Speciation of McMurray Formation Inclined Heterolithic Strata: Varying Depositional Character Along a Riverine Estuary System

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ABSTRACT

Introduction

Within the Athabasca Oil Sands of northeastern Alberta, the lower Cretaceous (Aptian and older) McMurray Formation forms the most volumetrically significant portion of the deposit. Inclined Heterolithic Strata (IHS) and associated sand accumulations comprise a significant portion of the McMurray Formation, and represent some of the thickest and richest pay zones (Mossop, 1980). Through sedimentological and ichnological investigation (Pemberton et al., 1982; Ranger and Pemberton, 1992), and comparison to modern deposits (Smith, 1988a), a model of channel bank accretion within a riverine estuary has emerged to explain the IHS. While IHS has been given a cursory treatment in many subsequent studies of the McMurray Formation, little explanation of their genetic aspects has been presented. Of particular interest is the great variation of character observed between sets of IHS, and the processes and timing reflected in the cyclic sand-mud interbeds. This presentation has been undertaken to demonstrate the breadth of character inherent to IHS of the McMurray Formation, and insomuch as is feasible, explain the depositional dynamics responsible for the observed character.

IHS and the Dynamics of Estuarine Sedimentation

Thomas et al. (1987) introduced the term Inclined Heterolithic Stratification as a descriptor for heterogeneous deposits which exhibit notable primary (depositional) dip. Prior to this, numerous clumsy, often genetically suggestive terms had been applied to such deposits (e.g. epsilon cross-stratification, lateral accretion bedding). While "the overwhelming majority are the products of point bar lateral accretion within meandering channels" (Thomas et al., 1987), IHS may also be generated through progradation of Gilbert-type deltas and suspension fall-out onto existing slopes. Within the McMurray Formation, IHS has been attributed to active channel bank deposition, owing to a typical upward-fining profile, and along-strike paleoflow (Mossop and Flach, 1983). The recognition of tidally generated structures (Smith, 1988b), and a brackish ichnological signature (Pemberton et al., 1982) has differentiated the system as estuarine.

Core based study of McMurray Formation IHS has demonstrated a greater range of depositional character than is readily observed in outcrop. IHS sets vary in style from those dominated by clean sand beds, to those composed almost exclusively of silty mud. Variability is also seen in the nature and abundance of biogenic structure within the sediment. This variation has been attributed to differing position within the estuarine channel system, which would lead to

differing influence of saltwater intrusion and suspended load deposition (Ranger and Pemberton, 1992). Temporal shifts in the freshwater-saltwater interface and associated turbidity maximum have been suggested as the mechanisms responsible for the generation of heterogeneous character within the IHS (Bechtel et al., 1994). The temporal scale of these shifts has not, however, been clearly demonstrated.

Within partly mixed estuaries, the concentration and localized deposition of suspended load sediment is a well known process (Allen et al., 1980). The resulting zone of high suspended load is known as a turbidity maximum. The maintenance of the turbidity maximum is facilitated during high fluvial influx through density stratification and circulation effects in the water column (*Fig1*). The dilution of saline water by low density fresh water leads to a convergence of bottom water current, resulting in the concentration of suspended load near the limit of salt water intrusion (the density node). During periods of low fluvial influx, suspended sediment transport is dominated by tidal forcing. Asymmetry of tidal flow leads to the concentration of fines near the landward limit of flow reversal (the tidal node). Allen et al. (1980) demonstrated that within the Gironde estuary, seasonal variation in fluvial discharge leads not only to an alternation in the character of the turbidity maximum, but also in its location. During low flow, the turbidity maximum is located in a landward position, and exhibits a transient tidal character. During high flow, it is located in a relatively stable seaward position, and is maintained through density circulation. The seasonal excursion of the turbidity maximum reaches approximately 100km (Allen, 1991).

<u>Utilizing Ichnology to Unlock Depositional Dynamics</u>

Low absolute salinity, rapid salinity fluctuation and high turbidity are all known to have considerable influence on the location and behavior of benthic organisms (Carriker, 1967, Howard et al, 1975). As such, the dynamics of water circulation and sedimentation within an estuarine system play an important role in dictating the spatial and temporal distribution of trace fossils.

Near the mouth of the system, a sandy substrate, hospitable salinity and low turbidity will promote the activity of filter feeding organisms, with burrows open to water column. At a position further landward, high turbidity, extreme salinity fluctuation (related to semidiurnal excursion of the freshwater–saltwater interface) and a muddy, organic-rich substrate will promote the activity of endobenthic deposit feeders, which are buffered from salinity variation by the pore water of the surrounding sediment.

Temporal changes in water chemistry and sedimentation can lead to drastic changes in biologic activity at a fixed location. Near the mouth of the system, filter feeders, which may be highly active during periods of low fluvial discharge, will be snuffed out during high discharge, when salinity drops off and the water column turns extremely turbid. Similarly, in positions further landward, quiescent conditions with moderate salinity will yield to high energy conditions and fresh water flushing during periods of high discharge.

Examples of IHS Variation

Core from Canadian Natural Resources' Horizon Project lease in townships 96 and 97, ranges 11 – 13 W4 has been employed in the study of McMurray Formation IHS. Intervals from 25 core have been examined. Four representative successions are presented to illustrate the systematic variation of IHS character along a conceptual McMurray riverine estuary (*Fig*2). Several additional short intervals will be on hand to illustrate additional key features of the IHS.

Observations and Interpretations

The following brief descriptions are present from landward to basinward.

AA/15-23-96-13W4 (174m to 197m)

Composed of numerous thin (2-5m) sets, IHS in this succession displays inconsistent dip orientation. Coarse members vary in thickness from 5cm to 1m, and are composed of relatively poorly sorted very fine to local medium sand. Sizable cross-beds (5-40cm) are seen throughout the succession, and carbonaceous debris is common. Burrowing is conspicuously absent in the coarse members. Fine members are typically finely laminated and locally suggestive of tidal deposition. Granular material within the fine members is markedly finer grained than that present within the coarse members, and starved ripples are common. *Planolites* is inconsistently found in rare to low abundance within the fines. Contacts between coarse and fine members are sharp, and opposition of bedform migration direction between them is locally evident.

Observations are consistent with deposition near the landward limit of tidal influence. The comparatively coarse, poorly sorted sands were deposited through fluvial processes during high flow, while the laminated fines accumulated as a result of tidal action during low river flow. The paucity of burrowing in the sands and limited endogenic burrowing within the fines suggest extreme salinity stress though the depositional cycle. The inconsistent character and thickness of inclined units indicates that deposition in this location was variable between subsequent events.

AA/01-06-97-11W4 (60m to 77m)

Two sets of IHS (6-10m thick) with broadly consistent character and orientation are present in this succession. Coarse members are composed of moderately well sorted silt and very fine sand, with adjacent beds often contrasting in grain size. Ripple cross-lamination in sets ~2cm thick is common, and some of the sand beds appear to be composed of amalgamated upward fining/muddying cycles. Burrowing within the coarse members is rare. The fine members are composed of finely interlaminated mud, silt, and lower very fine sand, with the suggestion of tidal periodicity and mud doublets. *Planolites*-dominant burrowing is present in moderate abundance within the fines. The inclined units exhibit fairly consistent thickness, and transitions between coarse and fine members may be sharp or gradational. Synaeresis cracks are common near the top of the succession, and are typically found in association with the transition from muddy to sandy sediment.

Observations are consistent with deposition in a position intermediate between the seaward and landward limits of turbidity maximum excursion. While the variable texture of the coarse members sands suggests fluvial bed load flux frequently reached this point, the regularity of inclined unit thickness, presence of significant burrowing and abundant fine-grained material indicate that fluvial processes were tempered by an overall estuarine environment.

<u>AA/12-31-96-11W4 (66m to 90m)</u>
This succession contains 20m of dense mud-dominated IHS containing two subtle discontinuities, overlying a “lag” of slump deposits and mud block breccia. The coarse fraction consists of a well sorted mix of silt to lower very fine sand occurring in clean to wavy interlaminated beds up to 10cm thick. In some cases, “coarse members” are composed solely of sand-filled burrows within mud where no other evidence of sandy deposition has been preserved. Fine members are composed of dense to finely laminated silty mud in accumulations up to 30 cm thick. Moderate abundance burrowing is concentrated on interlaminated mud and silt/sand, and is dominated by *Planolites* and *Teichichnus*. Coarse to fine member transitions are typically gradational, while fine to coarse transitions may be sharp or gradational. Inclined units are generally developed with consistent thickness.

Observations are consistent with deposition at the seaward limit of turbidity maximum excursion. The deposition of dense, structureless mud is known to take place from the turbidity maximum in modern estuarine systems at times of high fluvial influx, and strong density circulation (Meade, 1972). The minimal deposition of sand may be the result of bed load bypass across a scoured, cohesive (mud armored) substrate during periods of strong tidal flow.

<u>AA/16-06-97-12W4 (138m to 175m)</u>
This succession is comprised of 35m of sand-dominated IHS with a character similar to that seen in outcrop along the Steepbank River and the type section. While not overt, several subtle discontinuities are highlighted by trends in dipmeter, textural and ichnological data. The coarse members consist of 5cm to 1m thick accumulations of well sorted silt to lower very fine sand. While parallel lamination and 1-3cm thick sets of ripple cross-lamination dominate the observed structure, cross-beds 5-20cm thick are common near the base. The erosive amalgamation of coarse member sands is suggested in places. *Cylindrichnus* and *Skolithos* are present in low to moderate abundance within the sands. Fine members typically exhibit relatively coarse interlamination of mud and silt/sand, with no discernable fining of the granular material relative to coarse members.

Planolites, inclined muddy traces and nondescript mottling occur in the fine members. The transitions between coarse and fine members are typically sharp.

Observations are consistent with deposition seaward of the turbidity maximum. The deposition of well sorted, very fine sands associated with the development of vertical dwelling burrows indicates relatively consistent flow strength, texture of the supplied sediment and salinity. The intermittent development of poorly laminated fine members may reflect deposition from the periphery of the turbidity maximum, or tidal redistribution muddy sediment.

Conclusions

IHS from the McMurray Formation displays substantial variability with respect to lithic and ichnologic character. The distribution and morphology of trace fossils reflect systematic spatial and temporal variation in salinity and turbidity stress. By applying concepts gleaned through the study of modern estuarine systems, deposit character can be resolved into a fluvial to marine gradient. IHS character falls into a broadly tripartite distribution, with a sand-dominated seaward flux in the upper reach, a fine-grained zone of convergent flux in the middle reach, and sand-dominated landward flux in the lower reach. The sand dominated IHS deposits from each end of the system contrast strongly in terms of texture, structure, biogenic signature, and stratal organization. Similarly, fine members from the central portion of the system exhibit a progression of character from dense mud to finely interlaminated silt/sand and mud in a landward direction.

The dominant order of cyclicity within the IHS is seasonal, with subordinate semidiurnal and fortnightly tidal signature locally evident.

Successions of superficially consistent IHS can attain great thicknesses, but are typically broken by subtle discontinuities into several smaller depositional units. The significance of these discontinuities, and genetic relation of the units they define is not, however, apparent in core.

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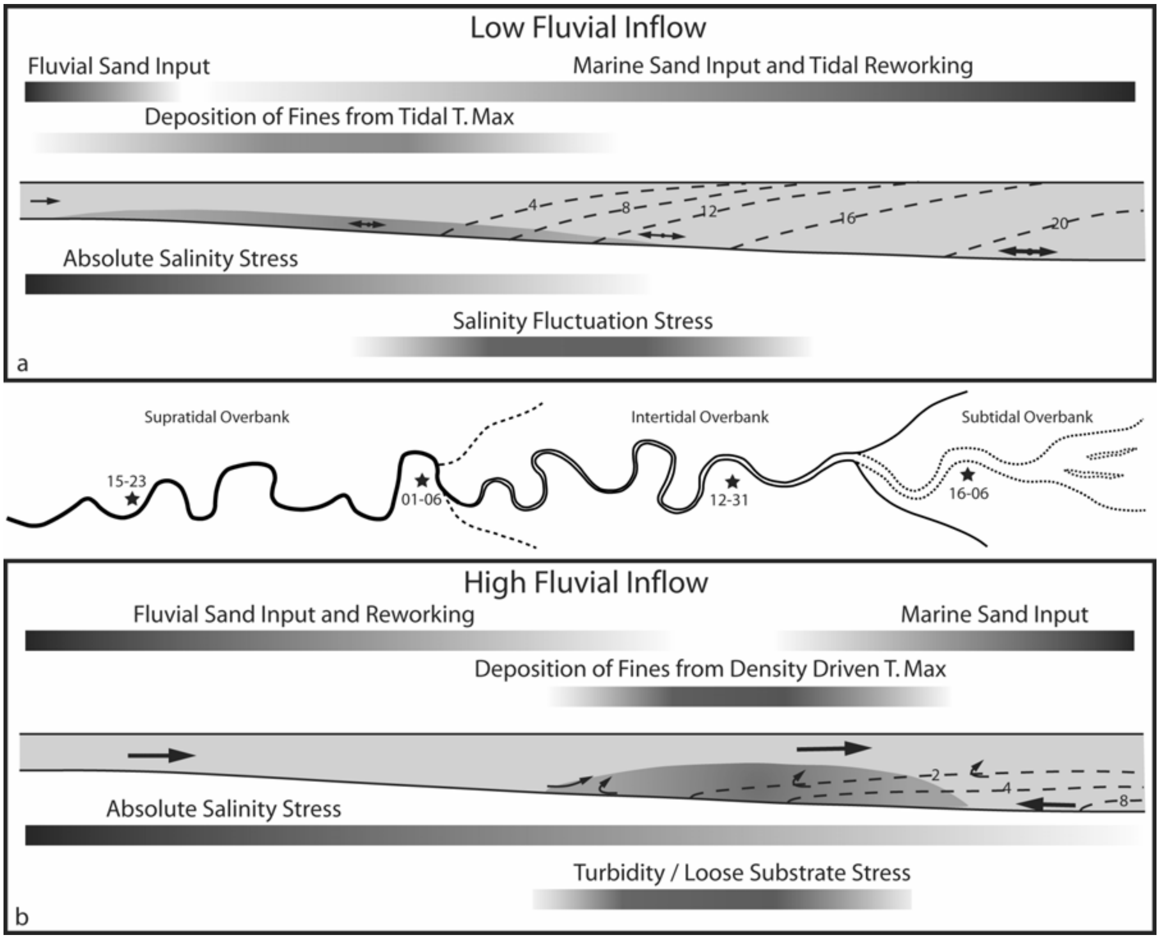

Figure 1 **Schematic showing spatial and temporal variation of depositional character within a riverine estuary.** ***a)*** **During periods of low fluvial inflow, tidal processes dominate over fluvial/density circulation processes and the system experiences a deep incursion of brackish water. Deposition of fines is skewed towards the fluvial end and has a laminated tidal character. The marine end of the system experiences tidal reworking with a net landward flux of sediment.** ***b)*** **During periods of high fluvial inflow, fluvial/density circulation processes dominate over tidal processes and brackish water is flushed from much of the system. Deposition of fines is skewed towards the marine end and has a largely structureless character. The fluvial end of the system experiences reworking with a net seaward flux of sediment. T. Max for turbidity maximum.**

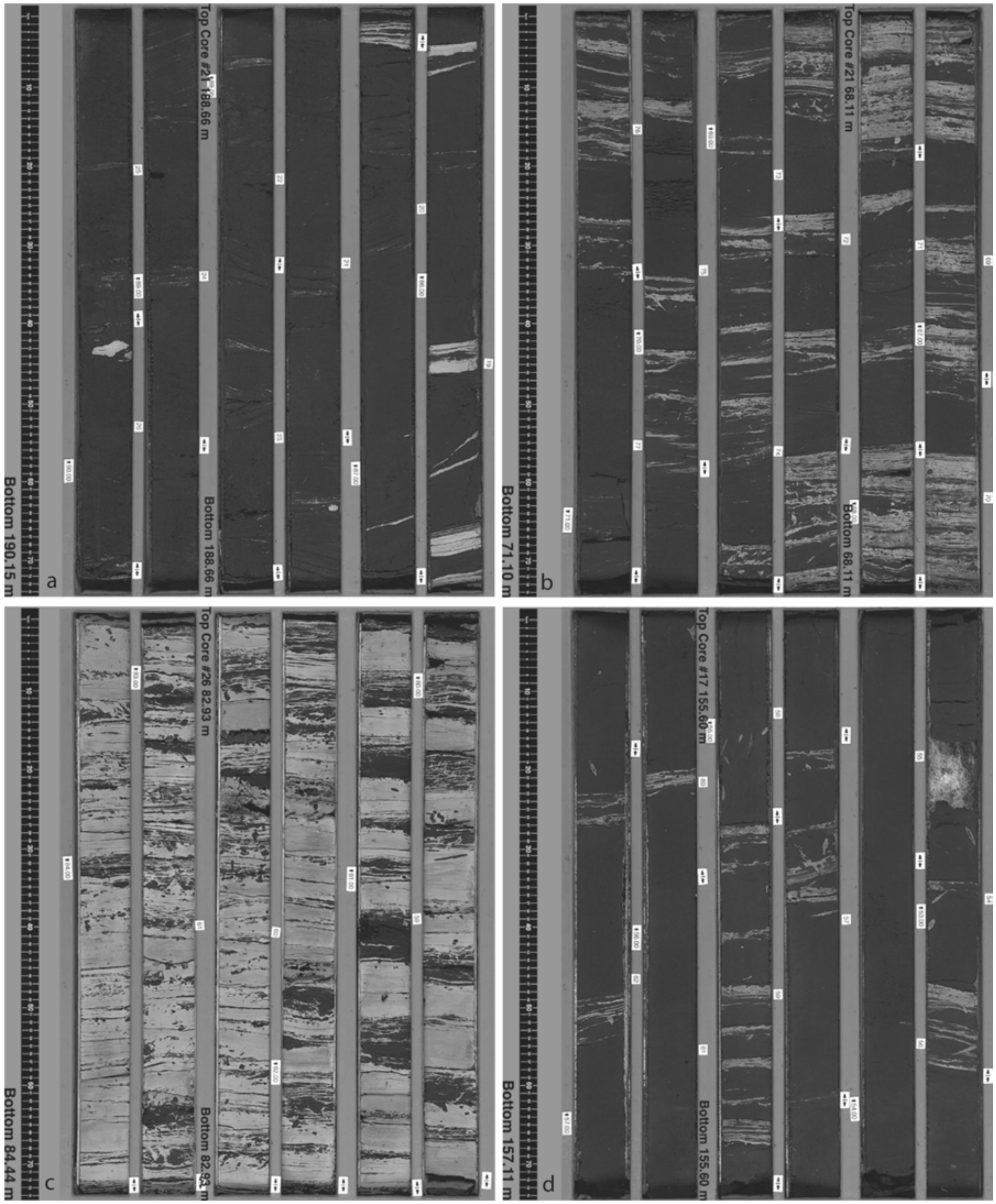

Figure 2. Representative intervals from the successions presented. Bottoms to lower left. ***a)*** **AA/15-23-96-13W4 - Sand-rich inclined units of inconsistent thickness. Mud clasts, carbonaceous material and sizable cross-beds are common.** ***b)*** **AA/01-06-97-11W4 - IHS with clean sands and interlaminated fine members. Burrowing is concentrated on the interlaminated material.** ***c)*** **AA/12-31-96-11W4 - IHS dominated by dense mud. Burrowing is found throughout, but is concentrated on interlaminated mud and silt/sand.** ***d)*** **AA/16-06-97-12W - Sand-rich inclined units of inconsistent thickness. Cylindrichnus and Skolithos are common in the well sorted silt/sand, and sedimentary structures are of relatively small scale.**

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