervasive oscillation-ripple lamination or rarer combined flow and current-ripple lamination. Ripples are locally aggradational. Surfaces between the sandstones and mudstones are commonly sharp and undulating, with evidence of minor scouring.

Facies 2b: Sporadically Burrowed Mudstone and Sandy Siltstone

Facies 2b consists of biogenically reworked mudstones and sandy siltstones that are commonly interbedded and may display a laminated-to-burrowed fabric, is used to distinguish it from Facies 2a and Facies 2c (Figure 3.2). Hummocky cross-stratification (HCS) and oscillation-ripple lamination are burrowed to varying degrees.
Rare, thin, silt-poor mudstones with abundant organic detritus mantle oscillation-rippled sandstone layers. Synaeresis cracks within mudstones are variable in abundance, and filled with fine-grained sandstone or siltstone.

Sandstone and siltstone beds are commonly normally graded. Sandstone layers are generally very fine to medium grained. Most sandstone layers occur as isolated oscillation ripples within lenticular-bedded units or as thin laminae. Carbonaceous detritus is locally common and forms thin laminae.

Facies 2c: Pinstripe-Laminated Mudstone and Siltstone

Facies 2c is distinguished from Facies 2a and Facies 2b by its characteristic mudstone interlaminated with thin siltstone or very fine-grained sandstone, resulting in delicate horizontal lamina-sets, giving the appearance of pinstriped bedding (Figure 3.4). Layers may be normally graded, and locally have scoured, undulatory, or sharp contacts. Synaeresis cracks are present in low abundances and are typically of small diameter. Oscillation-ripple lamination is extremely rare and is only associated with very fine-grained sandstone lenses.

Ichnology

Subfacies of Facies 2 show marked variations in bioturbation intensity (BI 0-5), which constitutes the principal basis for their differentiation. Trace fossils in all subfacies are sporadically distributed, but display variable trace fossil suites.

Facies 2a: Weakly Burrowed, Lenticular-Bedded Mudstone

Facies 2a shows low BI values and less marked variations in burrowing intensity (BI 0-2, with BI 1 most common). Biogenic structures are typically diminutive and suites show low diversity. Ichnogenera are more evenly distributed than apparent in other subfacies, and are commonly associated with the mudstones. Burrows are typically sand filled. Trace fossils include common Planolites, rare Skolithos and Cylindrichnus, and very rare Thalassinoides and navichnia (mantle and swirl structures) (Figure 3.2).
Facies 2b: Sporadically Burrowed Mudstone and Sandy Siltstone

Bioturbation within Facies 2b is sporadically distributed and commonly yields a laminated-to-burrowed fabric, differentiating it from the more weakly burrowed Facies 2a. Bioturbation values vary at the bed scale from BI 2-5, but typically average BI 3. Trace fossil diversities are generally low. Ichnogenera also show both robust and diminutive forms. Trace fossils suites are dominated by deposit-feeding structures, with secondary dwelling structures of inferred suspension-feeding organisms, and escape structures. Trace fossils include common Planolites, Gyroolithes, Cylindrichnus, Skolithos, Teichichnus, Asterosoma, Rosselia, fugichnia, navichnia, and very rare Rhizocorallium, Phycosiphon and Palaeophycus (Figure 3.3).

Facies 2c: Pinstripe Laminated Mudstone and Siltstone

Subfacies 2c is characterized by BI values of 1-2. Burrows are sporadically distributed. Trace fossils are typically infilled with silt or sand. Ichnogenera include low numbers of Planolites, Skolithos, Cylindrichnus and navichnia. Ichnologically, this facies is similar to Facies 2a, but has increased numbers of navichnia (Figure 3.4c).

Interpretation

Facies 2 contains oscillation ripples and rare HCS, indicating deposition in a subaqueous setting with orbital velocities sufficient to entrain sand-sized sediment. Oscillatory wave motion was generated by wind and storms, indicating that deposition occurred at and above storm-weather wave base. Synaeresis cracks are thought to form as a result of subaqueous clay shrinkage induced by salinity contrasts in the basin water (Plummer and Gostin, 1981). Normally graded beds indicate waning energy conditions. Navichnia in the mudstones indicates that soupy substrates were commonly present (Lobza and Schieber, 1999), which is consistent with rapid deposition of flocculated clays. The ichnological suite is generally of low diversity, and consists of inferred facies-crossing structures, many of which are markedly diminutive. Such characteristics are consistent with brackish-water ichnological models previously described (e.g., Beynon and Pemberton, 1992b; Gingras et al., 1999; Gingras et al., 2002a; Gingras et al., 2002b;
Buatois et al., 2005; Gingras et al., 2005; Boyd et al., 2006; MacEachern and Gingras, 2008).

**Facies 2a: Weakly Burrowed, Lenticular-Bedded Mudstone**

The lenticular-bedded, oscillation-rippled sandstones were deposited at or above storm-weather wave base. Abundant mudstone drapes on oscillation-ripple laminated sandstones were deposited as both flocculated mud and via suspension settling during low-energy periods. The paucity of bioturbation and rare aggradational ripples suggests an environment with persistent, elevated sedimentation rates, which differentiates this facies from Facies 2b and 2c. Rare current-ripple lamination indicates periods of unidirectional flow leading to traction sediment transport. Low diversity trace fossil suites, diminutive ichnogenera, and synaeresis cracks suggest an environment in which water salinities were persistently brackish (Beynon et al., 1988; Beynon, 1991; Beynon and Pemberton, 1992b; Buatois et al., 2005; Gingras et al., 2005; MacEachern et al., 2005; MacEachern and Gingras, 2008). Suites record stressed but more archetypal mixtures of elements attributable to the *Cruziana* Ichnofacies. This is hereafter referred to as a “stressed expression of the *Cruziana* Ichnofacies”. Such settings include brackish-water bays, bay-head prodeltas, estuaries, lagoons and other brackish-water environments.

**Facies 2b: Sporadically Burrowed Mudstone and Sandy Siltstone**

Laminated-to-burrowed fabrics characterize Facies 2b, indicating that sedimentation rates were highly variable. This facies contains increased amounts of thin-bedded HCS, consistent with shallow subaqueous deposition associated with storm events. Trace fossil suites are dominated by deposit-feeding structures and lesser vertical domiciles of inferred filter-feeding organisms, consistent with the introduction of suspended food resources. Low trace fossil diversities, diminutive ichnogenera, and locally common synaeresis cracks indicate that water salinities were variable, but commonly brackish (Beynon et al., 1988; Beynon, 1991; Beynon and Pemberton, 1992b; Buatois et al., 2005; Gingras et al., 2005; MacEachern et al., 2005; MacEachern and Gingras, 2008). Facies
2b contains trace fossils that are dominated by facies-crossing ichnogenera and ethologies that reflect deposit-feeding strategies. The suite is similar to the *Cruziana* Ichnofacies, but lacks the high diversities typical of the ichnofacies. It therefore a stressed expression of the *Cruziana* Ichnofacies. This term has been used by several other authors (MacEachern *et al.*, 2005; MacEachern *et al.*, 2007; MacEachern and Gingras, 2008) Settings that might yield deposits comparable to Facies 2b include deltas, estuaries, shallow brackish-water bays, and lagoons.

**Facies 2c: Pinstripe Laminated Mudstone and Siltstone**

Thin (typically less than 0.5 mm), normally graded siltstone and sandstone layers indicate periodic waning-energy conditions. The predominance of oscillation-generated structures demonstrates that the setting was subaqueous and lay above storm wave base. Decreased amounts of sediment coarser than very fine-grained sand indicate that deposition occurred in a more basinward position than Facies 2a and Facies 2b. Lowered trace fossil diversity, diminutive ichnogenera, and locally common synaeresis cracks imply that water salinities were variable, but commonly brackish (Beynon *et al.*, 1988; Beynon, 1991; Beynon and Pemberton, 1992b; Buatois *et al.*, 2005; Gingras *et al.*, 2005; MacEachern *et al.*, 2005; MacEachern and Gingras, 2008). Navichnia indicate that rapid deposition of mud was typical, leading to soupy substrates. Rare synaeresis cracks in thin, organic-rich mudstones suggest water with reduced salinity deposited sediment probably derived from a terrestrial source (MacEachern *et al.*, 2005). Possible depositional environments for Facies 2c include deltas, brackish-water bays, lacustrine settings, and lagoons.
Figure 3.2 Facies 2a: Weakly Burrowed, Lenticular-Bedded Mudstone

A) Sporadically bioturbated mudstones, with lenticular-bedded, oscillation-ripple-laminated sandstones. Note the 2 cm-thick siderite cemented mudstone beds. Ichnogenera include *Planolites* (P).

B) Weakly burrowed, lenticular-bedded mudstone. Note the thinly laminated siltstones and mudstones near the center of the photograph, as well as the synaeresis cracks (syn).

C) Sporadically bioturbated mudstones with sand-filled *Planolites* (P), *Skolithos* (S), and *Thalassinoïdes* (Th).

D) Lenticular-bedded oscillation-rippled sandstones, draped by mudstones with sporadic burrowing. Traces are dominated by *Planolites* (P).

E) Oscillation-rippled sandstone and siltstone encased in mudstone recording lenticular bedding. Note the rare occurrence of current-ripple lamination and convolute bedding.

F) Interbedded mudstones and oscillation-rippled sandstones. Rare navichnia (na) supports local development of soupy substrates.
Figure 3.3 Facies 2b: Sporadically Burrowed Mudstone and Sandy Siltstone

A) Oscillation-rippled sandstone with mudstone drapes. Bioturbation is sporadically distributed and traces are commonly sand filled. Trace fossils include *Planolites* (P), *Palaeophycus* (Pa), and *Cylindrichnus* (Cy).

B) Dark, organic-rich mudstone with a low diversity suite of sand-filled trace fossils. Sandstone is typically oscillation-ripple laminated. Mudstone beds are commonly normally graded. Trace fossils include *Planolites* (P), *Skolithos* (S), *Rosselia* (R), navichnia (na), and fugichnia (fu).

C) Mudstone interlaminated with normally graded, very fine-grained sandstone layers and rare, medium-grained sandstone laminae. Some siltstone bed contacts are erosional. Trace fossils are generally diminutive. Ichnogenera include *Planolites* (P), *Teichichnus* (T), *Cylindrichnus* (Cy), and *Phycosiphon* (Ph).

D) Interbedded mudstone and oscillation ripple-laminated siltstone, with diminutive *Rosselia* (R), *Cylindrichnus* (Cy), *Planolites* (P), and *Gyrolithes* (G). Local synaeresis cracks (syn) are present.

E) Mudstone and interbedded sandstone, displaying a laminated-to-burrowed fabric. Trace fossils include *Planolites* (P), *Skolithos* (S), *Asterosoma* (As), and *Cylindrichnus* (Cy).

F) Lenticular bedded sandstone and mudstone with carbonaceous laminae. Siltstone interbeds are normally graded and have low BI values. Laminated-to-burrowed fabrics may indicate a dominance of fair-weather processes alternating with event sedimentation. Trace fossils include *Planolites* (P), *Teichichnus* (T), *Cylindrichnus* (Cy), and rare *Chondrites* (Ch).
Figure 3.4 Facies 2c Pinstripe-Laminated Mudstone and Siltstone

A) Mudstone with normally graded siltstone laminae. Note the erosional contacts between mudstone layers. Rare synaeresis cracks (syn) are present. Trace fossils are rare and include Planolites (P) and navichnia (na).

B) Mudstone with thin, normally graded siltstone laminae. Some laminae are thicker and may exhibit oscillation-ripple lamination. Synaeresis cracks (syn) are rare, and bioturbation intensities are low, with isolated Cylindrichnus (Cy) and navichnia (na).

C) Pinstripe-laminated mudstone with overlying bioturbated mudstone and sandstone. The unit contains local coalified debris. Synaeresis cracks (syn) are present in low abundances. Trace fossils include Planolites (P), navichnia (na) and Skolithos (S).
3.3 Facies 3: Wavy-Bedded Mudstone and Sandstone Facies

Sedimentology

Facies 3 consists of 50% mudstone and siltstone, interbedded with sandstone forming wavy bedded composite bedsets (Figure 3.5). Contacts between layers are commonly sharp or undulatory. Mudstones locally occur as black-coloured drapes. Convolute lamination occurs locally. Synaeresis cracks are commonly associated with the mudstones, and are typically sand filled. Layers are horizontal or gently inclined and may possess small (less than 10 cm thick) zones with normal faults. Apparent fault displacement is typically less than 2cm. Some layers are normally graded from siltstone to mudstone.

Sandstone layers are dominated by oscillation-ripples, and contain rare combined flow ripples or very rare current-ripple lamination. Sandstone layer thicknesses are variable, ranging from 0.5-5.0 cm thick, and are typically 2.0 cm thick. Ripple foresets may be demarcated by mudstone drapes or carbonaceous detritus.

Ichnology

Bioturbation intensities range from BI 0-4 (commonly BI 2-3), and trace fossils are sporadically distributed. Mudstone beds commonly have higher bioturbation intensities, but lower trace fossil diversities than do the sandstones. Trace fossil sizes and diversities are variable. Ichnogenera associated with sandstone layers include Planolites, Gyrolithes, Cylindrichnus, Skolithos, Rosselia, Thalassinoides, rare Palaeophycus, Arenicolites, Teichichnus, Diplocraterion, Lockeia, Naktodemasis, fugichnia, and very rare Rhizocorallium. Ichnogenera associated with mudstone layers include Planolites, Skolithos, Cylindrichnus, Gyrolithes, Rosselia, navichnia, rare Palaeophycus, and rare Chondrites. In many suites, a single ichnogenus dominates, most commonly Gyrolithes, Cylindrichnus, or Planolites.
Figure 3.5 Facies 3: Wavy-bedded Mudstone and Sandstone Facies

A) Interbedded mudstone and oscillation-rippled sandstone with abundant synaeresis cracks (syn). Trace fossil distribution is sporadic and bioturbation is low (BI 0-2). Trace fossils include diminutive Planolites (P), and fugichnia (fu).

B) Thin, normally graded siltstone and mudstone layers interbedded with sandstone. Sandstones contain rare oscillation ripple lamination with internal laminae commonly demarcated by mud. Trace fossils are diminutive and ichnological diversity is low. Trace fossils include Teichichnus (T), Skolithos (S), Planolites (P), Cylindrichnus (Cy) and fugichnia (fu).

C) Oscillation rippled sandstone and mudstone with rare synaeresis cracks (syn). Trace fossils are more robust and diversities are higher relative to other localities, indicating reduced physico-chemical stresses. Trace fossils include Cylindrichnus (Cy), Rosselia (R), Arenicolites (Ar), Gyrolithes (G), Skolithos (S), and fugichnia (fu).

D) Oscillation ripple laminated sandstones interlaminated with organic-rich mudstones. Mudstones locally contain synaeresis cracks (syn). Mudstones occur as drapes or as part of normally graded layers. Mudstones typically have higher bioturbation intensities (BI 0-4). Trace fossil diversity is relatively high and locally contains Rhizocorallium (Rh). Other trace fossils include Thalassinoides (Th), Teichichnus (T), Planolites (P), Chondrites (Ch), navichnia (na), and Cylindrichnus (Cy).

E) Sandstones interbedded with mudstones showing variable bioturbation intensities (BI 1-3). Carbonaceous detritus commonly demarcates combined flow ripple lamination. Note that mudstone beds are typically dominated by only 1 or 2 trace fossil genera. Ichnogenera include Gyrolithes (G), fugichnia (fu), Planolites (P), and Skolithos (S).

F) Oscillation rippled sandstones interbedded with normally graded siltstone and mudstone beds. The unit shows BI 0-2. Trace fossils include Planolites (P), and Rhizocorallium (Rh).
Interpretation

The dominance of oscillation ripple lamination indicates that the facies records subaqueous deposition, with the bed agitated by oscillatory waves produced by winds and/or storms. Normally graded layers indicate waning energy conditions. Synaeresis cracks probably are the result of clay shrinkage associated with periodically reduced water salinities (Plummer and Gostin, 1981). Mudstone layers were deposited locally via suspension settling and clay flocculation. Mudstones locally occur as black-coloured drapes, interpreted to be of fluid mud origin. Convolute lamination may be the result of sediment dewatering and/or differential compaction. The presence of navichnia indicates that the mudstones were locally soupy, consistent with rapid mud deposition. The generally low diversity, diminutive trace fossils and common synaeresis cracks support the interpretation of a stressed environment, most likely owing to reduced salinities. However, the sporadic and localized presence of ichnogenera deemed to be intolerant of physico-chemically stressful conditions (e.g., Rhizocorallium; cf. MacEachern and Gingras, 2007) indicates that salinities closer to normal marine conditions may have been present periodically. Reduced trace fossil diversities, and the presence of fugichnia are typical of settings prone to high sedimentation rates. The localized occurrence of the continental trace fossil Naktodemasis may indicate periods of subaerial exposure (Smith et al., 2008). The trace fossil assemblage contains elements of both the Skolithos Ichnofacies and the Cruziana Ichnofacies. Possible depositional environments for Facies 3 include brackish-water embayments, proximal prodeltas to distal delta fronts, lagoons, and estuarine central basins.

3.4 Facies 4: Sandstone-Prone Heterolithic Facies

Facies 4 comprises a sand-dominated heterolithic succession and contains higher proportions of sandstone than mudstone. This contrasts with Facies 3, which is consists of subequal proportions of sandstone and mudstone, and Facies 2, which contains higher
proportions of mudstone than sandstone. Two sedimentologically similar subfacies can be identified, based primarily on their distinctive ichnological characteristics.

**Sedimentology**

Facies 4 heterolithic units consist of greater than 50% sandstone, with thin (1 cm thick and less) mudstone and siltstone layers. Mudstone layers contain rare synaeresis cracks. Contacts are commonly sharp, scoured or undulatory where bioturbation intensities are sufficiently low to preserve contacts. Mudstones are locally convolute bedded.

Sandstones are very fine to medium grained. They commonly contain oscillation ripple lamination, HCS, or locally display horizontal to inclined planar parallel lamination. Rare combined flow ripple lamination and current ripple lamination also may be present, some of which are aggradational. Sparse carbonaceous debris, where present, is thinly laminated and associated with HCS.

**Facies 4a: Oscillation-ripple-Laminated Sandstones and Interbedded Mudstones**

Mudstones of Facies 4a are thinly layered and may display subtle normal grading, rare synaeresis cracks, and a generally unburrowed expression, distinguishing them from Facies 4b (Figure 3.6). These layers commonly drape oscillation ripple laminated sandstones, or may sharply overlie horizontal planar parallel laminated sandstones. Sandstones commonly contain oscillation ripple lamination and less common HCS. Carbonaceous laminae are rare, but locally present.

**Facies 4b: Interbedded Burrowed Mudstones and Oscillation Ripple-Laminated Sandstones**

Mudstones of Facies 4b are typically thinner than those of Facies 4a, and have higher BI values (Figure 3.7). Layers either show horizontal planar parallel lamination, or are wavy or flaser bedded, forming composite bedsets. Locally, the facies contains soft-sediment deformation structures, normal grading and synaeresis cracks. Sandstones contain common oscillation ripple lamination, rare HCS, and horizontal planar parallel lamination.
Ichnology

Facies 4a: Interbedded Mudstones and Oscillation Ripple-Laminated Sandstones

Mudstones are weakly and sporadically burrowed, showing BI 0-2, and typically BI 1. Trace fossil suites are of low diversity, and commonly are characterized by diminutive trace fossils. Ichnogenera are dominated by facies-crossing structures, and include *Gyrolithes, Planolites, Skolithos, Rosselia, Cylindrichnus*, navichnia, and fugichnia (Figure 3.6). Sandstone layers show more variable burrowing, with BI values of 0-3, though commonly only BI 1. Trace fossil distributions, sizes, and diversities are locally variable. A few hummocky cross-stratified beds have been burrowed with *Planolites, Macaronichnus*, and apparent cryptic bioturbation, giving the laminae a disrupted, fuzzy appearance. Trace fossils include *Planolites, Skolithos, Rosselia, Diplocraterion, Naktodemasis*, cryptic bioturbation and fugichnia. Although rare, *Naktodemasis* indicates local periods of subaerial exposure (cf. Smith *et al.*, 2008).

Facies 4b: Interbedded Burrowed Mudstones and Oscillation Ripple-Laminated Sandstones

Facies 4b contains mudstones that show widely variable and locally intense burrowing (BI 1-5; typically BI 3). Units are sporadically burrowed. Trace fossil diversities and sizes are variable in comparison with those of Facies 4a. Suites are typically dominated by a single biogenic structure. Trace fossils include *Gyrolithes, Rosselia, Skolithos, Planolites, Lingulichnus, Cylindrichnus*, rare *Naktodemasis*, and navichnia (Figure 3.7). Locally, burrow fills have been replaced by pyrite nodules.

Sandstones show BI values of 0-2, typically made up of mudstone-filled structures that are commonly vertically oriented and penetrate from the overlying mudstone bed. Trace fossils include *Skolithos, Gyrolithes, Planolites, Rosselia, Cylindrichnus, Lingulichnus*, fugichnia, and rare *Diplocraterion* (Figure 3.7).
Figure 3.6 Facies 4a: Interbedded Mudstones and Oscillation Ripple-Laminated Sandstones

A) The presence of the continental trace fossil *Naktodemasis* (Nk) and marine to marginal marine trace fossil *Teichichnus* (T) suggests a period of subaerial exposure following initial deposition. Note the preferentially bioturbated mudstone interbeds containing *Planolites* (P). The unit shows BI 0-1.

B) *Rosselia* (R), probably showing the mud-ball partially sheared off by erosion and deposition of sandstone, followed by suspension settling of mud. *Fugichnia* (fu) indicates high sedimentation rates. The unit shows BI 0-1.

C) Oscillation ripple-laminated sandstones with normally graded fair-weather mudstones. Trace fossils include rare diminutive *Planolites* (P) and *Skolithos* (S). Note the undulatory contacts between mudstone and sandstone layers. The unit shows BI 0-1.

D) Oscillation ripple-laminated sandstones draped by normally graded mudstones, indicating a period of high-energy waves followed by fair-weather deposition. Note the presence of imparting a fuzzy appearance to the HCS. Trace fossils include *Fugichnia* (fu), *Planolites* (P), and *Teichichnus* (T). The unit shows BI 0-4.

E) Oscillation rippled-sandstone with interbedded, apparently massive mudstones. Note the carbonaceous laminae on the lowermost mudstone. *Planolites* (P) is the only trace fossil present, and is sand filled. The unit shows BI 0-1.

F) HCS sandstones with abundant carbonaceous laminae and thin mudstone interbeds. Laminae may be cryptically bioturbated and is demarcated by carbonaceous detritus. Traces are uncommon and comprise diminutive *Planolites* (P) and *Gyrolithes* (G). The unit shows BI 0-1.
**Interpretation**

Abundant oscillation ripple-lamination and rare HCS indicates subaqueous deposition dominated by wave energy. Storm events are recorded by HCS. Mudstone drapes on oscillation ripple-lamination indicate deposition from clay flocculation and suspension settling. Synaeresis cracks support reduced salinity conditions, resulting in the shrinkage of clay (Plummer and Gostin, 1981). The localized presence of the continental trace fossil *Naktodemasis* supports the interpretation of periods of subaerial exposure following initial deposition (Smith *et al.*, 2008).

**Facies 4a: Interbedded Mudstones and Oscillation-ripple-Laminated Sandstones**

Sedimentary and biogenic structures in the heterolithic units of Facies 4a reflect the interplay of fluctuating wave energy and variable sedimentation rates in the environment. Evenly distributed burrowing but reduced bioturbation intensities indicate high sedimentation rates and shifting substrates, compared with Facies 4b. Mudstone deposition occurred under low-energy conditions by suspension settling and clay flocculation. *Navichnia* supports the presence of fluid-mud deposition that led to soupy substrates. Organic-rich mudstones of fluid mud origin and carbonaceous detritus may indicate the presence of direct fluvial sediment input (MacEachern *et al.*, 2005; Bhattacharya, 2007; Goldsmith *et al.*, 2008). Low bioturbation intensities and diminutive biogenic structures associated with synaeresis cracks strongly support brackish-water conditions. Although the trace fossil suites are of low diversity, they contain trace fossil elements that are dominantly characterized as a stressed expression of the *Skolithos* Ichnofacies.

Possible depositional environments for Facies 4a include brackish-water embayments, wave- and storm-dominated delta fronts of bay-head or bay-margin deltas, and sandy lagoons.

**Facies 4b: Interbedded, Burrowed Mudstones and Oscillation Ripple-Laminated Sandstones**

Facies 4b reflects fluctuating wave-energy conditions and variable sedimentation rates. HCS indicates deposition in subaqueous environments subjected to storm-generated
surface waves. As in Facies 4a, mudstones were deposited by suspension settling and clay flocculation. Increased bioturbation intensities with sporadically distributed burrowing are consistent with fluctuating sedimentation rates and variable energy conditions. Facies 4b reflects less marked physico-chemical stresses than indicated by Facies 4a. Lowered trace fossil diversities, diminutive ichnogenera, and locally common synaeresis cracks imply that water salinities were variable but at least somewhat brackish (Beynon et al., 1988; Beynon, 1991; Beynon and Pemberton, 1992b; Buatois et al., 2005; Gingras et al., 2005; MacEachern et al., 2005; MacEachern and Gingras, 2008). The trace fossil suite contains elements that point to a stressed expression of the Skolithos Ichnofacies. Possible depositional environments for Facies 4a include brackish-water bays, wave- and storm-dominated delta fronts, and sandy lagoons.
Figure 3.7 Facies 4b: Interbedded, Burrowed Mudstones and Oscillation Ripple-Laminated Sandstones

A) Sandstone and mudstone event beds are colonized, probably by opportunistic tracemakers. Trace fossils include *Gyrolithes* (G), *Skolithos* (S), fugichnia (fu) and cryptic bioturbation (cb). The unit shows BI 1-3.

B) Trace fossil suites are dominated by *Gyrolithes* (G), which are mud filled and penetrate both mudstone and sandstone. Thin carbonaceous laminae are offset by micro-faults (black arrow). The unit shows BI 0-2.

C) Burrow fills of *Planolites* (P) and *Palaeophycus* (Pa) have been replaced by pyrite. Mudstone is thinly interlaminated with sandstone. Layers are typically less than 3cm thick. The facies contains diminutive *Arenicolites* (Ar), *Cylindrichnus* (Cy), *Teichichnus* (T), fugichnia (fu) and *Chondrites* (Ch). The unit shows BI 1-4.

D) Sandstones and interbedded mudstone, largely reworked with *Palaeophycus* (Pa), *Cylindrichnus* (Cy), *Arenicolites* (Ar), and fugichnia (fu). High bioturbation intensities reflect low sedimentation rates, and may indicate predominance of fair-weather conditions. The unit shows BI 2-4.

E) Sporadically bioturbated unit containing synaeresis cracks (syn). Trace fossils include *Planolites* (P), *Cylindrichnus* (Cy), *Teichichnus* (T), and fugichnia (fu). The unit shows BI 1-3.

F) Mudstone beds are dominated by *Gyrolithes* (G). Other ichnogenera include apparent cryptic bioturbation, *Arenicolites* (Ar), *Skolithos* (S), *Cylindrichnus*, and fugichnia (fu). Mudstones mantle oscillation ripples. The unit shows BI 0-2.
3.5 Facies 5: Inclined Heterolithic Stratification (IHS)

Sedimentology

Facies 5 consists of inclined (typically 10 degrees or less), very fine- to medium-grained sandstone layers alternating with mudstone and/or siltstone layers (Figure 3.8). Sandstone layers are commonly 1-3 cm thick, although where finer-grained sediment dominates, layers may be mm scale. Sandstone layers constitute approximately 30-60% of the facies. Sandstone beds locally contain combined flow ripple- or current ripple-lamination. Layers are also locally normally graded. Carbonaceous laminae and soft-sediment deformation are common. The facies locally contains intraformational silty mudstone clasts up to 10 cm in diameter, which are sub-angular, and thinly laminated. Mudstone interbed thicknesses are variable, but typically less than 1 cm thick. Facies thicknesses are typically 3-6 m.

Ichnology

The unit shows a bioturbation index of 0-3 (typically 0-1). Trace fossils are sporadically distributed. Mudstone beds tend to show higher bioturbation intensities than sandstone beds. Common trace fossils include Skolithos, Planolites, Gyrolithes, Cylindrichnus, navichnia, and fugichnia.

Interpretation

Trough cross-stratified sandstones were deposited under high-energy current-dominated conditions. As energy levels decreased, mudstones were deposited out of suspension. Fugichnia commonly indicates sporadic and generally high sedimentation rates. The presence of navichnia may indicate rapid clay flocculation leading to the rapid deposition of fluid mud. Current ripple lamination indicates unidirectional flow and traction sediment transport, although combined flow ripples suggest periods of standing water and oscillatory modification during current flow. Low-diversity and facies-crossing trace fossil suites are characteristic of a brackish-water setting rather than that of a normal marine- or fresh-water setting (see MacEachern and Gingras, 2007 for a summary). The overall low bioturbation intensities suggest that sedimentation rates were sufficiently high to preclude thorough reworking of sediments between deposition
cycles (Gingras et al., 2002b). Flow velocities were also sufficiently strong to move large mudstone rip-up clasts. There is a degree of uncertainty in identifying IHS using only core; consistent dip directions and predictable changes in dip angle can only be discerned using dip-meter and HMI log data. The trace fossil suite is attributable to a stressed expression of the Skolithos Ichnofacies. Possible environments that yield deposits similar to Facies 5 include tidal-fluvial and tidal point bars, delta plain distributary channels, and estuarine channels.
Figure 3.8 Facies 5: Inclined Heterolithic Stratification (IHS)

A) IHS displaying intraformational mudstone clasts with laminated sandstone. The unit shows BI 0.

B) Mudstone-dominated IHS with mudstone interbeds intensely bioturbated with Gyrolithes (G) and Planolites (P). The unit shows BI 4-5.

C) Heavily oil-stained sandy IHS. Mudstone beds are thin and less intensely oil stained. No trace fossils are identified, and the unit shows BI 0.

D) Mudstone-dominated IHS with rare Planolites (P), Teichichnus (T), navichnia (na), and Cylindrichnus (Cy). The unit shows BI 1-2.

E) Sandy IHS with current ripple-laminated sandstone interbeds containing rare Planolites (P) and Skolithos (S). The unit shows BI 1-3.

F) Intensely burrowed sandstone-dominated IHS. Common trace fossils include Planolites (P), Cylindrichnus (Cy), and Teichichnus (T). The unit shows BI 3-4.
3.6 Facies 6: Wave-Ripple to Hummocky Cross-Stratified Sandstone

Sedimentology

Facies 6 is characterized as having greater than 90% moderately sorted fine- to medium-grained sandstone beds dominated by oscillation ripple lamination and HCS. Oscillation ripples are locally aggradational or slightly asymmetrical. Some oscillation rippled beds alternate with very rare current ripple laminated layers. HCS beds are typically erosionally amalgamated and locally contain small, well-rounded mudstone rip-up clasts. HCS contains some carbonaceous laminae and spherulitic siderite. Soft-sediment deformation is present in the form of convolute bedding. Rare mudstone laminae are thin and may contain synaeresis cracks. Bedding is variable from 20 cm up to 1.5 m thick.

Ichnology

Bioturbation intensity is typically BI 0-1 and ichnogenera are sporadically distributed. Trace fossils include Diplocraterion, Skolithos, fugichnia, and rare Planolites and cryptic bioturbation. Cryptic bioturbation gives laminae a blurred or fuzzy appearance (cf. Pemberton et al., in press).

Interpretation

Oscillation ripple lamination and HCS indicate subaqueous deposition with surface waves generated by wind and/or storms. Storm waves produce HCS, followed by waning storm energy conditions forming oscillation-ripples (Johnson and Baldwin, 1996). Some oscillation ripples are not associated with HCS, suggesting either weak storm events or deposition by fair-weather waves. The trace fossil suite is characterized as a stressed (low diversity) expression of the Skolithos Ichnofacies. Deep-tier structures such as Diplocraterion and Skolithos suggest that organism dwellings were resistant to migrating bedforms (Bann and Fielding, 2004). The common presence of fugichnia reflects organism responses to episodic and/or rapid sedimentation (Frey, 1973; Frey and Pemberton, 1985; Gingras et al., 1998). The aggradational oscillation ripple lamination indicates locally high sedimentation rates (Allen, 1970). Rare mudstone rip-up clasts suggest that flow velocities were sufficiently high to move large, cohesive clasts, possibly derived from intervening mudstone drapes. Spherulitic siderite and organic detritus
suggests that sediment was supplied from the adjacent coastal plain, and the reworking of incipient paleosol deposits (Leckie *et al.*, 1989). Possible depositional environments for Facies 6 are numerous, and include sandy open bays of estuaries, lower and middle shorefaces, delta fronts, bays, lagoons, and barrier islands.
Figure 3.9 Facies 6: Sandstone with Oscillation-Generated Structures

A) Oscillation rippled sandstone with siderite cement and convolute bedding. Trace fossils include *Planolites* (P), and fugichnia (fu). The unit shows BI 0-1.

B) Erosionally amalgamated oscillation rippled sandstone, overlying a thin mudstone layer containing synaeresis cracks (syn). Trace fossils include *Skolithos* (S), *Planolites* (P) and fugichnia (fu). The unit shows BI 0-1.

C) Hummocky cross-stratified sandstone with rare, subrounded mudstone rip-up clasts (black arrow). Trace fossils include fugichnia (fu) and cryptic bioturbation (cb). The unit shows BI 0-1.

D) Micro-HCS with abundant carbonaceous detritus and spherulitic siderite (black arrow) indicating a nearby terrestrial source for the sediment. Trace fossils include *Planolites* (P), fugichnia (fu), and cryptic bioturbation (cb). The unit shows BI 0-1.

E) Oil stained oscillation ripple- and combined flow ripple-laminated sandstone with diminutive fugichnia (fu) and possible cryptic bioturbation. The unit shows BI 0-1.

F) Oscillation rippled sandstone containing common aggradational forms and thin current-rippled layers (black arrow). Traces comprise *Diplocraterion* (D) and fugichnia (fu), consistent with elevated sedimentation rates. The unit shows BI 0-1.
3.7 Facies 7: Current Ripple- to Trough Cross-Stratified Sandstone

Sedimentology

Facies 7 encompasses upper fine-grained to lower coarse-grained sandstone containing current-generated sedimentary structures (Figure 3.10). Bed thicknesses range from 20 cm to 2.0 m thick (typically less than 1 m). The sandstone is moderately well sorted. The most common structures are trough cross-stratification and current ripple lamination, although combined flow ripples are present locally. Aggradational current ripples are rare. Moderate amounts of carbonaceous detritus locally demarcate internal laminae. Trough cross-stratification is recognized by the upward steepening of laminae from tangential toesets to foresets overlying an erosional basal contact. Trough cross-bed thicknesses range from 10 cm up to 40 cm. Mudstone rip-up clasts are present locally, and are subrounded to angular, equant or discoid shaped, with locally derived resistant siderite nodules. Some clasts preserve original mudstone and sandstone interlamination within the clast. Clast sizes vary from granules to cobbles. Spherulitic siderite is locally present within laminae.

Ichnology

Bioturbation intensity corresponds to BI 0-2. Trace fossils include very rare Planolites, Skolithos, Cylindrichnus, and fugichnia. Biogenic structures are more commonly associated with combined flow ripple lamination, and are extremely rare in association with current ripple lamination or trough cross-stratification.

Interpretation

Facies 7 was deposited in a subaqueous environment subject to conditions of quasi-steady unidirectional flow. The trace fossil suite contains elements that correspond to a stressed expression of the Skolithos Ichnofacies. Rare aggradational ripples reflect periodic heightened sedimentation rates. Sub-rounded mudstone rip-up clasts associated
with resistant siderite nodules indicate that some sediment was semi-consolidated during erosion and transport, and that flow velocities were sufficient to transport these clasts. Spherulitic siderite and coal fragments indicate a nearby terrestrial source, likely units of Facies 9.

Settings that might yield deposits comparable to Facies 7 include proximal delta fronts, estuaries (channels and estuary mouth complexes), shallow brackish-water bays, lagoons, tidal channels, distributary channels, and upper shorefaces.
Figure 3.10 Facies 7: Current Ripple- to Trough Cross-Stratified Sandstone

A) Oil-stained, trough cross-stratified sandstone indicating dune-scale bedforms generated by current flow. Lamination is partially demarcated by carbonaceous detritus. The unit shows BI 0.

B) Trough cross-stratified sandstone with abundant sub-rounded mudstone rip-up clasts and resistant siderite nodules (probably derived from eroded mudstone). Unit shows BI 0.

C) Trough cross-stratified sandstone with abundant sub-rounded mudstone rip-up clasts and resistant siderite nodules (probably derived from eroded mudstone). Unit shows BI 0.

D) Trough cross-stratified sandstone with spherulite siderite demarcating foresets. Spherulitic siderite indicates a potential terrestrial source. Unit shows BI 1, with fugichnia (fu).

E) Sandstone with current ripple lamination. Laminae are demarcated by carbonaceous detritus. The unit shows BI 1, with possible cryptic bioturbation and fugichnia (fu).

F) Sandstone with aggradational current ripple lamination. Laminae are demarcated by carbonaceous detritus. Unit shows BI 0.
3.8 Facies 8: Coal

Sedimentology

Facies 8 consists of coal. Coals vary from black to dark grey, depending upon the proportion of intercalated sandstone, siltstone and/or mudstone constituents (Figure 3.11). The coal typically has a dull luster, locally alternating with slightly brighter layers, and bears minor cleating. Organic contents increase upward from organic-rich sandstones to true coal. Coals are crudely bedded from a macroscopic perspective. Most occurrences of Facies 8 overlie rooted examples of underlying facies (commonly sandstones or mudstones of Facies 9). Horizontal fractures are common and may give the coal a crudely stratified appearance. Beds are generally less than 50 cm thick.

Ichnology

No ichnological structures are associated with this unit.

Interpretation

Facies 8 formed from the accumulation of compacted plant material and organic matter, such as peat. Cleating indicates that the coal was derived from wood debris. Coal may appear within any given unit, but unless it overlies Facies 9, it is likely allochthonous wood, which was deposited rather than formed from vegetative growth in situ. An allochthonous origin excludes it from Facies 8. Coal formation generally takes place in association with poorly drained soils, and occurs near or within floodplains, lakes, estuaries, quagmires, lagoons, delta plains, and coastal plains.
Figure 3.11  Facies 8: Coal

A) Coal displaying rare cleats and a dull luster.

B) Coal, well bedded, showing variable luster and maceral contents.

C) Coalified wood perched on a slightly leached surface with no rootlets. Such coaly material is allochthonous and does not constitute Facies 8.
3.9 Facies 9: Rooted Mudstones, Siltstones and Sandstones

Sedimentology

Facies 9 consists of mudstones, siltstones and sandstones that contain abundant rootlets (Figure 3.12). Sandstones are fine to coarse grained, moderately well sorted and may be interbedded with siltstone and mudstones. Rootlets are commonly preserved as casts or as carbonaceous material. The unit is generally 20 cm to 1.0 m thick. Mudstones and siltstones locally possess pedogenic slickensides, characterized by their shiny (glossy to waxy) appearance with variable orientations. Convolute bedding is locally common. The facies contains carbonaceous or coalified material in variable abundances, and has a bleached (or leached) appearance. Spherulitic siderite, and siderite nodules are locally abundant.

Ichnology

BI varies from 0-2 with sporadically distributed trace fossils. Trace fossils include Naktodemasis, Planolites, and very rare Skolithos.

Interpretation

Rootlets are indicative of plants that occupied a subaerially exposed substrate. Mudstones and siltstones with pedogenic slickensides are indicative of sediment compaction associated with prolonged subaerial exposure (Collinson, 1996). The trace fossil Naktodemasis is also taken to be the dwelling/foraging structure of terrestrial beetles, consistent with a setting prone to subaerial exposure (Smith et al., 2008). Siderite precipitation is favoured by reducing conditions associated with a high water table and the accumulation organic matter. Leached substrates commonly occur as acidic pore water dissolves cations (Collinson, 1996).
Figure 3.12 Facies 9: Rooted Mudstones, Siltstones and Sandstones

A) Muddy sandstone with common *Naktodemasis* (Nk), and common siderite preserved as nodules and spherules (black arrows). Unit shows BI 3.

B) Sandstone with abundant coal debris, rootlets and rare *Planolites* (P). Unit shows BI 1.

C) Silty mudstone with abundant carbonaceous material and very small rootlets. Mudstone beds have pedogenic slickensides owing to compaction around cutains, typical of incipient paleosols. Unit shows BI 0.
CHAPTER 4: FACIES ASSOCIATIONS

4.1 Facies Associations

In the previous chapter, the Grand Rapids Formation and Upper Mannville Group were subdivided into 9 depositional facies. These facies were separated on the basis of recurring lithologies, physical sedimentary structures, ichnological characteristics (bioturbation intensity, trace fossil diversity, etc.), and lithologic accessories observed within cores located across the study area (Table 4.1). When taken individually these depositional facies, have interpretational limitations. It is, therefore, important to view these facies in relation to one another, both vertically and laterally prior to assigning an environmental interpretation. Facies associations comprise recurring groups of facies that are genetically or environmentally related, and form the underpinning of facies analysis and paleoenvironmental interpretation (Reading and Levell, 1996). A facies succession consists of a series of genetically related facies that are arranged vertically in a somewhat predictable manner (Walker, 1992; Reading and Levell, 1996). A facies association encompasses both vertical and spatial recurring groups of genetically related facies, as evaluated by facies successions in cores and their mapped distribution within a study area (Walker, 1992; Reading and Levell, 1996). This distinction is important; facies associations lead to more coherent environmental interpretations. A single facies may occur in multiple facies associations if the depositional process responsible operates in several environments. For example, trough cross-stratified and current-ripple laminated sandstones (Facies 7) can occur in any environment characterized by traction sediment transport as a result of unidirectional flow. Environments containing Facies 7 could include the upper shoreface, fluvial systems, delta complexes, and tidal channels, etc. It is, therefore, important to include an examination of overlying and underlying units, in addition to the lateral equivalents of the facies succession.
Lithologs and core photographs are included throughout this chapter in order to show the recurring facies successions that comprise the facies associations. Figure 4.1 contains the legend for the lithologs used.
4.2 Facies Association 1: Open-Coast, Mixed-Influence Prodelta to Delta Front

FA1 records recurring coarsening-upward successions, made up of (in order) Facies 2b/2c, 3, 6, and locally 9 (see Chapter 3 and Table 4.1). The mudstone-prone heterolithic units of Facies 2b and Facies 2c reflect subaqueous deposition. Facies 2b is dominated by siltstone and mudstone with lenticular-bedded sandstone layers. Oscillation-generated structures, normally graded beds with sharp or erosional contacts, rare convolute bedding, abundant synaeresis cracks, and rare carbonaceous debris are all common, and are characteristic of deltaic deposition. Mudstones that commonly drape sandstone layers indicate fluctuating sedimentation rates, elevated water turbidity and clay flocculation. Sporadic bioturbation and laminated-to-burrowed fabrics suggest variable energies and episodic sedimentation rates. Graded siltstone to mudstone layers with scoured contacts, locally containing synaeresis cracks and soft-sediment deformation, may be characteristic of hyperpycnal discharge during river freshet. Thin, fine-grained turbidites are dominated by Bouma intervals D and E (TDE), indicating low-concentration flows transporting mainly silt- and clay-sized particles.

Bioturbation intensities in Facies 2c are typically very low (BI 0-2). The paucity of suspension-feeding structures and an increased proportion of inferred deposit-feeding structures may indicate elevated water turbidites near the sediment-water interface (Moslow and Pemberton, 1988; Gingras et al., 1998; MacEachern et al., 2005). Increased levels of water turbidity in deltaic settings may be attributed to hypopycnal mud-plumes from fluvial discharge, as well as through rapid flocculation of clay during the mixing of fresh and marine water (Reading and Collinson, 1996). Heightened turbidity levels tend to: 1) effectively reduce the ratio of food resources to suspended sediment; and 2) clog the delicate filter-feeding apparatuses of infaunal organisms. As a result, deposit-feeding behaviours are favoured over suspension/filter feeding in these settings (Moslow and Pemberton, 1988; MacEachern et al., 2005; MacEachern et al., 2007a). Common facies-crossing trace fossils near the top of beds are indicative of opportunistic organisms that are capable of colonizing an environment rapidly, are tolerant of stressful environments, and employ r-selected population dynamics, wherein a
population grows faster than the resources available to maintain it (e.g., Slobodkin and Sanders 1969; Remane and Schlieper 1971; Grassle and Grassle 1974; Croghan 1983; Knox 1986; Barnes 1989). This living strategy results in lowered diversities, high abundances, and a prevalence of facies-crossing trace fossil suites (e.g., Planolites, Teichichnus, Cylindrichnus; cf. MacEachern and Gingras, 2008 for a summary). Trace fossils recording the activities of organisms considered less tolerant of stress include Rhizocorallium and Phycosiphon (Figure 4.2). The juxtaposition of facies-crossing trace fossil suites and more stable suites indicates that physico-chemical stresses were present, but that the environment was not persistently so. This is characteristic of deltaic deposits in more marine environments; nevertheless, the ichnological characteristics of Facies Association 1 indicates that fully marine conditions were never achieved. Facies 2c is gradationally overlain by Facies 3.

Individual bedsets in Facies 3 are typically normally graded from sandstone to mudstone, indicating waning-energy conditions. Facies 3 (Figure 3.5) also contains rare micro-HCS with thin, intervening organic-rich mudstones that drape the sandstone layers. Sandstone beds contain oscillation-ripples, rare current-ripples, occurrences of horizontal planar parallel lamination, and combined-flow ripples, indicating a mixture of wave processes and unidirectional currents. Facies 3 contains trace fossil suites that suggest less suspended mud occurred in the water column, permitting some suspension-feeding behaviours. Common synaeresis cracks are associated with the mudstone drapes, consistent with fluctuating salinities (Plummer and Gostin, 1981). Fine-grained turbidites are dominated by Bouma TDE cycles, with very rare T_CDE and T_CE divisions. Bioturbation is sporadically distributed, burrowing intensities are variable, and trace fossil suites show considerable ranges in diversity. Nevertheless, suites are impoverished overall in comparison to those of Facies 2b, indicating heightened stress. Facies 3 is gradationally overlain by Facies 6.

Facies 6 contains HCS-dominated sandstones with rare synaeresis cracks in the uncommon intervening mudstone layers. Aggradational current ripples are very rare, and indicate periods of rapid deposition. Spherulitic siderite, nodular siderite, and organic debris are locally common and point to a nearby terrestrial sediment source. Bioturbation intensities range from BI 1-4, with mudstones more susceptible to burrowing. Diversities
decrease markedly in Facies 6, and ichnological suites consist entirely of facies-crossing elements, suggesting the prevalence of physicochemical stresses. Facies 6 is locally overlain by more proximal deltaic intervals, including fluvial deposits and coals (Facies 8) of the delta plain. Facies 9 contains abundant coalified material and both nodular and spherulitic siderite. The trace fossil *Naktodemasis* (Smith *et al.*, 2008; possibly a variant of *Taenidium*) is locally preserved, and is interpreted to be the result of burrowing terrestrial beetles, consistent with subaerial exposure.

Pinstripe bedding reflects suspension sediment fallout. Normal grading indicates waning flow. Oscillation ripples and thin tempestites indicate a wave and storm influence. These beds are commonly draped by dark claystone layers of probable fluid-mud origin. The relatively common occurrence of navichnia (sediment-swimming behaviour; cf. Gingras *et al.*, 2007) supports the rapid deposition of fluid muds, leading to soupy substrates (Lobza and Schieber, 1999). Common fugichnia reflect episodic and rapidly emplaced sediment. Synaeresis cracks are widely regarded to form in response to changing and generally reduced salinities, inducing clay shrinkage (Plummer and Gostin, 1981).

Localized sporadic distributions of bioturbation, relatively low trace fossil diversities, low bioturbation intensities, and generally diminutive trace fossils preserved within FA1 attest to stressful environments. Such stresses are interpreted to reflect deltaic conditions, including turbidite emplacement, high sedimentation rates, periods of lowered salinity, and tempestite emplacement (e.g., Beynon and Pemberton, 1992b; Pemberton and MacEachern, 1997; Gingras *et al.*, 1998; Gingras *et al.*, 1999; Gingras *et al.*, 2002a; Gingras *et al.*, 2002b; Buatois *et al.*, 2005; Gingras *et al.*, 2005; MacEachern *et al.*, 2005; Boyd *et al.*, 2006; MacEachern *et al.*, 2007a; MacEachern and Gingras, 2008; Bann *et al.*, 2008; MacEachern and Bann, 2008).

Navichnia are consistent with a setting prone to rapid clay flocculation and soupy substrates. Navichnia occur in Facies 2b, Facies 2c, Facies 3, and within the rare mudstone interbeds of Facies 6.

Synaeresis cracks are preserved in Facies 2b, 2c, and 3 with sporadically distributed ichnogenera (Figure 4.2) considered typical of more marine conditions (e.g.,
Rhizocorallium and Phycosiphon. These variations occur at the bed scale and indicate periods of reduced salinity in an otherwise stable less salinity-stressed basin. Such short-lived salinity reductions within a marine basin are attributed to the effects of river discharge at the coast (see MacEachern et al., 2005; MacEachern et al., 2007a). River floods may result from either seasonality in fluvial discharge or from marked increases in precipitation, such as commonly accompany large storms.

Trace fossils considered more typical of stronger marine influence, such as Rhizocorallium and Phycosiphon are rare (Figure 4.2), indicating that salinities may have increased during ambient conditions. Although indicative of more marine conditions compared to units of FA2, FA3 and FA4, the overall characteristics of the basin point to general salinity reduction.

Deformation processes affect the prodelta and delta front, primarily as a result of high sedimentation rates, as well as from storm and wave action. Ichnological characteristics within the prodelta are variable and depend upon the relative interplay of river, storm, wave, and tide processes (MacEachern et al., 2005; MacEachern and Bann, 2008; Bann et al., 2008).

The delta front lies in shallower water, and records the interaction of fluvial and basinal processes (e.g., tides, waves and storms). The interaction of these processes results in a variety of discrete subenvironments, including interdistributary bays, terminal distributary channels (with or without mouth bars), and shallow-water delta-front shorelines. At the distributary mouth, river flow expands laterally and vertically, decelerates, and deposits sediment (Elliott, 1986; Collinson and Thompson, 1989). Depending on the relative strength of basinal and fluvial processes, a delta-front environments may possess slump deposits, sandy delta-front turbidites, tidal bedding, and HCS or SCS associated with storms.

Clay can be deposited through flocculation and settling on sand layers from buoyant (hypopycnal) sediment plumes, and/or from hyperpycnal discharge at the distributary mouth. This multiplicity of interacting processes results in a complex, dynamic environment.
The processes operating in deltaic settings create stressful living conditions for organisms, including salinity fluctuations, heightened turbidity, event sedimentation, fluid mud deposition, and reduced oxygen. A brief summary of organism responses to these stresses will be discussed. For a more in depth discussion, see MacEachern et al. (2005), MacEachern et al. (2007a), MacEachern and Bann, (2008). Salinity stresses result in trace fossil suites that are attributable to the brackish-water ichnological model, described in comprehensive detail in the literature (e.g., Beynon et al., 1988; Beynon and Pemberton, 1992b; Gingras et al., 2002b; Buatois et al., 2005; Gingras et al., 2005; MacEachern and Gingras, 2008). High-turbidity conditions, such as those characterizing many delta-front environments, result from persistent introduction of hypopycnal buoyant mud-plumes, rapid clay flocculation, and fluid mud deposition.

### Table 4.1 Recurring facies discussed in Chapter 3.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Lithological Description</th>
<th>Primary Features</th>
<th>Secondary Features</th>
<th>BH</th>
<th>Trace Fossils</th>
<th>Ichnofacies</th>
<th>Depositional Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>6. Wave-ripple to HCS sandstone</td>
<td>Erosionally amalgamated sandstone. May have rare mudstone beds with wave ripples. Rare wave-rippled sandstone.</td>
<td></td>
<td></td>
<td></td>
<td>No Ichnofacies identified</td>
<td>Sandstone deposited as suspension settling or as bioclastic mud.</td>
<td>Deposition above the wave base. Variable water salinities. Deposition above the wave base. Overall brackish-water conditions. Deposits identified by wave processes. Event related deposits. Variable water salinities, brackish-water common. Predominantly buried products.</td>
</tr>
<tr>
<td>7. Current ripple to trough cross-stratified sandstone</td>
<td>Current ripple to trough cross-stratified sandstone. Sandstone as either stringers or lenses.</td>
<td></td>
<td></td>
<td></td>
<td>No Ichnofacies identified</td>
<td>Sandstone deposited as suspension settling or as bioclastic mud.</td>
<td>Deposition above the wave base. Variable water salinities. Deposition above the wave base. Overall brackish-water conditions. Deposits identified by wave processes. Event related deposits. Variable water salinities, brackish-water common. Predominantly buried products.</td>
</tr>
</tbody>
</table>

Trace fossil legend: Ch=Chondrites; cb=crystal burinature; Cy=Cylindrichnus; D=Diplocraterion; fa=fugichnia; G=Graptolites; Li=Lingulichnus; Lo=Locomia; N=nakodensia; na=naviculina; Pa=Palaophycus; Ph=Phycosphor; Pl=Planolites; R=Rhizocorallium; r=rotolites; R=Russelia; S=Spinichnium; S=Scolichnus; T=Tichichnus; Th=Thalassinoidea.
Figure 4.1 Legend for core lithologs.

These processes result in lowered bioturbation intensities, reduced trace fossil diversities, and a general paucity of ichnogenera attributable to suspension-feeding infauna (e.g., Moslow and Pemberton, 1988; MacEachern et al., 2005; MacEachern et al., 2007a; MacEachern and Gingras, 2008). Event sedimentation includes tempestites, turbidites, grain flows, and crevasse splays. Emplacement of event beds has a pronounced effect on benthic organisms and, as a result, their traces. Ichnological characteristics depend upon the conditions of the environment prior to the event, the nature of the event itself, and conditions immediately following the event. For example, pre-event conditions may favour ichnological suites attributable to the *Cruziana* Ichnofacies, while the event-suites may consist of elements of the *Skolithos* Ichnofacies, creating a composite suite (Pemberton and Frey, 1984; Vossler and Pemberton, 1989; MacEachern et al., 2007a).

Fluid mud deposition occurs in settings prone to high suspended-sediment loads, coupled with the mixing of marine and freshwater. When initially deposited, soupground...
conditions are created. Soupground conditions favour surface grazing, mobile deposit feeding, and sediment swimming behaviours (Lobza and Schieber, 1999; MacEachern and Gingras, 2008). The conditions creating reduced oxygenation have long been debated. One model suggests that depletion of oxygen at the sediment-water interface may occur as a result of the breakdown of organic carbon supplied by phytodetrital pulses in water columns with poor circulation (Wignall and Pickering, 1993). Current models of organism responses to oxygen depletion have not been subjected to rigorous testing however, and tend to focus on 3 main points: 1) impoverishment of trace diversity; 2) reduction of ichnogenera sizes; and 3) decreasing depth of infaunal tiering (Martin, 2004).

Summary:

FA1 records a coarsening- and shallowing-upward succession (see Chapter 3 and Table. 4.1). This succession corresponds to the most marine-influenced, open-coast environments of the Upper Mannville Group and Grand Rapids Formation. The succession, nevertheless, indicates generally brackish-water conditions, though less markedly so than successions lying further toward the east. FA1 successions comprise mudstone-prone heterolithic intervals with variable bioturbation intensities (Facies 2b and 2c), overlain by interbedded mudstones and sandstones (Facies 3), and capped by HCS-dominated sandstones (Facies 6). Facies 9 is locally preserved and contains leached sandstones and mudstones with abundant rootlets, spherulitic and nodular siderite, and may be locally burrowed with Naktodemasis. Sandstones may contain current ripple lamination. Successions are variable with respect to sandstone content, and range from 10% near the base to virtually 100% at the top. Successions vary from 8-12 m in thickness. The base of the succession generally sits on a transgressive surface of erosion (TSE) or a marine flooding surface (MFS) (see Chapter 5).

FA1 shows a succession that progressively changes from predominantly low-energy conditions, in which suspension-sediment settling alternates with weak storm agitation and thin, fine-grained turbidite emplacement, to high-energy accumulation of sandy tempestites. This recurring facies association is well expressed in the core of well 10-05-69-21W4 (Figures 4.2 and 4.3).
The sedimentological and ichnological characteristics of FA1 indicate subaqueous deposition under variable energy regimes. FA1 coarsens- and sands-upward, supporting proximal facies (Facies 3 and 6; interpreted to lie above fair-weather wave base) overlying distal facies (Facies 2b and 2c; positioned below fair-weather wave base). Most of the sandstones within FA1 were deposited by oscillatory processes (i.e., waves and storms). The localized presence of trace fossils considered less tolerant of physicochemical stress (e.g., Rhizocorallium, Phycosiphon and Chondrites), suggests periods of somewhat stronger marine influence (cf. Gingras et al., 2007; and MacEachern et al., 2007a; MacEachern and Gingras, 2008). These conditions can be found in deltaic environments.

FA1 is dominated by basinal processes associated with storms and waves. Secondary overprinting influences appear to be attributable to fluvial processes. These secondary processes include fluid mud deposition, synaeresis cracks, high sedimentation rates, and an abundance of terrestrially derived materials (e.g., organic detritus, and spherulitic siderite). More intensely burrowed horizons probably occurred when sedimentation rates were temporarily lowered, and river discharge reduced.

The characteristics outlined above provide compelling evidence for deposition within a prodelta (Facies 2b, and 2c) and delta front (Facies 3 and 6) complex prograding into a marine-influenced (though generally brackish), open-coast environment. Facies Association 1 is more commonly preserved in the western portions of the study area.
Figure 4.2 Trace-fossils typical of more marine conditions, identified in basinal and prodelta deposits of FA1.

A) Burrowed mudstone and siltstone showing BI 4-5 with abundant, diminutive *Planolites* (P), *Chondrites* (Ch), *Teichichnus* (T), *Phycosiphon* (Ph), isolated *Siphonichnus* (Si) and *Palaeophycus* (Pa).

B) Inset of (A). Trace fossils include *Phycosiphon* (Ph), *Teichichnus* (Te), *Siphonichnus* (Si), *Chondrites* (Ch), and *Palaeophycus* (Pa).

C) Normally graded siltstone and mudstone with interbedded oscillation rippled sandstone, forming wavy bedding. Sand beds are commonly mantled by mudstone. Common synaeresis cracks (syn) are present. Robust *Rhizocorallium* (Rh), are associated with *Teichichnus* (Te), *Planolites* (P), and *Phycosiphon* (Ph). The juxtaposition of the more marine trace fossils with impoverished trace fossil suites and synaeresis cracks indicates generally reduced but fluctuating salinities, periodically sufficiently saline to permit some the introduction of some marine organisms.

D) Inset of (C). Trace fossils include *Phycosiphon* (Ph) and *Rhizocorallium* (Rh) alternating at the bed scale with synaeresis-bearing units (syn).

E) Normally graded siltstone and mudstone with interbedded oscillation rippled sandstone forming wavy bedding. Sand beds are commonly mantled by mudstone. Synaeresis cracks (syn) are common. Trace fossils include robust *Rhizocorallium* (Rh) with associated *Planolites* (P) and *Phycosiphon* (Ph).

F) Inset of (E). Trace fossils include *Phycosiphon* (Ph) and *Rhizocorallium* (Rh).
Figure 4.3 Core litholog of Well 10-5-69-21W4 exhibiting FA1.
Figure 4.4 Box shot of well 10-05-069-21 W4; 384-402.3m.
Figure 4.4 exhibits an overall coarsening- and sanding- upward succession of prodelta mudstones (Facies 2b,c) and delta-front deposits (Facies 3 and 6), capped by delta plain deposits (Facies 9). Facies 2b consists of pervasively burrowed, oscillation rippled sandstones in wavy bedded composite bedsets. Oscillation ripple lamination and normally graded beds indicate waning energy conditions associated with storms and waves. High bioturbation intensities (BI 3-5) are interpreted to reflect periods of lowered rates of sedimentation. The unit contains trace fossils that are deemed to record the activities of animals less tolerant of stress; particularly intolerant of lowered salinity (e.g., *Rhizocorallium*, *Phycosiphon*, and *Chondrites*). Facies 2c has low bioturbation intensities and contains abundant navichnia and fugichnia, indicating periods of rapid sedimentation. Normally graded beds with scoured basal surfaces are common. The facies contains both marine trace fossils (e.g., *Rhizocorallium*, and rare *Phycosiphon*), and facies-crossing structures (e.g., *Planolites*, and *Teichichnus*). Facies 3 gradationally overlies Facies 2c. Facies 3 consists of oscillation-rippled and micro-HCS sandstones and normally graded beds. Synaeresis cracks are pervasive and commonly alternate at the bed scale with intervals containing more marine trace fossils. Facies 6 gradationally overlies Facies 3. Facies 6 consists of oscillation-rippled and micro-HCS sandstone, with common carbonaceous detritus demarcating laminae. Bioturbation intensities are low (BI 0-2), and ichnological suites are dominated by structures produced by suspension feeding organisms. Facies 9 overlies Facies 6. Facies 9 is made up of sandstones and mudstones and contains abundant nodular and spherulitic siderite, rootlets, carbonaceous debris, and soft-sediment deformation. Bioturbation is sporadically distributed.
4.3 Facies Association 2: Bay-Head Delta

Facies Association 2 (FA2) consists of a shallowing and coarsening upward succession composed of (in order) facies 2b, 1, 2a, and 6/7 (Figure 4.4 and 4.5, Table 4.1). Interbedded sandstone and mudstones of Facies 2b vary in thickness. Facies 2b contains higher proportions of mudstone to sandstone with rare oscillation-ripple lamination and micro-HCS generated by oscillation processes. Current-ripples are commonly draped by mudstone, or may be overlain by laminated siltstone and mudstone forming sandy turbidites, that are dominated by thin Bouma T_{DE} cycles with rare T_{CDE} and T_{CE} divisions. Thin (2-5cm) convolute bedding is rare and is resultant of high sedimentation rates. Synaeresis cracks record a reduction of salinity leading to clay shrinkage. Sharp based sandstone laminae commonly grading into mudstone are common, recording waning energy conditions. Siderite nodules are locally common indicating a potentially terristem derived sediment source. Facies 2b has the highest bioturbation intensity (BI 0-5, typically 3-4) (Figure 3.3) and is sporadically distributed. Sporadically distributed bioturbation intensities reflect high, yet variable, sedimentation rates. Trace fossil suites are of low diversity, commonly containing less than 3 ichnogenera, are typically diminutive, and contain facies crossing ichnogenera. Common traces include *Cylindrichnus, Gyrolithes, Planolites, Teichichnus, navichnia, and fugichnia*. No trace fossils more typical of marine settings were observed within the facies. These ichnological characteristics are consistent with brackish-water settings (Beynon and Pemberton, 1992b; Gingras et al., 2002a; Gingras et al., 2002b; Bann et al., 2004; Buatois et al., 2005; MacEachern et al., 2007a; MacEachern and Gingras, 2008).

Facies 2b is gradationally overlain by Facies 1.

Facies 1 consists of thick laminae of structureless mudstone with rare, thin siltstone laminae (Figure 3.1). Mudstones are commonly fissile and contain thin (1-3cm) siderite cemented layers. Bioturbation intensities are low 0-1, trace fossil diversity is low, dominantly containing navichnia, *Planolites*, and fugichnia. Navichnia and fugichnia are common in settings with high sedimentation rates. Oscillation-ripple lamination is very rare and is only present near the top of the facies as it transitions to overlying facies suggesting the unit shallows upward. Facies 1 grades into Facies 2a.
Facies 2a is lenticular bedded, and contains oscillation-ripple lamination mantled by mudstone and siltstone (Figure 3.2). Synaeresis cracks are variable in abundance, and record reduced salinity. Aggradational oscillation-ripple lamination indicates rapid sedimentation rates. Rare current and combined flow ripple lamination is locally common. Bioturbation intensity is low (0-2) and structures are limited to simple feeding behaviours, escape structures and rare sediment swimming indicating a stressed setting. Burrows are commonly sand filled and include Planolites, Skolithos, Teichichnus, fugichnia, and navichnia. Teichichnus, fugichnia, and navichnia, indicate high sedimentation rates. Abundant mudstone and siltstone couplets within Facies 2a are commonly normally graded, and drape oscillation-ripple laminated sandstones indicating waning energy conditions. Facies 2a is gradational or sharply overlain by a complex mix of Facies 6 and Facies 7.

The uppermost facies records a complex combination of oscillatory processes (Facies 6), and current processes (Facies 7). Aggradational forms of both current and oscillation-ripple lamination records high sedimentation rates (Figure 3.9). Locally preserved convolute bedding associated with micro-faults likely indicate rapid sediment loading. The localized presence of Diplocraterion, are generated as organisms readjust burrow openings to be near the sediment-water interface, further indicate that high sedimentation rates were common (Gingras et al., 2007; MacEachern et al., 2007a) (Figure 3.9). These two facies are not interbedded nor appear to interfinger. Rather, processes that dominate each facies occur within the same unit, suggesting multiple processes occurred at once.

In FA2, depositional energy varies from low-energy suspension settling to high-energy oscillation and unidirectional current processes. This recurring facies association is expressed in the cored interval 06-21-059-10W4 (Figure 4.5 and 4.6).

Summary
Facies association 2 (FA2) corresponds to deposits of a bay-head delta prograding into a brackish-water basin. Bay-head deltas are similar to river dominated deltas but may be differentiated ichnologically and sedimentologically. Bay-head deltas may develop in wave-dominated estuaries, lagoons and bays. These environments may have
characteristics making them indistinguishable from one another. Water salinities may be persistently brackish depending on the level of fluvial input and its accessibility to the open-marine realm. Wave and tidal processes may also be present in bay-head delta settings depending on the morphology of the bay, estuary or lagoon. Bays may be enclosed or semi-enclosed to the open-marine realm. Bay-head deltas generally consist of a shallowing and coarsening upward succession. Energy conditions within bay-head deltas increase landward as fluvial processes begin to dominate. Bay-head delta successions may overlie alluvial deposits, or more typically, bay deposits (van Heerden and Roberts, 1988; Reading and Collinson, 1996; Olariu and Bhattacharya, 2006).

The succession coarsens and sands upward with proximal facies (Facies 3 and 6/7) overlying distal facies (2b, 1 and 2a). The ichnology of Facies Association 2 shows reduced and sporadic bioturbation intensities, sporadically distributed ichnogenera, and reduced trace fossil diversities characteristic of brackish-water suites (Beynon and Pemberton, 1992b; Gingras et al., 2002a; Gingras et al., 2002b; Bann et al., 2004; Buatois et al., 2005; MacEachern et al., 2007a; MacEachern and Gingras, 2008). Trace fossil suites are dominated by deposit-feeding structures, and a paucity of suspension-feeding structures. These characteristics are an indication of physicochemical stress, attributable to both fluctuating salinity and high sedimentation rates. Trace fossil suites commonly contain facies crossing forms (e.g., Rosselia, Gyrolithes). Notably absent are ichnogenera deemed sensitive to physicochemical stresses (e.g. Phycisiphon, Rhizocorallium). This indicates that the environment was persistently stressed in comparison to FA1, which was only periodically stressed, and was dominated by marine processes.

Facies deposited in shallow water (6/7) have a complex combination of oscillation and current processes. Current processes typically dominate. Horizontal planar parallel lamination is locally preserved indicating high flow velocities. More basinward facies (Facies 2b, 1, and 2a) have low energy, mixed processes, or are dominated by oscillation processes (waves and storms). Estuaries show similar energy conditions in the central basin (low, mixed energy) and bay-head (river processes) (Dalrymple et al., 1992). The presence of navichnia in mudstones throughout the succession indicates soupy substrates occurred as a result of rapid clay flocculation and deposition. Carbonaceous detritus, and
spherulitic siderite indicates a terrestrial sediment source consistent with deltaic sedimentation. Thick, largely unburrowed mudstone accumulations in Facies 1 indicate rapid sediment deposition. High sedimentation rates are commonly associated with deltaic environments (Moslow and Pemberton, 1988; MacEachern and Pemberton, 1992; Gingras et al., 1998; Bann et al., 2004; MacEachern et al., 2005; MacEachern et al., 2007a). Such conditions could reflect switching of the main sediment plume.

Facies Association 2 contains an overall reduction of bioturbation intensities upward as energy conditions and sedimentation rates increase. Turbidites are more common within FA2 than in FA1, and may indicate that sediment gravity flows are more common. Additionally, current generated structures can be observed more basinward, and landward reflecting an increased fluvial influence in comparison with FA1.

Differentiating bay-head delta deposits (FA2) from sandy brackish-bay (FA3) deposits can be challenging, as the two often occur in close proximity. However, the overall reduction of trace fossil diversity, reduction of bioturbation intensities, interbedded turbidites, common presence of current generated structures, and suggestion of higher sedimentation rates in FA 2 aid in distinguishing the two deposits. A more in depth discussion of distinguishing these deposits will be addressed in FA3.
Figure 4.5 Core litholog for well 6-21-059-10w4 showing FA2.
Figure 4.6 exhibits FA2 which records an overall coarsening- and sanding-upward succession of distal bay-head delta front sandstones and mudstones (Facies 2b and 1) gradationally overlain by lenticular bedded, oscillation-rippled sandstones and mudstones (Facies 2a) and sharply overlain by proximal delta front sandstones (Facies 6 and 7) (Figure 3.9). Facies 2b consists of thin Bouma T_{DE} cycles with rare T_{CDE} and T_{CE} divisions. Finer grained intervals have a high bioturbation intensity (BI 3-5) and consist of diminutive, facies crossing ichnogenera (e.g., *Rosselia* and *Gyrolithes*). Orange siderite cemented zones, and spherulitic siderite is common, indicating a terrestrial sediment source. Facies 1 contains thick, apparently structureless mudstones with thin siltstone laminae. Common trace fossils include fugichnia and navichnia indicating high sedimentation rates, and deposition of fluid mud. As sandstone content increases, Facies 1 passes gradationally into Facies 2a which contains abundant oscillation-ripple lamination, and rare current-ripple lamination often draped in siltstone and sandstone couplets. Bioturbation is sporadically distributed with low bioturbation intensities (BI 0-2). Facies 6 overlies Facies 2a and contains a complex mix of current and oscillation generated structures. Aggradational forms of these structures are common, indicating high sedimentation rates. Trace fossils include rare *Diplocraterion* and fugichnia.
4.3 Facies Association 3: Brackish-Water Bay

Facies Association 3 consists of (in order) Facies 2b, 1 (locally), 4a or 4b, 6 and is locally capped by Facies 9 and 8 (Figures 4.6 and 4.7, Table 4.1). Local variations occur as a result of physicochemical stresses and variable sedimentation rates associated with river-dominated delta lobes. FA3 typically ranges from 4-18m thick, and averages 10m thick. Facies 2b consists of greater than 70% mudstone and siltstone. Oscillation-ripples and micro-HCS are commonly preserved where bioturbation intensities are sufficiently low. Bioturbation intensities range from BI 2-5. Burrowing is sporadically distributed within facies 2b (Figure 3.3). Trace fossils include Gyrolithes, Cylindrichnus, Skolithos, Planolites, Teichichnus, rare Lingulichnus, navichnia and fugichnia. Facies 1 locally overlies Facies 2b. This facies is commonly poorly preserved, and can be entirely broken up with only siderite-cemented zones remaining intact. Facies 4a and 4b sharply overlie Facies 1. Facies 4a is largely unburrowed (BI 0-2), and consists of more than 60% sandstone. Sandstones are commonly flaser bedded, and contain oscillation-ripple lamination or micro-HCS. Mudstones and siltstones are commonly normally graded, and contain rare synaeresis cracks. Common trace fossils in Facies 4a include Planolites, Skolithos, fugichnia, and rare Arenicolites. Facies 4b (Figure 3.7) is broadly sedimentologically similar to Facies 4a (Figure 3.6), but tends to be more intensely burrowed (BI 1-5) and has a higher trace fossil diversity. Trace fossils include Cylindrichnus, Gyrolithes, diminutive Rosselia, Planolites, Skolithos, fugichnia, and Arenicolites. Facies 4a and 4b are typically sharply overlain by Facies 6. Facies 6 is commonly heavily oil stained or oil saturated, making identification of biogenic and physical structures challenging. Spherulitic siderite is locally common within both facies. Facies 6 is dominated by oscillation-ripples and HCS (Figure 3.9). Bioturbation intensities are low (BI 0-2), with suites dominated by Skolithos, Gyrolithes, Arenicolites, fugichnia, and rare Planolites. Bioturbation intensities are low (BI 0-2). Common trace fossils include Skolithos, Gyrolithes, Planolites, and fugichnia. This unit is commonly overlain by Facies 9, which consists of sandy mudstones that may be soft-sediment deformed. Facies 9 contains rootlet structures, spherulitic siderite, nodular siderite, and abundant carbonaceous debris. Facies 8 coals gradationally overlie Facies 9. This
recurring facies association is displayed in the cored interval of well 07-01-062-02W4; (Figures 4.7 and 4.8).

Summary

Facies Association 3 (FA3) is interpreted to correspond to brackish-water bay deposits, and is the most commonly observed facies association within the study area. Bays are either restricted or open to the marine realm. Brackish-water conditions in bays and estuaries are the result of 1) limited interaction with the marine realm and/or 2) heightened fresh-water input associated with rivers. Brackish-water conditions characterize many marginal marine environments, including bays, bay-head deltas, and estuaries (drowned river valleys). Deposits of these environments are not easily distinguished from one another. Bay deposits, like estuaries and lagoons, generally record coarsening-upward successions, from mudstone-dominated central bay deposits, to sandstone-dominated bay margins. Bays and estuaries can be dominated by tide or wave processes, and can also display river influences.

The sedimentological and ichnological characteristics of FA3 indicate subaqueous deposition under variable energy regimes. The facies association coarsens and sands upward reflecting deposition of proximal facies (Facies 4a/4b and 6) over distal facies (Facies 2b). Oscillatory processes (i.e., waves and storms) deposited most of the sandstones within FA3. Normally graded siltstone to mudstone layers indicate that suspension settling processes were more typical than rapid clay flocculation. Some rapid clay flocculation occurred locally, as indicated by the presence of naviculina.

Fine-grained units typically have high bioturbation intensities (BI 2-5). Trace fossil suites consist of diminutive ichnogenera, and display low diversities. Ichnogenera consist mostly of facies-crossing elements (e.g., Gyrolithes and Cylindrichnus), and contain no (or very rare) ichnogenera deemed to record the activities of organisms sensitive to physicochemical stresses (e.g., Spiroraphe, Helminthopsis). Such trace fossil suites are characteristic of brackish-water conditions, indicating that deposition did not occur within a normal marine environment (Beynon and Pemberton, 1992b; Gingras et al., 1999; Bann et al., 2004; Buatois et al., 2005; Gingras et al., 2005; MacEachern et al.,
Synaeresis cracks are locally common and may be pervasive, further supporting the interpretation that salinities were reduced.

Abundant micro-HCS and oscillation-ripples owing to storm-induced episodic deposition and concomitant variations in substrate consistency contributed to environmental stresses. This storm and wave influence is mostly observed in proximal settings within the succession. The tops of tempestites display higher bioturbation intensities, reflecting post-event recolonization (Pemberton and Frey, 1984; MacEachern et al., 2007a). Mudstones deposited between tempestites display variable bioturbation intensities and typically grade upward from sandstone to mudstone, indicating waning-energy conditions and moderate storm frequencies. The setting is dominated by opportunistic trace fossil suites, making the distinction between pre- and post-event trace fossil suites challenging. This is a common characteristic of brackish-water settings (MacEachern et al., 2007a).

Sporadic trace fossil distribution, overall increased bioturbation intensities, rare fugichnia, and very rare navichnia coupled with HCS and oscillation-ripples, indicates sedimentation rates were relatively low, with periods of high sedimentation associated with storms.

Facies 9 and 8 contain common rootlets, spherulitic siderite, pedogenic slickensides, and coal. This indicates local subaerial exposure, and/or a low water table, coupled with an accumulation of organic debris.

The above features indicate that FA3 was deposited in a brackish-water embayment or possibly an estuary. Northern localities typically show higher wave and storm influences, as HCS becomes more common, successions become erosionally amalgamated, and interbedded burrowed mudstones become thinner. The typical FA3 succession is broken into 3 parts; 1) central bay deposits (Facies 2b and Facies 1); 2) bay margin deposits (Facies 4a/4b, and Facies 6) (excluding the bay-head delta [FA2]), and 3) rare swamp/marsh deposits/accumulations (Facies 9 and 8). Shallow, proximal facies are not commonly preserved as a result of erosion due to base level changes.

Differentiating brackish-water bay deposits of FA3 from FA2 bay-head delta deposits is challenging. Similar conditions exist in bays as in bay-head deltas, as a result
of their close depositional proximity. The two facies associations exhibit similar characteristics, reflecting comparable conditions in more basinward positions where fluvial influences decrease or are absent. In both deposits, trace fossils are diminutive, suites are of low diversity and are dominated by facies crossing ichnogenera indicating reduced salinities (Beynon and Pemberton, 1992b; Gingras et al., 2002a; Gingras et al., 2002b; Bann et al., 2004; Buatois et al., 2005; MacEachern et al., 2007a; MacEachern and Gingras, 2008). FA3 deposits possess higher bioturbation intensities and higher trace fossil diversities, which record slightly lower stresses than in FA2. Sedimentation rates are interpreted to be lower in FA3 than in FA2. This is likely attributable to reduced fluvial influences in the bay compared to the bay-head delta per se. Fluvial input commonly leads to elevated sedimentation rates, heightened water turbidities, and reduced salinities. Additionally, the influence of basinal processes (storms and waves) tends to decrease as fluvial processes begin to dominate, as in the bay-head delta systems of FA2.
Figure 4.7 Core litholog from well 07-1-062-2W4; 323.6-335.0 m showing FA3.
Facies Association 3 consists of a coarsening- and sanding-upward succession, reflecting proximal environments (Facies 4a, and 4b) overlying distal environments (Facies 2b and 1). Wave and storm influences increase upward, and overall bioturbation intensities decrease. Facies 6 is not present in this example. Facies 2b exhibits the highest bioturbation intensities and trace fossil diversities. Facies 1 is poorly preserved, yielding little sedimentological or ichnological data. Facies 4a and 4b sandstones were largely deposited by oscillation processes (waves and storms). Mudstones were deposited via suspension settling during waning- or low-energy conditions. Facies 4a is weakly burrowed (BI 0-1). Facies 4b displays higher bioturbation intensities (BI 2-3). Trace fossils throughout the succession are diminutive, with suites being dominated by facies-crossing forms. Synaeresis cracks are locally common. Facies 9 gradationally overlies Facies 4b, and contains abundant rootlets and carbonaceous debris. Facies 8 is very thin and gradationally overlies Facies 9.
4.4 Facies Association 4: Distributary Channels

Facies Association 4 is sharp-based, fines upward, and consists of (in order) Facies 7, 5, 9, and 8. Facies 7 consists of trough cross-bedded sandstone and commonly contains intraformationally derived mudstone and thinly laminated mudstone and sandstone rip-up clasts interpreted indicating flow velocities sufficiently high to transport cohesive blocks of sediment (Figure 3.10). Oil saturation is commonly high, making identification of biogenic and physical structures difficult. Facies 7 grades into Facies 5. Facies 5 contains inclined heterolithic stratification (IHS) with current-rippled sandstone beds and indicates marked fluctuations in energy levels (Thomas et al., 1987; Smith, 1988; Gingras et al., 2002b; Choi et al., 2004; Pearson and Gingras, 2006). Sandstones were deposited by current processes, while the mudstones were deposited as suspended sediment either that flocculated or fell from suspension. Facies 5 is not preserved in all cases and possesses variable proportions of mudstone and sandstone. Bioturbation intensities vary considerably (BI 0-4), but are typically BI 0-2 consistent with variable sedimentation rates. Trace fossils include rare Planolites, Arenicolites, fugichnia, and Skolithos. Traces fossils are diminutive, sporadically distributed, form low-diversity suites and are consistent with existing brackish-water models (Beynon and Pemberton, 1992b; Gingras et al., 2002a; Gingras et al., 2002b; Bann et al., 2004; Buatois et al., 2005; MacEachern et al., 2007a; MacEachern and Gingras, 2008). Facies 9 consists of mudstones and sandstones with common rootlets, spherulitic siderite, pedogenic slickensides, and carbonaceous detritus were likely subaerial exposed. Facies 8 (coal) gradationally overlies Facies 9. Facies 9 and 8 are not encountered in all localities.

Facies Association 4 records channel-fill deposits, shallowing and fining upward into point-bar and marsh deposits. This succession is exhibited in core of well 04-33-62-6W4 (Figures 4.9 and 4.10).

Discussion

Facies Association 4 (FA4) is interpreted to correspond to distributary channel deposits. Distributary channels are common in the delta plain, and are dominated by fluvial processes although they can be influenced by tidal processes (Reading and
Collinson, 1996). Unidirectional flow tends to predominate in these settings. Distributary channels are broadly similar to fluvial channels, but unlike them, distributary channels also can be influenced by basinal processes, they are subject to greater degrees of switching and avulsion, and they may be shallower (Reading and Collinson, 1996). Distributary channels operate as the primary source of sediment input into the deltaic regime. The presence of distributary channels is important in establishing that a shallow-marine unit was deposited under deltaic conditions. In comparison with fluvial-dominated deltas, wave-dominated deltas tend to preserve few distributary channels (Reading and Collinson, 1996; Olariu and Bhattacharya, 2006). Distributary channels tend to form fining-upward successions, and typically record the main channel, point bars and deposition from suspension into overbank areas. In deltaic settings, gradients are low and sedimentation rates are high, resulting in aggradation, compaction and subsidence; such conditions serve to induce distributary channels to change direction. Between the channels, bays, floodplains, lakes, tidal flats, marshes and/or swamps may occur.

FA4 successions fine-upward from sandstone into units consisting of thinly laminated mudstones and siltstones (locally pedogenically altered), and coal. The close proximity of bay deposits (Facies Association 3) indicates that the channels migrated near a marginal marine environment.

This ichnological suite of FA4 is characteristic of brackish-water environments. This indicates the presence of brackish-water influences within channels. Distributary channels can be tidally influenced even where tidal ranges are low, especially where gradients are low on the delta plain. In the Mississippi river, for example, low tidal ranges penetrate distributaries during low river stages and large areas of the lower delta plain are permanently covered by brackish water, 50 km from the coast (Gould, 1970).

The overall decreasing grain-size and bedform scale sedimentary structures upward through the succession is consistent with lateral migration and/or abandonment of distributary channels. Facies 5 consists of inclined (IHS) with variable sandstone: mudstone ratios. IHS overlying trough cross-stratified sandstone is taken to record lateral accretion of point bars within the distributary channels. Many of these IHS units are dominated by mudstone. Suspended sediment load carried by rivers commonly mix with
saltier basin waters enhancing clay flocculation, resulting in rapid deposition of fluid mud at the bed. Identification of IHS solely in core is uncertain. However, the succession this part of the succession is still interpreted as lateral point bar accretion. A detailed summary of IHS and its occurrence can be found in (Thomas et al., 1987). Soft-sediment deformation is common within the facies, especially in the mudstone-dominated mudstone heterolithic intervals. The lack of gravel- and pebble-sized sediment, coupled with the presence of mudstone-dominated IHS units indicates that river sediments were very fine-grained, with a sandy bedload and a high suspended load.

In some localities, FA4 contains successions solely consisting of Facies 7 and contains abundant intraformational mudstone clasts that are subangular, laminated, and crudely imbricated. These clasts are interpreted to have been derived as a result of large blocks of sediment, that slid or fell, from the cutbank, and accumulated with little erosion or reworking. Some mudstone rip-ups may also have been supplied from eroded mud interbeds of the IHS successions themselves, particularly during elevated flow velocities within the channel (e.g., flood discharge).
Figure 4.9 Core litholog for the well 04-33-062-6W4 showing FA4.
Facies Association 4 consists of a fining upward succession. Facies 7 lies at the base of the succession and consists of trough cross-stratification with abundant mudstone rip-up clasts. Facies 5 overlies Facies 7. Facies 5 is dominated by inclined heterolithic stratification (IHS), current-ripple lamination and local convolute bedding. Facies 9 locally overlies Facies 5. Facies 9 consists of mudstones with abundant rootlets, carbonaceous detritus, and spherulitic siderite. The succession is overlain by bay deposits of FA3.
CHAPTER 5: STRATIGRAPHY

The integration of sedimentological and ichnological characteristics have led to the identification of 9 depositional facies (see Chapter 3 and Table 4.1). The recurrence of these facies in predictable vertical successions and spatial distributions has permitted the grouping of these depositional facies into 4 facies associations, which were discussed in Chapter 4. The analysis of 56-cored wells, coupled with the interpretation of more than 250 geophysical well logs permit the identification of major stratigraphic surfaces. This database has been employed to produce 2 depositional strike-parallel stratigraphic cross-sections, and 3 depositional dip-oriented stratigraphic cross-sections. These cross-sections illustrate the spatial and stratigraphic distributions of facies associations throughout the Grand Rapids Formation and Upper Mannville Group. These cross-sections constitute a key element in the evaluation of along-strike variations in the depositional character of the study interval in the study area.

5.1 Stratigraphic Surfaces

The Grand Rapids Formation consists of 6 parasequences, each of which are bounded above and below by marine flooding surfaces (MFS) (Figure 5.1). Locally, allocyclic surfaces are challenging to differentiate from the less regionally extensive autocyclic surfaces present within the Grand Rapids Formation and Upper Mannville Group. Allostratigraphic surfaces are typically used in regional correlations, and include both erosional and non-erosional discontinuities (Walker, 1992). The Joli Fou Formation unconformably overlies the Grand Rapids Formation, separated by a regionally extensive transgressive surface of erosion (TSE) or ravinement surface. This surface is used as the datum for cross-sections throughout the study area. Although an unconformity is not an ideal datum, owing to possible paleotopographic relief associated with its generation, it is
deemed acceptable for correlations in this study. Firstly, wave-generated transgressive surfaces of erosion (wave ravinement surfaces) tend to display limited topographic relief. Given the general low-gradient coastal profile during the Albian, when the Grand Rapids was deposited, this TSE is considered by most workers to be an essentially planar, gently seaward-dipping surface (e.g., Hayes et al., 1994). This surface should be essentially horizontal and planar along depositional strike. Greater concern surrounds its utility in dip-oriented sections, because TSE dip seaward, and will distort correlations in more distal positions (cf. MacEachern et al., 1998) when made horizontal. Nevertheless, the dip-oriented sections only extend 90 km basinward, and distortion is deemed to be minimal. Additionally, the TSE at the base of the Joli Fou is present in every well and easily recognizable in core and on geophysical well logs. There are no surfaces within the Grand Rapids Formation that are sufficiently continuous or are taken to be originally horizontal. Another possible datum (Base of Fish Scales marker) lies above the unconformity and may correspond to a maximum flooding surface. Such non-erosional surfaces are generally more reliable as low angle surfaces with minimal relief, but this occurs over 80 m above the Grand Rapids Formation. Post-depositional compaction and differential subsidence following the Grand Rapids but prior to accumulation of the Base of Fish Scales cannot be removed and does not lead to accurate reconstruction of the original depositional architecture of the study interval.

In the uppermost parasequences of the Grand Rapids Formation, discontinuities are characterized by bay or deltaic deposits, sharply overlying thin coals and organic-rich bay-margin or delta-plain deposits. Locally, central-bay deposits overlie delta-front successions or other proximal facies; such facies juxtapositions are regarded as minor (autocyclic) flooding surfaces (FS). Most of the internal discontinuities within the study interval constitute minor flooding surfaces, and could not be mapped across the study area. These minor flooding surfaces probably separate individual delta lobes, and probably reflect autocyclic abandonment of the lobes.
5.2 Stratigraphic Cross-Sections and Their Interpretations

The analysis of cores and geophysical logs forms the basis of identifying and correlating the major stratigraphic discontinuities within the Grand Rapids Formation and Upper Mannville Group. These surfaces are located above and below prograding parasequences, and have been employed to define the architectural framework of the 3 dip-oriented cross-sections and 2 depositional strike-oriented (paleo-shore-parallel) cross-sections across the study area (Figure 5.2). The cross-sections seek to reconstruct the architectures and spatial distributions of depositional complexes in the study area, and therefore employ a stratigraphic datum (i.e., stratigraphic cross sections). In addition to correlating the bounding discontinuities, the stratigraphic cross-sections also show vertical and spatial distributions of facies associations throughout the study area.

The depositional strike-oriented (paleo-shoreline parallel) cross-sections were constructed to show along-strike variations in the depositional character of the units, manifest by the changing influences of wave, storm, and river processes on the facies associations. These cross-sections, in particular, show the relationship of bay-head deltas with their associated bay deposits. The transition from rivers feeding into semi-restricted bay to wave- and storm-dominated open-coastal settings as one moves from east to west is also demonstrated. Core control within the central portion of the basin is poor, and the surfaces identified in cores were identified on the corresponding logs. This surface was then carried to adjacent wells where logs exist but lack core data.

The depositional dip-oriented stratigraphic cross-sections display correlations from landward positions seaward, providing the spatial limits and depositional geometries of the parasequences.

Depositional Strike (Paloeshoreline Parallel) Stratigraphic Cross-Section A-A’

Cross-section A-A’ is oriented roughly parallel to the uppermost Grand Rapids parasequence trend (i.e., paleoshoreline parallel), and is the most basinward cross-section in the study area (Figure 5.2). The cross-section establishes correlations over a distance of 412 km, and consists of 21 geophysical well logs as well as 4 cored intervals (Figure
5.3). Not all well logs are shown on the figured cross-section; rather only those illustrating the depositional framework (and changes in the architecture) are employed for the sake of presentation (so-called “skeletonised” cross-sections). Additional logs (not shown on the cross-section) were, nevertheless, used to establish the correlations and refine the interpretations. The cross-section shows gamma-ray well log signatures for the selected wells. The bounding surfaces are considered autocyclic (minor flooding surface) and have limited lateral extents.

In the western portion of the basin, wave- and storm-dominated delta successions are thick and extensive. Although core data is very limited in this part of the cross-section, the thick, overall coarsening-upward successions, and the basinward position relative to other wave- and storm-dominated deltas are consistent with the wave- and storm-dominated interpretation. Few stratigraphic surfaces were identified in cores within this cross-section. Successions gradually thin eastward and pass into bay-head delta deposits. Bay-head delta deposits are thin, have limited lateral extents and pass into brackish-water bay successions east in the study area. Wave- and storm-dominated deltas are identified in logs by a serrated gamma-ray response (90+ API) near the bottom, with the response decreasing (<60 API) and becoming blocky upward, as mudstone contents decline. This gamma-ray profile reflects a succession of fine-grained prodelta deposits coarsening upward into erosionally amalgamated HCS of the delta front, and capped by a minor flooding surface. One core does penetrate the succession, aiding the interpretation and correlation. In comparison with cross-section B-B’, the succession contains generally less blocky responses, consistent with decreasing sediment calibres and thinning of the successions basinward. Bay-head deltas are identified on logs by a similar high gamma-ray response decreasing to a low response, reflecting the overall decrease in mudstone content upward (coarsening upward and sanding upward), but successions are thinner and laterally limited in comparison to wave- and storm-dominated successions further to the west. Bay-head delta deposits are not as widespread in this cross-section, which is consistent with a more basinward position for the line of section. Bay complexes yield highly serrated gamma-ray profiles near the base and with the
gamma-ray response decreasing toward the top. The low gamma-ray response intervals are thicker than those of the bay-head deltas, and less than those of the wave- and storm-dominated deltas of the open coast. This may be a reflection of a relatively stable sedimentation rate and autocyclic delta lobe switching not readily affecting the brackish-water bay. Thinner deltaic cycles may indicate that lobe switching was more frequent within the bay-head delta system in comparison to within the wave- and storm-dominated delta complexes lying to the west.

The stratigraphic cross-section shows wave- and storm-dominated deltaic lobes passing along strike into bay-head delta and bay complexes in the east. Poor core control makes the nature of this transition uncertain.

The Grand Rapids Formation is overlain regionally by a transgressive surface of erosion (TSE), which represents the unconformity between the Grand Rapids Formation and the Joli Fou Formation. The surface shows limited erosional relief and is regarded as a wave-ravinement surface.
Figure 5.1 Stratigraphic surfaces visible in core of the Grand Rapids Formation

A) 11-30-64-4W4 344.5-347.5 m
   Core photograph displays the Upper Mannville Group/Joli Fou Formation unconformity. Grand Rapids sandstones are overlain by shales of the Joli Fou Formation, separated by a regionally extensive transgressive surface of erosion (TSE) generated by wave ravinement.

B) 6-1-66-18W4 435.0 m
   This sample exhibits bioturbated sandy mudstones of a brackish-water bay, overlying delta plain deposits. This contact marks the MFS, placing distal sediments over more proximal deposits. Trace fossils include *Rosselia* (R), *Planolites* (P), and *Cylindrichnus* (Cy).

C) 6-20-59-10W4 463.0-466.0 m
   Photograph of bay-head delta sandstones (FA2) overlain by sporadically burrowed sandy mudstones and siltstones of a brackish-water muddy bay. The bounding surface correspond to a marine flooding surface (MFS) displaying little or no erosion.

D) 6-20-59-10W4 463.5.0 m
   Close-up photograph of inset box in photograph C, exhibiting thinly laminated mudstones and sandstones overlying more proximal, horizontal to inclined, planar parallel laminated sandstones of the bay-head delta front. The surface separating them corresponds to the MFS. Trace fossils include *Planolites* (P), navichnia (na), and *Diplocraterion* (D).
Figure 5.2 Location map showing the stratigraphic cross-section distributions and their orientations. Cross-sections consist of two depositional strike-parallel (A-A' and B-B'), and three depositional dip-oriented cross-sections (C-C', D-D', E-
Depositional Strike Cross-Section A-A’

West

Datum

18031.9 m 20745.1 m 27660.7 m 52940.7 m 26871.8 m 33399.2 m


TSE


A’

Datum

29221.3 m 26570.0 m 21321.1 m 9303.9 m 24559.0 m 14205.6 m 21700.3 m


TSE

Total Cross-Section Width = 412.06 km

Cored Interval 20 m Vertical Scale Marine Shale Wave- and Storm-Dominated Delta Bay-Head Delta Brackish-Water Bay Distributary Channel Minor Flooding Surface Transgressive Surface of Erosion (TSE)
Figure 5.3 Stratigraphic cross-section A-A' is an along-strike oriented transect through the uppermost parasequences of the Upper Mannville Group and Grand Rapids Formation. The datum is the wave ravinement surface marking the contact between the Mannville Group and the Joli Fou Formation. The vertical line through the logs corresponds to 75 API (out of 150) and serves as a point of reference for gamma-ray response. The transect covers 412 km. The western portion of the basin consists of wave- and storm-dominated deltaic successions, and passes into bay-head deltas and brackish-water bays towards the east. Successions are thickest in the wave- and storm-dominated deltas and in the bay complexes. The wave- and storm-dominated delta successions are not taken to reflect a single deltaic system, but rather the area has been categorized as FA1 based on log responses and core data. The area reflects time-averaged progradation and aggradation of multiple wave- and storm-dominated deltas.
Depositional Strike (Paleoshoreline Parallel) Stratigraphic Cross-Section B-B’

Depositional strike parallel stratigraphic cross-section B-B’ is the most proximal along-strike correlation within the study area. Core control, although sub-optimal, is superior to that of cross-section A-A’. The cross-section consists of 9-cored intervals and 24 geophysical well logs, and establishes correlations over 464 km (Figure 5.4). Over 70 geophysical well logs were used to refine the interpretation, but a skeletonised version is presented here. It is important to note on this cross-section that there is an especially long distance between wells 06-21-060-1W5 and 11-24-059-16W4 (approximately 152 km). The facies association lying between these two wells is interpreted as wave-and storm-dominated delta deposits along an open coast, and are laterally very extensive. Similar to the wave-and storm-dominated deposits identified in cross-section A-A’, these reflect an area dominated by deltaic sedimentation along an open coast, but do not define a single deltaic system. The dataset does not permit the high-resolution differentiation of discrete deltaic complexes, but rather illustrates that wave-and storm-influences were stronger in the west than in the east, which formed broad progradational parasequences.

The southeastern part of the study area is dominated by coarsening-upward successions of brackish-water bay deposits that progressively interfinger with bay-head delta deposits westward. Autocyclic flooding surfaces were identified within the deltaic complexes, and have limited lateral extents. One MFS was identified (yellow line) but also has a limited along-strike extent. The brackish-water bay deposits are generally thicker than the bay-head delta deposits.

Bay-head delta deposits are thin and discontinuous. Each succession feathers out from sandstone to mudstone, and terminates by downlap into the bay deposits. Distributary channels are identifiable on geophysical logs by their upward-increasing gamma-ray responses (<60API to >90 API). This response reflects a fining-upward succession of sandstones to mudstones. Bay-head delta successions grade progressively into wave- and storm-dominated deltaic successions in a westward direction, in like manner to that of cross-section A-A’.

Profiles for individual successions are similar to those illustrated in cross-section A-A’. There are notable differences, however, in the wave-and storm-dominated deltas.
The proximal gamma-ray response records overall thicker units than distal expressions, especially in amalgamated HCS units, which are indicated by the blocky low API values overlying serrated, high API responses of the prodelta. Bay complexes in the proximal setting tend to be thinner than those lying further basinward. Delta plain deposits have a serrated- to blocky appearance, and the API values may indicate a fining-upward profile.

Wave- and storm-dominated deltaic successions are typically thicker than the bayhead delta successions. Wave- and storm-dominated deltaic successions coarsen upward and pass laterally into intermittent delta-plain deposits westward, or into bay-head delta deposits lying to the east. The transition from wave- and storm-dominated delta successions into bay-head successions can be difficult to pinpoint. The cored interval in well 11-24-059-16W4 has been interpreted as FA1 (wave- and storm-dominated delta). The cored interval of well 06-20-059-10W4 has been interpreted as FA2 (bay-head delta). The area between these two cored intervals must possess a transition from more river-dominated conditions to wave-and storm-dominated conditions. Sandstones appear to thicken westward, and may indicate amalgamation of tempestites in the delta front. Distributary channels are not observed as commonly in the wave- and storm-dominated deltaic successions as they are in the bay-head delta deposits. This provides further support for wave and storm domination, because such deltas tend to possess fewer distributary channels than fluvial-dominated counterparts (Reading and Collinson, 1996). Autocyclic surfaces were the only identifiable boundaries within the cored intervals.

In the most westward part of the cross-section, successions become very thick with few identifiable stratigraphic breaks. Cored intervals from this part of the study area are dominated by erosionally amalgamated HCS, indicating marked wave and storm influences. Delta plain deposits are also commonly recorded in this part of the study area, consistent with the interpretation of a more landward position for the cross-section.
Depositional Strike (Shore Parallel) Cross-Section B-B’

West

7-10-60-20W5  7-13-60-19W5  8-18-60-17W5  4-27-60-15W5  7-19-60-14W5  10-24-60-13W5  2-25-60-12W5  5-10-61-7W5

Datum I

13284.4 m  11986.9 m  24581.4 m  5861.5 m  17951.1 m  9944.5 m  45312.9 m  12535.7 m

5-26-61-6W5  7-2-62-4W5  13-26-61-3W5  7-4-61-2W5  11-24-59-16W4  6-24-59-14W4  1-23-59-13W4

20418.6 m  19484.9 m  8842.1 m

East


11062.9 m  12998.2 m  12053.2 m  10942.5 m  10862.0 m  14105.2 m  23146.5 m  14368.8 m

Total cross-section width = 464.43 km

Sequence Boundary  Cored Interval  Vertical Scale  Bay-Head Delta  Brackish-Water Bay  Open Marine  Wave- and Storm-Dominated Delta  Delta Plain  Distributary Channel

Minor Flooding Surface  Transgressive Surface of Erosion (TSE)  Marine Flooding Surface
Figure 5.4 Depositional strike (shore parallel) cross-section B-B’ consists of 9 cored intervals and 24 geophysical well logs. The vertical line through the gamma-ray logs corresponds to 75 API (out of 150) and serves as a reference point. Bay-head delta successions are relatively thin in comparison to the wave- and storm-influenced deltaic complexes lying westward, as well as to the brackish-water bay deposits further eastward. A single MFS (Figure 5.1b) is identified (yellow line). This surface was identified in core 13-11-060-2W4 and correlated to nearby wells using geophysical wells logs.
Depositional Dip-Oriented Stratigraphic Cross-Section C-C’
Depositional dip-oriented stratigraphic cross-section C-C’ is a southwest-northeast transect, consisting of 16 geophysical logs and 2 cored intervals (Figures 5.6), and running roughly perpendicular to the inferred uppermost Grand Rapids Formation paleoshoreline. The cross-section establishes correlations across a length of approximately 100 km. The base of Joli Fou Formation/top Upper Mannville Group TSE is used as the datum. One MFS (Figure 5.1b) was identified in core, which separates brackish-water bay deposits from underlying wave- and storm-dominated delta deposits; which were also identified from the cores. Wave- and storm-dominated deltas are identified on logs by a serrated gamma-ray response near the bottom that decreases in API values and becomes blocky upward. This gamma-ray profile reflects a succession of fine-grained prodelta deposits coarsening upward into erosionally amalgamated HCS in the delta front, capped by a minor flooding surface. Bay complexes display very serrated gamma-ray responses near the base decreasing near the top, reflecting a coarsening-upward succession. The wave- and storm-dominated deltaic successions are considerably thicker than the bay deposits in this part of the study area.

Deltaic successions become finer grained basinward. Bay deposits are fairly uniform in thickness, become finer-grained basinward like the bay-head delta deposits, and onlap landward.

Depositional Dip-Oriented Stratigraphic Cross-Section D-D’
Stratigraphic cross-section D-D’ is a north-south transect, oriented roughly perpendicular to the inferred upper Grand Rapids Formation paleoshoreline (Figure 5.7). This cross-section consists of 18 geophysical well logs and 7 cored intervals, and covers a distance of about 91 km. Open-marine shales of the Joli Fou Formation unconformably overlie the Upper Mannville Group. This cross-section illustrates the overall progradation of the Grand Rapids Formation. The area dominantly consists of heterolithic bay-head delta deposits (FA2). Distributary channels are easily identified by their low gamma-ray responses near the bottom, which increases upward as interstitial clay and mudstone interbeds become more abundant. A fining-upward distributary channel is identified in the core of well 06-29-60-8W4, and is overlain by bay-head prodelta deposits, indicating
that the distributary channel preceded the lowstand event. The distributary channel and overlying bay-head delta deposits are separated by a minor flooding surface. Three MFS were identified in cored intervals (Figure 5.1) and correlated to nearby wells using logs.

Thick sandstone units that subend from the TSE/ SB unconformity at the base of the Joli Fou Fm are trough cross-stratified and locally contain mudstone rip-up clasts. On well logs, they are readily identifiable by their sharp bases, thick intervals, and very blocky gamma-ray responses with low API values. In core, these sandstones erosionally overlie bay-head prodelta mudstones (Figure 5.7). These thick sandstones are commonly heavily oil stained, making the identification of biogenic and physical structures challenging. It is unlikely that these thick sandstones are distributary channels associated with the bay-head deltas, because they are thick, widespread, and cut through most individual parasequences to prodelta and bay deposits, and subend from the unconformity acting as the datum. These sandstones are interpreted to reflect incised fluvial valleys cut into the top of the Grand Rapids Fm during a lowstand systems tract, prior to the TSE forming the base of the Joli Fou Formation. No elements of the Glossifungites Ichnofacies have been identified in association with these incised valley deposits. This may indicate that there was no depositional hiatus between the incision event and the accumulation of overlying sediments, that energy conditions were too high to permit organism colonization, or that the discontinuity was not exposed to marine inundation (i.e., the fill is fluvial). The unconformity between the Upper Mannville Group and base Joli Fou Formation represents a time gap, wherein the middle Albian is missing (Leckie and Smith, 1992). Bay-head delta mudstones locally overlie coals of the delta plain, indicating continued transgression.

Bay-head delta deposits have limited lateral extents, and terminate by downlap onto other bay-head delta successions. Bay-head delta successions coarsen upward and become finer-grained basinward, where they grade into brackish-water bay deposits. Minor flooding surfaces were identified and are interpreted to represent autocyclic lobe switching of these deltas. Brackish-water bay deposits associated laterally with them are likely interdistributary in origin.
Figure 5.5 Cored interval in the well 05-18-064-9W4; 424-431.5 m. Unit A is interpreted as upper delta front/delta plain deposits of a bay-head delta. Unit B comprises the prodelta of a bay-head delta. Unit C has been interpreted as a fluvial incised valley that subtends from the base Joli Fou Formation (TSE/ SB), and is considered part of a lowstand systems tract.
Figure 5.6 Depositional dip-oriented stratigraphic cross-section C-C' consists of 16 geophysical logs and 2 cored intervals. Vertical line through the gamma-ray log represents 75 API as a point of reference. Successions feather out basinward from sandstone to mudstone and terminate by downlap. A single MFS was identified (yellow line) in cored intervals and correlated to nearby wells using logs, and indicates deposition of brackish-water bay deposits over older wave- and storm-dominated delta deposits.
Figure 5.7 Depositional dip-oriented stratigraphic cross-section D-D' records bay-head delta progradation into brackish-water bays. Bay-head delta successions are thin and feather out basinward from sandstone to mudstone of the bays. Fluvial incised valleys subtending from the overlying unconformity are outlined with red and indicate the presence of a lowstand systems tract prior to regional transgression. Locality 06-29-60-8W4 contains a distributary channel that preceded the lowstand event. 3 MFS were identified (labelled with yellow lines) in core and correlated to adjacent wells using logs.
Depositional Dip-Oriented Stratigraphic Cross-Section E-E’

Stratigraphic cross-section E-E’ is a north-south transect that is oriented obliquely to the inferred uppermost Grand Rapids Formation paleoshoreline. The cross-section establishes correlations over 73.4 km, and consists of 13 geophysical logs and 5 cored intervals. Individual bay-head delta successions become finer-grained basinward and terminate by downlap. Bay deposits are identified in logs by their low API value serrated gamma-ray responses decreasing upward to a thin low-API block. These bay deposits appear to lie landward of bay-head deltas on the section, but this is a function of the cross-section’s oblique trend. Deltaic systems are, therefore, interpreted to have prograded north-northeast, whereas the cross-section transect is oriented roughly north-south. Two MFS were identified in core and separate bay deposits. Three prograding packages are identifiable, and each is likely the result of autocyclic lobe switching of the bay-head delta. No core penetrated these intervals, so the nature of the contacts separating them is uncertain. The red line indicates the bases of fluvial incised valleys associated with a lowstand systems tract. Incised valleys are identified on logs by a sharp decrease in their gamma-ray responses. On the cross-section, incised valleys directly overlie bay-head delta prodeltaic deposits. These incised valleys have the same approximate latitude (townships 64-66) as incised valleys identified in cross-section D-D’.

Bay-head delta deposits are identified on logs similarly to bay complexes; however, they have proportionally more sandstone layers (low API gamma-ray response) and are relatively thin. The similarities in logs of these two environments make it difficult to distinguish between them. This is addressed in the discussion section of Chapter 5.
Figure 5.8 Stratigraphic cross-section E-E’ is oriented obliquely to the inferred Grand Rapids Formation depositional-dip orientation. This oblique orientation results in brackish-water bay deposits appearing to lie in a landward position relative to the bay-head deltas. Two MFS (yellow lines) were identified in core and were correlated using logs. The three prograding packages likely represent autoecyclic lobe switching of the bay-head delta. The red outline indicates the base of fluvial incised valleys associated with a lowstand systems tract. Bay-head delta successions are thin and become finer-grained basinward, prior to terminating via downlap into the bay deposits.
5.3 Stratigraphy Discussion

The Grand Rapids Formation is interpreted to record brackish-water bay, distributary channel, and bay-head delta environments, with contemporaneous wave- and storm-dominated deltaic settings lying further to the west along depositional strike (undifferentiated Mannville Group). The cross-section illustrates that the western part of the study area was dominated by deltaic deposition as FA1, but likely do not represent a single deltaic system. The Grand Rapids Formation comprises 6 coarsening-upward parasequences, the uppermost 3 of which were analyzed in this study. Each parasequence is bounded by a marine flooding surface. Marine flooding surfaces (MFS) separate discrete delta complexes, and record periods of slower deposition, locally with subaqueous erosion. These surfaces are identifiable by distinct changes in trace fossil contents, corresponding to changes in salinity and/or increases in relative water depths above the stratigraphic surface. These surfaces can be correlated to nearby uncored wells through the identification of changes in the well log character, expressed as pronounced API value increases on gamma-ray logs that indicate an increase in clay lithologies associated with marine flooding. These surfaces have limited lateral extents, however, and are difficult to correlate for long distances, particularly into the deposits of the undifferentiated Upper Mannville Group. Further west, stratigraphic surface identification is problematic in successions consisting of stacked distributary channels in the undifferentiated Upper Mannville Group as well. Parasequence correlations are correspondingly challenging. Correlations through these stacked distributary channels were picked at the base of the lowest channel overlying an interpreted coarsening-upward succession. In some cases, as in well 10-24-60-13W5 of cross-section B-B’, core data aided correlations, although they are difficult to pick on adjacent logs and are shown as a facies change. Additional cored intervals through these units and their transitions might have yielded more confident correlations through the stacked channels and wave- and storm-dominated deltaic successions.

Correlations from the bay-head delta to bay complexes and the along-strike transitions from one to the other are difficult to delineate, because they have similar log responses. This is particularly evident in dip-oriented cross-section E-E’, where bay
deposits are more commonly identified than in the other cross-sections. Pin-pointing the change from bay-head delta prodeltaic mudstones to muddy central-bay deposits is challenging on logs because the responses for both units are similar and effectively, they grade into one another. Further complicating the analysis of this transition is the presence of fluvial incised valleys in cored intervals in the area, which cut out the uppermost bay-head delta and brackish-water bay parasequences. Core that penetrates further below the incised valleys could provide a better understanding of this transition. In core, the differences between these two fine-grained units are very subtle (see discussion in Chapter 4).

Fluvial incised valleys associated with lowstand systems tracts are identified within cross-sections B-B’, D-D’ and E-E’, and are truncated by the TSE formed by wave ravinement at the base of the Joli Fou Formation. This indicates that there is a sequence boundary below the incised valleys, which is amalgamated (or co-planar) with the TSE in interfluve areas. The incised valleys can be easily mapped in the eastern portion of the study area because of the anomalously thick nature of the sandstones.

The dominant wave-and storm influences on the coastline in the west produced an approximately linear coastline. In the east, these influences are mixed with fluvial processes creating an irregular and embayed coastline. The depositional strike transition from wave-and storm-dominated deltas to bay-head deltas is uncertain from the core dataset. The orientation of the coastline may have had a sheltering effect, minimizing the wave action in the embayments. Other workers have postulated that further basinward, a prograding barrier island complex acted as a buffer from waves and storms, creating the brackish-embayment southward (Leckie and Smith, 1992; Cant and Abrahamson, 1997). This is discussed further in Chapter 6.
CHAPTER 6: DISCUSSION AND CONCLUSIONS

6.1 Discussion

Sedimentological and ichnological data were collected from 56 cored wells of the Grand Rapids Formation and Upper Mannville Group, encompassed within a study area extending from Township 59, Range 1W4 to Township 69, Range 24W5. This analysis led to the identification of 9 recurring depositional facies. These facies are defined by their physical sedimentary structures, lithologies, bioturbation intensities, presence of particular ichnogenera, and overall trace fossil diversities. The depositional facies can be grouped into 4 recurring Facies Associations that reflect deposition within continental, brackish-water, and marine-influenced settings. The integration of these datasets with well log analysis and mapped distributions leads to an interpretation indicating that deposition along an irregular, semi-restricted, shallow, brackish-water embayed coast in the eastern portion of the study area. In the western portion of the study area, salinities appear to have been less brackish, wave- and storm-processes more predominant, and the coastal zone less embayed.

Identification of stratigraphic surfaces in the cored intervals, including non-erosional marine flooding surfaces (MFS), minor flooding surfaces (FS), transgressive surfaces of erosion (TSE), and fluvially incised sequence boundaries, were correlated using more than 250 geophysical logs of nearby wells. This enabled the construction of 5 stratigraphic cross-sections used to display the facies association distributions and sequence stratigraphic relationships of the uppermost Grand Rapids Formation and undifferentiated Upper Mannville Group parasequences.

Delta Progradation on Open-Coastal Shorelines Compared to Bay-Head Delta Progradation into Brackish-Water Bays

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The integration of sedimentology with ichnology in the facies analysis of the Grand Rapids Formation demonstrates predictable variations in the characteristics of deltaic sedimentation and their receiving basins. Distinguishing between deltas prograding into open-coastal basins of more marine character and those prograding into brackish-water settings could only be achieved through the integration of these data sets. Indeed, the processes that operate in these discrete deltaic scenarios are broadly similar. The main differences between these two depositional settings surround the combination of stresses placed upon organisms living in their respective environments. Both settings record stresses induced by elevated sedimentation rates and generally reduced salinity. However, when evaluating these, it is important to differentiate between scenarios in which stresses are only periodically imposed and those in which they are persistent.

Organisms living in settings where deltas have prograded into more marine-influenced, open-coast settings (FA1) are mainly stressed by elevated sedimentation rates coupled with periodic reductions in salinity. Such conditions may be associated with one another during periods of heightened river discharge. Heightened river discharge may occur seasonally or may accompany large storm events. FA1 is dominated by basinal processes associated with storms and waves, and the combination of storm frequency and/or storm intensity largely controls the biogenic fabric of the succession (e.g., Frey and Pemberton, 1984; Pemberton and MacEachern, 1997; MacEachern et al., 2007a). Secondary overprinting influences on FA1 are attributable to fluvial processes directly interacting with marine conditions. These secondary processes include clay flocculation and fluid-mud deposition, periodic salinity reductions indicated by the prevalence of synaeresis cracks, high sedimentation rates reflected by fugichnia and re-adjustment structures as well as soft-sediment deformation, and an abundance of terrestrially derived materials (e.g., organic detritus and spherulitic siderite). The localized presence of trace fossils considered to reflect the activities of organisms intolerant of physicochemical stress (e.g., *Rhizocorallium* and *Phycosiphon*), suggest that FA1 deltas experienced intermittent marine conditions or at least less markedly brackish-water conditions (cf. Gingras et al., 2007; MacEachern et al., 2007a,b; MacEachern and Gingras, 2008). Sporadically distributed bioturbation, relatively low trace fossil diversities, low bioturbation intensities, and generally diminutive trace fossils preserved within FA1
attest to stressed environments. In FA1, the main stresses are associated with tempestite emplacement, turbidite emplacement, high sedimentation rates, and periods of lowered salinity (cf. Beynon and Pemberton, 1992b; Gingras et al., 1998; Gingras et al., 1999; Gingras et al., 2002a; Gingras et al., 2002b; Buatois et al., 2005; Gingras et al., 2005; MacEachern et al., 2005; Boyd et al., 2006; MacEachern et al., 2007a; Bann et al., 2008; MacEachern and Gingras, 2008).

The ichnology of FA2 (bay-head delta successions) shows spatially variable bioturbation, reduced burrowing intensities, sporadically distributed ichnogenera, and reduced trace fossil diversities as well. Trace fossil suites are dominated by deposit-feeding structures, and typified by a paucity of suspension-feeding structures. These characteristics support conditions of physicochemical stress that are attributable to both reduced salinity, high sedimentation rates and elevated water turbidity. Trace fossil suites exclusively contain strongly facies-crossing forms (e.g., Planolites, Cylindrichnus, Gyrolithes, and Teichichnus); forms known to dominate in brackish-water regimes. Notably absent are ichnogenera deemed to record the activities of organisms sensitive to physicochemical stresses such as reduced salinity (e.g., Phycosiphon and Rhizocorallium). This supports the interpretation that the environments of FA2 were persistently salinity stressed, compared to the periodically imposed stresses of FA1.

Sandstones of FA2 were deposited by both current and oscillatory processes. Aggradational forms of both oscillation and current ripples support the contention that the setting was typified by rapid sedimentation. The juxtaposition of oscillatory- and current-generated structures shows that the setting was characterized by variable depositional processes. Current processes typically dominate the more proximal facies. Delta-front turbidites appear to be more common in bay-head deltas prograding into brackish-water basins. This may be the result of a greater ease of achieving hyperpycnal states, because there is less density contrast to overcome between the river water and the highly brackish water of the receiving basin (brackish bays of FA3). The introduction of suspended sediment in the river water can lead to hyperpycnal (denser) discharge.

The trace fossil suites of FA3 (brackish-water bay successions) consist of diminutive ichnogenera and display low diversities. Ichnogenera consist mostly of facies-crossing elements (e.g., Gyrolithes and Cylindrichnus) and contain no ichnogenera
deemed to record the activities of organisms sensitive to physicochemical stresses (e.g., *Rhizocorallium* and *Phycosiphon*). Such impoverished trace fossil suites are characteristic of brackish-water conditions (Beynon and Pemberton, 1992b; Gingras et al., 1999; Bann et al., 2004; Buatois et al., 2005; Gingras et al., 2005; MacEachern et al., 2007a; MacEachern and Gingras, 2008). Synaeresis cracks are locally common to pervasive, further supporting the interpretation that salinities fluctuated with some frequency. FA3 also contains abundant micro-HCS and oscillation-ripples, indicating that the setting was sheltered from open coast waves. Nevertheless, the incremental accumulation of such event beds would have contributed to environmental stresses on the faunal community.

**Distributary Channels**

Distributary channel deposits (FA4) within the Grand Rapids Formation occur in association with both the wave-and storm-dominated delta complexes and the bay-head deltas. The distributary channels that subtend from the TSE commonly overlie bay-head delta prodelta deposits and bay complexes, are thick and truncate the bulk of the underlying parasequences. This indicates that a relative sea-level lowstand occurred, causing the distributaries to become re-incised by fluvial processes. The base of these channels, therefore, represents a sequence boundary cut into the top of the Grand Rapids Formation. Later wave ravinement during the Joli Fou transgression truncated the tops of these fluvial infills, and locally amalgamated with the sequence boundaries in the interfluve areas to produce a FS/SB.

The distributary channels associated with delta complexes in wave-and storm-dominated settings are thinner, and occur at scales appropriate to the thicknesses of the parasequences. In most cases, they are cut into the delta-front deposits of the delta complexes. FA4 successions associated with the open-coast wave- and storm-dominated deltas of FA1 are uncommon, owing to the reduced number of distributaries in such systems. FA4 successions are more commonly associated with the bay-head delta complexes of FA2. Distributary channel deposits typically exhibit characteristics consistent with subaerial exposure, in that associated facies (e.g., Facies 8 and 9) contain abundant *Naktodemasis*, pedogenic modification, and coal development. Distributary
channels associated with bay-head deltas also contain more mudstone rip-up clasts and possible inclined heterolithic stratification (IHS) of tidal-fluvial point bars. Identification of IHS is problematic based solely on core; dip-meter logs, FMI logs, etc., lead to more convincing evidence of large-scale lateral accretion bedding. Nevertheless, FA 4 does indicate a succession consistent with channel, point bar, and overbank deposition. Evidence for subaerial exposure in bay-head delta distributary channels is rarely observed. The differences in channel character may indicate that channels were more stable (less prone to avulsion, switching and abandonment) in wave-and storm-dominated successions compared to the more laterally dynamic conditions associated with progradation of more river-influenced bay-head delta settings.

**Along-Strike Variations**

Brackish-water conditions appear to have been persistent and of lower overall salinity in the Grand Rapids Formation toward the eastern part of the study area. Bay successions (FA3) are the most commonly observed deposits, with associated bay-head delta (FA2) and distributary channel (FA4) deposits occurring in close proximity with one another. Wave- and storm-dominated deltas (FA1) occur only as far east as the 16-1-65-19W4 well (included in cross-section C-C'). Oscillatory processes are common to every succession except FA4, which is dominated by current processes. Wave- and storm-influences appear to increase westward within the study area. The nature of the transition from wave- and storm-dominated deltas into bay-head deltas is uncertain. The irregular and embayed coastline that appears to have dominated in the east may have provided a certain degree of shelter from open coastal waves and storms that characterized coastlines further west. Other workers have theorized that a barrier island chain lying further basinward (north) may have sheltered the eastern part of the coastline from large waves and storms, and led to a broad bay separated from the open-marine realm (Leckie and Smith, 1992; Cant, 1996). These barrier islands, if present, were not encountered in this study, and would have to have been located north of the study area. The generally brackish-water character of the basinal facies towards the west (though not so marked as those in the east) may suggest that the entire seaway was somewhat salinity reduced, and therefore a barrier may not have been required to shelter the eastern shorelines.
Freshwater influx from rivers feeding to an embayed shoreline might easily have led to pronounced and persistent salinity reductions along the eastern portion of the shoreline.

6.2 Conclusions

1. The uppermost parasequences of the Grand Rapids Formation can be characterized by nine depositional facies. The facies combined to form four recurring facies associations recording wave- and storm-influenced deltaic sedimentation (FA1), bay-head deltas (FA2), brackish-water bays (FA3), and distributary channels (FA4).

2. Grand Rapids Formation successions coarsen and shallow upward from mudstone-dominated units into sandstone-dominated units, which are bounded by marine flooding surfaces or transgressive surfaces of erosion.

3. Distributary channels (FA4) commonly subtend from a regional transgressive surface of erosion (TSE) cut by wave ravinement during the Joli Fou transgression. Deeply incised fluvial channels may record fluvial re-incision of distributaries, and record lowstand incision prior to the Joli Fou transgression. Other distributary channel successions occur in association with the delta complexes of FA1 and FA2. These successions reflect lateral migration and/or abandonment of distributary channels. Units interpreted as inclined heterolithic stratification (IHS) locally overlie trough cross-bedded sandstones, and record laterally migrating tidal-fluvial point-bar accretion in the channels.

4. Integration of the ichnological and sedimentological characteristics of the facies of these successions demonstrate that there are recurring features that can be used to distinguish between deltas prograding into less salinity stressed open-coast settings (FA1) and bay-head deltas (FA2) feeding into persistently brackish-water bays (FA3). Open-coast deltas of FA1 contain trace fossil suites that are low diversity, with diminutive ichnogenera, an abundance of structures that reflect opportunistic colonization, and highly variable bioturbation intensities (BI-0-5). Additionally, rare occurrences of trace fossils interpreted to reflect the activity of organisms intolerant of salinity induced stresses (e.g., *Rhizocorallium* and *Phycosiphon*) indicates that these environments were not persistently stressed and
showed greater marine influence. Bay-head deltas (FA2) in brackish-water bay settings contain broadly similar ichnological characteristics, but careful analysis shows that trace fossil diversities are more strongly reduced, bioturbation intensities are generally lower, ichnogenera are diminutive, and suites entirely lack trace fossils that are typical of organisms intolerant of salinity reduction. Additionally, delta-front turbidites appear to be more common in bay-head deltas of brackish-water basins, attesting to a greater tendency of distributary channels to achieve hyperpycnal conditions. Bay-head delta distributary discharge would require lower sediment loads in order to raise flow densities above those of the brackish water characterizing the bay.

5. Differentiating brackish-water bay deposits (FA3) from bay-head delta deposits (FA2) is challenging. Similar environmental conditions exist in bays as in bay-head deltas, as a result of their close proximity. Indeed, the two facies associations exhibit less contrast in more basinward positions where fluvial influences decrease, and the two effectively grade into one another. In both environments, salinities are persistently reduced. Bay successions of FA3 tend to show higher bioturbation intensities in distal facies and slightly higher trace fossil diversities than facies of FA2, records slightly lower stresses Bays show less marked temporal changes in depositional conditions, particularly with respect to salinity variations and depositional episodicity. Additionally, bay successions generally show slightly lower rates of deposition than the bay-head delta deposits of FA2. Most of these stresses are associated with fluvial-sediment influx, which is more prevalent in the bay-head deltas than in the bay per se.

6. Parasequences are progressively more wave- and storm-influenced from east to west. Ichnological suites suggest that salinities were subtly higher in a westward direction, though they never achieved fully marine levels. All ichnological suites in the study area display overall impoverishment and indicate brackish-water conditions.
CHAPTER 7: REFERENCES


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Appendices

Appendix A: Supplementary material is attached to this thesis document in the form of a CD-ROM disk. The disk contains a PDF of the core database and location map for the study area. PDF files Filename: Appendix A – Data