SEDIMENTOLOGY, ICHNOLOGY, AND STRATIGRAPHY OF THE SPARKY, WASECA, AND MCLAREN ALLOFORMATIONS, WEST-CENTRAL SASKATCHEWAN, CANADA

by

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ABSTRACT

The Lower Cretaceous Sparky, Waseca, and McLaren alloformations (Upper Mannville Group) of west-central Saskatchewan comprise an interval up to 60 m thick, consisting of weakly consolidated sandstones, shales, heterolithic bedsets and minor coals deposited in shallow-marine to coastal plain/delta plain environments. Thirteen facies are recognized. These facies are grouped into six spatially recurring facies associations. Facies Association 1 (FA1) corresponds to sediments deposited below fairweather wave base but above storm wave base. Facies associations 2 and 3 (FA2 and FA3) coarsen upward and represent the progradation of wave- and storm-dominated shorefaces as well as mixed river- and wave-influenced deltas, respectively. Facies Association 4 (FA4) commonly displays fining-upward successions, interpreted as distributary channel or fluvio-estuarine deposits, depending upon their stratigraphic context. Facies Association 5 (FA5) is broadly similar to FA2, but is ichnologically distinct. The succession is characterized by low-diversity, impoverished trace-fossil suites with variable bioturbation intensities that are interpreted to record deposition in shallow brackish-water bays. Facies Association 6 (FA6) successions are interpreted as coastal plain/delta plain deposits.

Upper Mannville strata can be separated into parts of two depositional sequences. The main deposits of the lower sequence comprise two highstand systems tracts (HST), corresponding to the Sparky Alloformation and the Lower Waseca Allomember. The base of the Lower Waseca marks the onset of a transgressive systems tract (TST). A maximum flooding surface (MFS) marks the end of transgression and the resumption of progradation for the remainder of the Lower Waseca. Following highstand progradation a relative base-level fall produced a subaerial unconformity, which marks the base of the upper sequence. Fluvial valley incision led to sediment bypass, and deposition of forced regressive and lowstand shoreface and delta complexes of the falling stage systems tract (FSST) and lowstand systems tract (LST) towards the northern part of the study area. TST accumulation is largely confined to estuarine infill of the incised valleys of the
Upper Waseca Allomember. The Upper Waseca is separated from the McLaren Alloformation by a maximum flooding surface (MFS). The overlying McLaren Alloformation marks a return to regional shoreline progradation, and corresponds to a highstand systems tract (HST).

**Keywords:** Mannville Group, Brackish Water, Deltas, Shorefaces, Ichnology, Sequence Stratigraphy, Lloydminster.

**Subject Terms:** Ichnology, Sedimentology, Stratigraphy, Geology
DEDICATION

To Mila, my little motivation pill.
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CHAPTER 1: INTRODUCTION

1.1 Introduction

The Lower Cretaceous Mannville Group in the Lloydminster area of Saskatchewan contains approximately 3 billion m$^3$ (19 billion barrels) of oil in place (Saskatchewan Energy and Resources, 2008). The deposits correspond to complex successions of well cemented to weakly consolidated sandstones, siltstones, mudstones, heterolithic bedsets of sandstone and mudstone, and minor coals. To better predict the position and distribution of sandstone reservoirs, it is critical to thoroughly understand the sedimentological, ichnological and stratigraphic characteristics of these strata. The purpose of this thesis is to provide a clearer picture of the depositional history of the upper part of the Mannville Group (Sparky, Waseca, and McLaren alloformations) within the Lloydminster area.

Identifications and interpretations of depositional successions are commonly made on the basis of sedimentological analysis coupled with regional correlations and mapping. When these data are integrated with ichnological data, the resulting depositional model facilitates the recognition and differentiation of the physico-chemical conditions at the time of sediment deposition and infaunal colonization. Such refinements in facies characterizations yield superior interpretations. With respect to ichnology, this is mainly because trace fossils can be evaluated as biogenic sedimentary structures recording organism behaviour (i.e., ethology), which is dictated by various physical, chemical processes operating within the depositional environment (e.g., wave energy, tidal flux, fluvial sediment input, oxygenation, salinity). Correspondingly, trace fossils are strongly facies controlled, and therefore are ideal for facies analysis (e.g., Seilacher, 1964; Frey and Pemberton, 1985; Pemberton et al., 1992; MacEachern et al., 2007; MacEachern and Bann, 2008).
Trace fossils are considered to represent evidence of organism’s behaviour. These behaviours are directly dictated by various environmental parameters and can be grouped into eight categories (Ekdale, 1985; Bromley, 1990; Gingras et al., 2007; MacEachern et al., 2007): 1) resting traces (cubichnia), 2) locomotion or crawling traces (repichnia), 3) grazing traces (pascichnia), 4) feeding traces (fodinichnia), 5) dwelling traces (domichnia), 6) traps and farming systems (agrichnia), 7) predation traces (praedichnia), and escape traces (fugichnia). It must be emphasized, however, that due to complexities in organism behaviour, some traces may reflect multiple ethologies. This is particularly true for biodeformational structures such as mantle and swirl structures (Lobza and Schieber, 1999). In soupy substrates, such as fluid muds, fine-grained deposits can commonly contain up to 70% water; correspondingly sediment-swimming (navichnia) is a preferred strategy for organisms occupying such substrates, and may represent a component of escape (fugichnia) or locomotion (repichnia). In such settings, overlap between these ethological groupings is unavoidable.

One of the greatest geological challenges in exploring for hydrocarbons in the Upper Mannville Group in Lloydminster area is differentiating deltaic successions from shoreface complexes. Both shoreface and wave-dominated delta deposits are characterized by wave- and storm-generated sedimentary structures. As a result, the preserved lithologies as well as most of the primary sedimentary structures are virtually identical (e.g., abundant HCS and SCS). This is particularly apparent in successions wherein storms have extensively reworked shallow water deposits, obliterating features distinctive of deltaic processes (e.g., DesRoche, 2008). Numerous researchers have recognized that organisms are extremely sensitive to environmental conditions, and therefore, their biogenic structures lend great insight into depositional controls on facies (e.g., Seilacher, 1967; Howard and Frey, 1973; Ekdale et al., 1984; Savrda and Bottjer, 1986; Pemberton et al., 1992; Beynon et al., 1998 Pemberton et al., 2001; Gingras et al., 2007; MacEachern et al., 2005, 2007a,b; Gingras et al., 1998, 2011). Deltaic environments are best differentiated from non-deltaic shallow-marine settings by recognizing the presence of direct fluvial-sediment input and the resulting fluctuations in environmental conditions. River-induced physico-chemical changes in the environment impart significant stress on infaunal organisms (e.g., Gingras et al., 1998, 2011). River-
derived stresses include high sedimentation rates, salinity fluctuations (locally seasonal) due to freshwater input, sediment gravity flow emplacement (including those that are hyperpycnal), elevated water turbidity, distributary flood discharges with accompanying phytodetrital pulses, and fluid-mud deposition (e.g., Moslow and Pemberton, 1988; MacEachern et al., 1999; 2005; Mulder et al., 2003; Bhattacharya and MacEachern, 2009). Such stresses affect organisms’ feeding strategies and their interactions with the substrate, leading to trace-fossil suites whose interpreted ethological implications depart from the archetypal “Seilacherian” ichnofacies that typify non-deltaic shorelines. Most commonly, suspension-feeding behaviours are generally suppressed within deltaic intervals, and most suites are dominated by deposit-feeding behaviours, although this depends on the degree of fluvial influence (Moslow and Pemberton, 1988; Coates and MacEachern, 1999, 2007; MacEachern et al., 2005). Deltaic successions typically show marked reductions in bioturbation intensities, sporadically distributed burrowed intervals, and overall impoverishment of ichnological diversities, relative to non-deltaic marine successions (e.g., Moslow and Pemberton, 1988; Raychaudhuri and Pemberton, 1992; Gingras et al., 1998; Coates and MacEachern, 1999, 2007; Bann and Fielding, 2004; McIlroy, 2004; Hansen and MacEachern, 2007; MacEachern et al., 2007a, b; Buatois et al., 2008; MacEachern and Bann, 2008; MacEachern et al., 2010).

Many investigations have indicated that most units within the middle and upper parts of the Mannville Group in Alberta were deposited in a brackish to brackish-marine water environments (e.g., Kauffman, 1984; Beynon et al., 1988; Beynon and Pemberton, 1992; Holmden et al., 1997a; 1997b; Ranger and Pemberton, 1997; Hubbard et al., 2004). Similar characteristics can also be observed within the Lloydminster area of Saskatchewan (MacEachern, 1984; Morshedian et al; 2009; Morshedian et al., 2011). This probably indicates that the basin never reached fully marine conditions during Mannville time. Generally, salinity reduction and fluctuation in salinity are two of the more persistent stresses within inshore marginal-marine settings, and are largely the result of the interplay of: 1) the amount of freshwater input from rivers and runoff from land; 2) precipitation; 3) evaporation; 4) size and landward penetration of the tidal prism; 5) salinity content in the adjacent coastal waters; 7) morphology of the coastal area; and,
8) differences in wind direction and velocity (e.g., Dörjes and Howard, 1975; Beynon et al., 1988; Pemberton and Wightman, 1992; Gingras et al., 2001).

As previously discussed, deltaic settings commonly experience salinity fluctuations, owing to variations in river discharge, particularly within lower-delta plain settings, interdistributary bay complexes, and distributary-mouth bars. However, prodelta, delta-front, and positions lying updrift of distributary channels tend to be less persistently affected by salinity fluctuations, and therefore, yield facies that largely display fully marine characteristics. Brackish-water environments are commonly inhabited by organisms with specialized adaptations for regulating their biochemistry under fluctuating, and generally lower, salinity concentrations (Croghan, 1983; Pemberton and Wightman, 1992). This restriction of infaunal diversity forms the foundation of the brackish-water ichnological model, first proposed by Pemberton et al. (1982). Brackish-water facies today are recognized predominantly on the basis of impoverished trace-fossil diversities, reductions in burrow size (i.e., diminutive traces), predominance of simple structures generated by trophic generalists, and local development of monogeneric suites (e.g., Beynon et al., 1988; Pemberton and Wightman, 1992; Bann and Fielding, 2004; Buatois et al., 2005; MacEachern and Gingras, 2007; MacEachern et al., 2007; Morshedian et al., 2009, 2011).

No depositional model can be constructed without some reference to the genetic stratigraphic relationships. Genetic stratigraphy subdivides rock units on the basis of their bounding discontinuities. There are three main approaches: 1) genetic stratigraphy (cf. Galloway, 1989a, 1989b); 2) allostratigraphy (cf., Walker and James, 1992); and, 3) sequence stratigraphy (cf. Van Wagoner et al., 1990).

The term parasequence is defined as a stratigraphic unit of relatively conformable successions that are genetically related and are bounded by flooding surfaces (Van Wagoner et al., 1987; Van Wagoner, 1995). In coastal to shallow-marine settings, parasequences are typically progradational and therefore are characterized by coarsening- and shallowing-upward. Depending upon their scale of observation, these coarsening- and shallowing-upward successions are separated into two types. Those that are large scale (i.e., basin wide) and are associated with allogenic processes and those that their
bounding surfaces are local in distribution and thus their development has nothing to do with allogenic mechanisms that generate sequences (e.g., deltaic lobe accumulation as a result of autogenic shifting). These two types of cycles are commonly indistinguishable in the field from one another and the correct interpretation depends on regional mapping and determines the extent and correctability of each surface.

One of the confusions within the concept of parasequence lies within its bounding surfaces (i.e., flooding surfaces). Flooding surfaces that are generated by autogenic processes are unrelated to sequence controls; as a result within deltaic environments where such autogenic processes are common, different stratigraphic patterns are produced compared to their adjacent shoreface deposits. As a result, some parasequence set within the deltaic intervals are in equivalent rank as shoreface parasequence. Moreover, in recent years experimental studies showed that steady (unchanged) external forces can also generate stratigraphic surfaces, similar to those that are produced by allogenic mechanisms (Muto and steel et al., 2007). The other issue regarding the term “flooding surface” is that, the term can have multiple meanings, such as transgressive ravinement surface, maximum regressive surface, maximum flooding surface, or within-trend of facies contact (Catuneanu, 2006). Many authors (e.g., Walker, 1992) stated that the term parasequence should only be applied for those sequences that are bounded by allogenic generated surfaces. It is now recommended that the term “parasequence” should be devoid of scale and sea-level implication, and should be restricted to defining prograding successions in coastal to shallow-water settings, where evidence of abrupt water deepening (flooding surfaces) can be produced (Catuneanu, 2006; Catuneanu et al., 2011). It is noteworthy that only allogenic surfaces have sequence stratigraphic significance. Ichnology has proven to be a useful tool in the recognition and interpretation of allogenic discontinuities (Pemberton and MacEachern, 1995; MacEachern et al., 2007b) in two main ways: 1) through identification of discontinuities using palimpsest substrate-controlled ichnofacies (e.g., Glossifungites Ichnofacies); and, 2) through the recognition of vertically and laterally juxtaposed ichnological suites that do not adhere to Walther’s Law.
This thesis describes the sedimentology, ichnology, and stratigraphy of a vertical succession of stacked deltaic, shoreface, and estuarine embayment deposits from the Lower Cretaceous Mannville Group (Sparky, Waseca, and McLaren alloformations) of the Lloydminster heavy oil region of Saskatchewan. In the study area, the Sparky, Waseca, and McLaren alloformations contain broadly similar lithologies, but can be differentiated into discrete stratigraphic packages through the integration of ichnology and sedimentology. Based on this analysis, a sequence stratigraphic model for the succession is presented.

This thesis seeks to answer the following scientific questions:

1) Can shoreface and deltaic successions be effectively differentiated in shallow water, storm-influenced regimes using a combination of ichnological and sedimentological characteristics?

2) In paralic successions deposited into basins with less than normal marine salinities, it is possible to accurately differentiate shoreface, delta and estuary successions?

3) Can an allostratigraphic framework and sequence stratigraphic depositional model be established for the upper Mannville strata in the Lloydminster area? Can through-going stratigraphic discontinuities be identified in core and correlated using wireline logs?
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CHAPTER 2: GEOLOGICAL SETTING OF THE WESTERN CANADA FORELAND BASIN, AND THE EVOLUTION OF THE MANNVILLE GROUP

2.1 Introduction

One of the most important aspects of basin analysis is understanding the geological/tectonic setting and basin type. Different geological settings yield different basin types, which in turn, directly influences sedimentation patterns and the resulting geometries of the deposited strata. Other features, such as deformation of the basin and eustatic sea-level fluctuations, also influence the evolution of the resulting sedimentary sequences (Jervey, 1992). From the perspective of petroleum exploration, understanding the basin type is crucial, since it directly affects hydrocarbon generation, migration, and accumulation within sedimentary strata.

The Lower Cretaceous Mannville Group was deposited within the Cordilleran Foreland Basin. The strata hold enormous reserves of coal, natural gas, and both conventional and heavy oils. The economic importance of this unit has attracted significant research attention focused on understanding the Mannville Group’s depositional history and evolution. This chapter provides an overview of the geology, tectonic setting, and character of fill of the Western Canadian Foreland basin as it applies to the Mannville Group.

2.2 Foreland Basin Development

A foreland basin is generally defined as an elongate trough formed on continental crust between a linear contractional orogenic belt and the adjacent stable craton. Basin formation is mainly a response to the flexural subsidence resulting from thrust-sheet loading in the orogen (see Price, 1973; Dickinson, 1974; Beaumont, 1981; Jordan 1981; 1995; DeCelles and Giles, 1996). Foreland basin fills are typically wedge-shaped in
transverse cross-section. The thickest part of the foreland basin is commonly located directly adjacent, or even partially beneath, the associated thrust belt (Jordan, 1995). The majority of the sediment derived from the thrust belt, and lesser contributions are sourced from the non-tectonic side of the basin (Dickenson and Suczek, 1979; Schwab, 1986; DeCelles and Hartel, 1989). A flexural topographic high, or forebulge, may separate the main part of the foreland basin from the craton (Fig 2.1)(Jakobi, 1981; Karner and Watts, 1983; Quinlan and Beaumont, 1984; Crampton and Allen, 1995).

Foreland basins can be divided into two categories (Dickenson, 1974). The “peripheral” foreland basin forms on subducting plates in front of thrust belts that are synthetic to the subduction direction. “Retro-arc” foreland basins develop on the overriding plates inboard of the continental-margin magmatic arcs: associated thrust belts are antithetic to the subduction direction. The modern Persian Gulf is an example of a peripheral foreland basin system, which is located along the southwest side of the Zagros collisional orogenic belt (Burberry et al., 2011). The Western Canada Foreland Basin represents a retro-arc foreland basin, where the basin is positioned above continental crust (i.e., the opposite side of the subduction plate from peripheral foreland basins) (Leckie and Smith, 1992).
**Figure 2.1** A) The general accepted notion of foreland-basin geometry in transverse cross-section. B) Schematic cross-section depicting a revised concept of a foreland basin system. A flexural bulge may separate the main part of the foreland basin from the craton. The topographic front of the thrust belt is labeled TF. The foreland basin system is shown in coarse stipple; the diagonally ruled area indicates pre-existing platformal strata. A schematic duplex (D) is depicted in the hinterland part of the orogenic wedge, and a frontal triangle zone (TZ) and progressive deformation in the wedge top depozone are also shown (Modified after Decelles and Giles, 1996).

### 2.3 Development of the Western Canada Foreland Basin

#### 2.3.1 Tectonostratigraphic Belts and Complexes

The foreland stage of the Western Canadian Sedimentary Basin (WCSB) is asymmetric in east-west cross-section. At its greatest dimensions (end of the Early Cretaceous), the basin was 6000 km long (north-south), 1600 km wide (Leckie and Smith, 1992), and likely 150 -to 300m deep (Winn et al., 1987; West et al., 1998). The bulk of the basin fill (greater than 6 km thick) was derived from the active orogenic belt
to the west, which resulted from the collision between the North American continent and allochthonous terranes that accreted to the western margin of the continent (Porter et al., 1982; Leckie and Smith, 1992). Minor volumes of sediment were supplied from the eastern craton, where the basin-fill onlaps the Canadian Shield (Jackson, 1984; Leckie and Smith, 1992). The collisional events that occurred from the Middle Jurassic to the Early Tertiary resulted in the formation of five geomorphological belts that can be broadly subdivided into tectonostratigraphic zones across British Columbia and western Alberta (Cant and Stockmal, 1989; Leckie and Smith, 1992; Cook, 1995) (Fig 2.2). From west to east, these include the Insular Belt, the Coast Plutonic Complex, the Intermontane Belt, the Omineca Crystalline Belt, and the Rocky Mountain Belt.

The Rocky Mountain, Intermontane, and Insular Belts mainly consist of unmetamorphosed and low-grade metamorphosed volcanic and sedimentary strata (Leckie and Smith, 1992). These belts are separated by two structural complexes: the Omineca Belt, and the Coast Belt, both of which comprise high-grade metamorphic and plutonic rocks (Leckie and Smith, 1992). It is generally accepted that the formation of the Rocky Mountain Belt had the most influence on the development of the foreland basin (Leckie and Smith, 1992).
Additional tectonic elements (Fig 2.3) that were active, and which influenced Mannville Group sedimentation include: 1) the Peace River Arch, 2) the Sweetgrass Arch, 3) the Punnichy Arch, 4) the Williston Basin, and 5) the Swift Current Platform. 1) The Peace River Arch (PRA) is a block-faulted structure in northwestern Alberta and northeastern British Columbia. The PRA was uplifted during the Early Cambrian and persisted as a high until Late Devonian time. The arch began to subside during the Early Cretaceous (O’Connell, 1990). The thickest Mannville intervals in the WCSB are preserved where the PRA and the foredeep of the foreland basin converge in northeastern British Columbia. 2) The Sweetgrass Arch (SGA), which is located in northern Montana.
Figure 2.3 Map showing the major structural elements of the Western Canadian Sedimentary Basin that were active during sedimentation. Modified after Leckie and Smith (1992).

and southern Alberta, was a large structural complex separating the intracratonic Williston Basin from the Alberta Foreland Basin. The SGA was topographically high during the Early Cretaceous, and remained emergent until much later during Mannville Group deposition (Podruski, 1988). 3) The Punnichy Arch is positioned in the northeastern part of the Williston Basin. This structure was formed as a consequence of dissolution of the Devonian Prairie Evaporite, a potash succession that accumulated during restriction of part of the Alberta Basin (Christopher, 1984). Salt dissolution provided abundant accommodation space for clastics supplied during deposition of the Mannville Group. The bulk of the sediment comprising the Punnichy Arch was supplied from the Precambrian Shield (Jackson, 1984). 4) The Williston Basin is an intercratonic structural basin that lies above the Precambrian basement and extends across parts of Saskatchewan, Manitoba, Montana, and North Dakota. During the Mesozoic, the basin constituted part of the foreland basin. The Williston Basin likely had little impact on Mannville sedimentation, as it was formed during the Mississippian and ceased to subside in the Jurassic. Regional subsidence resumed during late Mannville deposition.
(Shurr et al., 1989; Hayes et al., 1994). 5) The Swift Current Platform, located in southwestern Saskatchewan, is a triangular region of thin Middle Devonian strata. It corresponds to the area of ‘no salt’ in the Middle Devonian Prairie Evaporite. The platform dips south-eastward into the Williston Basin. It started to rise by some 150 m during the Neocomian and resulted in incision of deep valleys (Christopher, 1964), but subsided again during Middle Albian time (Christopher, 2007). This tectonic restlessness is probably due to emplacement of anorogenic granite in the basement rocks of the Swift Current Platform (Collerson and Lewry, 1985).

2.3.2 Evolution of the Cordillera and Western Canada Foreland Basin

The distribution and the tectonic history of the five morpho-geological belts indicate that the evolution of the Western Canada Cordillera and its associated foreland can be separated into three stages: stages 1, 2, and 3 (Porter et al., 1982; Leckie and Smith, 1992; Fermor and Moffat, 1992).

**Stage 1** is the transition from a passive continental margin to an early stage foreland basin, which occurred during Late Triassic and Early Jurassic time. Along much of the western paleo-margin of North America, a passive continental margin existed from latest Proterozoic-early Paleozoic to Late Triassic time (Gordey et al., 1987) where a 20 km thick succession of mainly carbonate platformal sediments accumulated (Price, 1981). During the late Proterozoic, Late Devonian-Carboniferous, and the Triassic, the entire passive margin was influenced by rapid subsidence, rifting, and earlier foreland basin fill (Thompson et al., 1987). During the Late Triassic, extensive island arc volcanism within the terranes that now comprise the Intermontane Belt occurred prior to their accretion to the western margin of the continent (Armstrong, 1988). A large part of the Intermontane Belt consists of amalgamated terranes composed of oceanic volcanic arc assemblages on a basement of Triassic and Upper Paleozoic rocks (Price et al., 1985).

**Stage 2** marks the accretion of the Intermontane terranes to the western paleo-margin of North America, and the onset of the Columbian Orogeny (Leckie and Smith, 1992) from Early Jurassic to Early Cretaceous time. The accretion resulted in extensive
compressional deformation, crustal thickening and metamorphism within the Omineca Belt (Price, 1985). The Columbian Orogeny was driven by oblique collision of the Intermontane terranes with the westward-moving North American Craton. This resulted in the compression of the western part of the passive margin wedge, which was caught between the Intermontane Belt and the North American Craton (Leckie and Smith, 1992). The junction zone of the Intermontane Belt with the craton is referred to as the Omineca Belt, and is composed of high-grade metamorphic and granitic rocks. Deformation and metamorphism of the Omineca Belt began in the Early Jurassic (Price et al., 1985), and based on the metamorphic mineral assemblages, it is thought that the burial depth was about 20-27 km, which is probably the result of the westward-dipping subduction that occurred in this region (Ghent et al., 1977; Price et al., 1985).

Following the convergence of the Intermontane Belt with the craton, a period of tectonic quiescence occurred during the mid-Cretaceous (Price and Mountjoy, 1970). Large-scale downflexing of the craton likely occurred in response to changes in plate motion and within-plate stress regimes (Lambeck et al., 1987). The Mid-Cretaceous period of tectonic quiescence also coincided with a mid-Cretaceous global sea-level rise on the order of 200-300 m (Haq et al., 1987). Correspondingly, the global rise in sea level led to the development of the Western Interior Seaway (WIS) and the deposition of a thick marine shale succession within the zone of maximum subsidence.

**Stage 3** represents oblique convergence, which occurred during the Late Cretaceous to Paleocene Laramide Orogeny. During this period a second major terrane, the Insular Superterrane, collided with the North American craton, which included the previously accreted Intermontane Belt (Leckie and Smith, 1992). The Coastal Plutonic Complex represents the structure zone formed as a result of accretion of the Insular Belt to North America. Renewed thrusting and stacking resulted in the eastward expansion of the Foreland Basin, and the deposition of predominantly terrigenous sediments (Leckie and Smith, 1992). The Laramide Orogeny was also responsible for >200 km of east-west shortening within the cratonic and overlying foreland basin strata in the southern Canadian Rocky Mountains (Price, 1981). The compressive system and foreland basin-
type sedimentation ceased during the Eocene, with the deposition and subsequent folding of the sediments in the eastern fold-and-thrust belt (Price, 1981; Wernicke et al., 1987).

From the middle Maastrichtian to the Late Paleocene (about 70 to 60 Ma), most magmatic activity in the Cordillera ceased, leading to a massive isostatic uplift of the fold-and-thrust belt and the foreland basin, and development of a major surface of erosion. This magmatic quiescence was followed by intense magmatism from Paleocene to milled Miocene (64 to 40 Ma) in the Western Canadian Cordillera (Leckie and Smith, 1992; Prince, 1994).

2.3.3 Physical Elements of the Western Canada Foreland Basin

Thrust-plate loading in the orogenic belt caused maximum subsidence to occur close to the thrust sheet (Fig 2.4). In the Western Canadian Sedimentary Basin, the accumulation of six, westward-thickening clastic wedges have been correlated to discrete tectonic loading events (Stockmal et al., 1992). Many authors have subdivided the foreland basin into five paleo-physiographic zones, each distinguished by different water depths, sedimentation rates, facies, subsidence rates, and tectonic stability (Kauffman, 1977; McNeil and Caldwell, 1981; Leckie and Smith, 1992). The major components (from west to east) are: 1) a tectonically active highland; 2) a zone of maximum subsidence; 3) a zone of high subsidence; 4) a broad tectonic hinge zone; and 5) a stable platform (Kauffman, 1977; McNeil and Caldwell, 1981) (Fig 2.5).
Figure 2.4 Model describing formation of the Western Canadian Foreland Basin. Supercrustal rocks are overthrust as a result of terrane accretion and compression. This results in isostatic flexure of the lithosphere and the formation of the Foreland Basin into which synorogenic detritus is deposited (modified after Price, 1973).
Figure 2.5 Schematic diagram of the Canadian Foreland Basin, outlining the paleophysiographic components (modified after Leckie and Smith 1992).
2.4 The Evolution of the Mannville Group

The term “Mannville Group” applies to Lower Cretaceous strata from the base of the sub-Cretaceous unconformity (an angular unconformity) to the base of the Joli Fou Fm marine shales of the Colorado Group (Fig 2.6). The hiatus represented by this unconformity is more than 27 million years long, and is possibly associated with a worldwide eustatic sea-level fall (Leckie and Smith, 1992). During this stratigraphic break, several regionally extensive valleys were incised into the underlying strata, generating a very irregular topography that largely controlled sedimentation patterns during the Early Cretaceous. Three major drainage systems were developed on the sub-Cretaceous Unconformity (Ranger, 1984; Hayes, 1986; Hayes et al., 1994; Ranger and Pemberton, 1994) (Fig 2.7). In the western part of the basin, the Spirit River Valley trends from southeast to northwest. The basal strata in the Spirit River Valley are composed of terrestrial coarse clastics of the Cadomin Formation and Cut-Bank Member. The more centrally located drainage system is known as the Edmonton Channel, and displays a northwest-southeast orientation. The Edmonton Valley’s highest gradient was on the Swift Current Platform of southern Alberta and southwestern Saskatchewan (William, 1963). The continental (non-marine) deposits forming the base of Edmonton Channel constitute the Cadomin, Ellerslie, and Gething formations. The third major drainage system is known as the McMurray Valley, and is located east of the Wainwright Ridge in eastern Alberta (Fig 2.7). The Athabasca oil sands deposits of the McMurray Formation are contained within this system, and comprise one of the largest hydrocarbon accumulations in the world. Lower McMurray deposits comprise regolith and fluvial channel deposits (Keith et al., 1988; Ranger et al., 1988).
**Figure 2.6** Stratigraphic position of the Mannville Group within the Alberta and Saskatchewan (modified after Christopher, 1997).
Figure 2.7 Map of Lower Mannville fluvial systems, the first phase of Mannville Group deposition (Modified after Jackson, 1984).
A series of smaller drainage systems on the sub-Cretaceous Unconformity are located within east-central Alberta and west-central Saskatchewan. These valleys, known as Bellshill Lake Channel, St. Paul Channel system (Jackson, 1984), and Assiniboia valleys (Leckie and Smith, 1992), host the basal Mannville Group where it is commonly known as the Dina Formation. Dissolution of salt from the underlying Middle Devonian Prairie Evaporite and subsequent collapse of overlying strata controlled the location of some of these eastern valleys (Christopher, 1997). Early deposition of the Mannville Group reflects the relative rise of base level of the Boreal Sea (Leckie and Smith, 1992), which shifted the system from one of predominantly sediment bypass to one characterized by largely continental accumulation.

Continued relative sea level rise led to marine inundation of the continent, and subsequent fill of the regional valley systems. In northeastern Alberta, this gradual transgression is recorded as the middle and upper parts of the McMurray Formation (Ranger et al., 1988). Detailed studies of the ichnology and sedimentology, coupled with palynological analyses of the middle and upper McMurray clearly demonstrate a persistent and generally upward increase in marine influence (Pemberton et al., 1982; Keith et al., 1988; Ranger et al., 1988). In south and central Alberta, the Ostracod Member, which sits disconformably on the Elleslie Member, marks this flooding event. The Ostracod Member constitutes a laterally extensive biozone marker that is correlatable across the basin (see Karvonen and Pemberton, 1997). During the deposition of the Ostracod Member, and the laterally equivalent Cummings Member (Fig 2.6), the WCSB was a broad, shallow, brackish-water embayment (Karvonen and Pemberton, 1997). The Ostracod Member is correlatable westward to the Gladstone Formation in British Columbia (Glaister, 1959). In western Saskatchewan, this transgression is characterized by brackish-water deposits of the Cummings Formation overlying the fluvial deposits of the Dina Formation (Christopher, 1997).

By the end of the Early Cretaceous transgression in the WCSB, most of west-central Saskatchewan and east-central Alberta (the study area) was covered by the seaway. A subsequent relative drop in sea level during early Albian time resulted in the incision of valleys (Jackson, 1984). Renewed transgression of the Boreal Sea during
Albian time led to the infilling of the incised valleys and deposition of the Wabiskaw Member in northeastern Alberta. Similar expressions can also be seen in Glauconite Fm in the southern part of Alberta (Wood and Hopkins, 1989). The Bluesky Formation in north and central Alberta comprises an overall backstepping set of shorefaces and barrier islands (Jackson, 1984). Based on work by O’Connell et al. (1990) and O’Connell (1992) in Peace River Arch area of Alberta, the Bluesky Fm consists of a series of lowstand delta and fluvial valley-fills, deposited during relative base level fall and during the subsequent transgression. Continued transgression of the Boreal Sea ultimately resulted in the deposition of the marine shales of the Moosebar Formation and Wilrich Member in northwestern Alberta and northeastern British Columbia; the Clearwater Fm in central and northeastern Alberta; and, the Lloydminster Fm of eastern Alberta and west-central Saskatchewan.

Following deposition of the marine shales in early Albian time, rejuvenated Cordilleran tectonics led to high rates of sedimentation from the mountains. This is recorded by the overall progradational stacking pattern of the Gates Formation in the British Columbian foothills, (Leckie and Walker, 1982), the Falher Member of the Spirit River Formation in northwestern Alberta (Rouble et al., 1997), the Upper Mannville Group in northeastern Alberta, and the Upper Mannville in west-central Saskatchewan and east-central Alberta. The Notikwin Member, in the northwest regions of Alberta records the maximum progradation of the shoreline before another major transgression in the late Albian.

The top of the Mannville Group is commonly marked by an unconformity. Within Peace River area, the surface lies on top of the Cadott Member, which also correlates to the Boulder Creek Formation in northeastern British Columbia. Hayes et al. (1994) argue that these deposits along with Harmon Member should be included in the Mannville Group interval. Within west-central Saskatchewan and east-central Alberta this unconformity is marked by a series of incised valleys that subtend from the top of the Colony Formation at the top of the Mannville Group. The contact between the Upper Mannville Group and the basal Colorado Group is marked by a major regionally extensive transgressive surface. The overlying deposits of the Albian Joli Fou Formation
**Figure 2.8** Paleogeographic map of North America during early to mid-Cretaceous (after Blakey, 2006).
correspond to a period of global sea level rise. During this transgression, much of eastern British Columbia, Alberta, and western Saskatchewan were inundated by the Boreal Sea, which linked with the Gulfian Sea to form the Western Interior Seaway (WIS) (Jackson, 1984, Stott, 1984) (Fig 2.8).

2.5 Sequence Stratigraphy of the Mannville Group

The Lower Cretaceous Mannville Group can be divided into two subgroups (lower and upper). The lower Mannville accumulated during the lowstand and transgression of the Boreal Sea in the Aptian, and comprises stacked successions of fluvial valley fill deposits, brackish-water bay and estuary deposits, and retrogradationally stacked shorefaces. During deposition of the upper Mannville, high sedimentation rates from the rising Cordillera caused the paleo-shoreline to prograde rapidly into the Boreal Sea. Upper Mannville successions are mainly characterized by prograding shoreface and deltaic deposits. Taken together, the Mannville Group can be regarded as a second-order sequence within the first-order Zuni Sequence of Sloss (1963).

The lower and upper Mannville subgroups correspond to third-order sequences. In west-central Saskatchewan and east-central Alberta, the lower Mannville subgroup consists of the basal two members (Dina and Cummings), and the upper Mannville encompasses the overlying seven (Lloydminster to Colony) (Fig 2.9). The stratal stacking patterns of the Lower Mannville subgroup indicate sediment accumulated during lowstand and early transgression, and the upper seven members reflect deposition during a period of sea-level highstand (Cant, 1996). These two subgroups are separated by a maximum flooding surface. It is noteworthy that stratigraphic units of the Mannville Group have been defined at the scale of fifth-order cycles (McPhee, 1994).
Figure 2.9 The relationship between the second and third-order sequence found within the first-order Zuni Sequence of the Western Canadian Sedimentary Basin. Modified after McPhee, 1994.
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CHAPTER 3: INTEGRATED ICHNOLOGY, SEDIMENTOLOGY, AND STRATIGRAPHY OF THE LOWER CRETACEOUS MANNVILLE GROUP (SPARKY ALLOFORMATION), WEST-CENTRAL SASKATCHEWAN

3.1 Introduction

The Lower Cretaceous Mannville Group has been the subject of study since the early 1940s, and was first drilled in 1942 (Nauss, 1945). The succession consists of well cemented to weakly consolidated sandstones, siltstones, mudstones, heterolithic bedsets of sandstone and mudstone, and minor coals. The Mannville Group (Fig 3.1) unconformably overlies Paleozoic- to Jurassic-aged strata, and is disconformably overlain (due to transgression) by the Joli Fou marine shales of the Colorado Group (Christopher, 1974; 2003).

The “Mannville Formation” was originally proposed by Nauss (1945), based on his work on cores from oil and gas wells in the Vermillion area of east-central Alberta. The type section is based on the interval from the Northwest Mannville No. 1 well (01-18-050-8W4). Nauss (1945) subdivided the Mannville Formation (from top to bottom) into the O’Sullivan, Borradaile, Tovell, Islay, Cummings, and Dina members. Wickenden (1948) suggested that the Mannville could be divided into basal, middle, and upper units. The most commonly used stratigraphic nomenclature for the Mannville Group in the Lloydminster area of Saskatchewan and Alberta is based on unofficial driller’s terminology and electric log characteristics (Edmunds, 1948). These include (from top to bottom): Colony, McLaren, Waseca, Sparky, General Petroleum (G.P.), Rex, Lloydminster, Cummings, and Dina, although no formal type sections have been
established to date that formalizes this nomenclature. The Mannville was elevated to Group status by Badgley (1952). Vigrass (1977) and Orr et al. (1977) used the nine informal stratigraphic subdivisions of Edmunds (1948), although Vigrass (1977) referred to them as members and Orr et al. (1977) considered them as formations.

The Sparky Alloformation disconformably overlies the General Petroleum (G.P.) Alloformation and, in turn, is disconformably and locally unconformably is overlain by Waseca Alloformation. The Sparky Alloformation correlates with the Grand Rapids Formation towards the west, and southwards with the upper part of Cantuar Formation.

This paper employs an allostratigraphic framework in order to characterize the Sparky Formation. Allostratigraphy is only genetic stratigraphic framework currently approved by the NACSN (1983). Allostratigraphic units are defined on the basis of mappable stratigraphic discontinuities, and permits correlations that are independent of lithological constraints.

The Mannville Group is considered one of the most important hydrocarbon resources in Canada (Pemberton & James, 1997). In the Lloydminster area, heavy oil reservoirs are estimated to contain approximately 3 billion m³ (19 billion barrels) of oil in place (Saskatchewan Energy and Resources, 2008). The majority of heavy oil production in Lloydminster area occurs in the G.P., Sparky, and Waseca alloformations (cf. Orr et al., 1977). Owing to the high economic value of these depositional units, the interval has attracted considerable attention from both academia and the oil industry.

Historically, Nauss (1945) and Wickenden (1948) interpreted the Sparky Alloformation to correspond to the deposits of north- to north-eastward prograding deltas. Fuglem (1970) considered the Sparky Alloformation in the Lloydminster area to represent tidal flat and marsh deposits. He also analyzed the shale separating the G.P. and Sparky alloformations, and indicated that the contact is flooded with Ammobaculites, representing a marine incursion. Vigrass (1977) studied the Upper Mannville in the Epping, Chauvin South, Evesham, and Eyehill Cumming fields of the Lloydminster area. Based on foraminiferal suites, he indicated that local and temporary incursions of brackish to marine water occurred during deposition of Upper Mannville. He interpreted
Figure 3.1 Correlation of Lower Cretaceous strata in eastern Alberta and Western Saskatchewan (modified after Christopher, 2003); red dots indicate study interval.
that the G.P. and Sparky ‘members’ to have been deposited in deltaic environments. Robson (1980) interpreted the sand bodies within the Sparky Alloformation of the Dulwich and Silverdale area as an offshore sandbar in a tide-dominated environment. Smith et al. (1984) and Smith (1984) subdivided the Sparky Alloformation into two major facies associations: regional deposits and channel successions. These were interpreted to have been deposited in a northeastward prograding, wave-dominated deltaic setting. Van Hulten et al., (1984) also reached an interpretation stressing northeastward prograding, wave-dominated deltas, with the thick sandstone reservoirs representing tidal inlets. Leslie (1989) completed a detailed facies analysis of the Sparky Alloformation in the Wainwright area, and interpreted the interval to record three stacked delta lobes formed by the progradation into shallow-water.

3.2 Study Area and Methodology

The deposits of the Mannville Group comprise numerous major hydrocarbon fields in west-central Saskatchewan. The focus of this study is Sparky Alloformation, defined herein. Approximately sixty percent of the oil in place (oip) occurs within the Sparky. The study area extends from Township 48 to 54, and between Ranges 19 and 28 West of the 3rd Meridian, and comprises a total area of 5,400 km² (Fig 3.2).

IHS AccuMap® software was used to search for wells cored in the Upper Mannville Group. The study area contains approximately 19,200 wells, of which an estimated 1,730 include cored intervals that penetrate the Upper Mannville Group. A total of 127 cores were logged for this study (Fig 3.2) of which 60 of them penetrate the Sparky. All cores reside in the public domain, and were examined at the Saskatchewan Ministry of Energy and Resources Subsurface Geological Laboratory in Regina, Saskatchewan. A list of the well locations, cored intervals, and core lengths that were utilized is located in Appendix A. Also a compact disk (CD) is included containing PDF of all the lithologs and cross sections.

The cored intervals were evaluated both sedimentologically and ichnologically, in order to characterize the facies successions. Sedimentological analysis focused on
lithology, grain size, sorting, bed thicknesses, character of bedding contacts and bounding surfaces, and physical sedimentary structures. Ichnological appraisal included identification of ichnogenera, characterization of diversity, assessment of trace fossil sizes, evaluation of bioturbation intensity, evaluation of burrow distribution, and assignment of ethological groupings.

Trace fossil identification in core can be challenging, but protocols for assessing three dimensional morphologies from two dimensional transects have been well established, and are augmented by various photo atlases (e.g., Ekdale et al., 1984; Pemberton et al., 1992; Pemberton et al., 2001; MacEachern et al., 2007). Diversity assessment allows evaluation of ambient vs. stressful settings, particularly through recognition of environment-specific ichnogenera relative to facies-crossing elements (see Dashtgard and MacEachern, 2009). Recognition of persistent size reduction in ichnogenera, compared to fully marine counterparts (cf. ichnometry; McIlroy, 2004) is also a common indication of physico-chemically stressful environments (e.g., Beynon et al., 1988; Savrda and Bottjer, 1989; Wignall, 1994; Martin, 2004; McIlroy 2004; MacEachern and Gingras, 2007). Evaluating bioturbation intensity helps to assess the relative rates of deposition, as well as the processes responsible for sediment accumulation (e.g., Howard, 1975; Leithold, 1993; Moslow and Pemberton, 1988; Coates and MacEachern, 1999; Bann and Fielding, 2004; Gingras et al., 2007; MacEachern et al., 2010). The semi-quantitative measurement of bioturbation intensity was originally proposed by Reineck (1963) in order to describe the destruction of primary bedding by biogenic activity (cf. Reineck and Singh, 1980). Taylor and Goldring (1993) and Taylor et al., 2003 redefined this approach as “bioturbation index” (BI), based on a non-linear scale of BI 0 - 6. The BI framework has been employed in this study. Assessment of the distribution of bioturbation is important in characterizing the degree of episodicity on sedimentation. Sporadically distributed burrowing (e.g., laminated to bioturbated bedding) is typically indicative of event-style sedimentation with periods of recolonization (e.g., Crimes, 1973; 1977; Seilacher, 1982; Howard and Frey, 1984; Pemberton and Frey, 1984; Wetzel, 1984; Vossler and Pemberton, 1989; MacEachern and Pemberton, 1992; Pemberton and MacEachern, 1997), whereas uniformly distributed bioturbation is more typical of continuous sedimentation. Finally, an ethological
Figure 3.2 Location of the study area. A) Map of Canada showing the location of the study area, B) Detailed map of the study area with locations of logged core.
assessment of the identified suites allows characterization of animal-sediment responses to food resources, substrate consistency, and depositional energy, which forms the basis of the ichnofacies paradigm (see Seilacher, 1967; Ekdale et al., 1984; Frey et al., 1990; MacEachern et al., 2007; 2010).

3.3 Facies Description and Interpretation

Based on this integrated ichnological-sedimentological analysis, ten recurring facies have been identified from the Sparky Alloformation of the Mannville Group, designated F1 to F10 (Table 3.1). Ethologies (interpreted behaviors), associated with the different trace fossil genera observed in core are described in Table 3.2.

3.3.1 Facies 1: Bioturbated Sandy/Silty Mudstone

Sedimentology:

Facies 1 consists of mudstone passing upward into silty to sandy mudstone. Siltstone and sandstone layers comprise less than 20% of the facies. The facies is pervasively bioturbated (Fig 3.3A). Where primary stratification can be identified, it is generally on the scale of millimetres to centimetres in thickness. Sand is very fine-to-fine grained, and locally oil stained. Stratigraphically upward the sand content and preservation of sedimentary structures increases. Stratification generally displays oscillation ripples and small-scale hummocky-cross stratification (5-10cm) commonly known as “micro-HCS” (Dott and Bougeois, 1984). Bed contacts are sharp and locally erosional. Some sand layers display normal grading. Carbonaceous detritus, dispersed wood fragments, and pyrite are present throughout the facies.

Ichnology:

Facies 1 typically displays high bioturbation intensities. Most units display BI 5 but locally decline to BI 2 where the sand content increases. The facies generally displays high diversity of ichnogenera, with both robust and diminutive forms (Fig 3.3B). Trace
fossils are typically uniformly distributed and include *Planolites, Cylindrichnus, Palaeophycus, Teichichnus, Thalassinoides, Skolithos, Asterosoma, Rosselia, Chondrites, Piscichnus, Phycosiphon, Helminthopsis* and fugichnia. The suite reflects the activity of organisms mainly performing deposit-feeding and grazing behaviours.

**Interpretation:**

Facies 1 is interpreted to reflect deposition in a well-oxygenated, fully marine setting. The generally high bioturbation intensities and paucity of physical sedimentary structures preserved in these mudstone-dominated successions indicate deposition below fairweather wave-base in a quiet-water environment. The increase in sand content and concomitant preservation of sedimentary structures upward are interpreted to correspond to a shallowing-upward trend in deposition. The preserved sandstone lamina-sets reflect storm events that occurred within the environment. One of the distinctive characteristics of Facies 1 is the presence of traces recording the activity of organisms deemed intolerant of elevated physico-chemical stress. These distinctively marine (stenohaline) traces include *Asterosoma, Helminthopsis, and Phycosiphon* (cf. Gingras et al., 2007). The resulting suite corresponds to a slightly stressed expression of the archetypal *Cruziana* Ichnofacies, and is interpreted to reflect deposition within distal (basinal) portion of an offshore marine environment.
<table>
<thead>
<tr>
<th>Facies Association</th>
<th>Facies #</th>
<th>Facies</th>
<th>Sedimentology</th>
<th>Taxonomic suite</th>
<th>RL</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Marine Mudsone</td>
<td>1</td>
<td>Bioclastic Silty/Sandy Mudsone with Diverse Trace Fossil Assemblages</td>
<td>Thoroughly bioturbated locally micro-HCS.</td>
<td>Planolites, Skolithos, Cylindrichnus, Palaeophycus, Tischocaris, Chondrites, Asterosoma, Phycozoon, Nehringtus, Rosselia, Psilocalanus and fugichnia</td>
<td>2-5</td>
<td>Offshore Marine Deposits</td>
</tr>
<tr>
<td>4a</td>
<td>5</td>
<td>Thoroughly bioturbated sandstone with locally low-angle planar stratified, current ripple sandstone and aggradational current ripples</td>
<td>Cylindrichnus, Skolithos, Psilocalanus, fugichnia</td>
<td>Skolithos, Planolites, Cylindrichnus, fugichnia, navichnia</td>
<td>0-2</td>
<td>Upper Shorline</td>
</tr>
<tr>
<td>2) Wave-Storm-Dominated Embayed Shoreface</td>
<td>3a</td>
<td>Bioclastic Mudsone Interbedded with Sandstone</td>
<td>Mudstone interbedded with oscillation-rippled sandstone: locally micro-HCS, synnesosis cracks, and convolute bedding</td>
<td>Planolites, Skolithos, Cylindrichnus, Palaeophycus, Tischocaris, Chondrites, Asterosoma, Phycozoon, Nehringtus, Rosselia, Psilocalanus and fugichnia</td>
<td>2-5</td>
<td>Proximal Offshore</td>
</tr>
<tr>
<td>Thin Bed of 1</td>
<td>5</td>
<td>Bioclastic Silty/Sandy Mudsone with Diverse Trace Fossil Assemblages</td>
<td>Thoroughly bioturbated locally micro-HCS.</td>
<td>Planolites, Skolithos, Cylindrichnus, Palaeophycus, Tischocaris, Chondrites, Asterosoma, Phycozoon, Nehringtus, Rosselia, Psilocalanus and fugichnia</td>
<td>2-5</td>
<td>Offshore Marine Deposits</td>
</tr>
<tr>
<td>6b</td>
<td>6</td>
<td>Oscillation-Rippled Sandstone Interbedded with Cuttm Ripple Sandstone</td>
<td>Wave-rippled, combined flow ripple, and current ripple. Locally small-scale trough cross-bedding, abundant organic detritus and siderite.</td>
<td>Calymenichnus, Planolites, Skolithos, fugichnia</td>
<td>0-1</td>
<td>Proximal Delta Front / Distributary Mouth Bar</td>
</tr>
<tr>
<td>3b</td>
<td>3a</td>
<td>Sporoclastically Bioclastic Mudsone Interbedded with Sandstone</td>
<td>Wave-like lenticular bedded mudstones, interbedded with oscillation-rippled sandstone: micro-HCS, Local combined flow ripples, synnesosis cracks, and convolute bedding, siderite, organic detritus.</td>
<td>Planolites, Skolithos, Cylindrichnus, Palaeophycus, Gromphus, Thalassinoides, Ammonoides, Tischocaris, Chondrites, fugichnia, navichnia</td>
<td>0-2</td>
<td>Delta Front</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Pineapple to Lenticular Bedded Mudsone</td>
<td>Oscillation ripples, micro-HCS with sharp contacts locally convolute bedded, current ripples, and synnesosis cracks.</td>
<td>Planolites, Cylindrichnus, Tischocaris, Palaeophycus, Gromphus, Chondrites, Asterosoma, Phycozoon, fugichnia, and navichnia</td>
<td>0-3</td>
<td>Distal to Proximal Sediment</td>
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<tr>
<td>Thin Bed of 1</td>
<td>5</td>
<td>Bioclastic Silty/Sandy Mudsone with Diverse Trace Fossil Assemblages</td>
<td>Thoroughly bioturbated locally micro-HCS.</td>
<td>Planolites, Skolithos, Cylindrichnus, Palaeophycus, Tischocaris, Chondrites, Asterosoma, Phycozoon, Nehringtus, Rosselia, Psilocalanus and fugichnia</td>
<td>2-5</td>
<td>Offshore Marine Deposits</td>
</tr>
<tr>
<td>4) Distributary Channels</td>
<td>7</td>
<td>Induced Heterolith, Stratification (IHS)</td>
<td>Heterolithic mudstone and sandstone, sharp contacts, sandstone beds display small-scale trough cross-bedding and current ripple laminations. Organic detritus, fluid mud, soft-settled deformation, Rare oscillation ripples.</td>
<td>Planolites, Skolithos, Hemipelagic, Cylindrichnus, Palaeophycus, Gromphus, Tischocaris, Thalassinoides, Chondrites, fugichnia, navichnia</td>
<td>0-5</td>
<td>Lateral Deposition Barrier</td>
</tr>
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<td>6</td>
<td>6</td>
<td>Current-Rippled Laminated Sandstone</td>
<td>Current ripples, siderite, organic detritus, ocally aggradational and combined flow ripples and rare oscillation ripples.</td>
<td>Skolithos, Cylindrichnus, Planolites, fugichnia</td>
<td>0-2</td>
<td>Channel Bar Complex</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>Trough Cretate-G miềnelano Taller Cross-Bedded Sandstone</td>
<td>Cross-beded sandstone with locally low-angle planar stratified, current ripple sandstones and aggradational current ripple.</td>
<td>Cylindrichnus, Planolites, Skolithos, fugichnia</td>
<td>0-1</td>
<td>Migrating Dunes in Channels</td>
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<tr>
<td>10</td>
<td>10</td>
<td>Carbonaceous Mudstone and Coal</td>
<td>Crudely bedded, rare plant debris, locally high salt and silt content.</td>
<td>Planolites, roots</td>
<td>0-1</td>
<td>Terrestrial Peat &amp; Swamp</td>
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<td>9</td>
<td>9</td>
<td>Root-Channel Mudstone</td>
<td>Convoluted-beaded mudstone with root, organic detritus, current ripple laminations, and some pedogenic features.</td>
<td>Planolites, Nafodermatis, ang root</td>
<td>0-2</td>
<td>Flood Plain</td>
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<td>8</td>
<td>8</td>
<td>Cross-Bedded Carbonaceous Rich Sandstone</td>
<td>Sand with abundant coalized wood fragments, siderite, locally deformed.</td>
<td>Planolites, roots</td>
<td>0-1</td>
<td>Fluvial Channel</td>
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</table>

Table 3.1 Summary of facies characteristics and interpretations
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<thead>
<tr>
<th>Ichnogenera</th>
<th>Ethology</th>
<th>FA1</th>
<th>FA2</th>
<th>FA3</th>
<th>FA4</th>
<th>FA5</th>
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<td>Arenicolites</td>
<td>Dwelling; Suspension feeding</td>
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<td>Asterosoma</td>
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<tr>
<td>Chondrites</td>
<td>Sessile deposit feeding; Systematic feeding</td>
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<td>Cladiscina</td>
<td>Escape structure</td>
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<td>Gyrolithes</td>
<td>Permanent dwelling; Deposit feeding</td>
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<tr>
<td>Heimanthopsis</td>
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<td>Naikodemasis</td>
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<td>Navilchnia</td>
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<td>Piscinchnus</td>
<td>Carnivore</td>
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<td>Planolites</td>
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<td>Phycosiphon</td>
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<td>Rhabdocorallus</td>
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<td>Rosselia</td>
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<td>Scolicia</td>
<td>Locomotion; Deposit feeding</td>
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<td>Skolothos</td>
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<td>Teichichnus</td>
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<td>Thalassinooides</td>
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<td>Triphichnus</td>
<td>Dwelling; Suspension feeding</td>
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</table>

Table 3.2: Ethology of traces observed in the Sparky Alloformation.
3.3.2 Facies 2: Pinstripe to Lenticular Bedded Mudstone

Sedimentology:

Facies 2 is characterized by pinstripe to lenticular bedded composite bedsets (Fig 3.3C). Coarse-grained components are typified by millimetre-to centimetre-thick, sharp-based, locally normally graded siltstone and very fine-grained sandstone layers. These are interlaminated with mudstone layers with variable silt content. Low-angle parallel lamination, and starved combined-flow and oscillation ripple lamina dominates the physical sedimentary structures. Locally, current-ripple laminations are present. Organic detritus is common within the facies. Mudstone interlaminae are generally fissile, and are commonly accompanied by siderite-cemented bands and pyrite. Syneresis cracks and soft-sediment deformation features (e.g., micro-faults and convolute bedding) are locally present.

Ichnology:

Trace fossils within Facies 2 generally are diminutive and of low diversity. Most of the mud interbeds show BI 0 to 3. The sandstones possess lower bioturbation intensities (BI 0-1). Overall, the facies shows a decrease in BI values upward. Trace-fossil suites are dominated by deposit-feeding structures, with subordinate dwelling structures of inferred suspension-feeding organisms, and low abundances of grazing structures. Some of the thicker sandstone layers contain escape structures. Trace fossils include Planolites, Cylindrichnus, Palaeophycus, Chondrites, Asterosoma, Teichichnus, Gyrolithes, Phycosiphon, fugichnia, and navichnia.

Interpretation:

The predominance of oscillation structures suggests that the setting was subaqueous and lay above storm wave base. The presence of combined-flow ripples and current ripples indicate that unidirectional flows operated during the deposition. The low bioturbation intensity suggests that sedimentation rates were generally high. Reduced
trace-fossil diversities, diminutive ichnogenera, and locally common syneresis cracks support the interpretation that the salinities were variable and generally reduced. The local occurrence of more marine ichnogenera (e.g., Chondrites, Phycosiphon) within the facies suggests that normal marine salinities occurred periodically. The trace fossil suite is consistent with a stressed expression of the Cruziana Ichnofacies, and reflects deposition in brackish-water prodelta settings.

3.3.3 Facies 3: Sandstone and Mudstone Heterolithic Facies

Facies 3 comprises heterolithic composite bedsets consisting of interbedded mudstone and sandstone. Units vary from mud-dominated to sand-dominated. Bedding thicknesses of the mudstones are generally on the scale of several centimetres, whereas sandstones thicken from a few centimetres in the lower part of the interval to 20 cm towards the top of the facies. The sandstone beds are dominated by oscillatory-generated structures. Mudstone layers are typically massive or poorly laminated, and display biogenic reworking. Facies 3 has been subdivided into two subfacies on the basis of their sedimentological and ichnological features. Facies 3 commonly grades out of Facies 1 or Facies 2 and is overlain by Facies 4.

3.3.3.1 Facies 3a: Moderately to Pervasively Burrowed Interbedded Sandstone and Mudstone

Sedimentology:

Facies 3a comprises interbedded laminated to massive mudstones and fine- to very fine-grained sandstones. Bedding of both the mudstones and the sandstones is disrupted by bioturbation, and in some intervals the primary fabric is obliterated (Fig 3.3D & 3.3E). Sandstone interbeds range in thickness from 1 mm to 20 cm. Internally, sandstone layers display oscillation ripples and low-angle cross-stratification. Locally, micro-hummocky cross stratification is intercalated. The mudstones are poorly laminated and commonly pervasively bioturbated. Locally, mudstone layers are normally graded.
The facies locally contains syneresis cracks. Soft-sediment deformation features, such as microfaults and convolute beds, have been observed but are not common.

**Ichnology:**

Bioturbation values vary at the bed scale from BI 0 to BI 5, but typically average BI 3. Burrowing intensities are higher within the mudstone beds. Trace fossil elements include *Planolites, Skolithos, Arenicolites, Cylindrichnus, Gyrolithes, Teichichnus, Thalassinoides, Palaeophycus, Rhizocorallium, Chondrites, Asterosoma, Scolicia, Phycosiphon, Helminthopsis*, fugichnia, and navichnia. Sandstone beds typically display lower bioturbation intensities (BI 0-2). Common traces are those associated with mud-filled burrows such as *Cylindrichnus, Gyrolithes*, and small diameter single entrance shafts assigned to *Trichichnus*.

**Interpretation:**

Facies 3a is interpreted to reflect deposition within below fairweather wave-base of a standing body of water. The environment was characterized by generally low (though variable) rates of deposition, subject to event sedimentation. Increased bioturbation intensities with sporadically distributed burrowing is consistent with fluctuations in sedimentation rates and energy conditions. Salinity appears to have varied but was generally close to normal marine salinities. Trace fossil suites are dominated by deposit-feeding structures with lesser dwellings of inferred filter-feeding organisms; such suites correspond to stressed expressions of the archetypal *Cruziana* Ichnofacies. Facies 3a is interpreted to have been deposited in proximal offshore settings that were not subjected to pronounced depositional stress. Such embayed settings are generally less restricted and/or have fewer fluvial channels draining into them.
3.3.3.2  Facies 3b: Sporadically to Moderately Burrowed Interbedded Sandstone and Mudstone

Sedimentology:

Facies 3b consists of fine- to very fine-grained well to moderately well sorted sandstones. The bulk of sedimentary structures in the sandstones comprise of low-angle, parallel laminae and oscillation-ripples. Locally, micro-hummocky cross stratification, current ripples, and combined flow ripples are intercalated. Sandstone beds are intercalated with moderately bioturbated mudstone. The basal contacts of the sandstone beds are sharp and scoured, and may contain minor amounts of mudstone rip-up clasts. Intercalated mudstone beds contain thin siltstone and sandstone layers that locally display starved oscillation ripples. Most mudstone beds drape the underlying sand beds, and display normal grading. Basal contacts of some mudstone layers are sharp, and show erosional truncation of the underlying sandstone laminae. Subaqueous shrinkage cracks (syneresis cracks) filled with sand or silt are common, particularly associated with mudstone beds (Fig 3.3F). Soft-sediment deformation structures are locally present, and include convolute lamination, microfaults, and rare ball-and-pillow structures. Laminae are locally marked by carbonaceous detritus or spherulitic siderite.

Ichnology:

Mudstone beds commonly possess higher bioturbation intensities. Bioturbation ranges from BI (0-5) but is typically BI 0-3 Trace fossils are sporadically distributed and include Planolites, Skolithos, Arenicolites, Gyrolithes, Cylindrichnus, Chondrites, Teichichnus, Thalassinoides, navichnia, and fugichnia. Some intervals display monogeneric suites of Cylindrichnus or Gyrolithes (Fig 3.4A). Sandstone beds generally exhibit lower bioturbation values (BI 0-2), and common trace fossils are Planolites, Gyrolithes, Cylindrichnus, Palaeophycus, and fugichnia.
Figure 3.3  A) Thoroughly Burrowed Silty/Sandy Mudstone (Facies 1). Suite includes Planolites (P), Palaeophycus (Pa), Cylindrichnus (Cy), Teichichnus (T), Chondrites (Ch), Asterosoma (As), Helminthopsis (H), and fugichnia (fu). Well 13-01-052-27W3, 488.3m.  

B) Tempestite with opportunistic suite of Rosselia (Ro), and Asterosoma (As). Well 07-03-054-25W3, 496.1m  

C) Pinstripe laminated mudstone of the distal prodelta (Facies 2). Note the dark-coloured mudstone drapes, interpreted to be of fluid mud origin. Suites are Planolites (P), Cylindrichnus (Cy), fugichnia (fu), and navichnia (na). Well 04-25-048-28W3, 583m.  

D) Pervasively bioturbated heterolithic succession (Facies 3a), with an ichnological suite comprising Planolites (P), Palaeophycus (Pa), Cylindrichnus (Cy), Thalassinoides (Th), Chondrites (Ch), Asterosoma (As), and Gyrolithes (Gy). Well 05-04-051-22W3, 458.6m.  

E) Facies 3a, displaying oscillation rippled sandstone enclosed in mudstone with dark, isolated carbonaceous mudstone drapes, interpreted as fluid mud in origin. Suite comprises Planolites (P), Teichichnus (T), Cylindrichnus (Cy), Asterosoma (As), and Rhizocorallium (Rh). Well 07-29-051-25W3, 511.5m.  

F) Heterolithic composite bedsets of the proximal delta front to distal delta front. Containing abundant syneresis cracks (syn). Note the current ripple lamination and dark carbonaceous mudstone drape. Traces include Planolites (P), Cylindrichnus (Cy), and fugichnia (fu). Well 05-20-050-24W3, 538.9m.
**Interpretation:**

The heterolithic expression of the facies implies the alternation of two depositional processes: wave-driven processes that deposited the sand and suspension settling and/or flocculation of mud. Storm events are recorded by HCS and micro-HCS. The presence of current ripples and combined flow ripples indicate the presence of secondary unidirectional sediment transport processes. Low-diversity trace-fossil suites and diminutive ichnogenera suggest environments in which water salinities were persistently brackish (e.g., Beynon *et al.*, 1988; Beynon and Pemberton, 1992, Gingras *et al.*, 2005; MacEachern and Gingras, 2007). Low-intensity bioturbation may indicate a combination of stresses conditions including elevated depositional rates. The presence of syneresis cracks supports salinity reduction in the environment (e.g., Burst, 1965; Plummer and Gostin, 1981). These syneresis cracks are best developed at the sand and mud contacts, suggesting that the influx of freshwater was associated with the deposition of the sand. Soft-sediment deformation features supports heightened sedimentation rates. Some of the sandstones contain escape structures (fugichnia), consistent with rapid deposition. Concentration of carbonaceous detritus and organic-rich mudstone drapes supports the presence of fluid mud input (cf. MacEachern *et al.*, 2005; Bhattacharya and MacEachern, 2009). These fluid muds are interpreted to be associated with contemporaneous floodwater discharge from distributary channels. Navichnia (sediment-swimming structures; cf. Gingras *et al.*, 2007) or mantle-and-swirl structures (Lobza and Scheiber, 1999) are typical expressions of fluid mud layers. The trace fossils in the sandstone beds are interpreted to represent the activities of opportunistic organisms that rapidly colonized the surface when these sandy beds become available. Facies 3b contains trace fossil elements that are best characterized as a stressed expression of the *Cruziana* Ichnofacies. Such settings are consistent with distal to proximal prodelta settings.
3.3.4 Facies 4: Sandstone

Facies 4 main bodies consists of very fine to medium grained sandstone dominated by oscillation ripple lamination, HCS, combined-flow ripples and current-ripple lamination. Bedding thicknesses is variable within Facies 4 and commonly ranges between 20 cm up to 1.5 m. Facies 4 has been subdivided into two subfacies mainly on the basis of their sedimentological features.

3.3.4.1 Facies 4a: Oscillation Rippled to Hummocky Cross-stratified Sandstone

Sedimentology:

Facies 4a commonly overlies stacked coarsening-upward cycles. Beds consist of well-sorted, very fine- to fine-grained sandstone. Dominant sedimentary structures are low-angle (<15°) parallel laminae, interpreted as hummocky cross-stratification (HCS), oscillation-ripple lamination, and combined flow-ripple lamination. Individual beds are sharp-based, and typically centimeters to decimeters in thickness. These individual beds become more amalgamated towards the upper part of the facies (Fig 3.4B). Carbonaceous detritus and siderite nodules are locally present. Rare, small-scale rip-up clasts are distributed along the erosional bedding planes. Locally, millimeter- to centimeter-thick mudstone beds are intercalated. Mudstones comprise less than 10% of the facies. Mudstones are generally fissile, locally silty, and may display normal grading and syneresis cracks. Soft-sediment deformation is also present, manifested as convolute bedding and rare micro-faults, especially where thin beds of mudstone are intercalated (Fig 3.4C).

Ichnology:

Facies 4a generally shows low bioturbation intensities of BI 0-2. Trace fossils are of low diversity and are sporadically distributed. The trace fossil suite are characterized by mainly mobile deposit feeding, suspension-feeding, and escape structures associated with emplacement of HCS. Traces include *Skolithos, Cylindrichnus, Planolites,*
Palaeophycus, fugichnia, and navichnia in muds. Root structures are locally present and are typically restricted to the top of the facies.

**Interpretation**

Oscillatory-generated bedforms indicate a subaqueous depositional environment. Storm waves generally produce HCS and micro-HCS, followed by waning storm energies that form oscillation ripples and combine flow ripples (Johnson and Baldwin, 1996). The relative thickening and increase in numbers of HCS beds are interpreted to record progressive shallowing along the depositional profile. Intervalated mudstone drapes probably indicate suspension sediment settling or rapid flocculation of mud. In the case of fluid mud, the absence of bioturbation indicates that these muds were deposited rapidly. The presence of mantle-and-swirl structures or navichnia, graded bedded mudstone layers, and intervening silt and sand laminae are characteristic of fluid mud deposition (e.g., Bhattacharya and MacEachern, 2009). Mudstone rip-up clasts within the facies suggest that flow velocities were sufficiently energetic to erode mud layers and produce clasts. These rip-up clasts were probably derived from intervening mudstone drapes. Spherulitic siderite and nodules associated with organic detritus suggest sediment supply from the adjacent coastal/delta plain, and the reworking of incipient paleosol deposits (e.g., Leckie et al., 1989). The near absence of biogenic sedimentary structures is related to high-energy conditions. Nevertheless, the presence of localized bioturbated zones indicate that energy conditions were, at times, reduced and benthic organisms were able to colonize and rework the substrate. The trace-fossil suite is of low diversity and is dominated by facies-crossing dwelling structures that reflect both suspension-feeding and surface-detritus-feeding organisms. Such suites are typical of stressed expression of the Skolithos Ichnofacies. Such characteristics are typical of lower to middle shoreface and delta front environments.
3.3.4.2 Facies 4b: Oscillation Rippled Sandstone Interbedded with Current Rippled Sandstone

**Sedimentology:**

Facies 4b is represented by fine - to medium-grained sandstone. Sandstones are well sorted and generally show a coarsening-upward trend. The facies is dominated by 5-15 cm thick, erosionally truncated micro-HCS and amalgamated wave ripples that are interbedded with 5-10 cm thick, stacked current-ripple laminated and trough cross-stratified beds (Fig 3.4D). Organic detritus is common and delineate bedding planes, and generally increases in abundance upward. Rare mudstone interlaminae are also present.

**Ichnology:**

Bioturbation within Facies 4b is generally sporadic distributed and consists of low diversity suites. Most of the trace fossils are associated with the oscillation rippled and current rippled sandstones. HCS beds commonly unburrowed. Common trace fossils include *Cylindrichnus, Planolites, Skolithos*, and fugichnia.

**Interpretation:**

The erosionally amalgamated storm deposits, coupled with the intercalated oscillation rippled and trough cross-stratified beds indicated that both storm and wave-forced currents operated in the depositional environment. The intercalated carbonaceous detritus probably reflects storm-induced phytodetrital pulses of sediment, that were delivered to the delta front during periods of heightened fluvial influx following concomitant storm-induced precipitation (*e.g.*, Leithold and Bourgeois, 1984, MacEachern *et al.*, 2005). Ichnological suites within Facies 4b indicate both dwelling and suspension feeding behavioural groups within an environment typified by high-energy conditions. Concentration of reworked spherulitic siderite, carbonaceous detritus, and phytodetrital sediment suggests the presence of a fluvial point source within the environment (*e.g.*, Leckie *et al.*, 1989). Such characteristics are typical of proximal delta-front and mouth bar successions.
3.3.5 Facies 5: Trough Cross-Bedded to Tabular Cross-Bedded Sandstone

Sedimentology:

Facies 5 encompasses fine- to medium-grained sandstones dominated by trough-cross stratification (Fig. 3.4E). Current-ripple lamination, combined-flow ripples, and locally aggradational current ripples. Commonly, current-ripples are located where trough cross-stratification has low inclinations, marking the position of toesets. Mudstone drapes, spherulitic siderite, and carbonaceous detritus are common constituents.

Ichnology:

Bioturbation intensities within Facies 5 are generally low, and range from BI 0 to BI 2 at the bed scale. The facies locally contains Planolites, Cylindrichnus, and fugichnia.

Interpretation:

Deposits of Facies 5 reflect conditions of quasi-steady unidirectional flow, high sedimentation rates, and high- to moderate-energy hydrodynamic regimes. The bulk of the facies reflects asymmetric dune-scale bedforms and current ripples that migrated in response to traction current flow. The trace-fossil suite is of low diversity and contains traces that comprise facies-crossing forms. Facies 5 is interpreted to reflect the proximal upper shoreface setting and/or distributary channel deposits.

3.3.6 Facies 6: Current Ripple Laminated Sandstone

Sedimentology:

Facies 6 comprises unidirectional current ripples and, locally, planar parallel laminated siltstone and sandstone intervals, decimeter- to meter-scale in thickness (Fig. 3.4F). Sands are moderately to well sorted, and fine to lower medium grained.
Combined-flow ripples and aggradational current ripples are present locally. Stratification is marked by carbonaceous detritus and spherulitic siderite. Rare mudstone rip-up clasts 2-5 cm in diameter and thin mudstone flasers are also intercalated. Rare units display soft-sediment deformation and micro-faults.

**Ichnology:**

Bioturbation intensities are generally low, ranging from BI 0-2 at the bed scale. Burrowed zones locally display isolated *Skolithos, Cylindrichnus, Planolites,* and fugichnia. The ichnological suite displays diminutive burrows and reduction in diversity of the permanent dwellings (*e.g.*, domiciles of inferred suspension-feeding organisms). Episodic deposition favoured the presence of escape behaviours.

**Interpretation:**

Abundance of current-ripple lamination suggests that deposition occurred under moderate energy conditions. The trace-fossil suite is of low diversity and consists of predominantly facies-crossing forms. The presence of spherulitic siderite and organic detritus reflects a nearby terrestrial source, and probably indicates reworking of incipient paleosols (*e.g.*, Leckie *et al.*, 1989). Soft-sediment deformation and rip-up clasts suggest that the sediment was semi-consolidated during transport and deposition. Aggradational current ripples reflect periods of heightened sedimentation. Facies 6 is closely associated with Facies 5 and 7, and is interpreted as the shallow portions of point bars, interchannel bars and/or crevasse splays.

3.3.7 Facies 7: Inclined Heterolithic Stratification (IHS)

**Sedimentology:**

Facies 7 consists of inclined heterolithic bedsets of sandstone and mudstone. Bedsets vary from mud dominated to sand dominated. Dip angles are generally less than 15°. Sand is fine to medium grained, and moderately to well sorted. Sandstone beds are
commonly dominated by current-generated structures, including small stacked current ripples and small-scale trough cross-stratification. The scale of trough cross-stratification decreases upward. Oscillation ripples, and wavy parallel laminations are also present, though uncommon. The facies locally contains concentrations of intraformationally derived mudstone rip-up clasts or isolated shale clasts. Mudstone bed thicknesses vary from centimeter to decimeter scale. The proportion and thickness of mudstone beds generally increase upward. Where the facies is unburrowed, the contacts between mudstone and sandstone beds are commonly sharp and erosional. Generally, mudstone beds are structureless, but sandstone layers may be intercalated locally. Sandstone layers display small-scale current ripples and parallel lamination (Fig 3.5A). Some mudstone units may show normally grading. Carbonaceous detritus, pyrite, siderite nodules, coalified wood fragments and soft-sediment deformation features are locally present within the facies. Facies 7 is closely associated with Facies 5 and Facies 6.

Ichnology:

Facies 7 generally displays variable bioturbation intensities at the bed scale (BI 0-5). Sandstone beds are typically unburrowed or weakly burrowed (BI 0-1; locally 2). Trace fossils include *Cylindrichnus, Skolithos, Planolites*, and fugichnia. Mudstone beds vary from BI 0-5 (Fig 3.5B). Biogenic structures include *Cylindrichnus, Planolites, Skolithos, Arenicolites, Palaeophycus, Thalassinoides, Teichichnus, Gyrolithes, Chondrites*, and navichnia. The abundance of burrowing in both sandstone and mudstone beds generally increases upward. Trace fossils are diminutive and of low diversity.
Figure 3.4 A) Wavy-bedroom oscillation rippled sandstone and silty mudstone. Trace fossil suite is dominated by *Gyrolithes* (Gy) with isolated *Planolites* (P), *Cylindrichnus* (Cy), and *Palaeophycus* (Pa). Syneresis cracks (syn) are locally present. Well 06-01-050-27W3, 550.8m. B) Erosionally amalgamated oscillation-rippled sandstone of Facies 4a. Note the micro-HCS near the top of the unit. Trace fossils include *Planolites* (P) and *Cylindrichnus* (Cy). Well 04-25-048-28W3, 580.4m. C) Convolute bedding within Faces 4a. Well 11-03-051-22W3, 484.1m. D) Proximal delta-front sandstone displaying oscillation-ripples interbedded current ripples (Facies 4b). Carbonaceous detritus is abundant within the facies. Well 06-16-048-23W3, 496.5m. E) Highly oil-stained sandstone displaying trough-cross bedding (Facies 5). Well 05-30-048-20W3, 454.1m. F) Erosionally amalgamated current-rippled sandstone (Facies 6). Well 11-03-051-22W3 478.8m.
Interpretation:

The regular alternation of mudstone interbedded with sandstone, coupled with their inclined character is consistent with inclined heterolithic stratification (IHS) of Thomas et al., (1987). The presence of trough cross-stratification and current-ripple lamination suggest unidirectional or bidirectional flow and traction sediment transport. Small-scale oscillation ripples and combined flow ripples suggest periods of standing water and wave modification. Flow velocities were sufficiently strong to move mudstone rip-up clasts. The intervening mud beds within the facies were probably deposited from suspension or via clay flocculation. The paucity of burrowing and the presence of navichnia (mantle-and-swirl structures; cf. Lobza and Schieber, 1999), which record soupground conditions, support the flocculation of mud (Gingras et al., 2007). The flocculation of mud is due to the mixing of salt and freshwater (Krone, 1962; Meade, 1972; Allen et al., 1980; Clffroy et al., 2003). The low diversity and facies-crossing trace fossil suites are typical of brackish-water conditions (Beynon et al., 1988; Pemberton and Wightman, 1992; Beynon and Pemberton, 1992; MacEachern et al., 2005; MacEachern and Gingras, 2007). The paucity of bioturbation probably reflects reductions in salinity or higher depositional rates, indicating that the environment was probably under elevated conditions of physico-chemical stress. Zones showing more pervasive bioturbation possibly record elevated salinities and/or reductions in depositional rates. Facies 7 is interpreted to record lateral accretion deposits associated with migration of tidal-fluvial channels.

3.3.8 Facies 8: Cross-Bedded Carbonaceous-Rich Sandstone

Sedimentology:

Facies 8 consists of trough to planar tabular cross-bedded sandstone with abundant organic detritus (Fig 3.5C) marking stratification. The facies is generally 1 to 2 meters in thickness. Sands are fine to medium grained and moderately sorted. Current-ripple laminations are locally abundant. The top of the facies is commonly penetrated by
roots. Coal fragments, transported spherulitic siderite, and siderite nodules occur locally. Facies 8 is commonly overlain by Facies 9.

**Ichnology:**

Facies 8 generally displays low bioturbation intensities (BI 0-1). Traces within Facies 8 are dominated by roots and *Planolites*.

**Interpretation:**

The trough to planar tabular cross-bedded sandstone is interpreted to reflect dune-scale bedforms generated by persistent quasi-steady unidirectional flow. The presence of current-ripples indicates decreases in current velocity. Spherulitic siderite, siderite nodules, abundant organic detritus indicate that sediments were derived from nearby terrestrial sources (*e.g.*, Leckie *et al.*, 1989). The low bioturbation intensity of the facies suggests deposition within a stressful depositional setting (*e.g.*, low salinity, high sedimentation rates, etc.) Facies 8 is interpreted as fluvial channel deposits positioned within upper part of coastal/delta plain.

### 3.3.9 Facies 9: Root-Bearing Mudstone

**Sedimentology:**

Facies 9 is characterized by light-colored, silty to sandy mudstone with associated vertically oriented rootlets. Most units appear structureless and are recovered in the form of mudstone rubble (Fig 3.5D). Fragments locally display waxy pedogenic slickensides (*cf*. Leckie *et al.*, 1989). Carbonaceous detritus is present within the facies and locally demarcate lamination. Siderite nodules and coalified-wood fragments are present locally. Very fine-grained sandstone and siltstone beds are interbedded within the facies, and where present they commonly display small-scale gravity faults and convolute bedding. Locally, amalgamated current-ripple lamination with erosional bases are present within
the facies, which typically fines upward. Facies 9 commonly becomes massive (structureless) upward.

**Ichtyology:**

Facies 9 generally displays very low bioturbation intensities. The units show BI (0-1) (Figure 3.5E). Common biogenic structures are Planolites, Naktodemasis, and roots.

**Interpretation:**

Facies 9 records sedimentation of fine-grained materials within an upper delta plain or floodplain setting. Abundant carbonaceous material, rootlets subtending from coal seams (Facies 10), and the presence of Naktodemasis (“adhesive meniscate burrows”; cf. Smith *et al.*, 2008) reflects periods of subaerial exposure. It is noteworthy that the principal diagnostic criteria for most backfilled ichnogenera are the shape of the backfill, the burrow margin, and presence or absence of branching. Naktodemasis is an ichnogenus proposed by Smith *et al.* (2008), and is distinguished from Taenidium by the presence of backfill organized in nested, ellipsoid-shaped and asymmetric menisci. Krapovickas *et al.* (2009), by contrast, argues that the difference in meniscae arrangement should be regarded as an ichnotaxobase at an ichnospecific level, and therefore Naktodemasis is a junior synonym of Taenidium. They assert that the structure should be regarded as Taenidium bowni. In this thesis, Naktodemasis is employed, pending further ichnotaxonomic assessment.

The presence of siderite nodules along with organic detritus are interpreted as reworking of incipient paleosols (*e.g.*, Leckie *et al.*, 1989). Current-rippled sandstone layers are interpreted to represent elasic material introduced into the floodplain as crevasse splays.
3.3.10 Facies 10: Carbonaceous Mudstone and Coal

Sedimentology:

Facies 10 comprises highly carbonaceous mudstones and sub-bituminous coal (Fig 3.5F). The facies tend to be black to dark gray color, depending upon the amount of interstitial silt and sand. Organic contents appear to increase upward. Beds are generally 20 centimeters thick, but can reach up to 2 meters in thickness. The facies is commonly associated with underlying root zones, confirming its in situ condition. Pyrite is mainly associated with the upper part of the carbonaceous mudstones and coal beds.

Ichnology:

Bioturbation intensities within Facies 9 are very low (BI 0-1) and commonly confined to the lower section. Common traces are Planolites and roots.

Interpretation:

Facies 10 is interpreted to have been formed as a result of accumulation of plant material and organic matter on the coastal/delta plain, probably as swamps, bogs, and forested zones. Micro-lithotype analysis of the coal would be required in order to ascertain the particular coal-forming environments. In coastal regime, the preservation of coal is commonly associated with elevated and/or rising water tables. As such, coals may mark the early onset of transgression in the coastal regime.
**Figure 3.5**  
A) Sparsely bioturbated heterolithic interval of Facies 7, showing current-ripple lamination. Mudstones are silty and contain starved current ripples in sand, as well as isolated *Planolites* (P). Well 10-16-048-20W3, 455.3m.  
B) Highly burrowed heterolithic interval of Facies 7. Bioturbation is sufficiently intense that primary structures are obliterated. Trace fossil suite includes *Planolites* (P), *Cylindrichnus* (Cy), *Skolithos* (Sk), *Thalassinoides* (Th), *Gyrolithes* (Gy), *Chondrites* (Ch), and fugichnia (fu). Well 10-12-048-20W3, 441.0m.  
C) Trough cross-bedding with abundant spherulitic siderite and organic detritus (Facies 8). Well 03-22-050-27W3, 541.3m.  
F) Well-bedded coal (Facies 10). Well 05-12-051-24W3, 461.0m.
3.4 Facies Associations

Facies associations are recurring vertical successions of genetically related facies. They are considered to be the foundation of facies analysis and environmental interpretations (Reading & Levell, 1996). Interpretations of paleoenvironments are more accurate when analyzing relationships of genetically related facies both vertically in measured section as well as their lateral distributions. Based on similar attributes, facies from Sparky Alloformation are grouped into five different facies associations (FA1-FA5).

3.4.1 Facies Association 1: Offshore Marine Deposits

Facies Association 1 (FA1) comprises a single facies, characterized by pervasively bioturbated silty mudstones to sandy mudstones (Facies 1). The succession can be found in the northern part of the study area. Unfortunately, there are very few cores available from that region and mapping of the distribution of FA1 can be challenging. FA1 is characterized by gradual upward coarsening and an increase in sand content (Fig 3.7). The successions have an average thickness of 4 to 12 m. An idealized, complete succession begins with massive bioturbated mudstones with trace fossil assemblages dominated by Planolites, Chondrites, Helminthopsis, Phycosiphon, Palaeophycus, Cylindrichnus, Teichichnus, Piscichnus, Rosselia and Asterosoma. These bioturbated mudstones pass upwards into bioturbated sandy mudstones with intercalated small-scale wave-ripple cross-stratification and micro-HCS. Commonly, the relative degree of bioturbation decreases upward and traces become more robust. The intercalated sandstone beds are commonly devoid of biogenic structures.

The upward coarsening of grain size, combined with the association of physical and biogenic sedimentary structures, is interpreted to record a shallowing-upward trend that culminates with the deposition of wave ripples and micro-HCS. The pervasively bioturbated mudstone at the base of the facies, coupled with the predominance of grazing and deposit-feeding structures suggest slow accumulation of fine-grained material in a low energy setting, possibly near and below fairweather wave base in an offshore
position. Such suites are representative of the archetypal *Cruziana* Ichnofacies. The robust trace fossils and presence of ichnogenera that are characteristics of more normal marine conditions (*e.g.*, *Chondrites*, *Asterosoma*, *Helminthopsis*, *Phycosiphon*) suggest that salinities were normal at the time of deposition. The sharp-based intercalated sandstones are interpreted to reflect episodic emplacement sandstones by storms. The absence of biogenic sedimentary structures within these sandstone tempestites supports rapid emplacement under high-energy conditions (Howard and Frey, 1984; Vossler and Pemberton, 1989; Pemberton and MacEachern, 1997; MacEachern and Bann, 2008).
Figure 3.6 Legend of symbols used in lithologies.
Figure 3.7 Litholog of core from well 13-01-052-27W3, illustrating FA1 representing distal offshore marine deposits. Legend for lithologies is given in Figure 6.
3.4.2 Facies Association 2: Wave-/Storm-Dominated Shorefaces

Facies Association 2 (FA2) comprises a coarsening-upward and shallowing-upward succession, consisting of Facies 3a, 4a, and 5 (Fig 3.8). The succession is typical of central parts of the study area (e.g., Celtic, Golden Lake, Lashburn fields), comprising bioturbated sandy mudstone interbedded with sandstone (Facies 3a), oscillation-rippled to hummocky cross-stratified sandstone (Facies 4a), and trough cross-bedded to planar tabular cross-bedded sandstone (Facies 5). FA2 typically ranges from 5-10 meters in thickness. The base of the succession locally sits on a marine flooding surface (FS) or transgressive surface of erosion (TSE). In most successions, the percentage of sandstone varies markedly, with the base containing 20-30% sandstone, increasing to 90-100% toward the top of the succession.

Facies 3a is composed of interbedded sandstone and mudstone, wherein the sand contents increase upward and commonly display oscillation ripples and micro-HCS. The heterolithic character of the facies coupled with the predominance of oscillatory-generated structures reflects fluctuations in sedimentation rates and depositional energy (e.g., Howard and Frey, 1984; Bann et al., 2008; MacEachern and Bann, 2008). The sedimentary structures are commonly preserved where bioturbation intensities are sufficiently low. Interbedded mudstones within Facies 3a are typically thoroughly bioturbated, and contain uniform distributions of ichnogenera, consistent with suspension sediment settling below fairweather wave base (Howard and Frey, 1984; Frey, 1990). Some rapid clay flocculation is indicated by the presence of dark, fissile and laminated mudstones locally containing navichnia (sediment-swimming structures). The trace fossil suites within the mudstones of Facies 3a dominantly consist of deposit-feeding structures and rare grazing structures, and show elevated trace fossil diversities (Table 2). High diversity coupled with high BI values are consistent with deposition under well-oxygenated marine conditions with abundant food resources, which permitted the tracemaking organisms to flourish. The tempestites within Facies 3a tend to display low degree of bioturbation. Trace fossils in the sandstones commonly reflect opportunistic re-colonization of substrate following a storm event (e.g., Howard and Frey 1984; Vossler and Pemberton, 1989; Frey, 1990; Pemberton and MacEachern, 1997; MacEachern et al.,
Locally within the study area, the bioturbated silty/sandy mudstone (Facies 1) of Facies Association 1 sits at the base of the succession marking the initial transgression.

Facies 3a passes gradationally upwards into Facies 4a, and displays increased proportions and thicknesses of storm-generated event beds (tempestites). Facies 4a displays oscillation rippled sandstone and amalgamated HCS, representing deposition above fairweather wave base and an increase in the degree of storm influence on the setting. Locally, millimeter- to centimeter-thick mudstone beds are intercalated and are interpreted as rapid deposition of flocculated mud from adjacent deltas. Bioturbation intensity is commonly very low within the facies (BI 0-2). This is interpreted to be due to increased storm frequency and heightened storm intensity, which reduced the infaunal colonization windows for larvae and favoured erosional removal of fairweather beds, respectively (Pemberton et al., 1992; Pemberton and MacEachern, 1997). The gradational contact between Facies 3a and Facies 4a represents the transition from the proximal offshore into lower to middle shoreface environment.

The upper part of FA2 is represented by Facies 5. The facies is not commonly observed within the lower cycles, although the top of the succession is commonly oil stained, making the identification of physical and biogenic structures challenging. Facies 5 consists of trough cross-bedded sandstone, locally with current ripple and horizontal planar parallel laminated sandstone. Such structures are common within the upper shoreface and are interpreted as three dimensional dunes (Reinson, 1984). Like Facies 4a, bioturbation intensities within Facies 5 are low (BI 0-2). The migration of dunes generally prevents endobenthic organisms from colonizing the substrate (MacEachern and Pemberton, 1992), and as a result, such environments commonly display low bioturbation intensities. The low preservation potential of this facies within the lower cycles is probably due to erosion of these deposits during shoreline transgression by wave or tidal actions. In this scenario the eroded sediments are commonly reworked, transported and deposited in the lower shoreface and offshore environments (Kidwell, 1989; Van Wagoner et al., 1990; Cattaneo and Steel, 2003). The alternative interpretation would be that the progradation of Sparky within the study area was up to middle shoreface before the transgression.
Facies Association 2 (FA2) is interpreted to correspond to wave-/storm-dominated shoreface deposits. It is most commonly observed facies association within the central part of the study area. The succession represents the progradation from proximal offshore to upper shoreface environments. Locally, subtle deltaic overprints on some intervals are apparent. FA2 is commonly overlain by coastal plain deposits of FA5.
**Figure 3.8** Litholog of representative well 11-18-048-21W3, showing the facies of FA2, interpreted as wave-/storm-dominated shoreface successions. Legend for lithologies is given in Figure 6.
3.4.3 Facies Association 3: Mixed Wave- and River- Influenced Deltas

Facies Association 3 (FA3) consists of coarsening-upward and shallowing-upward successions, and includes (from bottom to top) intervals of Facies 2 (pinstripe to lenticular bedded mudstone), Facies 3b (sporadically to moderately bioturbated interbedded sandstone and mudstone), Facies 4a (oscillation-rippled to hummocky cross-stratified sandstone), and Facies 4b (oscillation-rippled sandstone interbedded with current-rippled sandstone) (Fig 3.9). Like FA2, FA3 shows an upward increase in the proportions of sandstone beds from the base of the succession (20-30%) to the top (90-100%), reflecting an upward increase in depositional energy. The base of the FA3 succession is separated from G.P. Alloformation sandstone by a marine flooding surface (FS) or transgressive surface of erosion (TSE), which passes into Facies 2.

Facies 2 reflects deposition of distal prodelta mudstone and sandstone. The setting is characterized by a mud-prone interbedded succession of mudstones and thin sandstones. Stratigraphically upwards, the proportion of sandstone to mudstone increases, with sandstones beds becoming thicker (up to 5 cm). This is consistent with upward shallowing, and change in the overall effectiveness of wave energy on the substrate. Sandstone beds generally contain oscillation ripples, combined flow ripples, rare current ripples, and/or micro-HCS. The mudstone interbeds are commonly carbonaceous, black in colour, sharp based, and laminated to fissile. Numerous units are normally graded. Syneresis cracks are locally common within the muddy part of the facies, and are generally filled with silt or very fine-grained sand. The interbedded character of Facies 2 records the alternation of fairweather deposition and event bed emplacement within the distal to proximal parts of a prodelta setting. Facies 2 commonly displays weak to moderate bioturbation intensities (BI 0-2, locally 3). Ichnological suites comprise diminutive trace fossils recording low diversity suites, and correspond to a stressed expression of the *Cruziana* Ichnofacies. The majority of trace fossils within Facies 2 reflects deposit-feeding behaviours and paucity of dwellings of inferred suspension-feeding organisms. Such associations in sand-prone units is typically taken to indicate elevated water turbidity near the sediment-water interface (*e.g.*, Moslow and Pemberton,
1988; Gingras et al., 1998; MacEachern et al., 2005, Coates and MacEachern, 2007; Hansen and MacEachern, 2007; Buatois et al., 2012).

Facies 2 passes upwards gradationally into Facies 3b, and displays increased amounts and thicknesses of sandstone beds. Facies 3b is interpreted to have been deposited below fairweather wave base within a proximal prodelta to distal delta-front setting subjected to persistent river-and storm-induced physico-chemical stresses. Sandstone beds contain oscillation ripples and micro-HCS. Current rippled sandstone beds are locally intercalated and are attributed to fluvial influence within the setting. The sandstone beds are locally draped with organic-rich mudstones. Carbonaceous mudstone drapes probably record hypopycnal-induced buoyant mud plumes and concomitant rapid flocculation of mud. Some mudstone beds are normally graded and display evidence of erosion at their bases, and are interpreted as mud turbidites deposited as a result of hyperpycnal discharge or from failure at the delta front. River flood-induced hyperpycnal processes are favoured for units showing syneresis cracks (e.g., MacEachern et al., 2005; Bhattacharya and MacEachern, 2009). These organic-rich beds, whether hyperpycnal or hypopycnal, commonly display little or no biogenic reworking. This probably indicates that the emplacement of these organic-rich muds, at least temporarily, resulted in dysaerobic conditions (oxidation of intercalated organic debris), which prevented or inhibited infaunal colonization of the substrate (e.g., Raychaudhuri and Pemberton, 1992; Coates and MacEachern, 1999; Bann et al., 2004; MacEachern et al., 2005; Bann et al., 2008). The facies is characterized by low intensities of bioturbation as well as low diversity trace fossil suites, consistent with heightened physico-chemical stress.

Facies 3b is overlain by Facies 4a, consisting of erosionally amalgamated sandstones. Facies 4a comprises fine- to very fine-grained sandstone, which commonly show preserved oscillation rippled and HCS beds. Locally, thin layers of mudstone are intercalated locally with syneresis cracks. The facies is interpreted to have been deposited above fairweather wave base within a delta-front setting.

Facies 4b, if preserved, commonly occurs at the top of FA3. The facies consists of oscillation rippled sandstone interbedded with current rippled sandstone. The presence of
current-ripple structures reflects a stronger fluvial influence on deposition within the setting. Aggradational current-ripples have also been observed and indicate periods of rapid deposition. The interbedded oscillation rippled sandstone within the unit suggests continuous wave reworking of sediments by waves. In most cases the FA3 lacks Facies 4b which indicates the distributary mouth-bar deposits completely reworked by waves (into oscillation ripples and HCS). Spherulitic siderite, siderite nodules, and carbonaceous detritus are locally common, and indicated that sediments were derived directly from soils in terrestrial settings (e.g., Leckie et al., 1989). Facies 4b displays exceedingly low intensities of burrowing and low trace fossil diversities, reflecting stressful environmental setting (e.g., high sedimentation rates). Such conditions are consistent with deposition within proximal delta front and distributary mouth bar complexes (e.g., Fielding et al., 2006; Bhattacharya and Walker, 1991).

Facies Association 3 is interpreted to represent the progradation of a mixed influence river-wave dominated delta. FA3 is commonly passes into FA2 along strike and is overlain by FA5, which reflects emergence and establishment of peat-forming swamps and marshes.
Figure 3.9 Litholog of 04-29-048-27W3, illustrating facies characteristics of a mixed river-wave influenced delta of the Sparky Alloformation. Legend for lithologies is given in Figure 6.
3.4.4 Facies Association 4: Distributary Channels

Facies Association 4 (FA4) comprises generally fining-upward succession, consisting of facies 5, 6, and 7 (Fig 3.10). These facies consist of trough cross-bedded to planar tabular cross-bedded sandstones, current rippled laminated sandstones, and inclined heterolithic stratification (IHS). The association is located in both the southeastern and southwestern parts of the study area.

The base of the association is commonly sharp and erosional, and is overlain by Facies 5. Facies 5 is represented by medium- to fine-grained, moderately sorted cross-stratified sandstone. Dominant sedimentary structures are trough and planar tabular-cross bedded sands, with locally stacked current ripples. The presence of such structures indicates a current-dominated depositional environment. Spherulitic siderite, carbonaceous detritus and coalified wood fragments are common throughout the facies, and reflect a nearby terrestrial sediment source (e.g., Leckie et al., 1989). Intraformational mudstone rip-up clasts are locally present, indicating that flow velocities were sufficiently high to erode and transport blocks of cohesive sediment. Bioturbation is generally absent, although rare zones showing BI 1-2 are present locally, probably indicating that there were periods of brackish water influx into the setting. Alternatively the paucity of bioturbation may be associated with high sedimentation rates. Facies 5 is interpreted to represent migration of dune-scale bedforms within a channel setting.

Facies 6 comprises sandstone characterized by abundant current ripples. Organic detritus are common throughout the facies and commonly demarcates stratification. Flaser bedding is present locally and is interpreted to reflect a tidal signature (e.g., Reineck and Singh, 1980; Allen et al., 1980). Ichnologically, the facies shows low bioturbation intensities (BI 0-2). The ichnological suite consists of diminutive burrows and displays reduced trace fossil diversities. Most of the bioturbated zones possess isolated trace fossils and indicate periodic brackish-water conditions.

Facies 7 consists of inclined heterolithic stratification. Sandstone beds are generally 2-30 cm in thickness. In most successions, the proportion of sand decreases
upward. Common sedimentary structures within the sandy beds are trough cross-stratification and current ripple lamination. These sandstone beds commonly contain abundant carbonaceous detritus and show very low bioturbation intensities. The interbedded mudstones are locally intensely bioturbated, may lack any structures, or possess millimeter- to centimeter-scale interlaminae of sand. These laminated sands commonly contain small-scale current ripple stratification. Such interbedded sandstone and mudstone bedsets resemble inclined heterolithic stratification (IHS) of Howard et al., (1975) and Thomas et al., (1987). These heterolithic intervals are interpreted as lateral accretion deposits, attributed to point bars within the channel complex. The low BI values of some of the mudstone beds may indicate that the salt-water wedge was present within the channels, and migrated along the channel length over the course of the tidal cycle. Distributary channels can be tidally influenced, even where tidal ranges are low especially within low-gradient settings. For example in the Mississippi river, low tidal ranges can migrate up to 50 km inland from the coast (Gould, 1970). This number can reach up to 400 km within tide-dominated Fly river delta distributary channels (Dalrymple, 2003). Suspended sediment loads carried by rivers commonly mix with saltier basin waters, leading to the flocculation of mud and its deposition as fluid mud within the channel and on the point bar (Meade, 1972; Allen et al., 1980; Clffroy, 2003). The trace fossil suites within Facies 8 correspond to mixed suites that contain elements typical of both the Skolithos and Cruziana ichnofacies. This suggests that food resources were abundant in both the substrate and water column (e.g., Beynon and Pemberton 1992; Gingras et al., 1999). This also supports persistent mixing of fresh and marine water within the channels. The colonization of the point bar by organisms probably reflects slower deposition and generally reduced fluctuations in salinity.

The overall decrease in grain sizes and bedform scales upward through FA 4 is interpreted to represent lateral migration of tidal-fluvial point bars complex within the distributary channels.
Figure 3.10 Interpretive litholog for the well 10-16-048-20W3. Legend for lithologies is given in Figure 6.
3.4.5 Facies Association 5: Coastal/Delta Plains

Facies Association 5 (FA5) comprises the deposits associated with the proximal positions of marginal marine settings. This association is represented by facies 8, 9 and 10 (Fig 3.11). FA5 commonly caps the uppermost parasequence, marking the top of the Sparky Alloformation. FA5 averages 3-5 m thick. The base of the succession locally displays an erosional or gradational contact with the underlying units.

Facies 8 forms the base of FA5, and consists of trough-cross bedded sandstone with abundant organic detritus. Organic detritus commonly demarcates the internal laminations. The facies generally displays a fining-upward trend. The top of the facies commonly contains abundant current ripples. The presence of transported spherulitic siderite grains reflects the reworking of nearby incipient paleosols (e.g., Leckie et al., 1989). Bioturbation intensities within Facies 9 are extremely low, although isolated Planolites is present. The top of the Facies 8 is commonly penetrated by roots from overlying coal and mudstone deposits (facies 9 and 10).

The contact between Facies 8 and root-bearing mudstone (Facies 9) is gradational. The facies is interpreted to reflect deposition within the floodplain capping point bars or from vertical accretion deposits recording the final stages of channel abandonment. Current-rippled sandstone beds within Facies 9 are less than 1 meter in thickness and commonly display a fining upward trend. These deposits are interpreted to represent episodic sedimentation as crevasse splays. Common rootlets, paleosol development and the localized presence of Naktodemasis are consistent with fluctuations in water level and periods of subaerial exposure (cf. Hasiotis, 2002; Smith et al., 2008). The contact between Facies 9 and Facies 10 is gradational, whereas the upper contact defining the base of the Waseca Alloformation is, in all locations, sharp. The most characteristic feature of Facies 10 is the abundance of carbonaceous mud and coal. Typically, the carbonaceous mudstones are parallel-laminated or possess a massive appearance. Such characteristics are consistent with the establishment and development of peat-forming swamps or marshes. In modern coastal environments, such deposits accumulate in marsh or swamp areas on the delta plain or coastal plain areas (Reading and Collinson, 1996).
Figure 3.11 Core litholog for the well 12-05-051-24W3, showing FA5 of the coastal/delta plain. Legend for lithologies is given in Figure 6.
3.5 Stratigraphy

Within the Lloydminster area, the Mannville Group has been divided into nine lithostratigraphic packages that have been informally named (Fig 3.1). For the purposes of genetic stratigraphy and the establishment of paleogeographic relationships, a lithostratigraphic breakdown is inadequate. Many of these units display bounding and internal discontinuities that can be linked to allogenic changes in deposition. An allostratigraphic framework for the upper Mannville Group, encompassing the Sparky is proposed. An allostratigraphic framework allows units to be correlated on the basis of bounding stratigraphic discontinuities (NACSN, 1983), and has proven to be useful in characterizing paleogeography and depositional architecture of complex succession (e.g., Bhattacharya and Walker, 1991; Pattison and Walker, 1994; Walker, 1995; Burton and Walker, 1999).

The discontinuity which separates the Sparky Alloformation from the underlying G.P Alloformation is designated major marine flooding surface (FS1) and where there is an evidence of erosion they are called transgressive surface of erosion (TSE1), while the discontinuity separating the Sparky Alloformation from the overlying Waseca Alloformation is designated FS2/TSE2. Locally, an intra-Waseca unconformity cuts through the lower Waseca Allomember and incises into the top of the Sparky Alloformation. In those locations, the contact between the Sparky and Waseca alloformations corresponds to a transgressively modified lowstand unconformity.

Within the study area the Sparky Alloformation can be divided into three coarsening upward succession based on the internal discontinuities that was recognized within the alloformation. These allogenic discontinuities reflect major rises in relative sea level and allowed us to further divide the Sparky Alloformation into Lower, Middle and Upper Sparky allomembers.

In order to better understand the distribution and architecture of the Sparky Alloformation, geophysical well logs and logged cores from the study area were used to
correlate major stratigraphic surfaces and construct both dip-oriented (A - A') and intersecting strike-oriented (B - B') cross sections.

Selection of a reliable, originally horizontal and laterally continuous datum for the Mannville Group is challenging. The Base of the Fish Scales Marker (BFS) is generally considered to be reliable datum by many authors (e.g., Putnam, 1982). However, this surface is separated from the Sparky Alloformation by more than 100 m of deposition, much of it fine grained, and hence, differential compaction and deformation may have distorted the stratigraphic relationships. Additionally, the BFS marker itself may not necessarily have been horizontal when formed, limiting its effectiveness.

The Joli Fou Formation unconformably overlies the Mannville Group, and is separated by from it by a transgressive surface of erosion (TSE) or ravinement surface. This TSE was chosen as the datum from the stratigraphic cross sections. The TSE was selected because it displays limited paleotopographic relief (based on truncation of underlying units), consistent with wave ravinement. Given that the study area appears to represent a low-gradient coastal profile during deposition of the Mannville, the surface is considered to be essentially planar. Moreover, the surface is readily apparent on logs and in core, is widespread, and occurs much closer to the study interval.

3.5.1 Cross-Section A – A`

Cross-section A - A' is oriented roughly parallel to inferred paleodepositional strike of the Sparky Alloformation, and comprises the most proximal (landward) correlation of facies associations within the study area (Fig 3.12). The cross-section is approximately 84 km in length. The base of the Sparky Alloformation is discriminated by a sharp increase in radioactivity as indicated on the gamma-ray log. This increase is correlatable all over the study area, and is interpreted to record a major marine flooding surface (FS1) or transgressive surface of erosion (TSE1). In core, the surface is characterized by thin layer of offshore mudstones (FA1) sharply overlying sandstone of General Petroleum Alloformation.
The Sparky Alloformation is interpreted to contain three coarsening-upward cycles overlying the bioturbated mudstones of FA1. Each cycle represents periods of progradation followed by minor transgressive events, forming flooding surfaces. These flooding surfaces are considered allogenic. These allogenic surfaces were typically used in regional correlation and may be characterized by erosional of non-erosional surfaces. Based on these allogenic surfaces the Sparky Alloformation can be divided into Lower, Middle and Upper allomembers. FA3 locally display stratigraphic surfaces that could not be mapped across the study area and are considered autogenic.

In the central part of the cross-section (Golden Lake, Lashburn, and Dee Valley fields), wave-and storm-dominated shorefaces are present (FA2) and contains three coarsening and shoaling upward successions of Lower, Middle and Upper Sparky allomembers. In cores, the successions are characterized by lower to middle shoreface (Facies 3a) coarsening upward into trough cross-bedded to tabular cross-bedded sandstone in the upper shoreface (Facies 5). Toward the east (Lashburn West and Silverdale Sparky fields) and west (Rush Lake, and EDAM West fields) the shoreface successions pass gradationally into mixed river-wave influenced deltas of FA3. Like shoreface successions, deltaic deposits display upward coarsening and thickening cycles, although the deltaic cycles are thicker compared to their wave and storm-dominated shoreface counterparts. FA3 cycles are characterized by prodelta to distal delta front deposits (Facies 2) passing upwards into proximal delta-front and distributary mouth bar deposits (Facies 4b).

Distributary channels (FA4) were identified both from geophysical well-logs and from cored intervals. In core, channel-fill deposits occur as multiple stacked beds of sandstone displaying trough-cross bedding, although some localities contain inclined heterolithic stratification (e.g., 10-16-48-20W3) recording lateral accretion of point bars. These channels can reach up to 18m in thickness (e.g., 09-24-048-21W3).
Figure 3.12 Cross-section A-A' representing an along-strike transect through the Sparky Alloformation. The cross-section is approximately 84 km in length. The western and eastern portion of the study area consists of mixed river and wave-influenced deltaic succession with associated distributary channels. The central part of the section is characterized by facies of the wave-/storm-dominated shoreface environment.
The distributary channels are mainly located both within eastern and western side of the cross-section oriented north and northwest, and incised into previously deposited deltaic deposits. The Sparky Alloformation is commonly capped by 0.5 – 2m coal. This coal can be correlated across most of the study area. The Sparky Alloformation is generally separated from the overlying Waseca Alloformation by a transgressive surface, corresponding to a major marine flooding surface (FS 2). Where the surface shows evidence of erosion, it is called transgressive surface of erosion (TSE2). In some locations (e.g., Pikes Peak field), the Sparky Alloformation is unconformably overlain by the Upper Waseca Allomember, marking subaerial unconformity that has been transgressively modified (Morshedian et al., 2011).

3.5.2 Cross-Section B – B’

Cross-section B - B' parallels depositional dip, and illustrate correlations of measured sections from the south-central part of the study area towards the northern limit of the area of investigation (Fig 3.13). At the southern part of the cross-section, the succession is largely composed three, allogenically generated coarsening-upward shoreface successions (FA2). The thickness of sand bodies from each cycle generally thickens towards the top of the succession, although these cycles become finer-grained towards the northern part of the study area (i.e., the paleo-seaward direction) and hence discriminating the contact between each allomember becomes challenging. The succession record progradation that terminated basinward by downlap onto the offshore marine deposits of FA1.

The correlation also displays that from south (Township 48) to north (Township 51), the uppermost shoreface is overlain by coastal plain deposits (FA5). The presence of FA5 indicates the maximum seaward limit of Sparky shoreline progradation. In the northern part of the study area, where the Sparky coal is not present, identifying the contact between the Sparky and Waseca
alloformations can be challenging. In core, the contact is sharp and displays increase in
the amount of finer grained deposits, and the common elevation in bioturbation intensity
and uniformity. On well logs, identifying the transgressive contact was mainly done by
gamma-ray logs. The transgressive contact displays an increase in radioactivity, which
reflects the increase in mudstone content. Where the contact between the Sparky and
Waseca alloformation is unconformable (e.g., Pikes Peak area), on well logs they are
readily identifiable by their sharp bases, thick intervals, and very block gamma-ray
responses with low API values. In core, the contact is sharp and erosional and is
characterized by heavily oil stained sandstone with through cross-beddings and abundant
mudstone rip-up clasts of the Upper Waseca Allomember overlying coastal/delta plain
deposits (FA5) of the Sparky Alloformation.
Figure 3.13 Cross-section B-B’ is a dip-oriented transect through Sparky Alloformation. The cross section is approximately 77 km in length, and displays shoreface deposits of the south-central part of the study area into marine offshore deposits toward north.
3.6 Discussion and Interpretation

The Sparky Alloformation is interpreted to record wave- and storm-dominated shoreface and contemporaneous mixed river- and wave-influenced delta environments distributed along depositional strike. The succession is bounded above and below by regionally extensive major marine flooding surfaces, which shifted distal facies over the proximal facies of the underlying succession. The Sparky Alloformation can be divided into three, broadly upward coarsening units (referred to, herein as the Lower, Middle and Upper Sparky allomembers), separated by minor marine flooding surfaces. The flooding surfaces reflect allogenic processes associated with the basin subsidence, and/or eustatic changes in sea level, such that the allomembers correspond to the scale of parasequences (Van Wagoner, et al., 1990). Towards the north, reliable differentiation of each allomember becomes challenging because facies become less sandy and lithological contrast across the flooding surfaces diminishes. Deltaic successions of FA3 also contain spatially restricted flooding surfaces interpreted to be autogenic in origin. These surfaces correspond to channel avulsion and deltaic lobe switching. These autogenic surfaces are not abundant within FA3 (up to 2 surfaces), characteristic of more wave-dominated deltas (cf., Bhattacharya, 1989); nevertheless, they can be confused with allogenic flooding surfaces locally. Such autogenically produced cycles within the deltaic successions do not correspond to parasequences. Single coarsening cycles within shoreface successions (FA2) commonly pass into 2 or more coarsening upward intervals within the deltaic complexes (FA3). Parasequences within the deltaic deposits are thicker than to their along-strike shoreface counterparts, attributed to the higher sedimentation rates associated with direct fluvial-sediment influx from the distributary channels (FA4).

The distributary channels are commonly similar to the thickness of the autogenic lobes. In most cases, they cut no deeper than into the delta-front deposits. Brown (1965) related these Sparky channels to a widespread disconformable surface, but Wickenden (1948), and Kent (1959) considered them to be deltaic distributary channels. Based on our correlations, we interpret that their occurrence is contemporaneous with deposition during Sparky time, since they occur below the Sparky Alloformation delta plain (FA5) that caps the prograding cycles. Based on their scale and association with the delta plain,
we concur with Wickenden (1948) and Kent (1959) that they represent the distributary channel network feeding the mixed river-wave influenced deltas of FA3.

The Sparky Alloformation parasequences represent shoreline progradation toward north and northwest and form an overall progradational parasequence set. The parasequences can be mapped across most of the study area, and based on correlations (see Fig 3.13), the maximum extent of shoreline progradation is located within Celtic area. In order to determine the extent of progradation, deposits of coastal/delta plain (FA5) capping the uppermost parasequence were used. The position of FA5 within the uppermost parasequence is also consistent with progradational parasequence set geometry. The Sparky Alloformation is interpreted to have been deposited during early to late highstand conditions; hence, corresponding to a highstand systems tract (HST).

Based on these characteristics, the Coasta de Nayarit in Western Mexico is proposed as a possible modern analogue for the Lower Cretaceous Sparky Alloformation. The Costa de Nayarit is a classic modern example of a progradational shoreface to wave-dominated delta succession situated in a wave- and storm-dominated depositional setting. The Nayarit coast has a tidal range of approximately 1 meter, and the majority of sediments are derived from longshore transport of sediments from three major river systems. A block diagram showing general depositional model for the Sparky Alloformation is summarized in Figure 3.14.
Figure 3.14 Block diagram depicting a paleogeographic reconstruction of the depositional setting for the Sparky Alloformation. Figure not drawn to scale.
3.7 Conclusion

The Lower Cretaceous Sparky Alloformation in the Lloydminster area can be subdivided into ten depositional facies based on the integration of sedimentological and ichnological characteristics observed in cored intervals. The sedimentary facies are organized into five facies associations, reflecting deposition along a wave-dominated shoreline composed of both storm-dominated beach-shorefaces and mixed wave-river influenced deltas.

Facies Association 1 (FA1) comprises of bioturbated sandy/silty mudstone and is the most marine facies within the study area. Intervals are characterized by high bioturbation intensities (BI 3-5) and tempestites. Tempestite preservation increases upward through this interval. Ichnogenera are commonly robust and diverse. The deposits are interpreted to record deposition in deeper and normal marine environments.

Facies Association 2 (FA2) represents shoreline progradation and vertical stacking of sediments deposited in proximal offshore to upper shoreface environments. FA2 is characterized by a coarsening upward profile and a high sand content. Sedimentary structures are mainly oscillatory structures and record strong wave influence on deposition. FA2 commonly displays pervasively bioturbated, high trace-fossil diversities, and more vertical dwelling structures of inferred suspension/filter feeding behaviour.

Facies Association 3 (FA3) consist of four facies and is interpreted to record progradation of the shoreline form distal prodelta to proximal delta front in a mix wave-river influence delta complex. Deposits generally show reduced bioturbation intensities, sporadic trace-fossil distributions, and diminutive ichnogenera. Physio-chemical stresses within deltaic deposits of the Sparky Alloformation include high sedimentation rates, fluctuations in salinity, hypopycnal induced turbidity, hyperpycnal-induced sediment gravity flows, and reduced oxygenation. The presence of interbedded sandstone and mudstone, the occurrence of HCS (in sandstones), and soft-sediment deformation features are indicative of variable sedimentation rates. Salinity fluctuation is interpreted from the
development of syneresis cracks in mud beds. Hypopycnal mud deposits are preserved as high carbonaceous mudstone draped over underlying tempestites. Hyperpycnal deposits are manifest as sharp based, normal graded mudstone with high carbonaceous content. Hyperpycnal mudstones are commonly unburrowed due to the high oxidation of organic material and the resultant oxygen depletion at the bed (Raychaudhuri and Pemberton, 1992; Coats and MacEachern 1999; MacEachern et al., 2005).

Facies Association 4 (FA4) represents distributary channels. Distributary channels are primarily filled with point-bar deposits, where the basal fill in deeper channels is sandy. IHS deposits typically overlie the sand-dominated facies. The trace fossil assemblage of IHS deposits typifies a brackish-water suite. Trace fossils are relatively diminutive, low diversity, and consists of facies crossing elements.

Facies Association 5 (FA5) commonly caps the Sparky Alloformation and consists of sandstone with abundant organic detritus and rootlets, which in turn is overlain by coal. FA5 represents establishment and development of peat-forming swamps or marshes within coastal/delta plain environments.

Low-diversity suites, the prevalence of facies-crossing elements and the diminutive character of ichnogenera within the recognized facies indicated that the environment was generally subject to physico-chemical stress. The most likely stress was one of reduced and fluctuating salinity, although the magnitude of salinity reduction was variable. The occurrence of more robust and more marine ichnogenera (e.g., Asterosoma, Rosselia, Rhizocorallium,) toward northern part of the study area suggest more marine condition further from the shoreline.

The Sparky Alloformation can be separated from the underlying G.P. and overlying Waseca alloformations by major marine flooding surfaces, which are typically associated with erosion (transgressive surface of erosion). These surfaces are widespread and can be traced over the entire study area. Locally, the contact between Sparky Alloformation and the overlying Waseca alloformation is unconformable. The unconformity as associated with an intra-Waseca low-stand unconformity that cuts
through the lower Waseca Allomember and incises into the top of the Sparky Alloformation.

In the SE and SW parts of the study area, the Sparky Alloformation comprises three to four coarsening and shoaling upward successions of mixed wave- and river-influenced deltaic deposits with associate distributary channels. Toward the central part of the study area these deltaic deposits pass laterally into wave-dominated shoreface deposits. The internal discontinuities within parasequences dominated by FA2 (shoreface deposits) are considered allogenic and permits us divide the Sparky Alloformation into Lower, Middle, and Upper allomembers. These allogenic surfaces along strike are correlatable into FA3. The deltaic successions of FA3 also contain localized flooding surfaces that do not correlate to the more regional allogenic surfaces preserved in parasequences of FA2. The flooding surfaces in FA3 (mixed-influence deltas) are considered autogenic (e.g., lobe abandonment). Parasequences of both FA2 and FA3 display progradational geometry and prograde as far north as township 51 (Celtic area). Beyond township 51, FA2/FA3 parasequences grade seaward (northward) into marine deposits of FA1. This progradational geometry corresponds to a highstand system tract (HST).
3.8 References


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CHAPTER 4: DEPOSITIONAL ARCHITECTURE OF LOWER CRE TACEOUS MANNVILLE GROUP (WASECA & MCLAREN ALLOFORMATIONS), WEST-CENTRAL SASKATCHEWAN, CANADA

4.1 Introduction

The Mannville Group in the Lloydminster area is a Lower Cretaceous siliciclastic unit located in the subsurface of Western Canadian Sedimentary Basin (WCSB). The Mannville Group is considered one of the most important hydrocarbon-bearing units in Canada (Pemberton and James, 1997). Currently, Mannville heavy-oil reservoirs are estimated to contain approximately 3 billion m³ (19 billion barrels) of oil in place in the Lloydminster area of Saskatchewan (Saskatchewan Energy and Resources, 2008). The bulk of the heavy oil is contained in the G.P., Sparky, and Waseca formations (Orr et al., 1977). In order to better predict the position and distribution of the heavy-oil reservoirs, a thorough understanding of their sedimentological, ichnological, and stratigraphic characteristics are required. These data enable facies mapping of sandstone bodies, correlation of facies to well logs, and the incorporation of high-resolution facies analysis. The aim of this paper is to integrate sedimentology, ichnology, and stratigraphy of the Waseca and McLaren alloformations in west-central Saskatchewan, in order to provide a paleogeographic and sequence stratigraphic interpretation of the interval.

4.2 General Geology and Previous Work

The Lower Cretaceous Mannville Group has been studied since the early 1940s, and was first drilled in 1942 (Nauss, 1945). The succession consists of weakly consolidated to well-cemented sandstones, siltstones, mudstones, heterolithic bedsets of sandstone and mudstone, and minor coals. The Mannville Group (Fig. 4.1) unconformably overlies Paleozoic- to Jurassic-aged strata, and is overlain disconformably
Figure 4.1 Correlation of Lower Cretaceous strata in eastern Alberta and western Saskatchewan (modified after Christopher, 2003); red dots indicate study interval.
by the transgressive marine shales of the Joli Fou Formation, Colorado Group (Christopher, 1974; 2003).

The nomenclature of the Mannville Group in the Lloydminster area has been a subject some contention, mainly owing to its internal stratigraphic complexity. The Mannville Group was initially assigned formation status by Nauss (1945). Wickenden (1948) suggested that the Mannville could be divided into basal, middle and upper units. Subsequent work by Edmunds (1948) in the Lloydminster area of Western Saskatchewan and Alberta incorporated unofficial driller’s terminology and log characteristics into the nomenclature. These include (from top to bottom): Colony, McLaren, Waseca, Sparky, General Petroleum, Rex, Lloydminster, Cummings, and Dina. The top of the each unit, with the exception of the Sparky, is defined by the contact of a sandy sequence overlain by a regionally extensive shale horizon. The top of the Sparky, by contrast, is defined by the top of a coal or its shale equivalent. Even today, no formal type section has been established to formalize this nomenclature. The Mannville was elevated to “Group” status by Badgley (1962). Vigrass (1977) and Orr et al. (1977) used the nine informal stratigraphic subdivisions of Edmunds (1948), with Vigrass (1977) regarding them as members and Orr et al. (1977) considering them as formations. The present study focuses on the Waseca and McLaren formations. The two formations correlate to the west with the Grand Rapids Formation and southward with the upper part of Cantuar Formation and Pense Formation, respectively (Christopher, 2003).

This paper employs an allostratigraphic framework in order to characterize the Waseca and McLaren alloformations. Allostratigraphy is the only genetic stratigraphic framework currently approved in the North American Code of Stratigraphic Nomenclature (NACSN, 1983). Allostratigraphy defines units on the basis of mappable stratigraphic discontinuities, and permits correlations that are independent of lithological constraints.
In Lloydminster area, the Waseca Alloformation erosionally overlies the Sparky Formation, and, in turn, is overlain by the McLaren Formation. The basal contact of the Waseca is a bounding discontinuity, whereas the upper contact is a regional discontinuous surface. The Waseca Formation has been recognized to comprise two successions (cf. MacEachern, 1984, 1986; Van Hulten, 1984) corresponding to a “regional succession” and a “channel succession”. The regional succession was interpreted as prograding wave-dominated shoreface and delta deposits (Dunning et al., 1980; Haidl, 1980, 1984; Lorsong, 1980, 1982; Dwyer, 1998) and tidal flats (Van Hulten, 1984; MacEachern 1984, 1986). The channel succession was considered to be estuarine (Lorsong, 1982; Putnam, 1982; MacEachern, 1984, 1986, 1989; Van Hulten, 1984; Harding, 1991).

The McLaren Alloformation in the area has received less attention than the Waseca. This is mainly because the majority of the reservoirs lie within Waseca Fm channels. Minor gas production comes from the McLaren Alloformation above the main oil horizons (Dwyer, 1998). The formation has been interpreted as comprising fluvial deposits (Kramers et al., 1989; Bradshaw, 1999), prograding shoreface deposits (Richardson and Vigrass, 1984), or both (Newsome, 1998; Buttle, 1999). The McLaren Alloformation is separated from the overlaying Colony Alloformation by a regional bounding discontinuity.

Existing environmental interpretations of the Waseca and McLaren alloformations are based mainly on the observation of primary sedimentary structures, lithofacies successions, and regional well-log correlations. Few studies incorporated ichnology into their interpretations (e.g., MacEachern et al., 1986, 1989). During the past four decades, the interpretation of non-deltaic shoreline deposits using both sedimentology and ichnology has become standard practice (e.g., Howard, 1972; Pemberton and Frey, 1984; MacEachern and Pemberton, 1992; MacEachern et al., 1999; MacEachern and Bann, 2008). As well, our understanding of the ichnology of deltaic settings has improved dramatically (e.g., Moslow and Pemberton, 1988; Raychaudhuri and Pemberton, 1992; Gingras et al., 1998; Coates and MacEachern, 1999; Bann and Fielding, 2004; MacEachern et al., 2005; Hansen and MacEachern, 2007; Bann et al., 2008; MacEachern
and Bann, 2008; Buatois et al., 2012). Analysis of numerous case studies demonstrates that organisms are extremely sensitive to environmental conditions, and that physico-chemical stresses are more pronounced in deltaic environments compared to their non-deltaic counterparts (MacEachern et al., 2005; MacEachern et al., 2007). Most of these stresses are imposed by fluvial input into the basin. The common physico-chemical stresses associated with deltaic environments include: 1) increases in sedimentation rates; 2) salinity fluctuations associated with variations in river discharge; 3) increases in water turbidity; 4) presence of distributary flood discharges with accompanying phytodetritus; 5) hyperpycnal flow-induced sediment gravity flows; and, 6) fluid-mud deposition (Rice et al., 1986; Nemec, 1990; Pemberton and Wightman, 1992; Pollard et al., 1993; MacEachern et al., 2005; Gingras 2007). Such stresses commonly result in organisms changing their feeding strategies, or produces marked changes in the faunal community, which typically leads to trace-fossil suites that depart from archetypal expressions of Seilacherian ichnofacies (e.g., MacEachern et al., 2007).

Ichnology has also proven to be essential in helping to identify and interpret brackish-water environments (e.g., bays and estuaries), and to differentiate them from fully marine environments (e.g., Pemberton et al., 1982; Beynon et al., 1988; Pemberton and Wightman, 1992; MacEachern and Gingras, 2007). The brackish-water ichnological model was derived mainly from studies of Cretaceous successions in the Western Canadian Sedimentary Basin (e.g., Pemberton et al., 1982; Beynon et al., 1988; Pemberton and Wightman, 1992; MacEachern and Pemberton, 1994; MacEachern et al., 2007; MacEachern and Gingras, 2007). Studies of modern settings, such as the Dutch and German North Sea coasts (e.g., Schäfer, 1956, 1962; Reineck et al., 1967; 1968; Dörjes, 1970; Hertweck, 1970); the Ogeechee River-Ossabaw Sound Estuary of Georgia (e.g., Howard et al., 1975; Howard and Frey, 1973; 1975), Willapa Bay, Washington, USA (Gingras et al., 1999; 2011), and the Fraser Delta (Swinbanks and Murray, 1981; Dashtgard, 2011a,b; Sisulak and Dashtgard, in press) are also integrated into the model. Trace-fossil suites within brackish-water environments are characterized by: 1) reductions in the diversity of ichnogenera and their ethological ranges; 2) overall size reductions of traces; 3) abundance of trophic generalist burrows (e.g., Planolites, Cylindrichnus, Teichichnus), which leads to domination by facies-crossing ichnogenera;
and, 4) both vertical and horizontal ichnofossils that are common to both the *Skolithos* Ichnofacies and the *Cruziana* Ichnofacies.

### 4.3 Study Area and Methodology

Abundant cored data in the Lloydminster area of west-central Saskatchewan is used to establish the facies characteristics and facies architecture of the Waseca and McLaren alloformations. The study area extends from Township 48 to 54 and from Range 19 to 28W3, comprising a total area of 5,400 km\(^2\). Within this region are several major hydrocarbon fields including Golden Lake, Lashburn, and Cold Lake (Fig. 4.2), and there are approximately 1,730 wells that penetrate the Waseca and McLaren alloformations. A total of 67 cores were logged for this study (Fig. 4.2).

Cored intervals were evaluated for lithology, sedimentary structures, stratigraphic discontinuities, and ichnology. The ichnological analysis was based on ichnogenera identification, bioturbation intensity (*cf.* Taylor and Goldring, 1993; Taylor *et al*., 2003; Bann *et al*., 2008), evaluation of trace-fossil sizes, characterization of burrowing distributions, and trace fossil ethological interpretations. In addition, 700 geophysical well logs were used to provide correlation between cored and non-cored wells. An allostratigraphic framework was employed to define the Waseca and McLaren alloformations, and to subdivide the Waseca Alloformation into a lower and upper allomember. A list of the well locations, cored intervals, and core lengths that were utilized is located in Appendix A. Also a compact disk (CD) is included containing PDF of all the lithologs and cross sections.
Figure 4.2 Location of the study area. A) Map of Canada showing the location of the study area, B) Detailed map of the study area with locations of logged core.


4.4 Facies Descriptions

The Waseca and McLaren alloformations contain 12 discrete facies (F1-F12), defined on the basis of physical sedimentological and ichnological characteristics. These are assigned to six different depositional environments (Table 4.1). Ethological (behavioural) interpretations of the trace-fossil genera observed in core are described in Table 4.2.

4.4.1 Facies 1: Bioturbated Mudstone

Facies 1 is characterized by moderately to thoroughly bioturbated (BI 2-5), medium to dark gray sandy to silty mudstone. Primary sedimentary structures are locally present. Based on ichnological characteristics, Facies 1 has been subdivided into two subfacies.

4.4.1.1 Subfacies 1a: Bioturbated Sandy to Silty Mudstone with Diverse Trace-Fossil Assemblages

Subfacies 1a consists of massive silty mudstone, passing upward into sandy mudstone. Siltstone and sandstone layers comprise less than 20% of the facies. The facies is commonly pervasively bioturbated (BI 2-5; Fig. 4.3A). Sandstone beds are sharp-based and contain oscillation ripples, combined flow ripples, and small-scale hummocky cross-stratification (5-10 cm thick), commonly known as “micro-HCS” (Fig. 4.3B; Dott and Bourgeois, 1982). Syneresis cracks and soft-sediment deformation features are rare. Lithological accessories are uncommon and include carbonaceous detritus, dispersed coalified wood fragments, siderite, and pyrite.
<table>
<thead>
<tr>
<th>Facies Association</th>
<th>Facies</th>
<th>Sedimentology</th>
<th>Trace-fossil Site</th>
<th>Biostratigraphic Interval</th>
<th>Depositional Environment</th>
</tr>
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<tr>
<td>1 Marine Mudstone</td>
<td>1a</td>
<td>Biocrust-bioturbated Mudstone with Distinct Trace Fossil Assemblages</td>
<td>Thoroughly bioturbated, locally micro-CHS</td>
<td>Planolites, Cylindrothyris, Palaeophycus, Textularia, Genera</td>
<td>2-5</td>
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<td>2</td>
<td>Trough-Crossbedded to Tabular Cross-stratified Sandstone</td>
<td>Cross-beded sandstone with locally low-angle planar stratification and current ripples sandstone.</td>
<td>Cylindrothyris, Planolites, foraminifera</td>
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<td>3a</td>
<td>Oscillation-Crossbedded Sandstone</td>
<td>Wave-rippled and HCS, locally mudstone drapes</td>
<td>Skolithos, Ammotrite, Planolites, Palaeophycus, Cylindrothyris, Loxechia, foraminifera</td>
<td>0-2</td>
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<tr>
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<td>4a</td>
<td>Bioclastic Mudstone Interbedded with Sandstone</td>
<td>Mudstone interbedded with oscillation-crossbedded sandstone, locally micro-CHS</td>
<td>Cylindrothyris, Thalassinoe, Ammotrite, Planolites, Cylindrothyris, Loxechia, foraminifera</td>
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<td>5</td>
<td>Oscillation-Crossbedded Sandstone with Current Ripples</td>
<td>Wave-rippled, combined flow ripples, and current ripples, locally small scale trough-cross bedded, abundant organic debris.</td>
<td>Cylindrothyris, Planolites, Loxochia, foraminifera</td>
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<td>6a</td>
<td>Oscillation-Crossbedded Sandstone</td>
<td>Wave-rippled, and HCS, locally bioturbated, and micro-CHS.</td>
<td>Skolithos, Planolites, Cylindrothyris, Loxochia, foraminifera</td>
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<td>7a</td>
<td>Sporadic, Bioturbated Mudstone Interbedded with Sandstone</td>
<td>Wave to bioturbated sandstone, interbedded with oscillation-crossbedded sandstone, micro-CHS. Locally, combined flow ripples, synoptic cross ripples.</td>
<td>Planolites, Skolithos, Cylindrothyris, Palaeophycus, Cylindrothyris, Thalassinoe, Ammotrite, Planolites, Cylindrothyris, Loxechia, foraminifera</td>
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<td>8a</td>
<td>Bioclastic Mudstone</td>
<td>Oscillation-ripples, with sharp contacts, locally bioturbated beds, current ripples, and synoptic cross ripples.</td>
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<td>Bioclastic Mudstone with Distinct Trace Fossil Assemblages</td>
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<td>Massive Mudstone Interbedded with Siliciclastics</td>
<td>Mm-to-mm scale siliciclastics, current ripples, abundant soft sediment deformation.</td>
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<td>11b</td>
<td>Alternating Massive Mudstone and Interbedded Skeletal Bioherm</td>
<td>Soft-sediment deformation, locally current ripples and wave ripples.</td>
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<td>Massive siliciclastics, lenticular sandstone and current ripples laminations. Organic detritus, fluid mud, rare oscillation ripples.</td>
<td>Planolites, Skolithos, Ammotrite, Cylindrothyris, Palaeophycus, Cylindrothyris, Planolites, Cylindrothyris, Thalassinoe, Ammonia, foraminifera</td>
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<td>Massive Mudstone with Distinct Trace Fossil Assemblages</td>
<td>Locally bioturbated sandstone with current ripples, abundant soft sediment deformation.</td>
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<td>Coastal Mudstone and Calcareous Mudstone</td>
<td>Crusader bioclastic mudstone with organo-detritus, claystone, current ripples laminations, and some pedogenetic features.</td>
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**Table 4.2:** Ethology of traces observed in the Waseca and McLaren alloformation.
Subfacies 1a displays BI 4-5, although units with BI 2 occur locally. Sandstone beds generally possess lower bioturbation intensities, and are commonly cross-cut by traces subtending from overlying muddier deposits. Trace fossils are diminutive and show moderate diversity. Trace fossils include Planolites, Cylindrichnus, Palaeophycus, Teichichnus, Skolithos, Arenicolites, Thalassinoides, Asterosoma, Rosselia, Chondrites, Schaubcylindrichnus freyi (“Terebellina”), Phycosiphon, Helminthopsis, Scolicia, fugichnia, and rare Gyrolithes.

4.4.1.2 Subfacies 1b: Bioturbated Silty/Sandy Mudstone with Impoverished Trace-Fossil Assemblages

Subfacies 1b corresponds to silty mudstone, which passes upward into sandy mudstone (Fig. 4.3C). Lithologically, Subfacies 1b is similar to Subfacies 1a; however, Subfacies 1a displays thinner (< 5 cm thick), sharp-based oscillation-rippled sandstones and micro-HCS. Soft-sediment deformation structures and syneresis cracks are present but uncommon. Subfacies 1b also contains siderite nodules, dispersed coalified wood fragments, and locally abundant organic detritus.

Bioturbation in Subfacies 1b is mostly pervasive (BI 4-5), but is locally punctuated by moderately burrowed (BI 2) zones, especially where the interbedded sandstones are present. The trace-fossil suite is of low-diversity, and individual trace fossils are diminutive and the suite is dominated by facies-crossing ichnogenera. The dominant observed trace fossils are Planolites, Skolithos, Teichichnus, Gyrolithes, Cylindrichnus, Palaeophycus, Thalassinoides, Chondrites and fugichnia. Phycosiphon is also rarely observed.

4.4.2 Pinstripe Laminated Mudstone

Facies 2 displays sharp-based, very fine- to fine-grained sandstones and siltstones layers, encased in mudstone (Fig. 4.3D). The interbedding occurs on a mm- to cm-scale, and shows well-developed normal grading. Physical sedimentary structures are dominated by low-angle parallel lamination, starved combined-flow ripples, oscillation
ripples and, locally, current ripples. Sandstone beds locally contain organic detritus and dispersed coalified wood fragments. Mudstone laminae are generally fissile, and are commonly accompanied by siderite-cemented bands and pyrite. Syneresis cracks and soft-sediment deformation features, such as micro-faults and convolute bedding, are locally present.

Ichnologically, Facies 2 is characterized by low bioturbation intensities (BI 0-3; typically 0-2). The intensity of burrowing generally decreases upward. Trace fossils are diminutive and form low-diversity suites. Trace fossils include Planolites, Cylindrichnus, Palaeophycus, Teichichnus, Gyrolithes, Chondrites, Asterosoma, Phycosiphon, fugichnia, and navichnia.

4.4.3 Heterolithic Sandstone and Mudstone Facies

Facies 3 comprises heterolithic composite bedsets of mudstone and sandstone. Units vary from mudstone-dominated to sandstone-dominated. Sandstone beds are characterized by oscillatory-generated structures, combined-flow ripples, and current ripples. Mudstone beds are typically massive or poorly laminated, and display biogenic reworking. Facies 3 is subdivided into two subfacies, primarily on the basis of their sedimentological and ichnological features.

4.4.3.1 Subfacies 3a: Moderately to Pervasively Burrowed Interbedded Sandstone and Mudstone

Subfacies 3a is characterized by fine- to very fine-grained sandstone, interbedded with moderately to pervasively bioturbated mudstone (Fig. 4.3E). The proportion of sandstone increases upward. Sandstone interbeds range in thickness from mm-scale to 25 cm thick. The contacts between the mudstone and sandstone beds are commonly bioturbated, but locally are sharp. Sandstone interbeds predominantly contain oscillation ripples, micro-HCS, combined-flow ripples, and rare aggradational oscillation ripples. Mudstone beds are poorly laminated and, in most occurrences, are pervasively bioturbated. Subfacies 3a locally contains syneresis cracks as well as normally graded
beds. Deformation features such as microfaults and convolute bedding are also present, but are not common. Accessory elements include coalified wood fragments, organic detritus, siderite nodules, and pyrite.

Units within Subfacies 3a are unburrowed to pervasively bioturbated (BI 0-5). However, the intensity of burrowing is commonly high (BI 3-4). Trace-fossil diversities are quite variable, and commonly observed ichnogenera include Planolites, Skolithos, Arenicolites, Gyrolithes, Cylindrichnus, Teichichnus, Thalassinoides, Palaeophycus, Chondrites, Asterosoma, Phycosiphon, Helminthopsis, Lockeia, fugichnia, and navichnia.

4.4.3.2 Subfacies 3b: Sporadically Bioturbated Mudstone Interbedded with Sandstone

Sedimentologically, Subfacies 3b is broadly similar to Subfacies 3a, although the sedimentary structures in 3b are better preserved owing to its lower intensity of bioturbation (Fig. 4.3F). Units vary from mud-dominated to sand-dominated composite bedsets. Subfacies 3b typically displays an increase in the proportion and thickness of sandstone beds upward. Sandstone beds are commonly sharp based, and consist of very fine- to fine-grained, moderately well- to well-sorted sand. The bulk of the sedimentary structures consist of low-angle parallel lamination, oscillation ripple lamination, and current ripple lamination. Locally, micro-HCS and combined-flow ripples are intercalated. Most mudstone beds drape the underlying sandstone beds and display normal grading. Thin, carbonaceous, dark mudstone beds are locally very common. The basal contacts of these fissile mudstone beds are typically sharp, and show truncation of the underlying sandstone laminae. Many of the mudstone beds contain syneresis cracks that are filled with sand or silt. Siderite nodules, carbonaceous detritus, gutter casts, and soft-sediment deformation structures are locally present.

Bioturbation ranges from absent to moderate intensities (BI 0-3), although the intensity of burrowing can locally reach BI 5 at the bed scale. Mudstone beds commonly possess higher bioturbation intensities. Trace fossils are diminutive and form low-diversity suites. Ichnogenera include Planolites, Gyrolithes, Cylindrichnus, Teichichnus,
Thalassinoides, *Palaeophycus, Chondrites*, and rare *Skolithos* and *Arenicolites*. Additional elements of the suite include navichnia and fugichnia.
Figure 4.3 A) Pervasively bioturbated sandy mudstone (BI 5) of offshore marine mudstone (Facies 1a). Suite includes *Planolites* (P), *Palaeophycus* (Pa), *Skolithos* (Sk), *Cylindrichnus* (Cy), *Gyrolithes* (Gy), *Thalassinoides* (Th), *Chondrites* (Ch), *Asterosoma* (As), *Helminthopsis* (H), and *Phycosiphon* (Ph). Well# 05-11-049-20W3, Depth 439.5m.

**B)** Pervasively bioturbated silty/sandy mudstone of Facies 1a with remnants of tempestite. Trace fossils include *Planolites* (P), *Palaeophycus* (Pa), *Teichichnus* (T), *Cylindrichnus* (Cy), *Skolithos* (Sk), *Chondrites* (Ch), *Phycosiphon* (Ph), *Helminthopsis* (H), and fugichnia (fu). Well# 09-12-049-24W3, Depth 527.3m.

**C)** Pervasively bioturbated (BI 4-5) sandy mudstone with remnants of oscillation-rippled sand lenses. Suite includes *Planolites* (P), *Cylindrichnus* (Cy), *Palaeophycus* (Pa), *Skolithos* (Sk), *Teichichnus* (T), *Gyrolithes* (Gy), *Thalassinoides* (Th), and *Chondrites* (Ch). Well# 10-12-048-20W3, Depth 419.5m.

**D)** Weakly burrowed pinstripe to lenticular-bedded mudstone from Facies 2; note the syneresis cracks (syn) in the middle of the photograph. Trace fossils include *Planolites* (P), *Cylindrichnus* (Cy); well 07-08-052-23W3, 444.2m.

**E)** Wavy parallel-laminated sandstone interbedded with moderately to pervasively bioturbated mudstone beds of facies 3a. The facies displays BI 3-4 with *Skolithos* (Sk), *Planolites* (P), *Cylindrichnus* (Cy), *Palaeophycus* (Pa), *Teichichnus* (T), *Gyrolithes* (Gy), *Asterosoma* (As), *Chondrites* (Ch), *Phycosiphon* (Ph), *Helminthopsis* (H), and fugichnia (fu). Well# 13-02-057-27W3, Depth 421.5m.

**F)** Sporadically bioturbated sandstone displaying oscillation ripples and combined-flow ripples mantled with dark mudstones; note the syneresis cracks (syn); trace fossil suite include *Planolites* (P), *Cylindrichnus* (Cy), *Palaeophycus* (Pa), *Teichichnus* (T), *Chondrites* (Ch), and navichnia (na). Well# 07-34-051-23W3, Depth 469m.
4.4.4 Facies 4: Sandstone

Facies 4 sandstone bodies consist of very fine- to medium-grained sandstone, dominated by oscillation ripples, HCS and SCS, combined-flow ripples, current ripples, and small-scale trough cross-stratification. Facies 4 is subdivided into three subfacies, mainly on the basis of their sedimentological features.

4.4.4.1 Subfacies 4a: Oscillation-Rippled to Hummocky Cross-Stratified Sandstone

Sandstones of Subfacies 4a have an average grain size ranging from very fine- to fine-grained sand. The beds typically contain low-angle parallel lamination, oscillation ripple lamination, and combined-flow ripple lamination (Fig. 4.4A). Individual beds are sharp-based, erosive, and are typically cm to dm in thickness. Individual beds are erosionally amalgamated in the upper part of the facies. Carbonaceous detritus is locally present and marks stratification. Rare, small-scale mudstone rip-up clasts are distributed along erosion surfaces. Mudstone beds comprise less than 10% of the facies. Mudstone layers are locally fissile, contain interstitial silt, and are normally graded. The facies also shows convolute bedding (Fig. 4.4B) and micro-faults, particularly where thin beds of mudstone are intercalated.

Subfacies 4a ranges from unburrowed to moderately bioturbated (BI 0-2). Trace-fossil suites are of low diversity and burrows are sporadically distributed. Trace fossils are characterized mainly by mobile deposit feeding, suspension feeding, escape, and rare resting structures. Trace fossils include Skolithos, Planolites, Palaeophycus, Cylindrichnus, Lockeia, fugichnia, and navichnia.

4.4.4.2 Subfacies 4b: Oscillation-Rippled Sandstone, Interbedded with Current-Rippled Sandstone

Subfacies 4b occurs locally and where present, caps coarsening-upward successions. Units are characterized by fine- to medium-grained, moderately to well-sorted sandstone. Sandstone beds are dominated by 5-15 cm thick, erosionally truncated
micro-HCS and amalgamated wave ripples, interbedded with 5-10 cm thick, stacked current-rippled sandstone and small-scale trough cross-stratified sandstone beds (Fig. 4.4C). Organic detritus is very common and locally demarcate stratification or define bedding planes. Soft-sediment deformation features and spherulitic siderite are present, as are rare occurrences of mudstone interlaminae.

Subfacies 4b generally displays very low bioturbation intensities (BI 0-2). Most of the burrows are associated with oscillation ripples and current-generated structures; micro-HCS beds are typically unburrowed. Common trace fossils include Cylindrichnus, Planolites, Skolithos, Lockeia, and fugichnia.

4.4.4.3 Facies 4c: Bioturbated Muddy Sandstone

Subfacies 4c is characterized by burrowed muddy sandstone (Fig. 4.4D). The facies ranges from 0.75 m to 3 m in thickness, and consists of moderately sorted, fine- to medium-grained sandstone. Where beds are evident, they are generally less than 10 cm thick, are sharp based and display oscillation ripples, micro-HCS, and rare combined-flow ripples. Preservation of these thin sandstone interbeds is greater toward the top of the interval. The mudstone content is variable, but generally decreases upward. A few intervals may contain thin (<2 cm), dark, fissile mudstone drapes. Carbonaceous detritus, coalified-wood fragments, and rare convolute bedding are locally present.

The bulk of Subfacies 4c lacks preserved primary physical sedimentary structures due to the high intensity of bioturbation. Bioturbation intensities typically range from BI 3 - 4. Laminated beds are largely unburrowed (BI 0-1). Trace fossils are diminutive, and suites show low diversity, commonly consisting of facies-crossing elements that comprise a mixture of deposit-feeding and suspension-feeding structures. Traces include Planolites, Teichichnus, Cylindrichnus, Thalassinoides, Skolithos, Arenicolites, Gyrolithes, Palaeophycus, Chondrites, and fugichnia.
4.4.5  Facies 5: Mudstone-Clast Breccia

Facies 5 comprises beds of abundant mudstone clasts encased in a sandstone matrix (Fig. 4.4E). Sand calibres range from fine to lower medium. Sandstones are poorly to moderately sorted and lack physical or biogenic structures. Mudstone clasts are angular to subangular and range from granule to cobble sized, some of which are larger than the core diameter. Facies 5 commonly grades into Facies 6, and ranges from dm- to m-scale in thickness. Coalified wood fragments and siderite nodules are present throughout the facies.

Facies 5 is generally unburrowed (BI 0), although the mudstone clasts, themselves, locally show bioturbation. These burrows, however, record the conditions under which the mudstones, themselves, were originally deposited (e.g., Facies 8).

4.4.6  Facies 6: Trough Cross-Stratified to Planar Tabular Cross-Stratified Sandstone

Facies 6 represents cross-stratified sandstones (Fig. 4.4F). Sandstone beds are upper fine to medium grained, and are moderately to well sorted. Cross-stratified beds are generally <50 cm thick, but are commonly erosionally amalgamated into dm-scale bedsets. Current ripple lamination occurs where laminae have low inclinations. Thin mudstone beds and carbonaceous detritus are locally interlaminated and may display rhythmicity. Spherulitic siderite, reworked or transported siderite nodules, and coalified wood fragments are common constituents.

Facies 6 is predominantly unburrowed (BI 0). In zones where mudstone layers are present, BI 1 may be achieved. Mudstone layers contain very rare Planolites, Cylindrichnus, fugichnia, and mantle-and-swirl structures (navichnia) (cf. Gingras et al., 2007).
Figure 4.4 A) Moderately oil-stained sandstone showing erosionally amalgamated HCS and oscillation ripples. Trace fossils include *Planolites* (P), and fugichnia (fu). Well# 07-03-054-25W3, Depth 480.2m. B) Thick interval of convolute bedding within delta-front deposits. Well# 13-01-052-27W3, Depth 469.8m. C) Proximal-delta front/distributary-mouth bar sandstone displaying oscillation-rippled sandstone interbedded with current-rippled sandstone (Facies 4b). Trace fossils include *Planolites* (P), *Cylindrichnus* (Cy), *Thalassinoides* (Th), and *Lockeia* (Lo). Well# 13-01-052-27W3, Depth 442.8m. D) Pervasively bioturbated muddy sandstone reflecting sandy bay-margin deposition. Suite consists of *Skolithos* (Sk), *Planolites* (P), *Cylindrichnus* (Cy), *Palaeophycus* (Pa), *Teichichnus* (T), *Gyrolithes* (Gy) and *Chondrites* (Ch). Well# 09-32-049-25W3, Depth 511m. E) Angular to subangular mudstone clasts within sandy matrix representing Facies 5. Well# 11-18-049-23W3, Depth 514m. F) Large-scale through cross-stratification, in medium-grained sand. Note abundant organic detritus marking stratification. Well# 11-18-047-23W3, Depth 531.4m.
4.4.7 Facies 7: Current-Rippled Laminated Sandstone

Facies 7 consists of very fine-grained and moderately well to well-sorted, current-rippled and planar-parallel laminated sandstones. Beds range from metres to decimetres in thickness (Fig. 4.5A). Combined-flow ripples and aggradational current ripples are present throughout the facies. Mudstone drapes are intercalated in some intervals. Units contain carbonaceous detritus marking stratification, rare mudstone rip-up clasts, and spherulitic siderite grains. Rare intervals display soft-sediment deformation and micro-faults.

Bioturbation intensities are generally low and range from BI 0-2 at the bed scale. Burrowed zones locally display isolated *Skolithos, Cylindrichnus, Planolites*, fugichnia, and navichnia. *Planolites* and navichnia are largely confined to mudstone drapes.

4.4.8 Facies 8: Inclined Heterolithic Stratification (IHS)

Facies 8 consists of inclined beds of alternating sandstones and mudstones (Fig. 4.5B, C). Units vary from mud-dominated to sand-dominated composite bedsets. Bed dip angles are generally less than 15°. Coarser-grained beds comprise moderately-well to well sorted, fine-to medium-grained sandstone, and exhibit current ripple cross-lamination and small-scale trough cross-stratification. Generally, bed thicknesses of trough cross-stratification decreases upward. Oscillation ripples and combined-flow ripples are uncommon, but locally occur. The contacts between mudstone and sandstone beds vary from sharp and erosional to pervasively bioturbated. Mudstone beds are typically structureless, but sandstone and siltstone layers may be intercalated locally. These coarser-grained layers display small-scale current ripples and parallel lamination. Some intervals show convolute bedding and other soft-sediment deformation structures, including micro-faults. Syneresis cracks are present but not abundant. Units also contain mudstone rip-up clasts, carbonaceous detritus, pyrite, siderite nodules, and coalified wood fragments.

Facies 8 generally displays variable bioturbation intensities at the bed scale (BI 0-5). The abundance of burrowing in both sandstone and mudstone beds increases upward.
Sandstones are generally unburrowed or weakly burrowed (BI 0-2). The majority of the burrows cross-cutting the sandstone beds subtend from overlying mudstone layers. Traces within the sandstones include Cylindrichnus, Skolithos, Arenicolites, Planolites, Palaeophycus, and fugichnia. Mudstone beds vary from BI 0-5. Most biogenic structures are diminutive and the facies displays low-diversity suites. Ichnogenera include Cylindrichnus, Planolites, Skolithos, Thalassinoides, Gyrolites, Teichichnus, Psilonichnus, Chondrites, and navichnia.

4.4.9 Facies 9: Massive Mudstone

Facies 9 generally comprises massive mudstone with locally convolute bedding and silt and sand lamination. Sandy beds, where present, are typically less than 2 cm thick, and display parallel lamination and current-ripple cross lamination. Facies 9 is subdivided into two subfacies on the basis of their sedimentological and ichnological features.

4.4.9.1 Subfacies 9a: Alternating Massive Mudstone and Bioturbated Mudstone

Subfacies 9a consists of structureless to laminated mudstone beds, which locally display thorough bioturbation (Fig. 4.5D). The facies generally ranges from less than 1 m up to 2 m in thickness. Intercalated sandstones occur as thin, normally graded, very fine-grained laminae. Siderite nodules and bands, as well as organic detritus are common. Soft-sediment deformation features, mainly in the form of convolute bedding and micro-faults, are present throughout the facies. Thicker intervals locally display evidence of pedogenesis and associated root structures. Fine- to medium-grained sandstone with sharp basal contacts are present locally. These sandy units range from mm-scale thicknesses up to 20 cm thick, and display current-ripple lamination and aggradational current ripples.

Bioturbation within Subfacies 9a is variable. Bioturbation intensity values range from BI 0-5. Ichnological suites are of low diversity and predominantly consist of facies-
crossing forms. Trace fossils are diminutive and include *Planolites, Palaeophycus, Cylindrichnus, Teichichnus, Thalassinoides, Gyrolithes*, and navichnia.

### 4.4.9.2 Subfacies 9b: Massive Mudstone Interlaminated with Siltstone and Sandstone

Subfacies 9b comprises massive mudstone, ranging from less than 1 m to over 15 m in thickness. The units are composed of apparently structureless mudstone with variable proportions of mm- to dm-thick beds of siltstone and sandstone (Fig. 4.5E). Sands are very fine to fine grained, and locally display current-ripple lamination. The contacts between coarser-grained and finer-grained members are generally sharp, but more rarely the contacts are disrupted by bioturbation. Siderite nodules and cemented bands, as well as organic detritus are common. Soft-sediment deformation features occur as convolute bedding, churned muddy slump deposits, and micro-faults.

Subfacies 9b generally displays very low bioturbation intensities (BI 0-2). Bioturbation is concentrated in the coarser grained units, and consists of *Planolites, Cylindrichnus*, and *Teichichnus*. Intensity of burrowing within the finer-grained members range from BI 0-1 and, where present, trace-fossil suites are dominated by *Planolites* and navichnia.

### 4.4.10 Facies 10: Bioturbated Structureless to Lenticular Bedded Mudstone

Facies 10 is a massive (apparently structureless) mudstone, with mm- to cm-thick sandstone and siltstone interbeds, forming wavy to lenticular bedded composite bedsets (Fig 4.5F). Sands are fine grained and moderately sorted. Typically, the proportion of sand decreases upward, generating a fining-upward succession. Primary sedimentary structures are generally obliterated, but may include planar parallel lamination and current-ripple lamination. Locally, small-scale wave ripples are also present. Organic detritus as well as siderite bands and nodules are abundant.

The facies displays variations in bioturbation intensity at the bed scale. BI values range from 3-5, with generally uniformly distributed burrowing. Where bioturbation
reaches BI 5, little of the original bedded character is apparent. Ichnological suites are of low diversity and trace fossils are diminutive. The trace-fossil assemblage consists of *Planolites, Cylindrichnus, Teichichnus, Skolithos*, and *Gyrolithes*. Some intervals display monogeneric suites of *Gyrolithes* or *Cylindrichnus*.

### 4.4.11 Facies 11: Root-Bearing Mudstone

Facies 11 is characterized by grey silty and sandy mudstones, with common root structures (Fig. 4.6A). Most units appear structureless and are recovered in the form of mudstone rubble. Fragments locally display waxy pedogenic slickensides (*cf.* Leckie *et al.*, 1989). Carbonaceous detritus is present and commonly marks lamination. Siderite nodules and coalified-wood fragments are present throughout the facies. Locally, very fine-grained sandstone and siltstone beds are interbedded, and where present they commonly display small-scale gravity faults and convolute bedding.

Ichnologically, Facies 11 displays very low bioturbation intensities (BI 0-1). Common biogenic structures are *Planolites* and roots.
Figure 4.5 A) Current-rippled sandstone with abundant organic detritus. Note the erosional contacts of ripples and a climbing ripple in the lower part of the photograph. Well# 05-17-050-22W3, Depth 444.6m. B) Moderately burrowed inclined-heterolithic stratification of Facies 8. Sandstone beds display current-ripple lamination. Mudstone layers are dense and are sparsely bioturbated. Note that near the sand and mud contact the intensity of bioturbation is higher. Trace fossils include Planolites (P), Cylindrichnus (Cy), Palaeophycus (Pa), Teichichnus (T), and Gyrolithes (Gy). Well# 07-08-052-23W3, Depth 439.3 m. C) Current-rippled sandstone interstratified with bioturbated mudstone. The lower mudstone interval displays remnant of parallel lamination of silt and sand. Suite include Planolites (P), Palaeophycus (Pa), Cylindrichnus (Cy), Gyrolithes (Gy), Skolithos (Sk), Arenicolites (Ar), Thalassinoides (Th), and Lockeia (Lo). Well#: 12-04-050-19W3, Depth 433.2m. D) Alternation of dense mudstone with bioturbated mudstone of Facies 9 Subfacies A. Note the lower portion displays dense, unburrowed mudstone and passing upward into pervasively bioturbated mudstone. Such units vary at the bed scale in many intervals. Traces include Planolites (P), Cylindrichnus (Cy), Teichichnus (T), and Palaeophycus (Pa). Well# 10-21-053-21W3, Depth 419.3m. E) Weakly-burrowed mudstone (BI 0-1) representing Facies 9b. The facies displays disperse wood fragments (wd) and micro-faulting. Trace fossils include Planolites (P), Cylindrichnus (Cy), Skolithos (Sk), Thalassinoides (Th), and navichnia. Well# 09-12-049-24W3, Depth 497.7m. F) Wavy- to lenticular-bedded mudstone of facies 2, containing small amounts of carbonaceous detritus and pyrite (pyr). Note the unit displays a monogenic suite at the top of the photograph. Traces fossils include Skolithos (Sk), Cylindrichnus (Cy), Arenicolites (Ar), and Gyrolithes (Gy). Well# 04-16-050-19W3, Depth 455.8m.
4.4.12 Facies 12: Carbonaceous Mudstone and Coal

Facies 12 is characterized by highly carbonaceous mudstones and sub-bituminous coal (Fig. 4.6B). Coal beds vary from a few centimeters to 0.5 m thick, and range from black to dark grey in color, depending upon the amount of interstitial silt and sand. Locally, beds display mm-scale laminae. Facies 12 is commonly associated with underlying rooted horizons, confirming that it represents in situ accumulation. Pyrite is associated with most carbonaceous mudstones and coal beds.

Bioturbation intensities within Facies 12 are very low (BI 0-1), with biogenic structures generally confined to the lower section. Common traces are Planolites and roots.

![Figure 4.6 A) Pedogenically modified mudstone. Trace fossil include Planolites (P) and root structure (r). Well# 10-04-052-23W3, Depth 418.6m B) Well-bedded coal. Well# 09-32-049-25W3, Depth 445.5m.](image-url)
4.5 Facies Associations

Based on similar attributes, facies defined from the Waseca and McLaren alloformations can be grouped into six recurring facies associations (FA1-FA6).

4.5.1 Facies Association 1: Offshore Marine Deposits

Facies Association 1 (FA1) consists of a single subfacies (Subfacies 1a; Fig. 4.8). The association occurs in the northern part of the study area, and locally at the bases of FA2 and FA3.

The upward increase in grain size, combined with the association of micro-HCS and wave ripples is interpreted to record a shallowing-upward trend. The pervasive bioturbation along with the dominance of trace fossils reflecting deposit-feeding and grazing ethologies (Table 2) suggest slow accumulation of fine-grained material in a low-energy setting, possibly near to, but below, fair-weather wave base. The local presence of soft-sediment deformation features suggests periods of higher sedimentation rates, possibly associated with nearby deltaic influence. Associated isolated syneresis cracks are suggestive of salinity fluctuations (Burst, 1965), and confirm the introduction of freshwater into the marine water body (*i.e.*, deltaic influence). The trace-fossil assemblages and their diminutive character can be attributed to physico-chemical stresses (*cf.* Pemberton *et al.*, 1982; Beynon *et al.*, 1988; MacEachern and Pemberton, 1994; MacEachern *et al.*, 1999; Pemberton *et al.*, 2001; MacEachern *et al.*, 2005; MacEachern *et al.*, 2007). The ichnological suite is typified by moderate diversity, and is dominated by grazing structures and deposit-feeding structures, with subordinate dwellings of inferred suspension-feeding organisms (Table 2). Such suites are representative of a slightly stressed expression of the archetypal *Cruziana* Ichnofacies.
Figure 4.7 Legend of symbols used in lithologies.
**Figure 4.8** Litholog of core from well 12-24-052-27W3, illustrating FA1 distal offshore marine deposits. Legend for lithologies in Fig. 4.7.
Facies Association 1 is interpreted to represent predominantly offshore marine deposits, based on the fine-grained nature of the deposit, presence of distal tempestites, and the marine ichnological characteristics. A weak deltaic overprint on sedimentation is indicated by the combination of soft-sediment deformation structures, present of syneresis cracks, and variable bioturbation intensities. The setting is interpreted as an offshore environment lying downdrift of an active delta complex.

4.5.2 Facies Association 2: Wave-/Storm-Dominated Shoreface Deposits

Facies Association 2 (FA2) displays a coarsening-and shallowing-upward succession that displays a corresponding upward decrease in bioturbation intensity. The association is represented by three facies (subfacies 3a and 4a, and Facies 6; Fig. 4.9). The succession typically ranges from 3-5 m in thickness. The base of the succession overlies a marine flooding surface (FS) or, locally, a transgressive surface of erosion (TSE). In most successions, the percentage of sandstone varies markedly, with the base containing 20-30% sandstone, increasing to 90-100% toward the top of the interval.

The alternation between sandstone and pervasively bioturbated mudstone layers within Subfacies 3a is interpreted to reflect variations in sedimentation rates. Sandstone beds represent deposition during high-energy periods, such as storms, with more thoroughly bioturbated units representing biogenic reworking of mud deposited from suspension during fair-weather periods in a well-oxygenated marine environment (e.g., Howard and Frey, 1984; Frey, 1990). Trace fossils are diminutive although diversities are moderate. Suites are dominated by deposit-feeding structures and lesser numbers of dwellings of inferred filter-feeding organisms, corresponding to a stressed expression of the archetypal Cruziana Ichnofacies. Subfacies 3a is interpreted as a proximal (upper) offshore deposit of a storm-influenced shoreline. Subfacies 3a passes gradationally upwards into Subfacies 4a.

Wave-formed structures dominate the character of Subfacies 4a, indicating a subaqueous depositional environment and deposition above fair-weather wave base (FWWB). Storm waves are interpreted to have been responsible for the abundant HCS, SCS, and micro-HCS. Waning storm-energy conditions were responsible for generating
the oscillation ripples and combined-flow ripples. The low bioturbation intensities within HCS beds, as well as the presence of convolute bedding are consistent with high deposition rates during tempestite accumulation (cf. Howard and Frey, 1975; Pemberton and Frey, 1984; Pemberton and MacEachern, 1997). Intervening mudstone beds within Subfacies 4a are interpreted as bedload transported fluid muds. This is supported by the paucity of bioturbation, presence of mantle-and-swirl structures (navichnia), graded mudstone layers, and the presence of intervening silt and sand laminae (e.g., Lobza and Schieber, 1999; Schieber, 2003; Gingras et al., 2007; Bhattacharya and MacEachern, 2009). Subfacies 4a, where associated with Subfacies 3a is interpreted to represent lower to middle shoreface deposits with localized deltaic overprints. Subfacies 4a is locally overlain by Facies 6.

Facies 6 reflects deposition in a subaqueous environment, and records the amalgamation of dune-scale bedforms and current ripples generated by persistent, quasi-steady flow (Reinson, 1984), interpreted to be produced by breaking waves. The general absence of bioturbation within the sandstone suggests that the depositional environment may have been inhospitable to benthic organisms. A high current velocity capable of mobilizing medium-grained sand and migrating large-scale bedforms makes colonization by infaunal organisms challenging (Dashtgard, 2011; Sisulak and Dashtgard, in press). The presence of mudstone drapes probably reflects rapid settling of floculated mud from distributary channels. The association of Facies 6 with the underlying facies (Subfacies 4a) suggests deposition within an upper shoreface environment. The low preservation potential of Facies 6 is attributed to the removal of these deposits by wave or tidal action during transgression and erosive shoreline retreat (e.g., Kidwell, 1989; Van Wagoner et al., 1990; Cattaneo and Steel, 2003). Alternatively, it is possible that within some parts of the study area, progradation of the shoreline only reached lower to middle shoreface conditions prior to transgression.
Figure 4.9 Litholog of representative well 13-02-052-27W3, showing the facies of FA2, interpreted as wave-/storm dominated shoreface succession. Legend for lithologies in Fig. 4.7.
Facies Association 2 (FA2) is interpreted to correspond to wave-/storm-dominated shoreface deposits. Locally, subtle deltaic overprints are apparent in some intervals, attesting to positions downdrift of time-equivalent deltaic progradation. The succession represents the progradation from proximal offshore to upper shoreface environments.

4.5.3 Facies Association 3: Mixed River-Wave Influenced Delta Deposits

Facies Association 3 (FA3) is characterized by shallowing- and coarsening-upward successions, manifest by an upward transition from Facies 2, through Subfacies 3b, Subfacies 4a, and Subfacies 4b (Fig. 4.10). Locally, a thin succession of FA1 sits at the base of FA3. The FA3 succession typically ranges from 3-7 m, but locally reaches 10 m in thickness.

The interbedded character of Facies 2 records the alternation of fair-weather deposition and event-bed deposition. The presence of combined-flow ripples and current ripples indicates that a quasi-steady current operated during deposition. High sedimentation rates are evidenced by the presence of episodically emplaced tempestites, the presence of soft-sediment deformation features, and common escape structures (fugichnia). The low bioturbation intensities of the facies are consistent with high depositional rates. Reduced trace-fossil diversities, diminutive ichnogenera, and locally common syneresis cracks suggests that the water salinities were variable. Local occurrences of ichnogenera attributed to more marine conditions (e.g., Chondrites, Phycosiphon) suggest, however, that normal marine salinities occurred regularly. The trace-fossil suite consists mainly of deposit-feeding structures with subordinate grazing structures, corresponding to a stressed expression of the Cruziana Ichnofacies. Facies 2 is interpreted as a distal prodelta environment.

Facies 2 passes gradationally upwards into Subfacies 3b. Units of Subfacies 3b contain reduced mud contents and thicker intervals with preserved primary sedimentary structures, suggesting deposition in a more proximal setting. Sandstone beds contain oscillation ripples and locally preserved micro-HCS, consistent with high-energy
conditions. Fluvial influence is recorded by the presence of current-ripple and combined-flow ripple lamination. Carbonaceous mudstone layers are interpreted as fluid mud deposits sourced from nearby riverine influx. These mudstone beds likely represent either hypopycnal or hyperpycnal deposits, and are recognized by their high carbonaceous contents consistent with phytodetrital input supplied from river-derived buoyant plumes (e.g., Rice et al., 1986). Reduced biogenic reworking probably indicates that the emplacement of these muds with concomitant oxidation of the organic detritus, at least temporarily, led to periods of dysaerobic conditions (e.g., Raychaudhuri and Pemberton, 1992; Coates and MacEachern, 1999; MacEachern et al., 2005; Bann et al., 2008; Bhattacharya and MacEachern, 2009). Salinity variations are evident from the presence of abundant syneresis cracks. The low diversities and size reductions of biogenic structures also indicate salinity fluctuations, which probably alternated between normal marine and brackish-water conditions. The ichnological suites are dominated by deposit-feeding behaviours with subordinate grazing structures, representing stressed proximal expressions of the Cruziana Ichnofacies. One of the main characteristics of Subfacies 3b is the paucity of biogenic structures indicative of suspension-feeding behaviours, which is consistent with elevations in water turbidity near the sediment-water interface (cf. Moslow and Pemberton, 1988; Gingras et al., 1998; MacEachern et al., 2005; Coates and MacEachern, 2007; Hansen and MacEachern, 2007). These sedimentological features, coupled with ichnologic aspects of Subfacies 3b are interpreted to record deposition within a proximal prodelta to distal delta-front environment.

Subfacies 4a represents deposition above fair-weather wave base, where fluvially derived sands were reworked by wave and storm action into oscillatory-generated bedforms. Where associated with Subfacies 3b and Subfacies 4b, Subfacies 4a is interpreted as delta-front deposits. Riverine influx is recorded by the occurrence of siderite-cemented mudstones, abundant organic detritus, mudstone rip-up clasts, convolute bedding, local syneresis cracks, and thin, organic-rich fissile mudstone drapes of inferred fluid-mud origin.
Figure 4.10 Litholog of well 06-14-049-17W3, illustrating facies characteristics of wave & river influence delta. Legend for lithologies in Fig. 4.7.
The alternation between oscillatory-generated structures and current-generated structures within Subfacies 4b indicates that both storms and wave-forced currents operated in the depositional environment. The presence of abundant organic detritus corresponds to storm-induced phytodetrital pulses of sediment, which were supplied to the delta-font during river floods resulting from precipitation concomitant with storm events (Leithold and Bourgeois, 1984; MacEachern et al., 2005). The presence of spherulitic siderite along with abundant organic detritus confirms a fluvial point source, where rivers flowed across floodplain and coastal plain settings to reach the coast (e.g., Leckie et al., 1989). Ichnological suites within Subfacies 4b indicate deposit-feeding behaviours, lesser suspension-feeding behaviours, and subordinate resting structures. Such suites are attributed to highly stressed, proximal expressions of the Cruziana Ichnofacies. The presence of soft-sediment deformation features and escape structures indicate overall high sedimentation rates. Subfacies 4b is interpreted as to reflect the proximal part of a delta-front or distributary-mouth bar deposit.

Facies Association 3 (FA3) is dominated by both basinal and fluvial processes and therefore, is interpreted to reflect progradation from distal prodelta through proximal delta-front environments of a mixed river-wave influenced delta.

4.5.4 **Facies Association 4: Distributary Channel and Tidal-Fluvial Estuary**

**Deposits**

Facies Association 4 (FA4) is characterized by a fining-upward succession manifest by a gradual increase in the proportion of fine-grained sediment (Fig. 4.11). In an idealized case, FA4 comprises six facies (facies 5, 6, 7, 8, and 9). The base of FA4 is commonly sharp and erosional, and is overlain by Facies 5.

Facies 5 contains abundant intraformational mudstone rip-up clasts. The facies is interpreted as resulting from slumping and/or erosion, and redeposition of cohesive mudstone clasts derived from the bank margin as a result of channel incision or lateral migration. The facies is unburrowed.
The contact between Facies 5 and Facies 6 is gradational. The dominance of trough and planar tabular cross-stratified sandstones with locally stacked current ripples indicates that Facies 6 accumulated in a current-dominated depositional environment. Abundant spherulitic siderite, carbonaceous detritus, and coalified wood fragments indicates a nearby terrestrial sediment source. Intraformational mudstone rip-up clasts are locally present, indicating that flow velocities were sufficiently high to erode and transport blocks of mudstone. The low intensity of bioturbation is probably a function of high hydraulic energy and rapid deposition rates. The present of rhythmicity within the facies probably reflect tidal activity. Facies 6, where associated with Facies 5 and Facies 7, is interpreted to represent migration of two- and three-dimensional dunes within a channel.

Facies 7 comprises abundant current ripple cross-lamination, suggesting that deposition occurred under moderately high-energy current-flow conditions. Flaser bedding is present locally, and is interpreted to reflect tidal deposition (e.g., Allen et al., 1980; Reineck and Singh, 1980). Low bioturbation intensities, soft-sediment deformation, intercalated aggradational current ripples, and localized mudstone rip-up clasts are consistent with high-energy conditions coupled with elevated deposition rates. Spherulitic siderite and abundant organic detritus probably indicate a nearby terrestrial source and the reworking of incipient paleosols (e.g., Leckie et al., 1989). Facies 7 is interpreted to reflect the shallow parts of a point bar or an interchannel bar (e.g., Ranger and Gingras, 2010; Sisulak and Dashtgard, in press).

The alternation of mudstone interbedded with sandstone within Facies 8, coupled with their low-angle dips are consistent with inclined heterolithic stratification (cf. Howard et al., 1975; Thomas et al., 1987; Shanley et al., 1992), and are interpreted to record deposition within a tidal-fluvial point bar. The predominance of trough cross-stratification and current ripple lamination indicates current-induced sediment transport in the channels. The presence of small-scale oscillation ripples and combined-flow ripples probably indicates periods of standing water within the channel and modification of the bed by waves, possibly during slackwater periods or in sheltered areas of the bar. The intervening mudstone beds are interpreted as being deposited from rapid suspended-
sediment settling, possibly augmented by clay flocculation. These structureless mudstone layers are consistent with accumulation near the turbidity maximum zone (e.g., Meade, 1972; Allen et al., 1980; Allen, 1991; Hughes et al., 1998; Ciffroy et al., 2003). The low-diversity and diminutive character of trace fossils, coupled with the presence of syneresis cracks also confirms that these channels were brackish at the time of deposition (e.g., Beynon et al., 1988; Pemberton and Wightman, 1992; cf. MacEachern and Gingras, 2007 for a review). The paucity of bioturbation probably reflects a combination of reduced salinity and elevated sedimentation rates. Zones of higher bioturbation likely record reductions in depositional rates. The trace-fossil assemblage represents a mixture of deposit-feeding structures and suspension-feeding structures, and is attributed to a stressed composite assemblage consisting of facies-crossing elements common to the Skolithos and Cruziana ichnofacies. Facies 8 is, therefore, interpreted to reflect the active fill of a laterally migrating, brackish-water tidal-fluvial channel.

Facies 9 is separated into two subfacies. Subfacies 9a is generally confined to the tops of the fining-upward cycles. The domination of mudstone and the intense bioturbation support slower rates of suspended-sediment settling in overbank areas, either during channel flooding events or the gradual abandonment of channels at meander-loop cut offs (Miall, 1992). Evidence of local pedogenesis with associated root structures suggests subaerial exposure and vegetative cover, followed by drowning during flooding. The predominance of simple biogenic structures produced by trophic generalists, their diminutive character, and the low diversity of the ichnological suite are indicative of a brackish-water environment (e.g., Beynon et al., 1988; Pemberton and Wightman, 1992; MacEachern and Gingras, 2007). The presence of thin (generally < 20 cm) interbeds of medium- to fine-grained sandstone may reflect local crevasse splay events.
Figure 4.11 Interpretive strip log for the well 11-18-049-23W3. Legend for lithologies in Fig 4.7.
Subfacies 9b is produced by rapid mud accumulation with concomitant current transport of sand and silt, interpreted to record the emplacement of fluid mud (e.g., Lobza and Schieber, 1999). The paucity of bioturbation indicates rapid accumulation, wherein the rate of sedimentation exceeded larval recruitment. The presence of bioturbation within the coarser-grained units suggests that conditions were less hospitable during mud deposition (e.g., higher sedimentation rates, unstable soupy substrates). Abundant soft-sediment deformation features also confirm high sedimentation rates within the subfacies. Such conditions are common within turbidity maximum zones, and are common to modern estuarine settings (e.g., Meade, 1972; Allen et al., 1980; Allen, 1991; Hughes et al., 1998; Ciffroy et al., 2003). Within such zones, mixing of freshwater and saltwater leads to rapid flocculation of clay and silt. Such flocculated muds are subsequently deposited from suspension as sand-sized particles, forming these mud-dominated units. The presence of navichnia (sediment-swimming structures; cf. Gingras et al., 2007) also supports the interpretation of fluid-mud accumulation (e.g., Lobza and Schieber, 1999).

The upward decrease in grain-sizes and scale of bedforms through FA4 successions is interpreted to represent the lateral migration of tidal-fluvial point-bar complexes. Additionally, the laterally restricted geographic distribution of FA4 supports a point bar interpretation. Locally, FA4 contains successions solely consisting of Facies 6 or Subfacies 9b. Differentiation of fluvio-estuarine distributary channels from incised tidal-fluvial estuaries requires the regional mapping of the FA4 succession and the distribution of its basal discontinuity (see the Stratigraphy section below).

4.5.5 Facies Association 5: Transgressive Bay Deposits

Facies Association 5 (FA5) is typical of the upper part of the Waseca Alloformation. The association is characterized by an upward-shoaling succession, and commonly consists of subfacies 1b, 4c, 4a, and Facies 10 (Fig. 4.12).

The fine-grained character of subfacies 1b and the presence of thin, oscillatory-generated bedforms indicate a shallow subaqueous environment. The presence of micro-HCS and soft-sediment deformation features indicates a setting prone to storm influence
and with generally high sedimentation rates. Salinity variations are evident from the presence of syneresis cracks. The trace-fossil suite comprises an impoverished suite of mainly deposit-feeding structures with subordinate suspension-feeding structures, and corresponds to a stressed expression of the *Cruziana* Ichnofacies. Subfacies 1b is interpreted to reflect deposition in a well-oxygenated, sheltered bay setting lying below fair-weather wave base.

The contact between subfacies 1b and 4c is gradational. Sediments of Subfacies 4c are interpreted as deposited near to, but probably above the fair-weather wave base, with a slow and generally continuous accumulation of sand transported by waves, and punctuated by minor storms. The paucity of thick oscillatory-generated bedforms probably indicates that storm waves were not sufficiently high to generate beds thick enough to survive bioturbation. Trace-fossil suites within this facies are characterized by a mixture of deposit-feeding structures and dwelling structures attributed to suspension-feeding organisms. Such an assemblage, along with generally high intensities of bioturbation is probably indicative of a well-oxygenated substrate in which food resources were available both on the bed and in the water column (*e.g.*, Howard and Frey, 1973; 1975; Howard *et al*., 1975; Beynon *et al*., 1988; MacEachern 2007a). Subfacies 4c is therefore interpreted to reflect the distal portions of a bay margin.

Subfacies 4c is overlain by Subfacies 4a, which consists of erosionally amalgamated sandstones. It is noteworthy that Subfacies 4a within FA5 is considerably thinner than in FA2 and FA3, and never exceeds 2 m thick. This suggests deposition within a very shallow-water environment. Locally, deposits of Subfacies 4a are overlain by Facies 10.

The wavy and lenticular bedded character of Facies 10, along with the associated trace-fossil suite, likely indicates deposition within a tidal-flat environment (*cf.* Reineck and Wunderlich, 1968). Current-rippled and planar-parallel laminated sandstones were probably deposited by tidal currents, whereas muds were deposited out of suspension during slack-water periods or by rapid deposition of mud due to clay flocculation. Wind action across a standing body of water is most likely responsible for forming small-scale wave ripples. The increase in the amount of mud within the facies is consistent with tidal-
flat progradation. The high intensity of bioturbation indicates slow rates of sedimentation. Abundant organic detritus and siderite nodules and bands correspond to material that was transported from terrestrial sources (e.g., Leckie et al., 1989). Low-diversity trace-fossil suites, diminutive ichnogenera, and the presence of local monogenic suites suggest an environment in which water salinities were persistently brackish (e.g., Beynon and Pemberton, 1992; MacEachern and Gingras, 2007; Wetzel et al., 2010). The alternation between suites common to the Skolithos Ichnofacies and the Cruziana Ichnofacies corresponds to fluctuations in energy conditions. Facies 10 is interpreted as a muddy tidal flat deposit.

Facies Association 5 is interpreted to represent the progradational infill of a shallow, restricted bay/lagoon from central bay to muddy tidal flat.
Figure 4.12 Litholog of core from well 10-12-048-20W3 showing FA5. Legend for lithologies in Fig 4.7.
4.5.6 Facies Association 6: Coastal/Delta Plain

Facies Association 6 (FA6) consists of two facies: Facies 11 and 12. The association commonly caps the uppermost parasequence of the Lower Waseca Allomember and the McLaren Alloformation. FA6 is discontinuous, and ranges in thickness from 0.25 to 0.75 m.

The presence of abundant organic detritus and coalified wood fragments within Facies 11 suggests that deposition occurred in a continental setting. Abundant rootlets subtending from the basal coal bed (Facies 12) and incipient paleosol development (e.g., pedogenic slickensides) reflect prolonged subaerial exposure of the unit and growth of vegetation.

Facies 12 is interpreted to have formed as a result of accumulation of plant material and organic matter on the coastal/delta plain, probably in swamps. In coastal/delta-plain settings, coal commonly forms on the flood plain, where a sufficient distance from active sedimentation near the channel allows for the growth of flora, while a slow rise in the water table preserves the organic material as coal (Reading and Collinson, 1996). Microscopic analysis of Waseca Fm coal in the Gully Lake and Golden Lake fields indicates that the deposition of plant material was mainly influenced by freshwater conditions (Stasiuk, 1984). This is largely due to the abundance of detrital quartz and the low amount of carbonate minerals and pyrite (Williams and Ross, 1979; Altschuler et al., 1983).

Facies Association 6 is interpreted as the deposits of a coastal/delta plain setting, depending upon its relationship to the underlying succession (i.e., FA2 vs. FA3).
4.6 Stratigraphy

Within the Lloydminster area, the Mannville Group is divided into nine informally named lithostratigraphic packages (Fig. 4.1). However, for the purposes of genetic stratigraphy and the establishment of paleogeographic relationships, a lithostratigraphic breakdown is inadequate. Many of these Mannville units display bounding and internal discontinuities that can be linked to allogenic changes in deposition. These discontinuities include unconformities, omission surfaces, ravinement surfaces, and flooding surfaces (Bhattacharya and Walker, 1991; Plint, 2000; Catuneanu et al., 2011). Herein, an allostratigraphic framework is proposed for the Upper Mannville Group, including the Waseca and McLaren alloformations. An allostratigraphic framework allows units to be correlated on the basis of bounding stratigraphic discontinuities (NACSN, 1983).

Based on regional correlations across the study area, a number of discontinuities have been recognized and allowed us to separate out allostratigraphic units. The base of each alloformation within the study interval is defined by mudstone of Subfacies 1a or Facies 2 overlying proximal facies (e.g., Facies 4). These surfaces are regionally extensive, are consistent with bounding discontinuities (e.g., Van Wagoner et al., 1988; 1990), and commonly represent significant deepening across the depositional surface. These surfaces locally show evidence of erosion. Erosion is identified largely on the presence of siderite nodule lags, abundant coarse-grained sands, abundant wood fragments, and palimpsest suites of trace fossils cross-cutting the original assemblage. Such surfaces are commonly referred to as transgressive surfaces of erosion (Posamentier and Vail, 1988) or ravinement surfaces (Galloway, 2001).

A subaerial unconformity was identified within the Waseca Alloformation. The interpretation of the surface was based on the evidence of deep fluvial incision and the presence of a root-bearing horizon and pedogenic modification within interfluve areas. This surface allows subdivision of the Waseca into two allomembers. Such discontinuities represent significant basinward shifts in facies, and are interpreted to have formed during relative sea-level lowstand (Van Wagoner et al., 1990).
In order to understand the architecture of the Upper Cretaceous Mannville Group (Waseca and McLaren alloformations), two cross-sections are presented (Figs. 4.13 and 4.14). The base of the Joli Fou transgressive surface of erosion (TSE) lies 10 to 15 m above the top of the study interval, and is characterized by a sharp increase in API on gamma-ray logs, and a decrease in ohms on resistivity logs. In core, the Mannville-Joli Fou contact is identified by dark marine mudstones overlying sandstones of the Colony Alloformation. Given that the study area appears to represent a low-gradient coastal profile during deposition of the Upper Mannville Group, the surface is considered to be essentially planar. Moreover, the surface is easy to recognize throughout the study area and is used as the datum for the stratigraphic cross-sections.

4.6.1 Waseca Alloformation

The Waseca Alloformation rests on the coal or sandstone marking the top of the Sparky Alloformation, and is separated from it by a marine flooding surface (FS1) (Morshedian et al. 2010; in review). This flooding surface is directly overlain by the offshore marine deposits of Subfacies 1a or the distal prodelta deposits of Facies 2. Locally, the contact between the Sparky and Waseca alloformations is associated with erosion that removed the coal and/or the upper part of the Sparky coastal/delta-plain deposits (e.g., 10-12-048-20W3). There, the contact is a transgressive surface of erosion (TSE1), and is characterized by abundant coalified wood fragments and lags of siderite-cemented clasts. The recognition of the contact between the Waseca and Sparky alloformations toward the northern part of the study area can be challenging, as lithological contrast across the flooding surface diminishes. In core, the contact is marked by an increase in the amount of finer-grained deposits, and more intense and uniformly distributed bioturbation above the contact. On well logs, identifying the transgressive contact is best accomplished using gamma-ray logs. The contact typically displays an increase in radioactivity (e.g., from 60 API to 105 API; 11-18-048-21W3), which reflects the increase in clay content within the facies.
Figure 4.13 Cross-section A-A’ is an along-strike transect through Waseca & McLaren alloformations. The cross-section is approximately 84 km in length. Correlations display spatial geometry of the Waseca and McLaren alloformations in the landward direction.
Figure 4.14 Cross-section B-B’ is a dip-oriented transect through Waseca and McLaren alloformations. The cross section is approximately 77 km in length.
A major erosional unconformity was identified within the Waseca Alloformation. The presence of this unconformity allows us to subdivide the Waseca Alloformation into two allomembers, which we refer to herein as the Lower Waseca Allomember and the Upper Waseca Allomember. This contact corresponds to a transgressively modified lowstand unconformity (see below). Locally, this internal unconformity cuts entirely through the Lower Waseca Allomember, and incises into the top of the Sparky Alloformation (e.g., the Pikes Peak area).

The Waseca Alloformation is separated from the overlying McLaren Alloformation by a regionally extensive marine mudstone, marking a marine flooding surface (FS2) that represents a widespread transgression. Where there is evidence of erosion, the surface is interpreted as transgressive surface of erosion (TSE2).

4.6.1.1 Lower Waseca Allomember

Lower Waseca Allomember, also known as “Regional Waseca” (Van Hulten, 1984; MacEachern, 1986) ranges from about 25 to 35 m thick and commonly contains 3 to 7 m thick coarsening- and shoaling-upward cycles of wave-/storm-dominated shoreface and mixed river-wave influenced deltas (FA2 and FA3, respectively), which show depositional dips towards the north to northwest, and pass gradationally into offshore marine deposits of FA1. The relationship between coarsening-upward cycles in the lower Waseca is complex. They commonly interfinger with one another, making the correlation of individual associations virtually impossible. Each of these cycles is separated by lower ranked (more areally limited) flooding surfaces. Some of the flooding surfaces, associated with FA3, display limited lateral extents and are likely autogenic. Complete cycles of FA2 and FA3 are capped by coastal plain/delta-plain deposits of FA6, unless erosionally removed by younger channels. Distributary channels that scoured parts of deltaic deposits have been observed both in core and on well logs. In core, these distributary channels display distal to proximal delta-front deposits truncated by 1 to 3 m of tabular-to trough cross-bedded sandstones of Facies 6 (e.g., 11-18-048-21W3; Fig. 4.13).
In general, the Lower Waseca Allomember is characterized by wave- and storm-dominated shoreface, and mixed river-wave influenced deltas with associated distributary channels reflecting progradation toward the north and northwest. These parasequences can be correlated northward to township 051-052 (e.g., the Celtic Field), where they gradually downlap onto the offshore marine deposits of FA1.

4.6.1.2 Upper Waseca Allomember

The boundary between the Lower Waseca and Upper Waseca allomembers is placed at a root-bearing and pedogenically modified horizon, which is interpreted as a subaerial unconformity (SU) (e.g., 05-11-049-20W3; Fig. 4.15A). This unconformity is associated with the incision of deep valleys and thus represents a disconformity. Most of the incised valleys are located within the central and eastern parts of the study area, and commonly display trends that indicate north and northwest drainage (e.g., the Pikes Peak and Edam fields). The amount of truncation varies locally, and in some cases the entire Lower Waseca Allomember has been removed (e.g., 10-08-049-23W3). Remnant intervals of the Lower Waseca Allomember are, however, locally preserved. In most locations, the incised valleys are filled by FA4, and erosionally overlie facies associations of the Lower Waseca Allomember (Fig. 4.15B). In the eastern part of the study area, the Waseca lowstand unconformity was subsequently transgressively modified along the valley margins, and locally hosts firmground trace-fossil omission suites attributable to the Glossifungites Ichnofacies (Fig. 4.15C).

Toward the northern part of the study area, the contact between the two Waseca allomembers is characterized by erosion, coupled with an abrupt increase in the amalgamation of wave- and storm-generated bedforms (Fig. 4.15D). A subtle increase in grain size also accompanies this abrupt facies changes. This discontinuity surface, interpreted as a regressive surface of marine erosion RSME), correlates landward into the interfluve area and to the bases of the valleys (Fig. 4.14). The overlying unit coarsens upwards and represents a forced regressive shoreface of the falling stage systems tract (FSST) (cf. Catuneanu et al., 2011). These forced regressive deposits are, in turn,
**Figure 4.15 A)** Pedogenically modified mudstone. Mudstone is leached and contains irregular fractures and coalified wood fragments (wd) (05-11-049-20W3; 446.5 m). **B)** Trough cross-bedded sandstone, interpreted as part of estuarine channel, sharply overlies offshore marine deposits. The contact is interpreted as an amalgamated tidal ravinement surface and subaerial unconformity (TRS/SU). *Planolites* (P), *Teichichnus* (T), *Cylindrichnus* (Cy), *Palaeophycus* (Pa), *Asterosoma* (As), *Helminthopsis* (H), *Phycosiphon* (Ph) (09-12-049-24W3; 527 m). **C)** Erosional discontinuity marked by firm ground *Thalassinoides* (Th), and *Skolithos* (Sk) of the *Glossifungites* Ichnofacies. The discontinuity is overlain by bioturbated mudstone of Facies 1b. *Planolites* (P), *Cylindrichnus* (Cy), *Teichichnus* (T), *Palaeophycus* (Pa), and *Thalassinoides* (Th) are indicative of the brackish-water conditions that persisted when this sediment was deposited (10-12-048-20W3; 427.8 m). **D)** Regressive surface of marine erosion (RSME), characterized by amalgamated hummocky-cross stratified sandstone beds of the delta front, truncating underlying marine bioturbated mudstones with *Planolites* (P), *Cylindrichnus* (Cy), *Teichichnus* (T), *Palaeophycus* (Pa), *Thalassinoides* (Th), *Asterosoma* (As), *Helminthopsis* (H), and navichnia (07-03-054-25W3; 476.3 m).
overlain by 5-6 m of mixed river- and wave-influenced delta deposits of FA3 (e.g., 07-03-054-25W3), corresponding to the lowstand systems tract (LST), separated by the correlative conformity (CC). The upper surface of these LST delta deposits correspond to the maximum regressive surface (MRS), marking the progradational limit of the sequence. This critical sequence stratigraphic relationship was encountered in only two cored intervals within the Butte Field (Township 054).

Core observations and regional correlation indicate that deposits of FA5 directly overlie the discontinuity associated with the interfluve area and the valley-fill deposits. The FA5 succession commonly ranges from 2 to 8 m in thickness, and consists of a single shoaling-upward cycle that splits northward into two shoaling-upward sand bodies.

### 4.6.2 McLaren Alloformation

A sharp contact between deposits of FA5 and overlying marine mudstones of FA1 or FA3 represents the boundary between the Upper Waseca Allomember and the McLaren Alloformation, and is interpreted as marine flooding surface (FS2). Locally, the contact between the two units is erosional and is mantled by siderite-cemented clasts; in such locations it interpreted as transgressive surface of erosion (TSE2). The overlying deposit extends over the entire study area and ranges in thickness from approximately 9 to 15 m. The base of the McLaren Alloformation consists of offshore marine (Subfacies 1a) or distal prodelta (Facies 2) mudstones. Like the Lower Waseca Allomember, the main deposits of the McLaren Alloformation within the study area consist of two to three coarsening-upward successions of FA2 and FA3, which commonly interfinger with one another. The thickness of the coarsening-upward successions ranges between 3 to 5 m. Locally, the uppermost cycle is capped by coastal/delta-plain deposits of FA6. Each of these coarsening-upward successions is bounded by flooding surfaces, recording periods of progradation punctuated by minor transgression. Locally, however, flooding surfaces associated with FA3 intervals display limited lateral extents. McLaren Alloformation deposits commonly terminate northward and north-westward, as they downlap onto the pervasively bioturbated offshore mudstones of FA1. Distributary channels are also present within the alloformation. Their recognition is based largely on geophysical well
logs, on which channels display 1-3 m thick intervals with a low-API, blocky gamma-ray response.

Several thick, sand/mud-filled channel deposits are also present, and reach 32 m in thickness. These channels locally have removed the entire McLaren Alloformation (e.g., 03-07-053-23W3), and correlations demonstrate that they subtend from the top of the Colony Alloformation and are not associated with McLaren deposition (Fig. 4.14).

The McLaren Alloformation is overlain by regionally extensive marine mudstones of the Colony Alloformation, marking a regionally extensive marine flooding surface (FS3). Locally, the contact displays evidence of erosion, which is commonly marked by thin lags of siderite-cemented clasts and/or gritty, muddy coarse sandstone lags. These occurrences are interpreted to represent a transgressive surface of erosion (TSE3). Where the contact between the McLaren Alloformation is associated with valleys that subtend from the top of the Colony Alloformation, the contact is unconformable.

4.7 Interpretation of Sedimentary Successions

In the previous section we showed that the upper part of the Mannville Group (Waseca and McLaren alloformations) can be divided into a number of discrete, mappable stratigraphic packages. These units typically show complex stratigraphic relationships that are related to a number of relative base-level changes during Lower Cretaceous time. Based on correlations of 10 cross-sections (e.g., Figs. 4.13 and 4.14) and the stratigraphic significance of the discontinuities, we propose the following sequence stratigraphic interpretation for the Waseca and McLaren alloformations within the Lloydminster area. The morphology and stratigraphy of the study interval are summarized in the block diagrams of Figure 4.16.

Progradation of the Sparky Alloformation was terminated by a regionally extensive transgression, locally showing wave ravinement to produce a TSE. Initial deposition of the Lower Waseca Allomember began with accumulation of pervasively bioturbated offshore mudstones of Subfacies 1a. Following transgression and the
generation of accommodation space, progradation of shorelines occurred toward the
north and northwest to produce coarsening-upward proximal offshore / prodelta to upper
shoreface / proximal delta-front parasequences of FA2 and FA3. At least five
parasequences were deposited, each of which is separated by a marine flooding surface.
The capping discontinuities within parasequences dominated by FA2 (shoreface deposits)
are considered allogenic and can be readily correlated to FA3 (deltaic deposits). Flooding
surfaces of limited lateral extent are particularly common in cycles of FA3, and are
interpreted to be autogenic in origin, corresponding to channel avulsion and delta-lobe
switching. The shorefaces of FA2 and the mixed river-wave influenced deltas of FA3 are
interpreted to have prograded into a highly embayed shoreline, leading to laterally
discontinuous cycles. Correspondingly, along-strike correlation of individual cycles is
virtually impossible, and the true nature of some of these lower rank discontinuities
remains enigmatic.

Sedimentological and ichnological analyses also indicate that the Lower Waseca
Allomember was deposited in a restricted (sheltered), brackish-water setting. This is
evidenced by the relatively small-scale wave-generated structures, and low-diversity
ichnological suites that consist of diminutive ichnogenera (cf. MacEachern and Gingras,
2007). Distributary channels (FA4) that cut into the proximal delta fronts of FA3
successions occur locally. These channels are commonly 1-3 m thick and are interpreted
as terminal distributary channels (e.g., Bhattacharya, 2006; Olariu and Bhattacharya,
2006). The parasequences of the Lower Waseca Allomember occur within an overall
progradational parasequence set, which in turn is interpreted as a highstand systems tract
(HST) (e.g., Van Wagoner et al., 1990; Posamentier and Allen, 1999). The Lower
Waseca HST is truncated by a regionally extensive subaerial unconformity (SU), marking
the base of the Upper Waseca Allomember.
Figure 4.16 Schematic block diagrams representing depositional environments during the evolution of the upper part of the Mannville Group (Waseca and McLaren alloformations). A) Lower Waseca Allomember was initiated by relative base-level rise. Concurrently sediment from fluvial systems resulted the progradation of the shoreline toward north-northwest. B) A relative fall in base level was accompanied by development of an incised valley systems and the formation of lowstand delta. C) A relative rise in base level resulted in the formation of estuaries and transgressive bay deposits. D) Deposition during McLaren is marked by deltaic and shoreface deposits prograding toward north and northwest.
This lower-upper Waseca unconformity, herein referred to as the Waseca Unconformity, is associated with the incision of deep valleys. Its interpretation as a subaerial unconformity is mainly based on the juxtaposition of proximal facies over distal facies at the base of the valleys fills, and evidence of root structures and pedogenic modification of Lower Waseca units, due to prolonged subaerial exposure in the interfluve areas.

Valleys are typically incised during a sea-level fall and during this time they commonly serve as zones of sediment bypass (Van Wagoner et al., 1990; Zaitlin et al., 1994). In the Lloydminster area of Saskatchewan, valleys are incised up to 34 m deep (e.g., Pikes Peak Field), removing the entire Lower Waseca Allomember as well as the upper part of the Sparky Alloformation. Locally, valley incision extends only to the top of the Sparky coal; coals tend to be resistant to erosion (e.g., Bromley et al., 1984), and may have controlled the depth of incision.

Regional correlations indicate that the falling stage and lowstand deposits associated with incision of the valleys at the Waseca unconformity occur at Townships 053-54 and Ranges 25-26 of the 3rd Meridian, some 20 km basinward of the Celtic Field. The falling stage system tracts deposits are separated from the underlying highstand deposits of the Lower Waseca Allomember by a subtle regressive surface of marine erosion (RSME). Base-level fall and the formation of deeply incised valleys led to the subaerial exposure of offshore deposits. Lowstand conditions such as this promote the incision of valleys and associated sediment bypass, leading to the accumulation of lowstand deltas and shorefaces (cf. Walker and Wiseman, 1995; Burton and Walker, 1999). The falling stage systems tract deposits developed within the study area are identified by their erosional basal contacts, an abrupt increase upward in the degree of erosional amalgamated tempestites, and an associated abrupt increase in grain size and sand content. Such a juxtaposition is assigned to the lowering of storm- and fairweather wave base, in response to a relative base-level fall. These deposits are overlain by 5-6 m thick coarsening upward parasequence which reflect deposition within mixed wave- and river- influenced delta (FA3). These deposits are interpreted as lowstand systems tract (LST) and are separated from the underlying FSST by correlative conformity (CC),
marking the end of base-level fall and the onset of base-level rise. Deposits of LST are capped by maximum regressive surface (MRS, which marks the end of regression (Catuneanu et al., 2011).

The Upper Waseca Allomember overlies the Waseca Unconformity, and was deposited during a period of relative base-level rise. The preservation potential of fluvial deposits within the incised valleys that accumulated during the lowstand is generally considered to be very low (Zaitlin et al., 1994). This is mainly because during lowstand, the valley itself acts as zone of bypass, and any lowstand deposits will be eroded and reworked during subsequent transgression by ravinement processes (e.g., MacEachern and Pemberton, 1994; Pemberton and MacEachern, 2005). As a result, the bases of incised valleys are interpreted to represent an amalgamated subaerial unconformity and tidal ravinement surface (i.e., an TRS/SU). At the bases of the valleys, these co-planar surfaces are overlain by deposits of FA4. Based on the integration of sedimentology and ichnology, we interpret these valley-fill deposits as estuarine channel / point-bar complexes, in which the influence of marine conditions increases towards the top of the succession.

Continuing transgression resulted in the filling of these valleys, and the deposition of shallow, transgressive brackish-water bay deposits of FA5 over the entire study area. These deposits are characterized by thin (4 to 5 m) intervals of coarsening-and shallowing-upward parasequences, and represent small-scale progradational events during the overall transgression. Ichnological observations indicate that marine influence increases to the north. This is manifest by the presence of trace fossils that are commonly associated with marine conditions (e.g., Phycosiphon and Chondrites). During relative base-level rise in the interfluve areas (e.g., Edam Field), the transgression was probably accompanied by erosion, and the lowstand Waseca Unconformity was transgressively modified by wave or tidal ravinement. This is evident in the sharp contact between the pervasively bioturbated silty/sandy mudstone of Subfacies 1b capping progradational deposits of the Lower Waseca Allomember. Here, the contact is marked by sharp-walled, passively filled, firmground Thalassinoides, Skolithos, and Arenicolites, which are attributed to the Glossifungites Ichnofacies.
The transition from estuarine to brackish-water bay deposits within Upper Waseca Allomember probably reflects a gradual increase in relative sea level. The resulting deposits are interpreted as a transgressive systems tract (TST).

Following the deposition of FA5 across the study area, a major transgression occurred. This is indicated by the presence of regionally extensive marine mudstones of Subfacies 1a or Facies 2 over the deposits of FA5. The contact is interpreted as a marine flooding surface (FS2), locally showing evidence of erosion, where it represents a transgressive surface of erosion (TSE2). This surface separates the Upper Waseca Allomember from the overlying McLaren Alloformation. Deposits of the McLaren Alloformation are broadly similar to those of Lower Waseca Allomember. The interval consists of two to three parasequences that represent progradation of wave- / storm-dominated shorefaces and mixed river-wave influenced deltas. Like the Lower Waseca Allomember, cycles within the McLaren Alloformation interdigitate making the correlation of individual associations problematic. Along-strike correlations show greater numbers of coarsening-upward cycles in areas of the FA3 deltaic successions, reflecting autogenic lobe abandonment. The marine flooding surfaces in FA2 coarsening-upward cycles are allogenic, and allow recognition of true parasequences within the FA3 delta complexes.

Parasequence stacking pattern in the McLaren is consistent with a progradational parasequence set, and is interpreted to represent a highstand systems tract (HST). This also indicates that the contact between the Lower Waseca Allomember and the base of the McLaren Alloformation corresponds to a maximum flooding surface (MFS). McLaren Alloformation deposits commonly terminate northward and north-westward, as they downlap onto the pervasively bioturbated offshore mudstones of FA1.

The local occurrences of thick sand or mud-filled channel deposits that have cut into McLaren Alloformation are interpreted as incised valleys that subtend from the base of an amalgamated subaerial unconformity and tidal ravinement surface (TRS/SU) that marks the Upper Mannville Group – Joli Fou Formation contact.
4.8 Conclusion

Evaluation of the ichnological and sedimentological characteristics of units from the Lower Cretaceous, Upper Mannville Group (Waseca and McLaren alloformations) in west-central Saskatchewan resulted in the identification of twelve recurring facies that are combined into six mappable facies associations. Common depositional facies record a variety of marine, marginal marine, and coastal environments, including open marine offshore settings (FA1), wave-and storm-dominated shorefaces (FA2), mixed river-and wave-influenced deltas (FA3), distributary and tidal-fluvial estuarine channels (including incised valley fills) (FA4), transgressive bays (FA5), and coastal/delta plains (FA6).

The predominance of low-diversity trace fossil suites, the prevalence of facies-crossing trace fossils, and the diminutive character of ichnogenera within facies indicate that most of these environments were subjected to marked physico-chemical stress, particularly reduced and fluctuating salinities, but also including elevated water turbidities, heightened and episodic deposition rates, and soupy substrates generated by the accumulation of fluid mud.

Characterization of the facies associations and their mapped distributions allows the recognition of stratigraphic discontinuities, forming the basis for proposing an allostratigraphic framework for these Upper Mannville successions. Abrupt facies juxtaposition and the local presence of palimpsest (omission) suites of trace fossils assist in the delineation and interpretation of the regional discontinuities.

The stratigraphic architecture of the Upper Mannville indicates an overall transgressive history, supported by the landward shift of the shoreline to the south and east, culminating in the regional transgression across the area during Joli Fou time. Most of the discontinuities within the succession correspond to relative base-level rises that separate periods of progradation. As such, the bulk of the study interval consists of a complex series of paralic parasequences. Regionally extensive marine flooding surfaces mark the base of both the Waseca and McLaren alloformations. The Waseca
Alloformation, however, can be subdivided into lower and upper allomembers on the basis of a widespread disconformity (Waseca Unconformity).

The Lower Waseca Allomember and the McLaren Alloformation consist, overall, of progradational parasequence sets that correspond to highstand systems tracts. The Waseca Unconformity marks a major base-level fall and corresponds to a subaerial unconformity. As a result, the deposits of two discrete sequences can be delineated within study interval. The lower sequence encompasses the highstand systems tract deposits of the Lower Waseca Allomember. The upper sequence comprises the lowstand and transgressive systems tracts of the Upper Waseca Allomember and the highstand systems tract of the McLaren Alloformation.

The Waseca Unconformity led to the incision of valleys up to 34 m deep that locally removed all of the Lower Waseca Allomember, and deposited a lowstand delta some 20 km seaward of the progradational limit (e.g., Celtic Field; Twp. 051) of the underlying highstand parasequences. In interfluve areas, this subaerial unconformity is characterized by a root-bearing horizon and the development of incipient paleosols. Ensuing, but incremental, transgression led to the accumulation of a 5 to 35 m thick succession of retrogradationally stacked parasequences, representing the transgressive system tract: this forms the bulk of the Upper Waseca Allomember. Initial transgression resulted in the backstepping of the shoreline at the lowstand delta position, and the tidal-fluvial estuarine infill of the incised valleys (e.g., Pikes Peak field). Continued transgression of the study area led to palimpsest marine colonization of the subaerial unconformity in interfluve areas, manifest by firmground trace-fossil suites attributable to the Glossifungites Ichnofacies. The valley and interfluve areas were ultimately capped by transgressive bay deposits, capping the retrogradational parasequence set. A maximum flooding surface separates the transgressive systems tract of the Upper Waseca Allomember from the overlying highstand parasequences of the McLaren Alloformation.
4.9 References


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CHAPTER 5: RECOGNITION OF BOUNDING SURFACES: AN EXAMPLE FROM THE LOWER CRETACEOUS, UPPER MANNVILLE GROUP (SPARKY, WASECA, AND MCLAREN FORMATIONS), WEST-CENTRAL SASKATCHEWAN, CANADA

5.1 Introduction

The Lower Cretaceous Mannville Group has been the subject of geological evaluation since the early 1940s, and was first drilled in 1942 in the Vermilion area of east-central Alberta (Nauss, 1945). The succession is considered to be one of the most important hydrocarbon-bearing intervals in Canada (Pemberton and James, 1997). The Mannville Group unconformably overlies Paleozoic to Jurassic-Cretaceous strata, and is disconformably overlain by the transgressive marine shales of the Joli Fou Formation, which marks the base of the Colorado Group (Fig. 5.1).

The most commonly used stratigraphic nomenclature for Mannville strata in the Lloydminster area of Saskatchewan and Alberta is based on unofficial driller’s terminology and electric-log characteristics (Edmunds, 1948). These include (from top to bottom): Colony, McLaren, Waseca, Sparky, General Petroleums (G.P.), Rex, Lloydminster, Cummings, and Dina. No formal type sections have been established to formalize this nomenclature. These informal units are referred to as “members” by Vigrass (1977) and “formations” by Orr et al. (1977). For the purpose of this study, the units are regarded to have formation status, a hierarchal level that is most commonly assigned by present-day workers.

The upper part of the Mannville Group (Sparky, Waseca, and McLaren formations) in the Lloydminster area comprises a complex siliciclastic sedimentary unit that is largely characterized by paralic, brackish-water, and marine deposits that have been juxtaposed against one another. Significant research has been focused on these
deposits, since hydrocarbon exploration became a priority in the 1940s (e.g., Nauss, 1944; Edmunds, 1948; Wickenden, 1948; Badgley, 1952; Fuglem, 1970; Christopher, 1975, 1980, 1984; Orr et al., 1977; Vigrass, 1977; Dunning et al., 1980; Haidl, 1980, 1984; Lorsong, 1980, 1982; Robson, 1980; Putnam, 1982; Caldwell, 1984; MacEachern 1984, 1986, 1989; Richardson and Vigrass, 1984; Smith 1984; Smith et al., 1984; Van Hulten and Smith, 1984; Kramers, et al., 1989; Leslie, 1989; Harding, 1991; Dwyer, 1998; Newsome, 1998; Bradshaw, 1999; Buttle, 1999; Morshedian et al., 2009, 2011, in review). Most of these studies were focused mainly on utilizing lithology and sedimentary structures to erect facies successions. Facies successions were defined to guide stratigraphic correlations, but were based largely on perpetuating existing lithostratigraphic correlations. Despite the abundance of core and geophysical well logs, few studies have attempted to resolve the regional geological history of the Upper Mannville. Notable exceptions include Christopher (1997), and Morshedian et al. (in review).

One of the persistent problems in unravelling the complexities of the Upper Mannville Group stratigraphy is the repeated alternations, both vertically and laterally, of similar-appearing, paralic (coastal margin) facies. When these strata are characterized solely on the basis of physical sedimentology and lithology, the resulting facies can be attributed to a number of possible subenvironments. However, when ichnology is integrated with the physical sedimentology, distinctive facies can be identified. The resulting facies successions and mapped facies associations more accurately reflect paleoenvironmental settings. These data, in turn, allow for recognition of recurring depositional architectures and permit high-resolution facies-driven stratigraphic correlations. The addition of palimpsest ichnological suites as well as recognition of juxtaposed facies that contravene Walther’s Law permit delineation of subtle stratigraphic discontinuities within a sequence stratigraphic framework. The construction of a facies-based sequence stratigraphic framework is crucial to accurate subsurface mapping and may provide possibilities for future hydrocarbon exploration.
Figure 5.1 Correlation of Lower Cretaceous strata in eastern Alberta and western Saskatchewan (modified after Christopher, 2003). Red dots indicate the study interval. The unconformity shown between the Lower and Upper Waseca Members in the Lloydminster area is defined in this study.
5.2 Study Area and Methodology

The study area extends from Townships 48 to 54, and lies between Ranges 19 and 28 west of the 3rd Meridian, comprising a total area of 5,400 km² (Fig. 5.2). The study area contains approximately 19,200 wells, of which an estimated 1,730 include cored intervals that penetrate the Mannville. A total of 127 cores were logged from the upper Mannville interval, totalling approximately 2,850 m. The cored wells penetrate a number of major hydrocarbon fields in west-central Saskatchewan (e.g., Golden Lake, Lloydminster, Lashburn, Pikes Peak, Cold Lake).

The cored intervals were evaluated with respect to their trace fossils, sedimentary structures, lithological features, and stratigraphic discontinuities in order to establish depositional facies. Ichnological appraisal included trace-fossil identification, assessments of trace-fossil sizes, estimations of bioturbation intensities, evaluations of burrow distributions, and ethological interpretations of the biogenic structures. Sedimentological studies focused on characterizing lithology, sedimentary texture, and primary and synsedimentary physical sedimentary structures. Facies are grouped into recurring, spatially distributed successions (facies associations) and assigned depositional interpretations. In addition, more than 700 geophysical well logs were used in the stratigraphic evaluation of the interval.
**Figure 5.2** Location of the study area. **A)** Map of Canada showing the location of the study area. **B)** Detailed map of the study area with locations of logged core.
5.3 Facies Analysis

Based on ichnological and sedimentological criteria, as well as the spatial distributions of the units, thirteen recurring facies are identified from the Sparky, Waseca, and McLaren formations (Morshedian et al., 2009). These facies are combined into six facies associations (FAs; Table 5.1), which comprise: 1) open-marine offshore settings; 2) mixed river- and wave-influenced deltas; 3) wave- and storm-dominated shorefaces; 4) distributary channels and tidal-fluvial estuaries; 5) transgressive bays; and 6) coastal plain/delta plain settings. Discrimination among these broadly similar depositional facies successions requires the full integration of ichnological and sedimentological criteria.

5.3.1 FA1: Offshore Marine Deposits

Facies Association 1 (FA1) consists of thoroughly bioturbated silty to sandy mudstones. The association records the most marine conditions within the study area. Intervals are characterized by high bioturbation intensities (BI 3-5) in mudstones, which are interbedded with sandstones with lower BI values (Fig. 5.3). Sandstone beds are interpreted as thin tempestites. Stratigraphically upwards, the abundance of tempestites increases and the degree of bioturbation decreases. Ichnogenera are commonly robust and diverse.

The pervasively bioturbated mudstones within FA1 indicate slow accumulation of fine-grained sediment in a low-energy setting, lying below fair-weather wave base but above storm wave base. Trace fossil suites are dominated by deposit-feeding structures and grazing structures. Such suites are representative of distal and archetypal expressions of the *Cruziana* Ichnofacies. Robust trace fossils and the presence of ichnogenera characteristic of marine conditions (*e.g.*, *Chondrites, Asterosoma, Helminthopsis*; cf. Gingras et al., 2007) suggest that salinities were close to fully marine at the time of deposition. The combination of sedimentological and ichnological characteristics is consistent with deposition in offshore positions. Sandy mudstones (proximal offshore) are regarded to reside slightly landward of the silty mudstone (lower offshore) facies.
<table>
<thead>
<tr>
<th>Facies Association</th>
<th>Facies #</th>
<th>Facies</th>
<th>Sedimentology</th>
<th>Trace fossil suite</th>
<th>Bioturbation Intensity</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Marine Mudstone</td>
<td>1a</td>
<td>Bioturbated Silt/Sandy Mudstone</td>
<td>Thoroughly bioturbated, locally micro-HCS.</td>
<td>Planolites, Cylindrichnus, Palaeeophycus, Teichichnus, Chondrites, Asterosoma, Hycrocoelites, Fimbriatichnus, Rosselia, Scolecia, &quot;Teichichnus&quot;, and fugichnina.</td>
<td>3-5</td>
<td>Offshore Marine Deposits</td>
</tr>
<tr>
<td>2) Wave-Stream Dominated Shoreface</td>
<td>6</td>
<td>Trough Cross-Bedded to Tabular Cross-Bedded Sandstone</td>
<td>Cross-bedded sandstone with lowly low-angle planar stratified and current-ripple sandstones.</td>
<td>Cylindrichnus, Pseudodolires, fugichnina.</td>
<td>0-2</td>
<td>Upper Shoreface</td>
</tr>
<tr>
<td></td>
<td>4a</td>
<td>Oscillation-Rolled to Hummocky Cross-Stratified Sandstone</td>
<td>HES, SCS, Wave-ripples, locally mudstone drapes.</td>
<td>Skolithos, Planolites, Cylindrichnus, fugichnina, naviculina.</td>
<td>0-2</td>
<td>Lower to Middle Shoreface</td>
</tr>
<tr>
<td>Thin bed of 1a</td>
<td>3a</td>
<td>Bioturbated mudstone interbedded with sandstone</td>
<td>Mudstone interbedded with oscillation-rippled sandstone, locally micro-HCS.</td>
<td>Cylindrichnus, Skolithos, Gyrolithus, Planolites, Chondrites, Teichichnus, Thalassinoides, Asterosoma, naviculina, fugichnina.</td>
<td>2-5</td>
<td>Proximal Offshore</td>
</tr>
<tr>
<td>4b</td>
<td>Oscillation Ripped Sandstone</td>
<td>Wave-ripple, combined flow ripple, and current ripple. Locally small scale trough cross bedding, abundant organic detritus</td>
<td>Planolites, Cylindrichnus, Planolites, Skolithos, fugichnina.</td>
<td>0-1</td>
<td>Proximal Delta Front</td>
<td></td>
</tr>
<tr>
<td>4a</td>
<td>Oscillation-Rolled to Hummocky Cross-Stratified Sandstone</td>
<td>HES, SCS, Wave-ripples, locally mudstone drapes.</td>
<td>Skolithos, Planolites, Cylindrichnus, fugichnina, naviculina.</td>
<td>0-2</td>
<td>Delta Front</td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td>Sporadically bioturbated mudstone interbedded with sandstone</td>
<td>Wavy to lenticular bioturbated sandstone, interbedded with oscillation-rippled sandstone, micro-HCS. Local combined flow ripples, synecrosis cracks, and gutter casts.</td>
<td>Planolites, Skolithos, Palaeeophycus, Gyrolithus, Thalassinoides, Arenicolites, Teichichnus, Chondrites, fugichnina, naviculina.</td>
<td>0-3</td>
<td>Proximal Prodelta o Distal Delta Frong</td>
<td></td>
</tr>
<tr>
<td>Thin bed of 1a</td>
<td>2</td>
<td>Pinstripe to Lenticular Bedded Mudstone</td>
<td>Oscillation ripples, with sharp contacts, locally synovolanic bedding, current ripples, and synecrosis cracks.</td>
<td>Planolites, Cylindrichnus, Palaeeophycus, Teichichnus, Chondrites, Asterosoma, Hycrocoelites, Fimbriatichnus, Rosselia, Scolecia, &quot;Teichichnus&quot;, and fugichnina.</td>
<td>0-3</td>
<td>Distal to Proximal Prodelta</td>
</tr>
<tr>
<td>1c</td>
<td>Alternating Massive Mudstone and Bioturbated Mudstone</td>
<td>Thoroughly bioturbated, locally micro-HCS.</td>
<td>Planolites, Cylindrichnus, Teichichnus, Gyrolithus, Thalassinoides, naviculina.</td>
<td>3-5</td>
<td>Offshore Marine Deposits</td>
<td></td>
</tr>
<tr>
<td>1d</td>
<td>Massive Mudstone Interlaminated with Siltstone and Sandstone</td>
<td>Thicker-than-scale wth/sand intercalations, current ripple, abundant soft-sediment deformation.</td>
<td>Planolites, Cylindrichnus, Teichichnus naviculina.</td>
<td>1-5</td>
<td>Abandoned Channel Complex</td>
<td></td>
</tr>
<tr>
<td>4) Distributary Channels and Tidal-Fluvial Estuarine</td>
<td>8</td>
<td>Inclined Heterolithic Stratification (IHS)</td>
<td>Heterolithic mudstone and sandstone, sharp contacts, sandstone beds display small-scale rough cross-bedding and current ripple lamination. Organic detritus, fluid mud. Rare oscillation ripples.</td>
<td>Planolites, Skolithos, Cylindrichnus, Gyrolithus, Teichichnus, Thalassinoides, Chondrites, fugichnina, naviculina.</td>
<td>0-5</td>
<td>Lateral Accretion Bedding</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Current Ripple Laminated Sandstone</td>
<td>Locally display diagonalvated and combined flow ripples and rarely oscillation ripples.</td>
<td>Skolithos, Cylindrichnus, Planolites, fugichnina.</td>
<td>0-2</td>
<td>Channel Bar Complex</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Trough Cross-Bedded to Tabular Cross-Bedded Sandstone</td>
<td>Cross-bedded sandstone with locally low-angle planar stratified and current ripple sandstones.</td>
<td>Cylindrichnus, Planolites, fugichnina.</td>
<td>0-1</td>
<td>Migrating Dunes in Channels</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Mud-Clast Breccia</td>
<td>Poorly sorted sandstone, precomminently angular mud clasts. Commonly interbedded with trough cross-bedded sandstone.</td>
<td>No trace fossils identified</td>
<td>0</td>
<td>Channel-Bank Collapse, Erosional Truncation,</td>
</tr>
</tbody>
</table>

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| 5) Tregressive Bay Despot (Bay/Lagoon) | 10 | Bioturbated Massive to Lenticular Bedded Mudstone | Largely preserved sedimentary structures, locally starved ripples, planar bedding, organic detritus | Gyrolithes Skolithus, Planolites | 3-5 | Muddy Tidal Flat |
| 4a | Oscillation-Ripple to Hummocky Cross Stratified Sandstone | Oscillatory ripple, low-angle undulatory parallel lamination, minor micro-HCS | Planolites, Cylindrichnus, Gyrolithus | 0-2 | Proximal Bay Margin |
| 9 | Bioturbated Muddy Sandstone | Thoroughly bioturbated, locally thin oscillation ripples and micro-HCS, organic detritus, coiled wood fragments | Planolites, Trichichnus, Gyrolithes, Cylindrichnus, Paleophycus | 1-5 | Distal Bay Margin |
| 1b | Stressed Bioturbated Silty/Sandy Mudstone | Thoroughly bioturbated, locally thin oscillation ripples and micro-HCS, carbonateous detritus | Planolites, Trichichnus, Gyrolithes, Cylindrichnus, Paleophycus, fucicinia | 2-5 | Central Bay |
| 6 Coastal/Delta Plain | 13 | Carbonaceous Mudstone and Coal | Crudely bedded, rare plant debris, locally high silt and sand content | Planolites, roots | 0-1 | Terrestrial Peat & Swamp |
| 7 | Current Ripple Laminated Sandstone | Largely display gradational and combined flow ripples and rarely oscillation ripples. | Skolithos, Cylindrichnus, Planolites, fugichnia | 0-2 | Crevasse splay |
| 12 | Root-Bearing Mudstone | Convoluted bedded mudstone with roots, organic detritus, current ripple lamination, and some prodogenic features. | Planolites, icksnademasis, and roots | 0-1 | Floodplain |
| 11 | Cross-Bedded Carbonaceous-Rich Sandstone | Sand with abundant coiled wood fragments, locally deformed | Planolites, roots | 0-1 | Fluvial Channel |

Table 5.1: Summary of facies characteristics and interpretations.
Figure 5.3  A) Pervasively bioturbated (BI 5) sandy and silty mudstones interpreted to reflect an offshore marine environment (Facies 1a). The suite includes Planolites (P), Palaeophycus (Pa), Skolithos (Sk), Cylindrichnus (Cy), Gyrolithes (Gy), Thalassinoides (Th), Chondrites (Ch), Asterosoma (AS), Helminthopsis (H), and Phycosiphon (Ph). Well 05-11-049-20W3, Depth 439.5 m. B) Pervasively bioturbated silty and sandy mudstones of Facies 1a with remnants of tempestites. Trace fossils include Planolites (P), Palaeophycus (Pa), Teichichnus (T), Cylindrichnus (Cy), Skolithos (Sk), Chondrites (Ch), Phycosiphon (Ph), Helminthopsis (H), and fugichnia (fu). Well 09-12-049-24W3, Depth 527.3m.
5.3.2 FA2: Wave- and Storm- Dominated Shoreface Deposits

Facies Association 2 (FA2) corresponds to coarsening-upward successions of wave- and storm-dominated shoreface deposits, displaying little or no evidence of overall physico-chemical stress (Table 5.1). Facies show higher bioturbation intensities and ichnological diversities than do those of the FA3 (interpreted as deltaic successions; see below). Bedding contacts range from pervasively bioturbated to sharp, although sharp contacts are more typical, particularly towards the top of the succession. The setting is characterized by wave- and combined flow-generated structures, as well as normally graded mudstone drapes, with zones of small-scale soft-sediment deformation (Fig. 5.4). Bioturbation intensities are highly variable (BI 0-5).

Facies Association 2 is interpreted to represent a progradational succession from proximal offshore to the upper shoreface. The abundance of wave- and storm-generated structures represents subaqueous deposition in progressively shallower water, wherein wave energies increase. The high diversity of trace fossils indicates that environmental conditions were favourable for marine benthic communities that included grazing, deposit-feeding and suspension-feeding organisms in settings of minimal physico-chemical stress.
Figure 5.4 Facies Association 2: Core box photograph of well 13-02-052-27W3 (432.25 to 427 m), displaying coarsening- and shallowing-upward succession of proximal offshore (Facies 3a) to lower-middle shoreface (Facies 4a) environments. In an idealized succession, the unit is overlain by trough cross-bedded sandstone of Facies 6.
5.3.3 FA3: Mixed River-and Wave-Influenced Delta Deposits

Facies Association 3 (FA3) is characterized by coarsening-upward successions that are dominated by sporadically distributed heterolithic beds (Fig. 5.5). Facies show abundant, organic-rich mudstone drapes of probable fluid-mud origin, syneresis cracks, soft-sediment deformation structures, carbonaceous detritus, normally graded beds, and wave-, current- and combined flow ripples. Beds of wavy parallel lamination interpreted as HCS are intercalated. The majority of trace-fossil suites are of low diversity, and are dominated by diminutive ichnogenera. Facies show highly variable bioturbation intensities (BI 0-5).

FA3 is interpreted to represent the progradation of a mixed river- and wave-influenced delta. The increase in the proportion of sandstone to mudstone within the facies association is consistent with upward shallowing and concomitant increase in the influence of wave energy. The presence of locally intercalated, current-rippled sandstone beds is interpreted to reflect fluvial influence. Carbonaceous-rich mudstones that commonly mantle sandstone beds are interpreted to record hypopycnal-induced (buoyant) mud plumes, and the concomitant rapid flocculation and settling of clay. Some of the mudstone beds are normally graded and display evidence of erosion at their bases, and are interpreted as mud turbidites, deposited as a result of hyperpycnal-induced freshet discharge (cf. Bhattacharya and MacEachern, 2009). FA3 is characterized by a low intensity of bioturbation as well as a low diversity of ichnogenera, both consistent with elevated physico-chemical stress. The local occurrence of more marine ichnogenera (e.g., Chondrites, Phycosiphon) within the facies suggests that normal marine salinities occurred periodically. The presence of syneresis cracks suggests that salinity fluctuations (mainly salinity reduction) represent one of these stresses, and are attributed to river floods and/or hyperpycnal discharge (e.g., MacEachern et al., 2005; MacEachern and Bann, 2008; Bhattacharya and MacEachern, 2009).
5.3.4 FA4: Distributary Channels and Tidal-Fluvial Estuaries

Facies Association 4 (FA4) overlies a sharp, erosional basal contact, and consists of massive (apparently structureless) to trough and planar tabular cross-stratified sandstones, as well as intraformational mud-clast breccias (Fig. 5.6A). Locally, thick, apparently structureless mudstones also occur. Sandstones pass upwards into depositionally inclined heterolithic bedsets of cross-stratified and current-rippled sandstone, alternating with laminated to graded mudstones showing variable bioturbation intensities (BI 1-5; Fig 5.6B). These inclined heterolithic composite bedsets display an overall upward decrease in sediment calibres and variable sandstone-to-mudstone ratios. There is also a corresponding upward decrease in the scale of bedforms, as inferred from the sedimentary structures. These composite bedsets show tidal influence locally. Detailed ichnological evaluation demonstrates highly variable bioturbation intensities, sporadically distributed burrowed zones, and the dominance of simple biogenic structures attributed to trophic generalists.

The presence of abundant trough cross-beds and current ripples is interpreted to record deposition in channels. The interbedded sandstone and mudstone are interpreted as inclined heterolithic stratification (IHS), assigned to tidal-fluvial point bar or in-channel bar complexes (cf. Howard et al., 1975; Thomas et al., 1987). Trace fossils within FA4 are diminutive, sporadically distributed, and form low-diversity suites, consistent with the brackish-water ichnological model (e.g., Pemberton et al., 1982; Beynon et al., 1988; MacEachern and Pemberton, 1994; Buatois et al., 2005; MacEachern and Gingras, 2007). The low BI value of some of the mudstone beds may indicate that saltwater incursion occurred within the channels and shifted longitudinally within the valley due to some combination of daily, monthly or seasonal tidal cycles. The suspended sediment load carried by rivers commonly mixes with saline basinal waters, leading to the flocculation of mud. Deposition of this flocculated mud may have led to accumulation of fluid muds within channels and on point bars (e.g., Meade, 1972; Allen et al., 1980; Cliffroy et al., 2003). The overall decrease in grain-size and bedform scales upward through FA4 succession is interpreted to represent lateral migration of point bars within estuarine channels. Differentiation of distributary channels from tidal-fluvial estuarine incised
Figure 5.5 Facies Association 3: Core box photograph of well 11-03-051-22W3 (492 to 484.1 m) depicting the contact with Facies 4a and the overall coarsening- and shallowing-upward successions of distal prodelta (Facies 2) to proximal delta-front (Facies 5b) environments. Note that Facies 4b is characterized by small-scale trough cross stratification and abundant current ripples.
valleys requires evaluation of the scale of the FA4 succession, and its association with the areal extent of its basal discontinuity.

5.3.5 FA5: Transgressive Bay Deposits

Transgressive bay deposits of Facies Association 5 (FA5) are sedimentologically similar to FA2 deposits, but possess different ichnological suites. Sediment deposition in FA5 appears to be dominated by oscillatory processes (Fig. 7). The mud content within the facies is variable, but generally decreases upward. Oscillation ripples, micro-HCS, and combined flow ripples are common structures within sandy beds. The preservation potential of oscillation structures increases towards the top of the succession. It is noteworthy that the thickness of Facies 4a units within FA5 (Table 1) is considerably thinner than those of FA2; never exceeding 2 meters.

Bioturbation intensities in FA5 are highly variable, ranging from BI 0-5. The diversity of ichnogenera is generally lower than that of the FA2 deposits, and consists mainly of facies-crossing elements.

Like FA2, successions of FA5 represent subaqueous deposition by wave processes. The lack of well-developed HCS and SCS within FA5 indicates generally lower wave energies within the sedimentary environment, which is likely attributable to deposition in a more sheltered setting. Low diversities and a predominance of diminutive trace fossils are interpreted to record increased environmental stresses, particularly salinity reduction (e.g., Beynon et al., 1988; Gingras et al., 2007; MacEachern et al., 2007a). FA5 is interpreted as short-lived periods of shoreline progradation within a sheltered bay during an overall transgression.
Figure 5.6 A) Angular to subangular mudstone clasts with a sandy matrix in well 11-18-049-23W3 (depth 514 m), representing Facies 5. The facies commonly sits at the base of FA4 successions. B) Facies Association 4: Core box photograph of well 10-18-050-23W3 (494.25 to 487 m). The interval displays trough cross-stratification (Facies 6), which passes gradually into current rippled sandstone (Facies 7) and weakly burrowed IHS (Facies 8).
5.3.6 FA6: Coastal Plain / Delta Plain

Facies Association 6 (FA6) includes the deposits that cap the progradational successions of FA2 and FA3. FA6 gradationally or, locally, sharply overlies the underlying deposits. The deposits are characterized by trough-cross bedded sandstone with abundant organic detritus and associated rootlets, paleosols, carbonaceous mudstones and coals (Fig.5.8).

FA6 is interpreted as the deposits of a coastal-plain or delta-plain setting, depending upon whether it overlies FA2 or FA3, respectively. The presence of cross-stratified sandstones, abundant organic detritus, and spherulitic siderite grains, is consistent with channels. Transported spherulitic siderite grains and siderite nodules suggest sediment derived from a nearby terrestrial source (Leckie et al., 1989). Common rootlets, paleosol development, and localized adhesive meniscate burrows attributable to the ichnogenus Naktodemasis (Smith et al., 2008), reflect fluctuations in water levels and periods of subaerial exposure, with concomitant growth of vegetation (cf. Hasiotis, 2002). The presence of coal is interpreted as the result of accumulation of plant material and organic matter as swamps, bogs and forested zones, possibly associated with initial base level rise.
Figure 5.7 Core photograph of Facies Association 5 in well 10-12-048-20W3 (421.2 to 415.2 m). The succession shows a shallowing-upward profile from distal bay deposits (Facies 1b) to muddy tidal flat (Facies 10) environments.
**Figure 5.8** Facies Association 6: Core box photograph of 11-03-051-22W3 (489.45 to 486.45 m). The interval displays cross-stratified carbonaceous-rich sandstone (Facies 11), root-bearing mudstone (Facies 12), and coal (Facies 13). The presence of current rippled sandstone within Facies 12 probably indicates that clastic material was introduced into the floodplain as crevasse splays.
5.4 Systems Tracts

In order to better understand the genetic stratigraphic relationships, the depositional succession has been subdivided into systems tracts. These systems tracts are recognized based on stratal properties, and include highstand systems tracts (HST), transgressive systems tracts (TST), Falling stage systems tract, and lowstand systems tracts (LST) (e.g., Van Wagoner, 1995; Posamentier and Allen, 1999; Catuneanu, 2006; Catuneanu et al., 2009; 2011).

5.4.1 Highstand Systems Tract (HST)

Deposits of highstand systems tracts (HST) are typically defined as those strata that overlie the maximum flooding surface (MFS) and are overlain either by a major marine flooding surface or a subaerial unconformity (SU). The HST is initiated when the rate of base-level rise has slowed to the point where it is less than the rate of sediment influx. HST deposits can also be overlain by major marine flooding surfaces (FS), representing regressive-transgressive pulses of sediment, due to either varying rates of sediment influx or varying rates of BL rise (Posamentier and Allen, 1999), and so can alternate with the transgressive systems tract (TST).

Within the study area, HST deposits are widespread and range from 20-30 m in thickness. In vertical successions, HST deposits are well expressed, and defined by upward-coarsening and upward-shallowing parasequences that can be grouped into parasequence sets (cf. Van Wagoner et al., 1988, 1990). These parasequences are stacked in a progradational pattern with the younger parasequences building successively seaward where they downlap onto offshore marine deposits of FA1. Following deposition of each progradational parasequence, a minor transgressive event led to the development of capping flooding surfaces (FS), recorded by an abrupt seaward shift of facies above the surface. Complete coarsening-upward cycles are characterized by the transition from proximal offshore/distal prodelta to upper shoreface/proximal delta front, and are interpreted as progradational parasequences of wave- and storm-dominated shorefaces.
(FA2) and mixed river- and wave-influenced deltas (FA3). The uppermost parasequence, where preserved, is capped by coastal plain/delta plain deposits of FA6. The flooding surfaces are commonly marked by the re-establishment of proximal offshore/distal prodelta deposition, and are typically abrupt. Parasequence contacts can be mapped regionally and are interpreted to develop due to a combination of allogenic controls, including eustasy, regional tectonics, and variations in sediment supply. Aside from these mappable flooding surfaces, deltaic deposits of FA3 also contain minor flooding surfaces that display limited lateral extents. These minor flooding surfaces do not correlate to the allogenic flooding surfaces that partition the FA2 shoreface parasequences. In fact, minor flooding surfaces are interpreted to correspond to autogenic abandonment of delta lobes or to local tectonic events. On well-logs, parasequences are characterized by high-API values in mudstone-dominated facies at the base, which become blocky upward (i.e., funnel shaped) as API values decrease. These profiles are interpreted to record the upwards coarsening and upwards increase in sandstone content observed in parasequences of the HST.

Distributary channels of FA4 are typically associated with deltaic deposits of FA3. The average thickness of these channels is about 5 meters and they commonly cut down into delta-front successions. Channel fills consist of multiple stacked sandstones displaying cross-bedding and inclined heterolithic stratification (IHS), recording deposition on laterally accreting point bars and/or in-channel bars. Gamma-ray well-log profiles of distributary channels tend to be blocky or bell-shaped, and commonly incise into older parasequences.

5.4.2 Falling Stage & Lowstand Systems Tracts (FSST & LST)

Falling stage systems tract (FSST) deposits include all the sediments that accumulate during a relative fall in sea level that allogenically forces deltas and shorefaces to shift seaward, and prior the start of the next relative sea level rise (Catuneanu, 2006; Catuneanu et al., 2011). Identification of the FSST requires the recognition of the underlying discontinuity. Within the study area, the contact between the FSST and the underlying HST deposits is erosional and displays a sharp transition
from bioturbated silty to sandy mudstone of the underlying facies to amalgamated HCS to oscillation rippled sandstone. The sandstones are typically medium to coarse grained. Such a relationship can only be achieved as a result of lowering storm and fairweather wave base in response to a relative sea level fall (i.e., forced regression; cf. Posamentier et al., 1992; Hunt and Tucker, 1992; 1995; Helland-Hansen and Gjelberg, 1994; MacEachern et al., 1999). The contact is corresponds to the regressive surface of marine erosion (RSME). Based on the position of both incised valleys cut during lowstand, and FSST deposits, it is likely that the FSST deposits were fed during sediment bypass by rivers occupying the incised valleys.

The lowstand systems tract (LST) encompasses deposits that accumulated after the maximum rate of relative sea level fall and prior to rapid relative sea level rise. LST units are separated from the underlying FSST by a correlative conformity (CC) (Catuneanu, 2006; Catuneanu et al., 2011). In the study area, the deposits of FSST are overlain by mixed river- and wave-influenced lowstand delta deposits of FA3. Deposits of the LST are commonly finer than those of the FSST, because during a decrease in the rate of sea level fall, the majority of the sediments supplied from the terrestrial realm are trapped within incised valleys (Catuneanu, 2006; Catuneanu et al., 2011). The LST deposits in the study area are capped by the maximum regressive surface (MRS), marking the progradational limit of the sequence. The MRS is overlain by TST deposits (Helland-Hansen and Martinsen, 1996). On well logs, FSST deposits are identified by their sharp lower contact and their low-API values leading to a blocky to serrated gamma-ray response. The contact between FSST and LST is indistinguishable on well logs and therefore requires core data. This is mainly due to the sand contents characterizing the two system tracks. The TST is more readily identified by the sharp transition from coarser- to finer-grained facies and a generally fining-upward profile (Catuneanu, 2006).

### 5.4.3 Transgressive Systems Tract (TST)

The transgressive systems tract includes sediments that accumulated during an overall landward shift of the shoreline as a result of a relative rise in sea level. TST strata are bounded by an underlying major flooding surface (FS) and the downlap surface of
overlying progradational parasequences of a highstand systems tract (HST). Transgressive systems tract deposits within the study area consist of three facies associations: offshore marine deposits (FA1); tidal-fluvial estuarine deposits (FA4); and transgressive bay deposits (FA5). TST successions occur in two main intervals: the lower occurrence overlies HST deposits of the underlying sequence, and the upper occurrence overlies an amalgamated FS/SB.

The base of the TST is indicated by deposits of pervasively bioturbated silty to sandy mudstone of FA1, interpreted as deposition within an offshore marine environment. These deposits sharply overlie proximal facies of the underlying progradational succession and indicate abrupt deepening. FA1, in turn, is commonly overlain by the progradational parasequence set of the overlying HST. The thickness of these deposits, where preserved, ranges from 0.1 to 1 m. Due to the thinness of TST deposits, they are indistinguishable on well logs from the base of the first highstand parasequence.

TST successions are well expressed within the estuarine fill of incised valleys (FA4) that overlie transgressively modified sequence boundaries (see below). The thicknesses of valley-fill deposits vary, and can reach up to 34 m. The basal contact of FA4 is sharp and erosional. The contact represents a lowstand-generated unconformity (sequence unconformity) amalgamated with a tidal ravinement surface (TRS/SU). The valleys served as a zone of sediment bypass during lowstand, so that the discontinuity separates the overlying transgressive systems tract (TST) deposits from the underlying highstand systems tract (HST) deposits. Deposits of FA4 are typically sand-dominated at the base, fining upward into mud-prone strata. These deposits are interpreted as channel and point-bar deposits. One of the important characteristics of these deposits is the increase of bioturbation toward the top of the succession, interpreted to reflect relative rise in sea level and marine transgression. On well logs, these deposits are readily identifiable by their sharp bases, and thick low-API intervals that tend to be blocky or bell-shaped.
FA5 comprises regionally extensive deposits that cap some valley-fill deposits (FA4) and interfluvés, as the coastline retreated landward. FA5 deposits are characterized by thin (4-5 m thick) intervals of coarsening- and shallowing-upward parasequences, representing short-lived progradational events during overall transgression. Coastal progradation during transgression is probably related to a decrease in the rate of relative sea level rise (Van Wagoner et al., 1988) or due to high sediment supply (e.g., Leckie, 1994; Goodbred and Kuehl, 2000). FA5 deposits are identified on well logs by their gamma-ray response, mainly high API values near the base of the succession, becoming blocky with low-API values upward.

5.5 Upper Mannville Stratigraphic Architecture

Core data in the Lloydminster area of west-central Saskatchewan enables sedimentological and ichnologic examination of stratal units and stratigraphic architecture of the Upper Mannville Group (Sparky, Waseca, and McLaren formations). Several key internal surfaces are recognized, and are used to separate the Upper Mannville Group into two discrete sequences separated by a regionally extensive, transgressively modified subaerial unconformity (named, herein, the “Waseca Unconformity”; Fig. 5.9). The interpretations presented in this paper utilize the terminology and concepts presented by Posamentier et al. (1988), Posamentier and Vail (1988), Van Wagoner et al. (1990), Van Wagoner (1995) and Catuneanu et al., 2011. The paleoenvironmental interpretation and stratigraphy of the study interval are also summarized in block diagrams of Figure 5.10.

5.5.1 Lower Sequence

The base of the lower sequence corresponds to the base of the Sparky Formation, and is separated from the underlying General Petroleums (GP) Formation by a sharp contact that is locally overlain by offshore marine mudstones of FA1. This contact is mapped across the study area, and is regarded to represent an allogenically produced marine flooding surface (FS) that marks the termination GP Formation deposition.
Locally, this contact is mantled by lags of small, siderite-cemented clasts and/or gritty, coarse-grained muddy sandstone layers, and is interpreted as a transgressive surface of erosion (TSE; Swift, 1968; Nummedal and Swift, 1987). The thin intervals of FA1 that overlie this surface are interpreted as the transgressive systems tract. A maximum flooding surface (MFS) directly overlies the FA1 deposits, and where FA1 is absent, the MFS coincides with the Sparky - GP boundary (Fig. 5.12).

Above the deposits of FA1 in the lower Sparky Fm, up to three coarsening-upward and shallowing-upward parasequences are identified (Fig. 5.12). Each parasequence is bounded above and below by regionally extensive marine flooding surfaces, interpreted as allogenic in origin. In the central part of the study area (e.g., Golden Lake, Lashburn, and Dee Valley fields), parasequences are pervasively bioturbated and display highly diverse trace-fossil suites. Vertical dwelling structures of inferred suspension-feeding organisms are common. The parasequences are dominated by oscillatory-formed sedimentary structures (e.g., oscillation ripples and HCS), and are interpreted as wave- and storm-dominated shorefaces of FA2. The uppermost parasequence is capped by deposits of coastal plain/delta plain (FA6).

Toward the eastern (Lashburn West and Silverdale Sparky fields) and western (Rush Lake, and EDAM West fields) limits of the study area, coarsening-upward cycles display ichnological and sedimentological characteristics that are associated with deposition and colonization in an environment subjected to physico-chemical stresses. Such characteristics include reduced bioturbation intensities, diminutive ichnogenera, suppression of inferred suspension-feeding behaviours, abundant syneresis cracks, soft-sediment deformation features, normally graded bedsets, and abundant carbonaceous mudstone drapes. The presence of these ichnological and sedimentological features, and the presence of abundant oscillation- and current-generated structures, suggests deposition within mixed river- and wave-influenced deltas (FA3).
**Figure 5.9** Schematic model showing the subdivision of the upper part of the Mannville Group within the Lloydminster area of west-central Saskatchewan. The study interval can be separated into two discrete sequences, separated by a regionally extensive, transgressively modified subaerial unconformity (Waseca Unconformity). The lower sequence consists of the Sparky Formation and Lower Waseca Member. The upper sequence consists of the Upper Waseca Member and McLaren Formation. The cross-section is based on well correlations from both geophysical well logs and cores, and is condensed from Morshedian *et al.*, 2011a,b).
Figure 5.10 Schematic block diagrams reflecting the depositional environments and theoretical relative sea-level curve during the evolution of the upper part of the Mannville Group in the Lloydminster area. A) Regional transgression was followed by north and northwest progradation of FA2 shorefaces and FA3 mixed river-wave deltas during slowly rising to stable relative base-level in Sparky time. The deposits constitute part of a transgressive systems tract and a highstand systems tract. B) The Lower Waseca Member was initiated by a relative base-level rise and regional transgression. A pause in the rate of transgression resulted in progradation of the shoreline toward north-northwest. C) A relative fall in base level was accompanied by development of a subaerial unconformity and the excavation of incised valleys. This resulted in the shifting of the shoreline towards the north and northwest, and the formation of a lowstand systems tract (lowstand delta of FA3) of the Upper Waseca Member. D) A relative rise in sea level resulted in the formation of estuaries and transgressive bay deposits over the subaerial unconformity of the Upper Waseca Member. E) This major transgression was followed by stable relative sea level, which permitted progradation of shorelines and deltas towards north and northwest during McLaren time.
Figure 5.11 Legend for symbols used in core descriptions.
**Figure 5.12** Lithology and gamma-ray geophysical log for Lashburn West 03-20-048-25W3, displaying an overall coarsening- and shallowing-succession within the Sparky Formation. The succession indicates overall progradation, bounded above and below by marine flooding surfaces. Legend to symbols in Fig. 5.11.
Correlation of FA3 deltaic successions indicates that some coarsening-upward cycles are bounded by more localized flooding surfaces that do not correlate to the allogenic flooding surfaces bounding the shoreface successions of FA2 in the central study area. These local flooding surfaces are interpreted to record autogenic lobe switching on the delta, and therefore do not correlate to the mappable allogenic bounding discontinuities that bound the true parasequences within FA2 shoreface complexes. Deltaic deposits (FA3) are also locally truncated by distributary channels of FA4. Distributary channels are primarily filled with IHS deposits, although the basal fill in deeper channels is commonly sandy. Based on our correlations, shoreface parasequences and deltaic lobes prograded towards the north and northwest, where they downlap onto the transgressive offshore marine deposits of FA1 that occurs at the base of the Sparky Fm. Correspondingly, the stratigraphic package is interpreted as a highstand systems tract.\( \text{(e.g., Van Wagoner et al., 1990; Posamentier and Allen, 1999).} \)

Deposits of highstand systems tract (HST) are sharply overlain by thin deposits of bioturbated sandy and silty mudstones with diverse trace-fossil suites. These overlying deposits are interpreted as offshore marine deposits (FA1), and the sharp contact at the base is interpreted to represent an allogenic marine flooding surface (FS). Locally, there is evidence of erosional truncation, and the surface is interpreted as a transgressive surface of erosion (TSE; Fig. 5.13). Consequently, the FA1 sediments deposited following development of the TSE constitute the second transgressive systems tract identified in the lower sequence. FA1 deposits are thin to absent in the southern part of the study area, but towards the north they form thicker deposits (up to 2 m). The maximum flooding surface (MFS) is positioned at the top of the FA1 deposits; where FA1 is absent, the MFS coincides with FS marking Sparky-Waseca contact (Fig. 5.12).

Following the early Waseca Formation transgression and generation of new accommodation space, shoreline progradation was initiated across the study area, producing another HST comprising coarsening-upward proximal offshore/prodelta to upper shoreface/proximal delta-front parasequences (FA2 and FA3). These parasequences dip toward the north to northwest, and gradually pass into offshore marine deposits of FA1. At least five parasequences are recognized, each of which is separated
by a minor discontinuity. Individual parasequences are relatively thin (less than 6 m thick), and commonly interfinger with one another, making correlation of individual cycles virtually impossible. This is exacerbated in FA3 intervals by the presence of autogenic flooding surfaces associated with lobe abandonment. The intercalated character of the FA2 parasequences and FA3 autogenic lobes and parasequences in the Lower Waseca Member is attributed to variations in their proximity to sediment sources, and/or to the localized influx of small fluvial systems into the basin. The inferred embayed coastal profile is unknown. As such, lines of section pass into and out of localized bays, leading to apparent pinchouts of bay-head and bay-margin complexes. The alloogenic marine flooding surfaces capping FA2 cycles correlate across to FA3 cycles, enabling recognition of FA3 parasequences. Distributary channels (FA4) cut into proximal delta-front deposits of FA3 successions locally. These channels are 1 to 3 m thick, and are interpreted as terminal distributary channels (e.g., Olariu and Bhattacharya, 2006). The parasequences of the Lower Waseca Member form an overall progradational parasequence set, which is truncated in turn by the Waseca Unconformity (subaerial unconformity).
Figure 5.13 Core description and gamma-ray geophysical well log for Dell Valley 11-18-048-21W3. The interval contains both transgressive and regressive successions within Waseca and McLaren formations. A subaerial unconformity (SU) divides the Waseca Formation into upper and lower members. This surface separates the underlying highstand systems tract from the overlying transgressive system tracts. Legend to symbols in Fig 5.11.
5.5.2 Waseca Unconformity

A regionally extensive, lowstand-generated unconformity – the Waseca Unconformity – is identified within the Waseca Formation and separates the Lower Waseca Member from the Upper Waseca Member (Figs. 5.13, 5.14). This unconformity is associated with the incision of valleys up to 34 m deep that locally erode through the entire Lower Waseca Member and truncate the upper part of the Sparky Formation (Fig. 5.14A). The locations of these valleys are mainly restricted to the central and eastern parts of the study area and trend north-northwest to south-southeast (e.g., Pikes Peak, Lashburn, EDAM fields). In interfluve areas lying outside of the valley margins, the subaerially exposed surface of the preceding HST corresponds to the unconformity. This is evident by the presence of root-bearing horizons and the development of paleosols (Fig. 5.14B). Based on these criteria, the base and the margins of the incised-valley systems as well as the correlative interfluve areas correspond to the subaerial unconformity (SU). The subaerial unconformity can be traced seaward (north to northwest), and correlates to the regressive surface of marine erosion (RSME) that underlies forced regressive shoreface deposits of the falling stage systems tract (FSST) deposits (see below).
Figure 5.14 A) Trough cross-stratified sandstone interpreted as part of an estuarine incised valley, sharply overlying offshore marine mudstones. The contact is interpreted as an amalgamated subaerial unconformity and tidal ravinement surface (TRS/SU). Offshore mudstones contain Planolites (P), Teichichnus (T), Cylindrical (Cy), Palaeophycus (Pa), Asterosoma (As), Helminthopsis (H), and Phycosiphon (Ph) (09-12-049-24W3; 527 m). B) Pedogenically modified mudstone with root traces (rt) from the interfluve of the incised valley. Mudstone is leached and contains irregular fractures and coalified wood fragments (wd) (well 05-11-049-20W3; 446.5 m).
5.5.3 Upper Sequence

The initial deposition of the upper sequence (Upper Waseca Member and the McLaren Formation) within the study area occurs in the Frenchman Butte field (Townships 053-54; Ranges 25-26 of the 3rd Meridian). In this area, the contact between the Lower and Upper Waseca members is sharp and erosional, and is characterized by pervasively bioturbated silty and sandy marine mudstones of FA1 abruptly overlain by amalgamated oscillation-rippled and HCS-bearing sandstone (Fig. 5.15). Such a facies juxtaposition can only be achieved as a result of the lowering of storm- and fairweather wave base in response to a relative sea level fall. The contact is interpreted as the distal (seaward) expression of the subaerial unconformity within the marine realm (i.e., the regressive surface of submarine erosion or RSME) (Plint, 1988; Hunt and Tucker, 1992, 1995; Plint and Nummedal, 2000). The RSME is overlain by a 1.5-2 m thick sandstone dominated by HCS, oscillation ripples and abundant organic detritus. These deposits are interpreted as part of the falling stage systems tract (FSST) that accumulated during the relative sea level fall. Deposits of the FSST, in turn, are overlain by a 5-6 m thick coarsening- and shallowing-upward succession interpreted to represent a mixed river-and wave-influenced delta complex (FA3; Fig. 5.15). The FA3 deposits in this locale comprise the lowstand systems tract (LST), separated from the underlying FSST deposits by a correlative conformity (CC). . The contact between the LST deposits and the overlying TST deposits represents the maximum regressive surface (MRS) (Helland-Hansen and Martinsen, 1996; Catuneanu, 2006; Catuneanu et al., 2011), reflecting the progradational limits of the shoreline in the sequence. The lowstand delta shows a truncated upper margin, reflecting amalgamation with a transgressive surface of erosion (TSE), and is capped by transgressive bay deposits of FA5.
Figure 5.15 A) Core box photo of well 07-03-054-25W3, displaying the forced regressive and lowstand systems tracts, wherein offshore marine deposits of the underlying highstand systems tract (HST) are erosionally overlain by amalgamated HCS and oscillation rippled shoreface sandstones of the falling stage systems tract (FSST). The FSST is overlain mixed river- and wave-influenced delta deposits of FA3, corresponding to the lowstand systems tract (LST). The FSST and LST are separated by a correlative conformity (CC). Deposits of the LST are capped by the maximum regressive surface (MRS). B) Erosional discontinuity surface characterized by amalgamated hummocky cross-stratified sandstone beds truncating the underlying bioturbated marine mudstone. The contact is interpreted as a regressive surface of marine erosion (RSME). Trace fossils include Planolites (P), Cylindrichnus (Cy), Teichichnus (T), Palaeophycus (Pa), Thalassinoides (Th), Asterosoma (As), Helminthopsis (H), and navichnia (na) (well 07-03-054-25W3; 476.3 m).
Valley-fill deposits have been recognized in the Waseca Formation since the 1980s (e.g., MacEachern, 1984, 1986; Van Hulten, 1984; Dwyer, 1998). These deposits overlie a marine flooding surface amalgamated with the subaerial unconformity. The preservation potential of fluvial deposits within these lowstand-generated valleys is considered to be very low, because during lowstand conditions the valleys act as zones of sediment bypass and lowstand deposits are commonly eroded and reworked by ravinement during subsequent transgression (e.g., Plint et al., 1992; Allen and Posamentier, 1993; MacEachern and Pemberton, 1994; Pemberton and MacEachern, 2005; Catuneanu et al., 2009). The base and margins of the Waseca valleys are interpreted as an amalgamated subaerial unconformity and tidal ravinement surface (TRS/SU). This composite discontinuity is overlain by tidal-fluvial estuarine channel-, in-channel bar-, and IHS point bar-deposits (FA4) (Fig. 5.16). The valleys superficially resemble the distributary channel deposits of FA4, but their scale is close to an order of magnitude thicker, and they are incised through several parasequences. Trace fossil suites within the valleys are characterized by low diversity, and are dominated by diminutive ichnogenera; features consistent with brackish-water conditions (e.g., Beynon et al., 1988; Pemberton and Wightman, 1992; MacEachern and Pemberton, 1994; Gingras et al., 1999; Buatois et al., 2005; MacEachern and Gingras, 2007). This is in contrast to the marine suites that characterize the parasequences into which these valleys are excavated.

Continued transgression and inundation of the study area resulted in the complete infill of the incised valleys and the deposition of transgressive brackish-water bay deposits of FA5. The transgression locally resulted in wave erosion of the tops of the estuarine valley fills as well as paleosols in interfluve positions. In the interfluve areas, paleosols followed by marine transgression are noted by the presence of firmground Skolithos, Thalassinoides, and Arenicolites of the Glossifungites Ichnofacies (Fig. 5.17). This indicates that the substrate was compacted and dewatered prior to marine flooding (Pemberton and Frey, 1985; MacEachern et al., 1992; MacEachern et al., 2007b).
Figure 5.16 Core descriptions and gamma-ray well log through the incised valley fill of well 09-12-049-24W3. The succession is interpreted to record a tidal-fluvial estuary erosionally overlying offshore marine mudstones across an amalgamated subaerial unconformity and tidal ravinement surface (TRS/SU). Legend to symbols in Fig 5.11.
This discontinuity shows little erosional relief and corresponds to a transgressively modified subaerial unconformity (WRS/SU) (e.g., MacEachern et al., 1999; MacEachern and Burton, 2000; Catuneanu, 2006). Transgressive bay deposits are characterized by thin (4 to 5 m) intervals of coarsening- and shallowing-upward parasequences (FA5), representing small-scale progradational events during an overall transgression. These deposits are sharply overlain by thin deposits of bioturbated sandy and silty mudstones with marine trace-fossil suites, interpreted to reflect offshore marine conditions (FA1). The contact is interpreted as a marine flooding surface (FS), and defines the boundary between the Upper Waseca Member and the McLaren Formation. Locally, this contact is erosional and corresponds to a transgressive surface of erosion (TSE). The transition from estuarine through brackish-water bay to offshore marine mudstones is consistent with a retrogradational parasequence set, marking the development of a transgressive systems tract during Upper Waseca Member and early McLaren Formation time. The maximum flooding surface (MFS) overlies the FA1 deposits in the lower McLaren Fm. Where FA1 is absent, the MFS is interpreted to coincide with Upper Waseca Member and McLaren boundary (Fig. 5.13).

The McLaren Formation in the study area consists of two to three coarsening-upward and shallowing-upward parasequences, reflecting wave- and storm-dominated shorefaces (FA2) that interfinger laterally with mixed river- and wave-influenced deltas (FA3). The uppermost parasequence locally is capped by coastal plain/delta plain deposits of FA6. The parasequences are 4-6 m thick, and are arranged in a progradational parasequence set. They terminate northward and north-westward as they downlap onto offshore marine mudstones of FA1. Along-strike correlation of FA2 and FA3 shows a greater number of coarsening-upward cycles in areas of FA3 deltaic successions, reflecting the presence of flooding surfaces generated by autogenic lobe abandonment. The marine flooding surfaces bounding FA2 coarsening-upward cycles, by contrast, are areally extensive and are considered allogenic, delineating true parasequences. The progradational parasequence-stacking pattern in the McLaren Formation is consistent with a highstand systems tract. This period of progradation was terminated by an abrupt deepening, and based on regional correlation corresponds to a marine flooding surface (FS). This FS marks the contact between the McLaren Formation and Colony Formation.
Figure 5.17 Underlying deposits of the Lower Waseca Member have been pedogenically modified by development of a subaerial unconformity and subsequently truncated by a wave ravinement surface (WRS/SU). The contact is associated with an interfluve area and is correlative with the base and margins of the incised valleys. The discontinuity is marked by firmground *Thalassinoides* and *Skolithos* of the *Glossifungites* Ichnofacies and is overlain by bioturbated mudstones of Facies 1b. *Planolites* (P), *Cylindrichnus* (Cy), *Teichichnus* (T), *Chondrites* (Ch), *Palaeophycus* (Pa), and *Thalassinoides* (Th) are indicative of the brackish-water conditions that prevailed during initial transgression (well 10-12-048-20W3; 427.8 m).
5.6 Conclusion

Stratigraphic relationships of six facies associations recognized in the upper part of the Mannville Group of the Lloydfminster area, Saskatchewan record a number of changes in relative sea level. These facies associations represent deposits of offshore marine environments, wave- and storm-dominated shorefaces, mixed river- and wave-influenced deltas, distributary channels and tidal-fluvial estuaries, transgressive bays, and coastal plain/delta plain settings.

Regionally extensive marine flooding surfaces (FS) mark the bases of the Sparky, Waseca, and McLaren formations. A subaerial unconformity within the Waseca Formation (the Waseca Unconformity), reflecting a major relative sea level fall, and permits subdivision of the formation into lower and upper members. The surface is sharp and erosional, and corresponds to a number of deeply incised (up to 34m) valleys. The subaerial unconformity extends regionally into interfluve areas, where it is manifest as a root-bearing horizon with incipient paleosol development directly below the surface. The subaerial unconformity also correlates towards the north and northwest into a regressive surface of marine erosion (RSME), overlain by deposits of the falling stage systems tract. Correspondingly, the deposits of two discrete sequences can be delineated within the study interval, separated by this subaerial unconformity. The falling stage systems tract is overlain by a lowstand delta complex, separated by a correlative conformity.

Transgressive systems tract deposits within the lower sequence are interpreted to be thin or absent and typically underlie HST deposits. Where the TST is absent, the maximum flooding surface (MFS) coincides with the basal marine flooding surface (FS) of the HST. The main deposits of the lower sequence comprise two highstand systems tracts, corresponding to the Sparky Formation and the Lower Waseca Member.

The upper sequence overlies the Waseca Unconformity, and comprises the Upper Waseca Member and the McLaren Formation. Subaerial exposure and erosion during development of the Waseca Unconformity led to the incision of valleys up to 34 m deep that locally removed the entire Lower Waseca Member, and deposited falling stage and
lowstand deltas seaward of the uppermost parasequence of the underlying highstand systems tract. Ensuing transgression in the Upper Waseca Member resulted in the accumulation of a 5 to 35 m thick succession of strata, interpreted as a transgressive systems tract. Initial transgression resulted in backstepping of the shoreline from the lowstand delta, and led to the tidal-fluvial estuarine infill of the incised valleys. Continued transgression across the study area led to palimpsest marine colonization of the subaerial unconformity in interfluve areas, producing firmground trace-fossil suites attributable to the *Glossifungites* Ichnofacies. The valley and interfluve areas were ultimately capped by transgressive bay deposits that form a retrogradational parasequence set. A maximum flooding surface (MFS) separates the transgressive systems tract of the Upper Waseca Member from the overlying progradational parasequence set of a highstand systems tract that corresponds to the McLaren Formation.
5.7 References


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CHAPTER 6: SUMMARY AND CONCLUSION

This thesis shows the value of integrating sedimentology, ichnology, and sequence stratigraphy in the analysis of the Upper Mannville Group (Sparky, Waseca, and McLaren alloformations) in Lloydminster area of west-central Saskatchewan. The dataset was used to provide a detailed facies analysis of the depositional units of each alloformation, identify and map the recurring facies associations, interpret the depositional environments and construct a model that includes the evaluation of along-strike changes in depositional character. The study also provides criteria for identifying key stratigraphic discontinuities and proposes a sequence stratigraphic framework for the studied interval.

The main concept presented within this thesis is the importance of understanding the application of ichnology to paleoenvironmental interpretations. Although previous case studies have demonstrated that tracemaking organisms are extremely sensitive to their environmental conditions, it was unclear whether discrimination between shoreface, delta and estuarine complexes could be reliably achieved in basins that were generally brackish. This study demonstrates that integrating ichnology with sedimentology allows the deposits of these settings to be differentiated. Deltaic deposits are typically characterized by high sedimentation rates, reflected by abundant soft-sediment deformation features, hyperpycnal sediment-gravity flows associated with flood discharge through the distributary channels, and the presence of dark fissile mud drapes associated with hypopycnal-induced buoyant mud plumes and concomitant rapid flocculation of clay. Deltaic environments are also subject rapid fluctuations in salinity mainly due to variations in river discharge. Salinity fluctuations are indicated by sporadically distributed syneresis cracks. Such environmental stresses commonly result in organisms changing their feeding strategies, which in turn lead to trace fossil suites that depart from archetypal expressions of the Seilacherian ichnofacies.
Detailed analysis of trace fossil suites can also provide valuable information about the salinity of the depositional environment and to differentiate brackish-water environments (e.g., bays, and estuarine) from fully marine environments. Ichnological suites within brackish-water settings are inherently variable, as a consequence of temporal and geographic variations, salinity gradient, magnitude of salinity fluctuations, presence and/or duration of subaerial exposure, sedimentation rates, water turbidity, oxygen content, fluctuations in hydrodynamic energy, and nature of the colonized substrate. Trace-fossil suites within brackish-water environments are characterized by reduction in the number and diversities, overall diminutive traces, abundance of trophic generalists which leads to domination by facies-crossing ichnogenera (e.g., *Planolites*, *Cylindrichnus*, *Teichichnus*), and vertical and horizontal ichnofossils that are common to both *Skolithos* and *Cruziana* Ichnofacies.

The concept of allostratigraphy allows subdivision of the study interval based on the recognition of their bounding discontinuities. Most of these stratigraphic breaks within the Upper Mannville Group correspond to relative base-level rises that separate periods of progradation. Hence, the bulk of the studied interval consists of a complex series of paralic parasequences. These parasequences are bounded by flooding surfaces and can be separated into those that are allogenic and those that are autogenic in origin. Autogenic flooding surfaces typically correspond to channel avulsion and deltaic lobe switching associated with localized increases in sedimentation relative to the adjacent settings. These surfaces are confined to deltaic units of FA3, but are largely indistinguishable from those that are generated allogenically. Regional correlation, however, reveals that these autogenic flooding surfaces do not correlate into the adjacent shoreface complexes of FA2.

The other contribution of this research is the identification of forced regressive delta deposits by correlating the subaerial unconformity in a paleoseaward direction. The depositional complex could be separated into the falling stage systems tract (FSST), overlying a regressive surface of marine erosion (RSME) and the overlying and seaward stepping lowstand systems tract (LST), overlying the correlative conformity (CC). Based on these studies, a number of key conclusions can be drawn.
The Upper Mannville Group (Sparky, Waseca, and McLaren formations), within the Lloydminster area consists of a complex succession of marine and marginal-marine deposits. The succession is subdivided into thirteen depositional facies, based on the integration of the sedimentological and ichnological characteristics observed in 127 cored intervals. The facies are grouped into six facies associations: open marine offshore settings (FA1); wave- and storm-dominated shorefaces (FA2); mixed river- and wave-influenced deltas (FA3); distributary and tidal-fluvial estuarine channels (including incised valley fills) (FA4); transgressive bays (FA5); and coastal plain/delta plains (FA6).

Facies Association 1 (FA1) consists of thoroughly and uniformly bioturbated sandy/silty mudstone with intercalated thin tempestites. The facies contains a diverse trace-fossil suite consistent with the *Cruziana* Ichnofacies. The association represents deposition within an offshore marine environment.

Facies Association 2 (FA2) represents progradation from proximal offshore to upper shoreface environments, and is characterized by coarsening-upward, sand-dominated successions deposited under strong wave influence. FA2 commonly displays high trace-fossil diversities, and common vertical structures of inferred suspension/filter feeding organisms. Burrowed zones are sporadically distributed reflecting episodic deposition associated with storms. The succession represents progradation of proximal offshore through to upper shoreface deposits.

Facies Association 3 (FA3) comprises coarsening-upward successions that record progradation of the shoreline from distal prodelta through to the proximal delta front in a mixed river- and wave-influenced delta complex. Riverine input is recorded by the presence of localized syneresis cracks, soft-sediment deformation features, carbonaceous mudstone drapes, reduced bioturbation intensities, a paucity of biogenic structures indicative of suspension-feeding activities, and the presence of distributary channels cutting into delta-front deposits.

Facies Association 4 (FA4) consists of fining-upward successions dominated by current-generated structures deposited during the lateral migration and/or abandonment of channels. The association corresponds variably to distributary channels or tidal-fluvial...
estuary deposits of incised valley fills, depending upon their stratigraphic context. Ichnological evaluation of FA4 successions indicates that they contain low-diversity suites characterized by small numbers of diminutive, facies-crossing ichnogenera, consistent with the brackish-water trace fossil model.

Facies Association 5 (FA5) is defined by coarsening-upward successions representing progradation of the shoreline within sheltered bays during an overall transgression. Deposits of FA5 are broadly similar to FA2 sedimentologically, but yield lower diversity ichnological suites of mainly facies-crossing elements. In addition, the thickness of Facies 4a units within FA5 is considerably thinner than those of FA2, which is attributable to deposition in a more sheltered setting.

Facies Association 6 (FA6) comprises fining-upward to heterolithic deposits that cap the progradational successions of FA2 and FA3. Intervals are characterized by trough cross-bedded sandstone with abundant organic detritus and associated rootlets, paleosols, and carbonaceous mudstone and coal. The association represents deposition within coastal plain or delta plain settings, depending upon whether they overlie FA2 or FA3, respectively.

Characterization of the facies associations and their mapped distributions allows recognition of stratigraphic discontinuities, and forms the basis for proposing an allostratigraphic framework for the Upper Mannville Group.

Regionally extensive marine flooding surfaces mark the base of the Sparky, Waseca and McLaren alloformations. Additionally, the Waseca Alloformation can be subdivided into lower and upper allomembers, based on the presence of a widespread subaerial unconformity (herein called the Waseca Unconformity).

The Sparky Alloformation is bounded above and below by regionally extensive, allogenically induced marine flooding surfaces, which record landward displacement of offshore marine/distal prodelta deposits over the more proximal facies of underlying successions. The Sparky Alloformation’s internal stratigraphy consists of three coarsening-upward progradational parasequences, which are locally punctuated by minor
transgressive events. Deltaic influences occur in the eastern and western parts of the study area and contain associated distributary channels. Deltaic successions within the Sparky Alloformation also contain localized parasequences that display limited lateral continuity, and are attributed to autogenic controls (e.g., delta lobe abandonment). Environmental stresses (e.g., low salinity) are less pronounced toward the central part of the study area, and correspond to mapped areas of FA2, reflecting deposition within wave-/storm-dominated shorefaces. The flooding surfaces separating FA2 shoreface parasequences are considered allogenically induced. These allogenic flooding surfaces allowed subdivision of the Sparky Alloformation into Lower, Middle, and Upper allomembers. The Upper Sparky Allomember commonly contains coastal plain / delta-plain deposits (FA6). These Sparky allomembers display progradational geometries and grade seaward (northward) into offshore marine deposits of FA1, defining a highstand systems tract (HST).

The Waseca Alloformation is separated from the Sparky and McLaren alloformations by regionally extensive marine flooding surfaces. In addition, several deep valleys occur within the Waseca succession and indicate the presence of a subaerial unconformity (SU). This unconformity surface marks the boundary between the Lower and Upper Waseca allomembers. The Lower Waseca Allomember consists of up to five coarsening-upward parasequences, reflecting the progradation of wave-/storm-dominated shorefaces and mixed river- and wave-influenced deltas that prograded toward the north and northwest. Shoreface and delta deposits gradually pass into offshore marine deposits towards the N-NW. Parasequences associated with the Lower Waseca Allomember are relatively thin (less than 7m) and commonly interfinger with one another. This suggests variations in their proximity to sediment sources and/or to the localized influx of small fluvial systems into the basin. Distributary channels (FA4) are associated with deltaic deposits (FA3) and cut into the proximal delta fronts. They are generally thin (1-3 m) and are interpreted as terminal distributary channels. The uppermost parasequence, where it is not truncated by the Waseca Unconformity, is capped by coastal plain/delta plain deposits (FA6).
The Waseca Unconformity is associated with the incision of valleys up to 34 m deep that locally erode through the entire Lower Waseca Allomember and the upper part of the Sparky Alloformation. In such localities, theUpper Waseca Allomember sits unconformably on the Sparky Alloformation. Within the interfluve areas, the Waseca Unconformity is marked by a root-bearing horizon and the development of paleosols.

The earliest deposits of the Upper Waseca Allomember are located at least 20 km north of the underlying highstand progradational limit, and are characterized by medium- to coarse-grained sandstones that display abundant oscillatory-generated structures. These deposits are interpreted as forced regressive shoreline deposits of the falling stage systems tract (FSST), and are separated from the underlying Lower Waseca Allomember by a regressive surface of marine erosion (RSME). The FSST deposits are in turn overlain by finer-grained deposits of FA3, which are interpreted as the lowstand systems tract (LST), and are separated from the FSST by a correlative conformity (CC). This surface marks the end of sea-level fall and the onset of initial sea-level rise. The contact between the LST deposits and the overlying unit is interpreted as the maximum regressive surface (MRS), and marks the limit of progradation of the sequence.

During falling stage and valley incision, Upper Waseca incised valleys operated as zones of sediment bypass. Valley infill was associated with ensuing base-level rise, and brackish-water estuary deposits directly overlie the valley surface. In such locations, the valley floor corresponds to an amalgamated subaerial unconformity and tidal ravinement surface (TRS/SU). These deposits consist of tidal-fluvial estuarine channel sandstones as well as point bar and interchannel bar heterolithic deposits, including inclined heterolithic stratification (IHS; FA4). Following valley infill, continued transgression resulted in the inundation of the study area by a shallow, brackish-water bay (FA5). Locally within the interfluve area, the transgression led to erosion and development of a wave ravinement surface amalgamated with subaerial unconformity (WRS/SU). This is marked by omission trace fossil suites along the transgressively modified subaerial unconformity. This colonization corresponds to firmground trace-fossil suites attributable to the *Glossifungites* Ichnofacies.
The McLaren Alloformation erodionally overlies the Upper Waseca Allomember as a result of regional transgression. In turn, it is separated from the Colony Alloformation by a regional discontinuity surface. Deposits of the McLaren Alloformation are broadly similar to those of the Lower Waseca Allomember, and are characterized by two to three parasequences of wave-/storm-dominated shorefaces (FA2) and mixed river- and wave-influenced deltas (FA3). These parasequences display progradational architectures and terminate toward the N-NW, where they downlap onto pervasively bioturbated offshore mudstone of FA1, consistent with a highstand systems tract (HST). Deep valleys that cut into the McLaren Alloformation subtend from the Joli Fou unconformity, and record lowstand incision at the top of the Mannville Group prior to the Joli Fou transgression.

From a sequence stratigraphic perspective, the Sparky Alloformation, the Lower Waseca Allomember and the McLaren Alloformation comprise overall progradational parasequence sets corresponding to highstand systems tracts. The unconformity within the Waseca Alloformation marks a major relative sea level fall. Correspondingly, the deposits of two sequences can be delineated within the study interval. The lower sequence encompasses the highstand systems tract of the Sparky Alloformation and the Lower Waseca Allomember, which are separated by a regional transgressive surface. The upper sequence comprises lowstand and transgressive systems tract deposits of the Upper Waseca Allomember, and highstand systems tract parasequences of the McLaren Alloformation. The contact between Upper Waseca Allomember and McLaren Alloformation corresponds to the maximum flooding surface.
APPENDICES

Appendix A

List of the Logged Upper Mannville (Sparky, Waseca, and McLaren formations) cores.

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<td>Waseca-McLaren</td>
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2851.31 m
Appendix B:

CD-ROM DATA OF LITHOLOGS AND CROSS SECTIONS

The CD-ROM attached contains PDF files of lithologs for 127 cored intervals that were logged and 6 constructed cross-sections as a part of this study. The PDF file was created with Adobe Acrobat, but may be opened in any PDF program.