Stratigraphic Framework for the Lower Cretaceous Upper Mannville Group (Sparky, Waseca, and McLaren Alloformations) in the Lloydminster Area, West-central Saskatchewan

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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. A sequence stratigraphic evaluation of the upper part of the Mannville Group is presented, based on the vertical and lateral distributions of facies associations and the presence of stratigraphic discontinuities. Thirteen facies are recognized. These facies are grouped into six spatially recurring facies associations. Facies Association 1 consists of a single facies, pervasively bioturbated silty/sandy mudstone. The facies contains marine trace fossil suites and is interpreted to record sediment accumulation in an open marine (offshore) environment. Wave-/storm-dominated shoreface deposits of Facies Association 2 (FA2) display sporadically distributed, but locally high bioturbation intensities. Units consist mainly of well-sorted, erosionally amalgamated hummocky cross-stratification and swaley cross-stratification sandstones with intervening bioturbated sandstone layers, passing into cross-stratified and planar-stratified sandstones. Facies Association 3 (FA3) corresponds to deltaic successions that lie laterally adjacent (along the same paleo-shoreline) to the wave-/storm-dominated shoreface deposits of FA2. The deltaic successions of FA3 exhibit lower bioturbation intensities and are generally thicker than along-strike shoreface counterparts of FA2. FA3 successions are characterized by heterolithic intervals passing upwards into massive (apparently structureless) sandstones. Evidence of riverine input is present in the form of abundant dark (organic-rich) mudstone drapes, low bioturbation intensities, soft-sediment deformation features, and syneresis cracks. These deltaic deposits were fed by associated distributary channels. Facies Association 4 (FA4) consists mainly of channel and point-bar deposits, dominated by thick trough cross-bedded sandstones passing upward into current-rippled sandstones. Point-bar deposits are commonly heterolithic and inclined and are interpreted to be tidally influenced inclined heterolithic stratification. FA4 successions variably correspond to distributary channels or tidal-fluvial estuary deposits of incised valley fills, depending upon their stratigraphic context. Deposits of Facies Association 5 (FA5) are broadly sedimentologically similar to FA3, but differ ichnologically. FA5 deposits generally display low diversity trace fossil suites, and a dominance of simple burrows produced by inferred trophic generalists. FA5 is interpreted to record sedimentation within a brackish-water bay. Complete depositional cycles are capped by coastal plain/delta plain deposits of Facies Association 6 (FA6). Deposits within FA6 are characterized by coals, organic-rich sediments and root-bearing paleosols that comprise fining-upward successions.

The stratigraphic architecture of the Upper Mannville indicates sediment deposition in an overall transgressive period, punctuated by highstand progradation and short-lived periods of base-level fall. The stratigraphic succession comprises parts of two depositional sequences. The lower sequence includes the Sparky alloformation and the lower part of the Waseca alloformation (Lower Waseca allomember), which reflects a highstand systems tract followed by a transgressive systems tract. Following the Lower Waseca allomember, a relative base-level fall produced a lowstand disconformity, overlain by lowstand to early transgressive systems tract accumulation confined to lowstand deltas and incised valleys of the Upper Waseca allomember. The Upper Waseca allomember is separated from the McLaren alloformation by a maximum flooding surface. The McLaren represents a return to regional shoreline progradation of a highstand systems tract.

Keywords: *Lower Cretaceous, Lloydminster, Mannville Group, brackish water, ichnology.*

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1. Introduction

The Lower Cretaceous Mannville Group has been the subject of study since the early 1940s, and was first drilled in 1942 in the Vermilion area of east-central Alberta (Nauss, 1945). The succession is considered as one of the most important hydrocarbon-bearing strata in Canada (Pemberton and James, 1997). The Mannville Group unconformably overlies Paleozoic to Jurassic-Cretaceous strata, and is disconformably overlain by the transgressive Joli Fou Formation marine shales of the Colorado Group (Figure 1). In the Lloydminster area, heavy oil reservoirs are estimated to contain approximately three billion m³ (19 billion barrels) of oil in place (Saskatchewan Energy and Resources, 2008). Owing to the high economic value of these depositional units, the interval has attracted considerable attention from both academia and the petroleum industry.

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 Petroleums, Rex, Lloydminster, Cummings, and Dina, although no formal type sections have been established to formalize this nomenclature. The informal Mannville Group 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 assigned formation status, a hierarchal level that is most commonly assigned to these units by present-day workers.

2. Study Area and Methodology

The study area for this project extends from Township 48 to 54, and lies between Ranges 19 and 28 west of the 3rd Meridian, comprising a total area of 5400 km^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 totalling approximately 2850 m. The cored wells penetrate a number of major hydrocarbon fields in west-central Saskatchewan (*e.g.,* Golden Lake, Lloydminster, Lashburn, Pikes Peak, and Cold Lake). The well locations employed in this study are shown in Figure 2.

The cored intervals were evaluated with respect to their trace fossils, sedimentary structures, lithological features, and stratigraphic discontinuities. Recurring spatially distributed successions (facies associations) have been assigned depositional interpretations. Ichnological appraisal includes trace fossil identification, assessments of trace fossil sizes, bioturbation intensities, distributions of burrowing, and ethological interpretations. In addition, more than 700 geophysical well logs have been employed for stratigraphic evaluation of the interval, in order to provide correlations between cored wells.

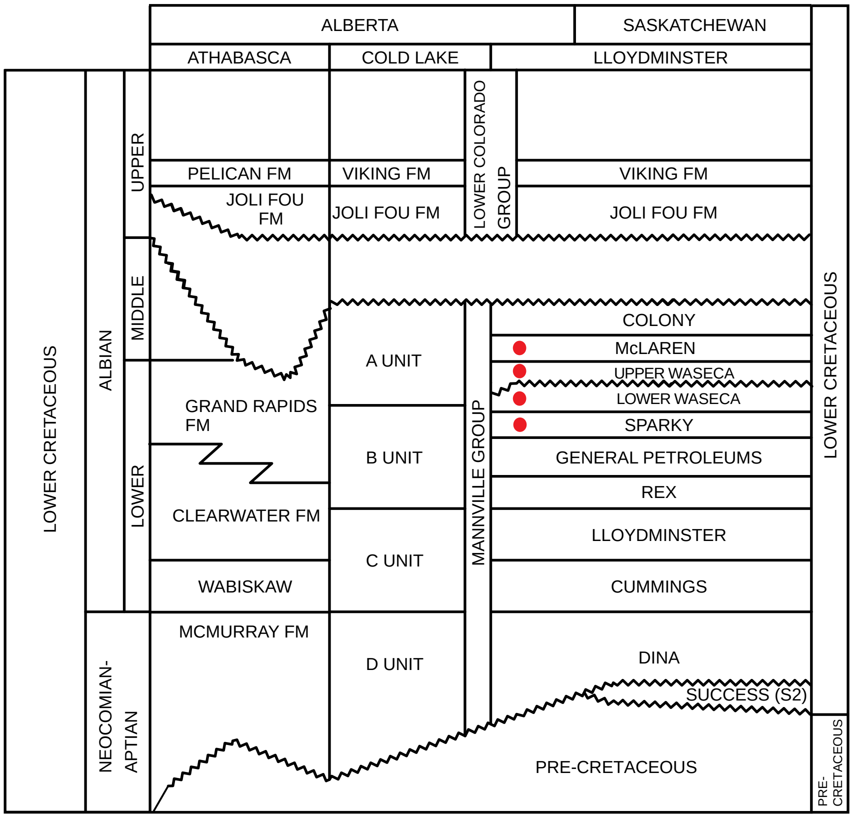

Figure 1 – Correlation of Lower Cretaceous strata in the Athabasca, Cold Lake, and Lloydminster areas in eastern Alberta and western Saskatchewan (modified after Christopher, 2003); red dots indicate the study interval. In this study, an unconformity has been defined within the Waseca and therefore this unit in divided into an upper and lower unit in the Lloydminster area.

3. Facies Analysis

Based on ichnological and sedimentological criteria, and the spatial distributions of the units, thirteen recurring facies have been identified from the Sparky, Waseca, and McLaren

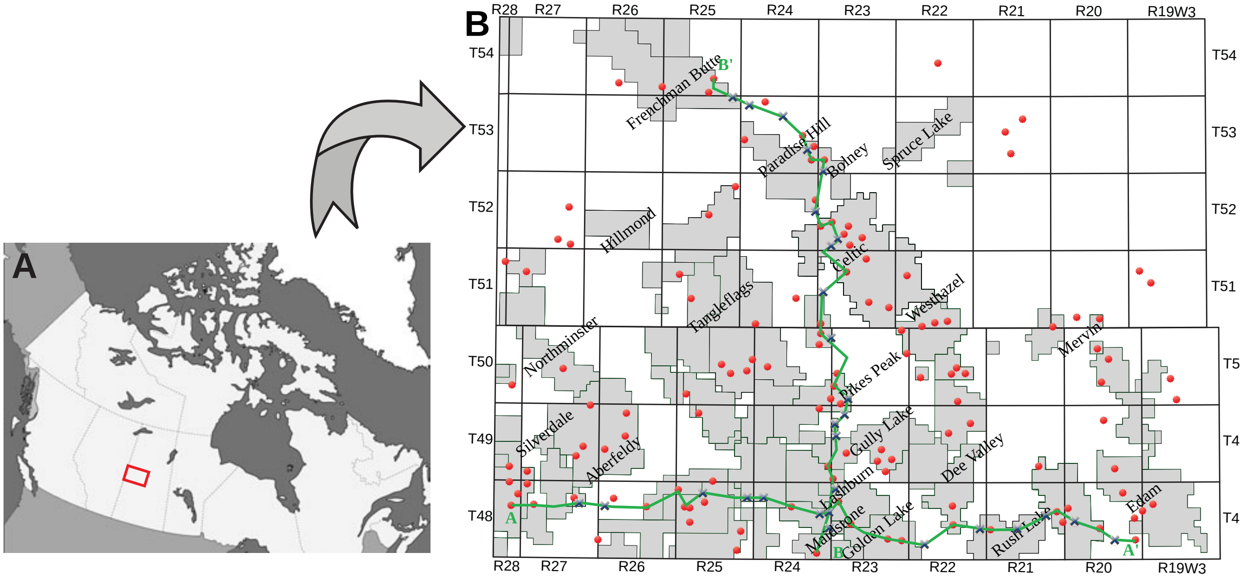

Figure 2 - Location of the study area: A) map of Canada showing the location of the study area; and B) detailed map of the study area with locations of logged core (red dots). Grey areas are oil fields. Also shown are the locations of cross-sections A–A' and B–B' (Figures 9 and 10).

formations (F1 to F13). These facies can be combined into six facies associations (Table 1), corresponding to: 1) open marine offshore settings; 2) wave- and storm-dominated shorefaces ; 3) mixed river- and wave-influenced deltas; 4) distributary channels and tidal-fluvial estuarine; 5) transgressive bays; and 6) coastal plain/delta plain. Discrimination between these broadly similar depositional facies successions requires the full integration of ichnological and sedimentological criteria.

a) Facies Association 1: Offshore Marine Deposits

Facies Association 1 (FA1) consists of only Facies 1a, a thoroughly bioturbated silty/sandy mudstone (Figure 3). The association records the most marine conditions within the study area. Intervals are characterized by high bioturbation intensities (BI 3 to 5) in mudstones interbedded with sandstones that are less bioturbated. Sandstone beds are interpreted as thin tempestites (storm deposits). Stratigraphically upwards, the abundance of tempestites increases and the relative degree of bioturbation decreases. Locally, sandstone intervals are oil stained, making the identification of physical and biogenic structures challenging. Ichnogenera are commonly robust and diverse. Trace fossils include *Planolites*, *Skolithos*, *Cylindrichnus*, *Palaeophycus*, *Teichichnus*, *Piscichnus*, *Thalassinoides*, *Helminthopsis*, *Phycosiphon*, *Chondrites*, *Asterosoma*, and fugichnia.

The pervasively bioturbated mudstones within FA1 suggest slow accumulation of fine-grained sediment in a low-energy setting, below fair-weather wave base, but above storm wave base. Trace fossil assemblages 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.

b) Facies Association 2: Wave- and Storm-dominated Shoreface Deposits

Facies Association 2 (FA2) displays less evidence of overall physico-chemical stress and, correspondingly, displays higher bioturbation intensities and ichnological diversities than do those of the Facies Association 3 (interpreted as deltaic successions). Bedding contacts range from pervasively bioturbated to sharp, where sharp contacts are more typical towards the top of the succession. Bioturbation intensities are highly variable, ranging from BI 0 to 5. Trace fossils include *Planolites*, *Cylindrichnus*, *Skolithos*, *Teichichnus*, *Palaeophycus*, *Thalassinoides*, *Rosselia*, *Chondrites*, *Asterosoma*, *Gyrolithes*, *Phycosiphon*, *Helminthopsis*, *Scolicia*, navichnia, and fugichnia. The setting is characterized by wave- and combined flow-generated structures, as well as normally graded mud drapes, with zones of small-scale soft-sediment deformation.

FA2 is interpreted to represent an overall progradational succession from distal lower shoreface to the upper shoreface (Figure 4). The abundance of wave- and storm-generated structures represents subaqueous deposition subjected to heightened basinal processes (*i.e.*, bigger waves). The high diversity of trace fossils indicates that environmental conditions where favourable for marine benthic communities consisting of both suspension- and

Table 1 – Summary of six facies associations, and characteristics and interpretation of each facies.

Facies Association	Facies No.	Facies	Sedimentology	Trace Fossil Suite	Bioturbation Intensity	Depositional Environment
1) Offshore marine deposits	1a	Bioturbated silty/sandy mudstone with diverse trace fossil assemblages	Thoroughly bioturbated, locally micro-hummocky cross-stratification.	*Planolites, Skolithos, Cylindrichnus, Palaeophycus, Thalassinoides, Teichichnus, Chondrites, Asterosoma, Phycosiphon, Helminthopsis, Rosselia, Scolicia, Piscichnus,* "Terebellina", and fugichnia.	3 to 5	Offshore marine deposits
2) Wave- and storm-dominated shoreface deposits	6	Trough cross-bedded to tabular cross-bedded sandstone	Cross-bedded sandstone with locally low-angle planar stratified and current-ripple sandstones.	*Cylindrichnus, Planolites,* and fugichnia.	0 to 2	Upper shoreface
	4a	Oscillation-rippled to hummocky cross-stratified sandstone	Hummocky cross-stratification, swaley cross-stratification, wave ripples, locally mudstone drapes.	*Skolithos, Planolites, Cylindrichnus,* fugichnia, and navichnia.	0 to 2	Lower to middle shoreface
	3a	Bioturbated mudstone interbedded with sandstone	Mudstone interbedded with oscillation-rippled sandstone, locally micro-hummocky cross-stratification.	*Cylindrichnus, Skolithos, Gyrolithes, Planolites, Chondrites, Teichichnus, Thalassinoides, Asterosoma,* navichnia, and fugichnia.	2 to 5	Proximal offshore
	Thin bed of 1a	Bioturbated silty/sandy mudstone with diverse trace fossil assemblages	Thoroughly bioturbated, locally micro-hummocky cross-stratification.	*Planolites, Skolithos, Cylindrichnus, Palaeophycus, Teichichnus, Chondrites, Asterosoma, Phycosiphon, Helminthopsis, Rosselia, Scolicia, Piscichnus, "Terebellina",* and fugichnia	3 to 5	Offshore marine deposits
3) Mixed river- and wave-influenced delta deposits	4b	Oscillation-rippled sandstone interbedded with current-rippled sandstone	Wave-ripple, combined flow ripple, and current ripple. Locally, small-scale trough cross-bedding, abundant organic detritus.	*Cylindrichnus, Planolites, Skolithos,* and fugichnia	0 to 1	Proximal delta front
	4a	Oscillation-rippled to hummocky cross-stratified sandstone	Wave-ripple, and hummocky cross-stratification, locally mudstone drapes.	*Skolithos, Planolites, Cylindrichnus,* fugichnia, and navichnia.	0 to 2	Delta front
	3b	Sporadically bioturbated mudstone interbedded with sandstone	Wavy to lenticular-bedded mudstone, interbedded with oscillation-rippled sandstone, micro-hummocky cross-stratification. Local combined flow ripples, syneresis cracks, and gutter casts.	*Planolites, Skolithos, Palaeophycus, Gyrolithes, Thalassinoides, Arenicolites, Teichichnus, Chondrites, Asterosoma, Rosselia,* fugichnia, and navichnia.	0 to 3	Proximal prodelta to distal delta front
	2	Pinstripe to lenticular-bedded mudstone	Oscillation ripples, with sharp contacts, locally convolute beddings, current ripples, and syneresis cracks.	*Planolites, Cylindrichnus, Teichichnus, Chondrites, Phycosiphon, Helminthopsis, Rhizocorallium,* fugichnia, and navichnia.	0 to 3	Distal to proximal prodelta
	Thin bed of 1a	Bioturbated silty/sandy mudstone with diverse trace fossil assemblages	Thoroughly bioturbated, locally micro-hummocky cross-stratification.	*Planolites, Skolithos, Cylindrichnus, Palaeophycus, Teichichnus, Chondrites, Asterosoma, Phycosiphon, Helminthopsis, Rosselia, Scolicia, Piscichnus,* "Terebellina", and fugichnia.	3 to 5	Offshore marine deposits
4) Distributary channels and tidal-fluvial estuary deposits	1c	Alternation of dense mudstone with bioturbated mudstone	Soft-sediment deformation, locally current ripples and wave ripples.	*Planolites, Cylindrichnus, Teichichnus, Palaeophycus, Gyrolithes, Thalassinoides,* and navichnia.	1 to 5	Abandoned channel complex
	1d	Dense mudstone interlaminated with siltstone/sandstone	Millimetre- to centimetre-scale silt/sand interlaminae, current ripple, abundant soft-sediment deformation.	*Planolites, Cylindrichnus, Teichichnus* , and navichnia.	0 to 2	Turbidity maximum zone
	8	Inclined heterolithic stratification	Heterolithic mudstone and sandstone, sharp contacts, sandstone beds display small-scale trough cross-bedding, and current-ripple lamination. Organic detritus, fluid mud. Rare oscillation ripples.	*Planolites, Skolithos, Cylindrichnus, Gyrolithes, Teichichnus, Thalassinoides, Palaeophycus, Chondrites,* fugichnia, and navichnia.	0 to 5	Lateral accretion bedding
	7	Current-rippled laminated sandstone	Locally display aggradational and combined flow ripples and rarely oscillation ripples.	*Skolithos, Cylindrichnus, Planolites,* and fugichnia.	0 to 2	Channel bar complex
	6	Trough cross-bedded to tabular cross-bedded sandstone	Cross-bedded sandstone with locally low-angle planar stratified and current-ripple sandstones.	*Cylindrichnus, Planolites,* and fugichnia.	0 to 1	Migrating dunes in channels
	5	Mud-clast breccia	Poorly sorted sandstone, predominantly angular mud clasts. Commonly interbedded with trough cross-bedded sandstone.	No trace fossils identified.	0	Channel-bank collapse, erosional truncation
5) Transgressive bay deposits	10	Bioturbated massive to lenticular-bedded mudstone	Rarely preserved sedimentary structures, locally starved ripples, planar bedding, organic detritus.	*Gyrolithes, Skolithos,* and *Planolites.*	3 to 5	Muddy tidal flat
	4a	Oscillation-ripple to hummocky cross-stratified sandstone	Oscillatory ripple, low-angle undulatory parallel lamination, minor micro-hummocky cross-stratification.	*Planolites, Cylindrichnus,* and *Gyrolithes.*	0 to 2	Proximal bay margin
	9	Bioturbated muddy sandstone	Thoroughly bioturbated, locally thin oscillation ripples and micro-hummocky cross-stratification, organic detritus, coalified wood fragments.	*Planolites, Teichichnus, Gyrolithes, Cylindrichnus,* and *Palaeophycus.*	1 to 5	Distal bay margin
	1b	Stressed bioturbated silty/sandy mudstone	Thoroughly bioturbated, locally thin oscillation ripples and micro-hummocky cross-stratification, carbonaceous detritus.	*Planolites, Teichichnus, Gyrolithes, Cylindrichnus, Palaeophycus,* and fugichnia.	2 to 5	Central bay
6) Coastal plain/delta plain deposits	13	Carbonaceous mudstone and coal	Crudely bedded, rare plant debris, locally high silt and sand content.	*Planolites* and roots	0 to 1	Terrestrial peat and swamp
	12	Root-bearing mudstone	Convolute-bedded mudstone with roots, organic detritus, current-ripple lamination, and some pedogenic features.	*Planolites, Naktodemasis,* and roots.	0 to 1	Floodplain
	11	Cross-bedded carbonaceous-rich sandstone	Sand with abundant coalified wood fragments, locally deformed.	*Planolites* and roots.	0 to 1	Fluvial channel

Figure 3 – Facies Association 1: Core box photograph of Facies 1a in well 13-01-052-27W3 core (487 to 482.5 m). Facies 1a is characterized by sandy mudstone with pervasive bioturbation (BI 3 to 5).

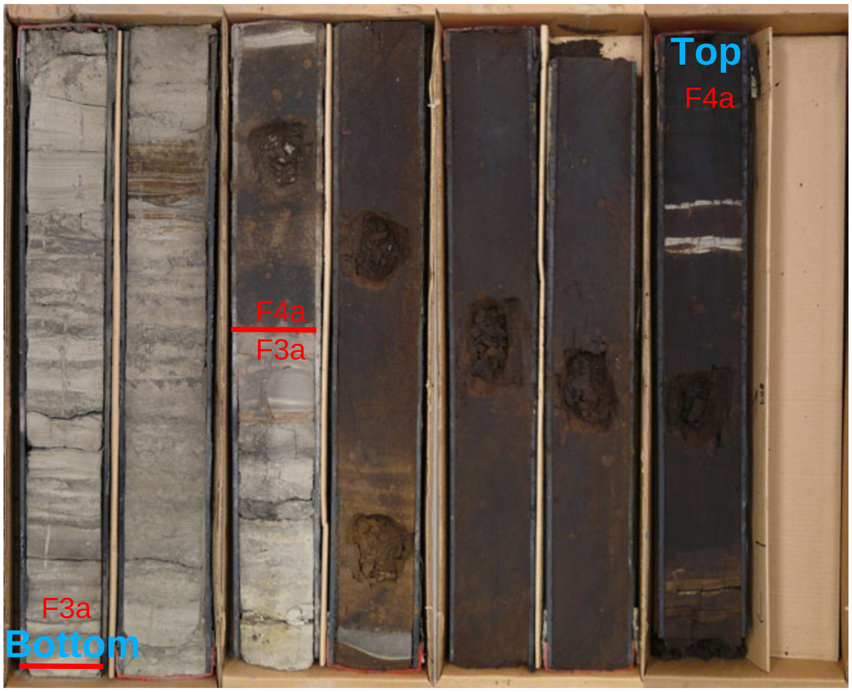

Figure 4 – Facies Association 2: Core box photograph of well 13-02-052-27W3 core (432.25 to 427 m) displaying coarsening- and shallowing-upward succession of proximal offshore (Facies 3a) to lower-middle shoreface (Facies 4a). In an idealized succession, the unit is overlain by trough cross-bedded sandstone of Facies 6.

deposit-feeding organisms. The general paucity of physico-chemical stress indicators is attributed to reduced fluvial influence in the setting.

c) Facies Association 3: Mixed River- and Wave-influenced Delta Deposits

Facies Association 3 (FA3) is characterized by coarsening-upward successions dominated by sporadically distributed heterolithic beds (Figure 5). Facies feature: 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-generated stratification. Trace-fossil suites are of low diversity, with highly variable bioturbation intensities (BI 0 to 5), which are dominated by diminutive ichnogenera. Common biogenic structures include *Gyrolithes, Teichichnus, Planolites, Palaeophycus, Cylindrichnus, Skolithos, Thalassinoides, Chondrites*, navichnia, and fugichnia. Additionally, rare occurrences of *Asterosoma, Phycosiphon, Helminthopsis, Rosselia,* and *Rhizocorallium* are also present.

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 increase in the influence of wave energy. The presence of locally intercalated current-rippled sandstone beds are interpreted to reflect fluvial influence. The carbonaceous-rich mudstones that commonly mantle sandstone beds are interpreted to record hypopycnal-induced (buoyant) mud plumes and their concomitant rapid flocculation and settling. 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-induced

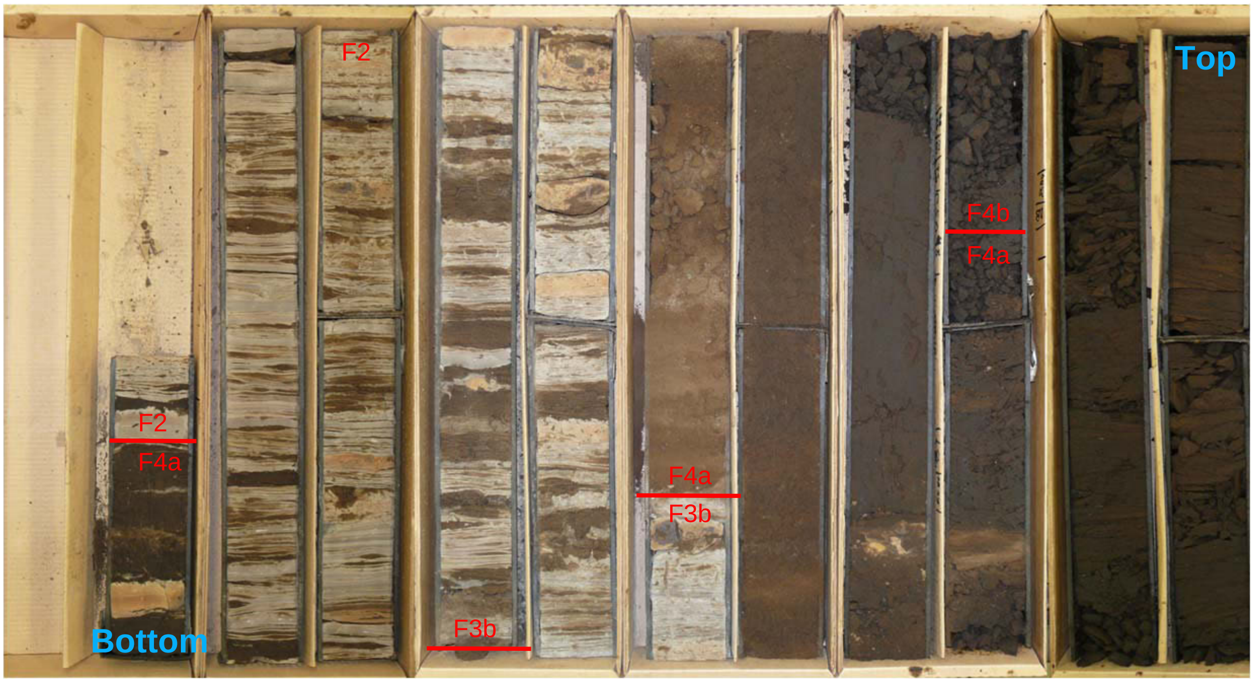

Figure 5 – Facies Association 3: Core box photograph of well 11-03-051-22W3 core (492 to 484.1 m) depicting the contact with Facies 4a and overall coarsening- and shallowing-upward successions of distal prodelta (Facies 2) to proximal delta front (Facies 4b). Note that Facies 4b is characterized by abundant current-rippled and small-scale trough cross-bedded sandstone.

freshet discharge (*cf.* Bhattacharya and MacEachern, 2009). FA3 is characterized by a low intensity of bioturbation (BI 0 to 2; locally 3 to 5) as well as a low diversity of ichnogenera, indicating elevated stress. Additionally the presence of syneresis cracks suggests that salinity fluctuations (mainly salinity reduction) occurred in the setting, attributed to river floods and/or hyperpycnal discharge (*e.g.,* MacEachern *et al.,* 2005; MacEachern and Bann, 2008; Bhattacharya and MacEachern, 2009), typical of deltaic environments.

d) Facies Association 4: Distributary Channels and Tidal-Fluvial Estuary Deposits

Facies Association 4 (FA4) overlies a sharp, erosional basal contact, and consists of massive to trough and planar tabular cross-stratified sandstones and intraformational mud-clast breccias (Figure 6). Sandstones pass upwards into heterolithic bedsets of cross-stratified and current-rippled sandstone alternating with laminated to graded mudstones showing variable bioturbation intensities (BI 0 to 5). The inclined heterolithic composite bedsets display an overall upward decrease in sediment calibres with variable sandstone-to-mudstone ratios. There is 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 sporadically distributed burrowed zones, and the dominance of simple biogenic structures attributed to trophic generalists. Common trace fossils are *Skolithos*, *Planolites, Palaeophycus, Gyrolithes, Cylindrichnus, Chondrites, Teichichnus*, navichnia, and fugichnia.

The presence of abundant trough cross-beds and current ripples indicates deposition in current-dominated depositional environments – in this case, channels. The interbedded sandstone and mudstone are interpreted as inclined heterolithic stratification (IHS), assigned to tidal-fluvial point bars 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; Beynon and Pemberton, 1992; MacEachern and Pemberton, 1994; Buatois *et al.*, 2005; MacEachern and Gingras, 2007). The low bioturbation intensity value of some of the mudstone beds may indicate that salt-water incursion occurred within the channels and shifted longitudinally within the valley due to some combination of daily, monthly or seasonal tidal cycles. Suspended sediment load carried by rivers commonly mix with saltier basin 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; Ciffroy *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 valleys requires evaluation of the scale of the FA4 succession and its association with the areal extent of its basal discontinuity (see below).

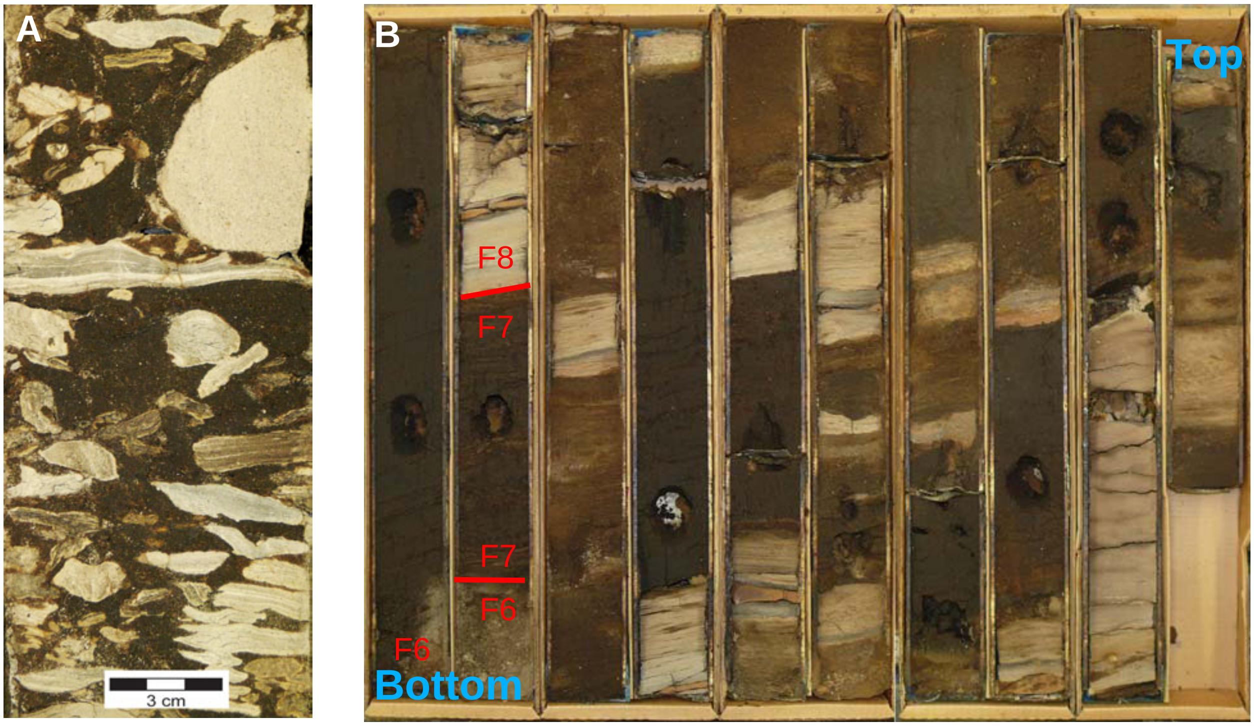

Figure 6 – Facies Association 4: A) Angular to subangular mudstone clasts with sandy matrix of well 11-18-049-23W3 (depth 514 m) representing Facies 5. The facies commonly sits at the base of FA4. B) Core box photograph of well 10-18-050-23W3 core (494.25 to 487 m). The interval displays trough cross-bedding (Facies 6) which gradually passes into current-rippled sandstone (Facies 7) and weakly burrowed inclined heterolithic stratification (Facies 8).

e) Facies Association 5: Transgressive Bay Deposits

Transgressive bay deposits of Facies Association 5 (FA5) (Figure 7) are sedimentologically similar to FA2 deposits, but yield different ichnological suites. Sediment deposition for FA5 appears to be dominated by wave processes. The mud content within the facies is variable, but generally decreases upward. Oscillation ripples, micro-hummocky cross-stratification (HCS), and combined flow ripples are common constituents within sandy beds. The preservation of oscillation structures is higher toward the top of the succession. It is noteworthy that Facies 4a within FA5 never exceeds 2 m which is considerably thinner than beds of this facies in FA2.

Bioturbation intensities in FA5 are highly variable, ranging from BI 0 to 5. The diversity of ichnogenera is generally lower than that of the FA2 deposits and consists mainly of facies crossing elements. Common trace fossils include *Planolites, Cylindrichnus, Skolithos, Teichichnus, Gyrolithes, Palaeophycus,* and fugichnia.

Like FA2, successions of FA5 represent subaqueous deposition by wave processes. The lack of well-developed HCS and swaley cross-stratification (SCS) within the FA5 successions indicates generally lower wave energy within the sedimentary environment, probably attributable to deposition in a more sheltered setting. Low diversities and predominance of diminutive trace fossils are attributable to increased environmental stress, particularly salinity reduction (*e.g.,* Beynon *et al*., 1988; Gingras *et al*., 2007; MacEachern, Pemberton *et al*., 2007). FA5 is interpreted as progradational shorelines within a sheltered bay during an overall transgression.

f) Facies Association 6: Coastal Plain/Delta Plain Deposits

Facies Association 6 (FA6) includes the deposits that cap progradational successions of FA2, FA3, and FA5 (Figure 8). The facies association gradationally or, locally, sharply overlies underlying deposits. FA6 deposits are characterized by trough cross-bedded sandstone with abundant organic detritus and associated rootlets, paleosols, and carbonaceous mudstones and coals.

FA6 is interpreted as the deposits of a coastal plain/delta plain setting, depending upon its relationship to the underlying succession. The presence of cross-stratified sandstones, abundant organic detritus, and spherulitic siderite grains, is consistent with channels. Transported spherulitic siderite grains and siderite nodules suggests sedimentation 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,

Figure 7 – Core box photograph of Facies Association 5 in well 10-12-048-20W3 core (421.2 to 415.2 m). The succession shows a shallowing-upward profile from central bay deposits (Facies 1b) to muddy tidal flat (Facies 10).

2002). The presence of coal is interpreted as the result of accumulation of plant material and organic matter as swamps, bogs, and forested zones.

4. Stratigraphy

Historically, the Mannville Group was divided into nine informally named stratigraphic units in the Lloydminster area. However, these packages, as presently defined are inherently lithostratigraphic, and do not conform consistently to through-going stratigraphic discontinuities. To that end, the assessment of facies associations and their mapped distributions are intended to lead to an allostratigraphic framework for the upper Mannville interval. An allostratigraphic framework allows units to be correlated on the basis of bounding stratigraphic discontinuities (North American Commission on Stratigraphic Nomenclature, 1983), and has proven extremely useful in characterizing the paleogeography and depositional architecture of complex successions built of recurring facies associations (*e.g.*, the Dunvegan Formation; Bhattacharya and Walker, 1991) or typified by erosionally amalgamated successions in low-accommodation settings (*e.g.,* the Viking Formation; Pattison and Walker, 1994; Walker, 1995; Burton and Walker, 1999). With an allostratigraphic framework established, a sequence stratigraphic interpretation can be developed for the study interval.

The regionally extensive discontinuities that separate the allostratigraphic units in the study area correspond to base-level changes during the Lower Cretaceous. Most surfaces are interpreted as marine-generated discontinuities, and are characterized by the juxtaposition of distal facies above proximal facies, reflecting a landward shift of facies associated with a significant increase in water depth. The internal flooding surfaces that are less areally extensive typically bound the facies associations and are interpreted to record periods of progradation; hence, these stratigraphic packages correspond to parasequences. These flooding surfaces bound FA2, FA3, and FA5

Figure 8 – Facies Association 6 in well 11-03-051-22W3 core (489.45 to 486.45 m). The succession displays a fining-upward trend. FA6 consists of cross-bedded 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 flood plain as crevasse splays.

successions. The deltaic successions of FA3 also contain localized flooding surfaces that are attributed to autogenic lobe abandonment. These surfaces are intra-parasequence discontinuity surfaces and do not correlate to the shoreface successions of FA2. Within the Waseca alloformation, a regional discontinuity occurs that corresponds to base-level fall, widespread subaerial exposure, and local valley incision (see below). This surface is also transgressively modified locally.

The Joli Fou Formation unconformity caps the Mannville Group, and is separated from the underlying unit by a transgressive surface of erosion (TSE) interpreted as a wave-ravinement surface. This TSE was chosen as the datum for stratigraphic correlations, as the surface is stratigraphically close to the studied interval, was likely near to horizontal when cut, and shows minor paleotopographic relief.

a) Sparky Alloformation

The base of the Sparky alloformation is characterized by lower shoreface deposits (FA2) or its deltaic counterpart (FA3), sharply overlying sandstones of the General Petroleums alloformation This surface is correlatable across the study area, and is interpreted as a major marine flooding surface. The Sparky alloformation is interpreted to contain two to three parasequences. Each cycle represents periods of progradation, followed by widespread transgressive events forming flooding surfaces. In the central portion of the study area, the Sparky parasequences are characterized by coarsening-upward and thickening-upward successions corresponding to wave-dominated shorefaces (FA2). In core, the Sparky alloformation shows lower shoreface HCS- and micro-HCS–bearing sandstones coarsening upward into erosionally amalgamated HCS and SCS sandstones of the middle to upper shoreface.

Towards both the eastern and western parts of the study area, the shoreface successions pass gradationally along strike into mixed river- and wave-influenced delta deposits of FA3 (Figure 9). Like the shoreface successions, the deltaic deposits display upward-coarsening and upward-thickening cycles, although the deltaic intervals are thicker than their wave- and storm-dominated shoreface counterparts. These deltaic cycles (FA3) are characterized by prodelta to distal delta-front successions, passing upward into proximal delta-front deposits. Deposits of FA3 contain intra-parasequence flooding surfaces. These intra-parasequence discontinuity surfaces are significantly less laterally extensive than parasequences containing them, and the surfaces do not correlate to discrete surfaces within FA2 successions. The mechanisms that controlled these minor stratigraphic discontinuities within FA3 are considered to develop due to autogenic changes in the delta (*e.g.*, lobe abandonment). Both FA2 and FA3 deposits downlap towards the north onto the offshore marine deposits of FA1 (Figure 10).

Distributary channels of FA4 are identified both from geophysical well logs and from cored intervals. In core, channel-fill deposits occur as multiple stacked sandstones displaying trough cross-bedding and, locally, IHS records laterally accretion point bars and/or in-channel bars. The average thicknesses of sediments deposited in the channel are about 5 m, but locally reach 18 m in some trunk channels. Distributary channel deposits occur in both the eastern and western parts of the study area, oriented towards the north and northwest, and cut into delta-front deposits of FA3. The erosional relationship between FA4 and FA3 successions are interpreted to be autogenic, and therefore do not correspond to stratigraphic discontinuities.

The Sparky alloformation is commonly capped by 0.5 to 4 m thick deposits of coastal plain/delta plain deposits of FA6. These deposits are characterized by fining-upward successions that generally are capped by widespread coal.

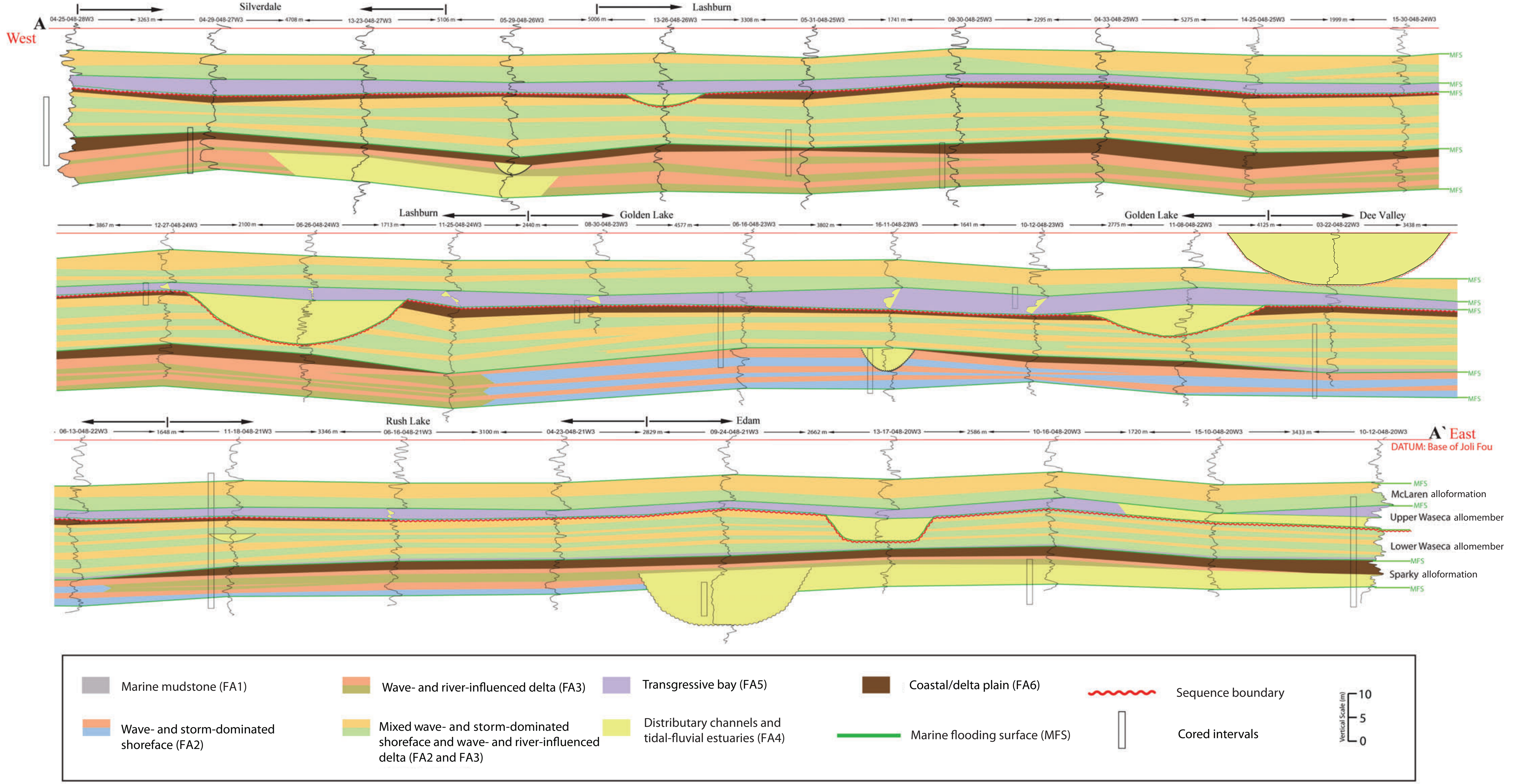

Figure 9 – West-east cross section through the study area. The cross section shows gamma-ray well log signatures for the selected wells. The orientation of this cross section is close to the along-strike orientation of the paleo-shoreline during Upper Mannville time; line of section shown in Figure 2.

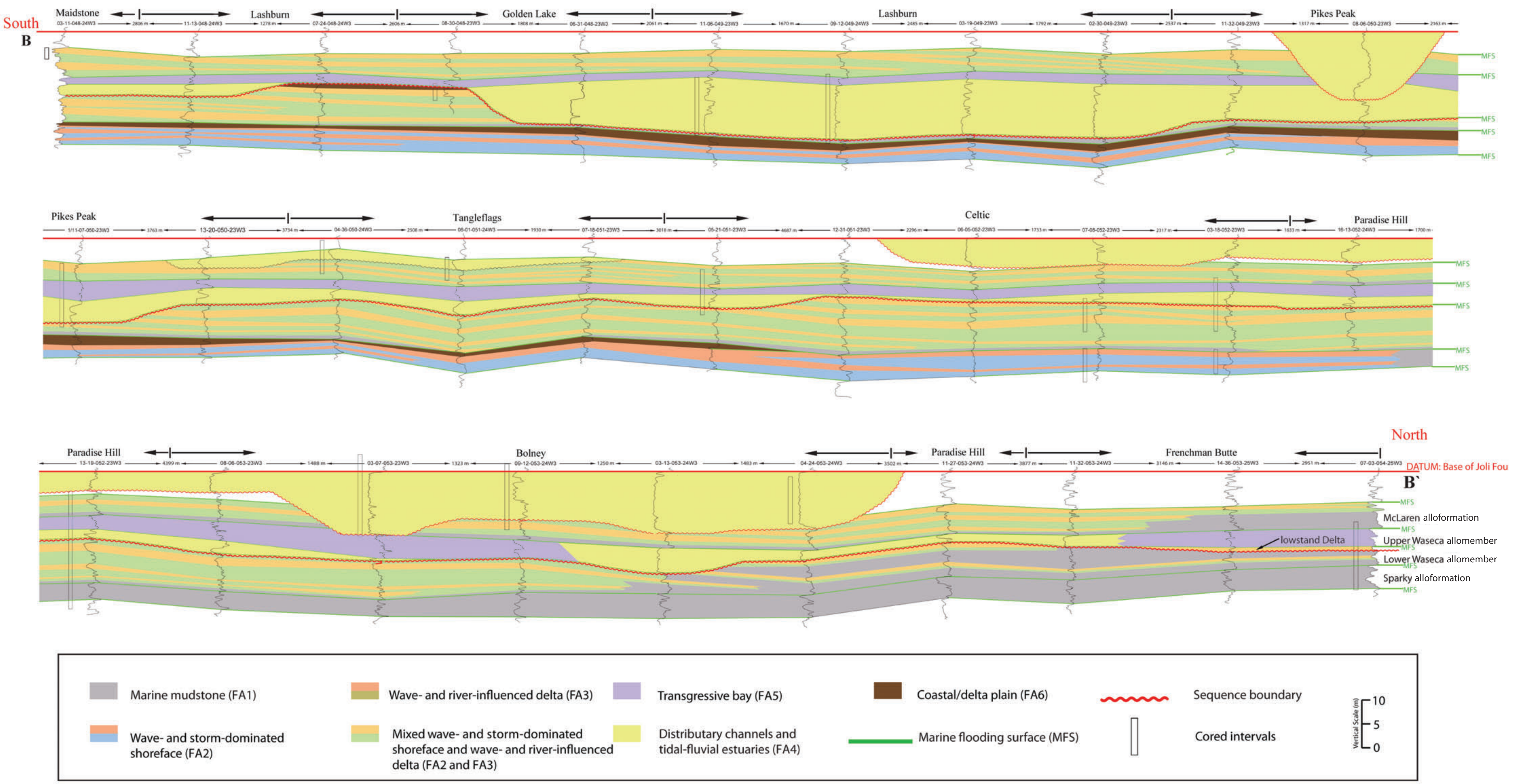

Figure 10 – South-north cross section that is oriented perpendicular to the depositional strike of the upper part of the Mannville Group. The cross section shows gamma-ray well log signatures for the selected wells; line of section shown in Figure 2.

Deposits of FA6 can be correlated across most of the southern part of the study area. The Sparky alloformation is separated from the overlying Waseca Formation by a widespread transgressive surface or marine flooding surface and, where there is evidence of erosion, it is called the TSE. Locally, an intra-Waseca unconformity cuts through the Lower Waseca allomember and incises into the top of the Sparky alloformation. In those localities, the contact between the Sparky and Waseca alloformations corresponds to a transgressively modified lowstand unconformity (see below). 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 an increase in the amount of fine-grained deposits directly above the contact. The overlying units of the Waseca alloformation commonly show more intense and uniformly distributed bioturbation. On well logs, identifying the transgressive contact between the Sparky and Waseca is mainly achieved using gamma-ray logs. The contact displays an increase in radioactivity, which reflects the increased amount of clay minerals in the fine-grained deposits of the basal Waseca. The deposits of the Sparky alloformation are interpreted as a progradational parasequence set of a highstand systems tract.

b) Waseca Alloformation

The lower part of Waseca alloformation transgressively overlies the Sparky alloformation and consists of a series of coarsening-upward and shallowing-upward parasequences (referred to, herein, as the Lower Waseca allomember). The Lower Waseca allomember is characterized by a series of wave-dominated shorefaces (FA2) and mixed river- and wave-influenced deltas (FA3) that dip toward the north to northwest and gradually pass into offshore marine deposits of FA1 (Figure 10). Individual parasequences are relatively thin (less than 6 m), and commonly interfinger with one another, which makes the correlation of individual cycles virtually impossible. This is exacerbated by the presence of autogenic flooding surfaces associated with lobe abandonment in FA3 intervals. The intercalated character of the FA2 parasequences and FA3 autogenic lobes and parasequences 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 precludes true along-strike orientations of cross sections; lines of section pass into and out of localized bays, leading to apparent pinchouts of bay-head and bay-margin complexes.

Sedimentological and ichnological analyses also indicate that the Lower Waseca allomember was deposited in a restricted (sheltered), brackish-water setting. This is evident by the relatively small-scale wave-generated structures, and low diversity ichnological suites consisting of diminutive ichnogenera (*cf.* MacEachern and Gingras, 2007). Distributary channels (FA4) that cut into the proximal delta fronts of FA3 successions are locally observed. These channels are commonly 1 to 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 truncated by a subaerial unconformity (sequence boundary). The Lower Waseca parasequence set is interpreted as a highstand systems tract (*e.g.,* Van Wagoner *et al.*, 1990; Posamentier and Allen, 1999).

A regionally extensive lowstand unconformity (Waseca unconformity) is identified within the Waseca alloformation, separating the Lower Waseca allomember and the Upper Waseca allomember. This unconformity is associated with the incision of a valley up to 34 m deep, which locally erodes through the Lower Waseca allomember and truncates the upper part of the Sparky alloformation. In interfluve areas lying outside of the valley margins, the Waseca unconformity is characterized by a root-bearing horizon and the development of paleosols on the subaerially exposed coastal plain. During the ensuing base-level rise, which was responsible for the estuarine infill of the Upper Waseca allomember valley, these interfluve areas were ultimately inundated with marine water. The lowstand Waseca unconformity was subsequently transgressively modified and locally hosts firmground trace-fossil suites attributable to the *Glossifungites* Ichnofacies.

Regional correlations indicate that the lowstand deltas associated with incision of the valleys at the Waseca unconformity lie 20 km north of Celtic field (Township 54 and Ranges 25 west of the 3rd Meridian), and are separated from the highstand deposits of the Lower Waseca allomember by a subtle regressive surface of marine erosion (Figure 10). Base-level fall and the formation of deeply incised valleys also forced the subaerial exposure of offshore deposits (Posamentier, 2001). This promoted incision and bypass of lowstand sediments through the valleys, and the accumulation of lowstand deltas and shorefaces (*cf.* Walker and Wiseman, 1995; Burton and Walker, 1999). The lowstand deltas developed within the study area are identified by an erosional lower contact, an abrupt increase upward in the amalgamation of wave- and storm-generated beds, and an associated abrupt increase in grain size and sand content (Figure 11A). Such juxtaposition can only be achieved as a result of the lowering of storm- and fair-weather wave base in response to base-level fall. The lowstand delta itself is characterized by the amalgamation of wave-rippled and HCS sandstones intercalated with organic-rich mudstone beds of probable fluid mud origin. These mudstones display low bioturbation intensities (BI 0 to 1, locally 2) and contain abundant syneresis cracks.

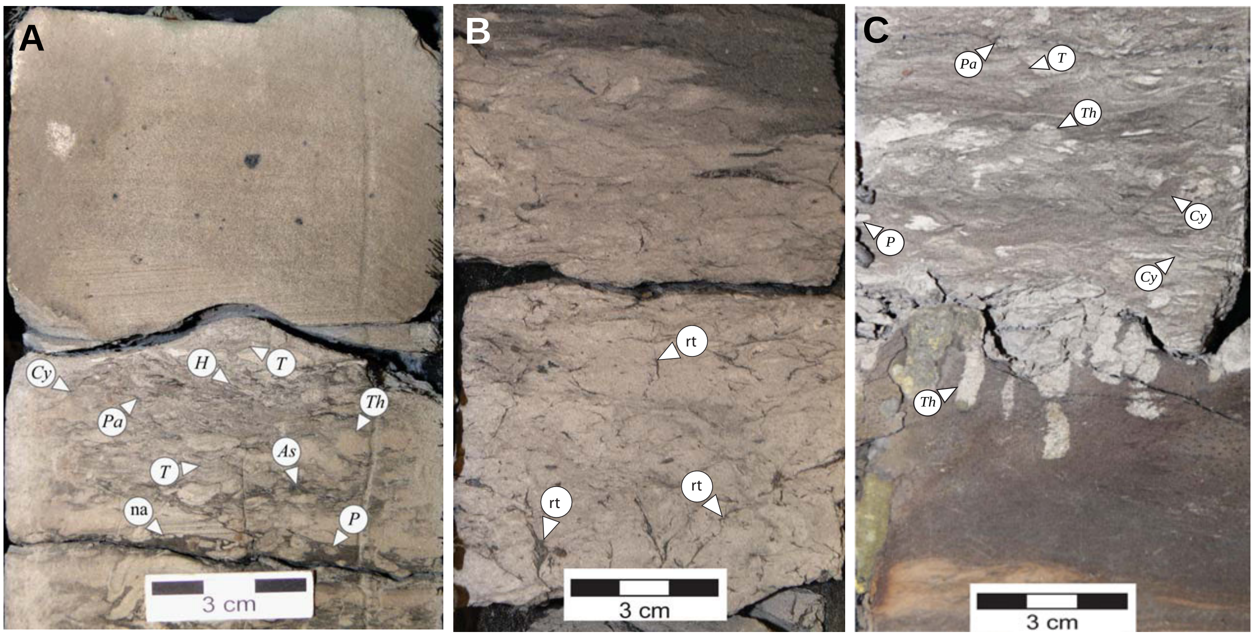

Figure 11 - A) Erosional discontinuity surface characterized by amalgamated hummocky cross-stratified sandstone beds of the delta front truncating the underling marine bioturbated mudstone with* Planolites *(P),* Cylindrichnus *(Cy),* Teichichnus *(T),* Palaeophycus *(Pa),* Thalassinoides *(Th),* Asterosoma *(As),* Helminthopsis *(H), and navichnia assemblages (na) (well 07-03-054-25W3; 476.3 m). B) Pedogenically modified mudstone with rhizoliths (rt) (well 05-11-049-20W3; 446.5 m). C) Erosional discontinuity marked by trace fossils typical 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 (well 10-12-048-20W3; 427.8 m).

The Upper Waseca allomember overlies the intra-Waseca sequence boundary and is capped by the TSE marking the base of the McLaren alloformation. The Upper Waseca is characterized by fluvio-estuarine valley fills of FA4 and transgressive bay deposits of FA5.

Within the Upper Waseca allomember, channelized deposits of FA4 that directly overlie the Waseca unconformity tend to be more deeply incised (up to 34 m deep; *e.g.,* Pikes Peak field) and consist of multi-story channel fills, compared to the normal distributary channel complexes elsewhere that average 7 m in thickness. These systems are interpreted as incised valley complexes. The position of these incised valleys was likely determined by the pre-existing fluvial and distributary channels feeding sediment to the Lower Waseca allomember shoreline (*e.g.,* Celtic and Westhazel fields) at the end of the Lower Waseca highstand systems tract. Ensuing base-level fall led to re-incision of pre-existing channels, and sediment bypass 20 km seaward to the position of the lowstand deltas and shorelines (Figure 10).

In many localities, valley incision at the Waseca unconformity during lowstand conditions led to valleys that cut entirely through the Lower Waseca allomember, and bottomed out on the Sparky allomember coal. The previous interpretation by MacEachern (1984, 1986) that the “Pikes Peak Channel” was an aggradational phenomenon during Waseca time is incorrect, particularly in light of the presence of a regionally extensive unconformity and lowstand shoreline. Van Hulten (1984) more accurately depicted the stratigraphic relationship of the Waseca Formation.

The valley-fill deposits of the Upper Waseca allomember are associated with ensuing base-level rise, and hence, overlie a coplanar surface that reflects an amalgamated sequence boundary and flooding surface. The valley shows tidal-fluvial estuarine channel and IHS point bar and in-channel bar deposits (MacEachern, 1984; 1986; Van Hulten, 1984) that accumulated during the early stages of relative sea-level rise. Trace fossil assemblages within the valleys are characterized by low-diversity suites of diminutive ichnogenera 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).

During lowstand and early transgression, interfluve areas were subaerially exposed. This period of exposure is evidenced by the presence of root structures and incipient paleosol development on facies of the Lower Waseca allomember (Figure 11B). Where sandy facies were subaerially exposed, the discontinuity surface is subtle, and difficult to recognize in core and on logs. In the eastern part of the study area, the exposure surface appears to have been transgressively removed by wave ravinement, and is demarcated by firmground *Skolithos, Thalassinoides,* and *Arenicolites* of the *Glossifungites* Ichnofacies (Figure 11C). This also indicates that the substrate was compacted and dewatered (*i.e.,* a firmground) (*e.g.,* Pemberton and Frey, 1985; MacEachern *et al.,* 1992; MacEachern, Gingras *et al*., 2007). This surface corresponds to a transgressively modified sequence boundary, and shows little erosional relief.

Continued transgression and inundation of the study area resulted in the complete infill of these valleys, and the deposition of transgressive brackish-water bay deposits of FA5. Transgressive bay deposits are characterized by thin (4 to 5 m) intervals of coarsening- and shallowing-upward parasequences, representing small-scale progradational events during the overall transgression. The stacking arrangement shows a net landward shift of depocentres, consistent with a retrogradational parasequence set, marking the development of a transgressive systems tract during Upper Waseca allomember time. The maximum flooding surface is characterized by regionally extensive marine mudstones of FA1, marking the base of the overlying McLaren alloformation. These FA1 deposits are very thin and therefore are difficult to identify on the well logs and only the thickest of these units are visible at the scale of the cross sections illustrated in Figures 9 and 10.

c) McLaren Alloformation

The McLaren alloformation is characterized by the interfingering of wave- and storm-dominated shorefaces (FA2) and mixed river- and wave-influenced delta (FA3) parasequences, similar to the Lower Waseca allomember. Each parasequence is interpreted as a progradational cycle, where successive cycles display a net basinward shift of the shoreline. This parasequence stacking pattern is consistent with a progradational parasequence set and is interpreted to represent a highstand systems tract. McLaren alloformation deposits commonly terminate northward and north-westward, as they downlap onto the pervasively bioturbated offshore mudstones of FA1 (Figure 10). Along-strike correlations show greater numbers of coarsening-upward cycles in areas of FA3 deltaic successions, reflecting the presence of 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.

Several thick sand- and mud-filled channel successions are incised into the McLaren alloformation. These are interpreted as incised valleys that subtend from the base of the amalgamated sequence boundary and transgressive surface of erosion marking the Upper Mannville allogroup–Joli Fou alloformation contact (Figures 9 and 10).

5. Conclusions

Evaluation of the ichnological and sedimentological characteristics of units from the Lower Cretaceous Upper Mannville Group (Sparky, Waseca, and McLaren alloformations) in west-central Saskatchewan allowed us to identify thirteen recurring facies that can be combined into six facies associations.

Common depositional facies record a variety of marine, marginal marine and coastal environments, including open marine offshore settings, mixed river- and wave-influenced deltas, wave- and storm-dominated shorefaces, distributary and tidal-fluvial estuarine channels (including incised valley fills), transgressive bays, and coastal/delta plains. The predominance of low-diversity suites, the prevalence of facies-crossing elements, and the diminutive character of ichnogenera within facies indicate that most of these environments were subjected to physico-chemical stress, particularly reduced and fluctuating salinities.

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

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 major 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 (base-level fall). 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 the Sparky, Waseca, and McLaren alloformations. The Waseca can be subdivided into lower and upper allomembers on the basis of a widespread unconformity.

The Sparky alloformation, the Lower Waseca allomember, and the McLaren alloformation show overall progradational parasequence sets corresponding to highstand systems tracts. The unconformity within the Waseca alloformation marks a major base-level fall. Correspondingly, the deposits of two discrete sequences can be delineated within the study interval. The lower sequence encompasses the highstand systems tract deposits of the Sparky alloformation and the Lower Waseca allomember. The upper sequence comprises the Upper Waseca allomember and the McLaren alloformation. The intra-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 20 km seaward of the underlying highstand parasequence at the Celtic field. In interfluve areas, this sequence boundary is characterized by a root-bearing horizon and the incipient development of paleosols. Ensuing transgression in the Upper Waseca allomember resulted in the accumulation of a 5 to 35 m thick succession of strata, interpreted as the transgressive system tract. Initial transgression resulted in back stepping of the shoreline from the lowstand delta, and the tidal-fluvial estuarine infill of the incised valleys. Continued transgression of the study area led to palimpsest marine colonization of the sequence boundary, 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, forming a 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.

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