PS Sedimentological and Ichnological Analysis of the McMurray IHS (Kearl Area)*

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Abstract

The Lower Cretaceous McMurray oil sands contain inclined heterolithic stratification (IHS), which formed due to lateral and locally vertical accretion within channels. Variable interpretations as to the depositional affinity of IHS have been put forth, and these range from fluvial to middle estuary. This paper attempts to integrate ichnological and sedimentological data to propose a refined paleogeographic interpretation for a local occurrence of the McMurray Formation IHS.

A detailed analysis of five wells from the Kearl area (57.21 N, 111.26 W) of the Athabasca oil sands was conducted. Research concentrated on establishing sedimentological and ichnological trends by: 1) core logging 2) facies analysis, and 3) analysis of the individual bed thicknesses, bioturbation indices, diversity and diameter of ichnofossils, and their distribution.

Two main facies associations were observed: 1) thickly bedded cross-stratified sandstone; and 2) IHS of variable bed thickness and sand-mud ratios. The thickly bedded sandstones are characterized by high-angle, trough cross-stratification and grain size striping. Overall, there is a lack of bioturbation, however rare thin mud beds and rip-up clasts can show low bioturbation intensities and an impoverished diversity. The cross-bedded units are the result of strong currents, and the sedimentary environment was brackish in its nature, which are consistent with the fluvio-tidal transition.

IHS units are characterized by interbedded sand- and mudstone, where the mud-to-sand ratio, bioturbation intensity, diversity and maximum trace diameter increase upwards. We interpret this trend to represent a subtidal channel grading to intertidal zone succession, wherein the lowered current energy upwards is associated with a drop in sedimentation rate, and promotes the accumulation of organic rich sediment, providing abundant food resources for deposit feeding organisms. Ichnological observations, including overall diminutive, low-diversity suites of trace fossils, and abrupt changes in the style and distribution of bioturbation, further indicate that the IHS units represent amalgamated geobodies and that sediment deposition occurred during changing salinity levels or within a brackish-water setting. In short, the presence of brackish-water trace-fossil assemblages, and evidence of shoaling into an intertidal zone are both strongly associated with sedimentation in tidally influenced channels of the inner estuary.

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Introduction and Study Area

- The oil sands of the Lower Cretaceous McMurray Formation contain the largest bitumen reserves in the world. The total calculated reserves constitute 1.68 trillion barrels of bitumen in-place [1,2] . The oil sands are contained within three main areas: Peace River, Athabasca (Fig. 1) and Cold Lake. The largest and most developed deposits are situated within the Athabasca area, which covers more than 140 000 km2 [3].

Fig. 1. Location of the Athabasca Oil Sands deposits and the Kearl study area in Alberta, Canada.

- The study area is located within the Kearl Oil Sands proposed mine area, around 70 km north of Fort McMurray (Fig. 1, 2). The ownership is subdivided between Imperial Oil Resources and Exxon-Mobil Canada Ltd. , which own 70% and 30% of the project, respectively.

- Analytical data for the project was collected from five wells situated within the Kearl area (Fig. 2).

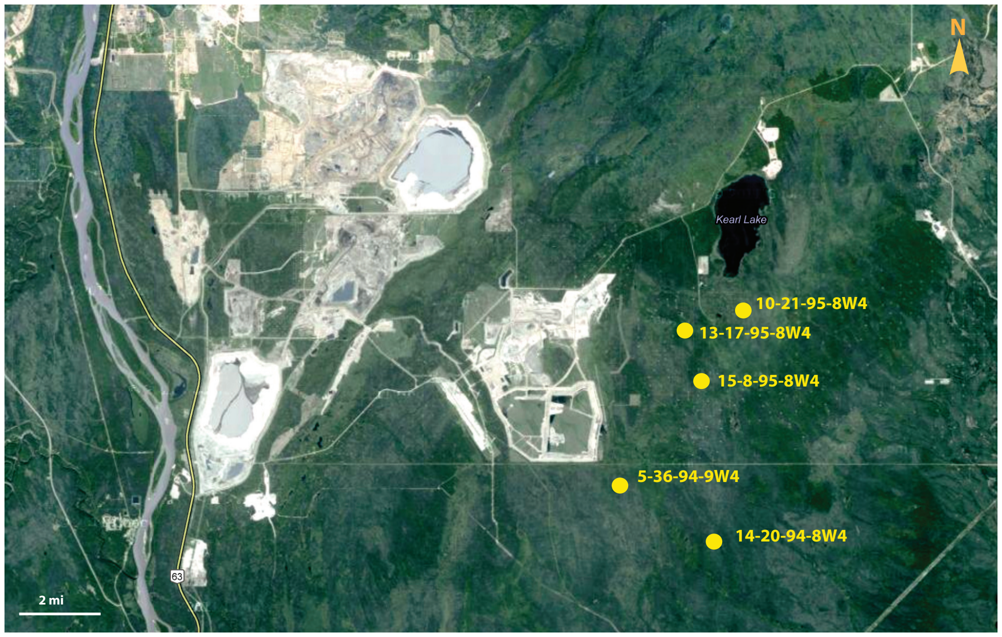


Fig. 2. Location of the analysed core data, Kearl Oil Sands project, Athabasca Oil Sands, Alberta, Canada.

Stratigraphy

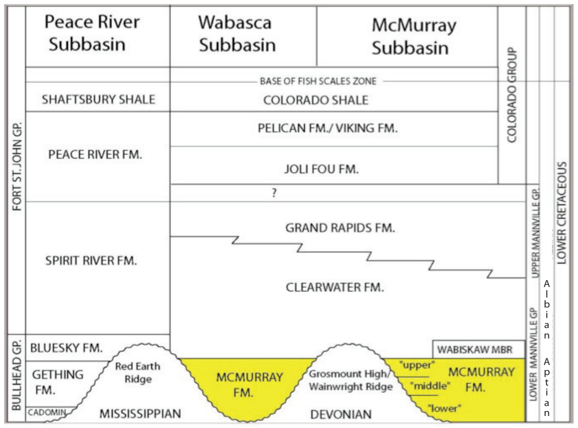


Fig. 3. Regional stratigraphy of the Athabasca Oil Sands deposits.

- In the Athabasca Oil Sands region the McMurray Formation was deposited within the topographic lows along the sub-Cretaceous unconformity (Fig. 3). The subcropping strata dips to the SW, and is represented by resistant Devonian carbonates in the McMurray Subbasin (Fig. 3, 5).

- The McMurray Formation is subdivided into three informal units: lower, middle and upper members (Fig. 4).

- The *lower member* constitutes thick bedded massive and cross-stratified sands of fluvial - brackish origin, capped by a floodplain unit.

- The *middle member* contains Inclined Heterolitic Stratification (IHS) up to 25 meters in thickness of varying lithological composition and complex lateral relationships.

- The *upper member* includes up to three coarsening-upward intervals, representing prograding shoreface deposits within the restricted bay environment.

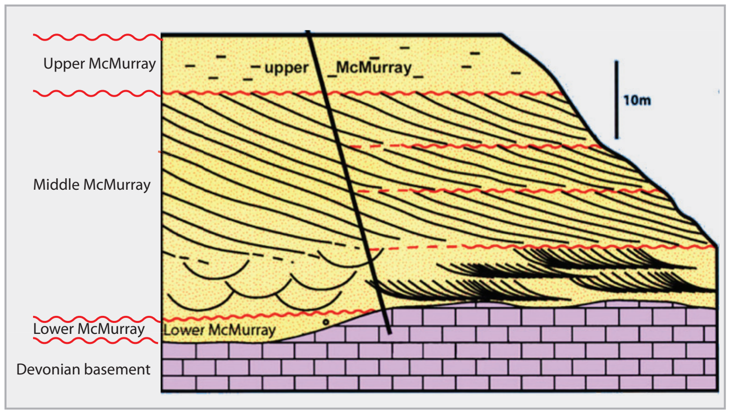


Fig. 4. Informal threefold stratigrafy of the McMurray Formation [4]. Outdated facies schematics on the left : large-scale deep channels. Modern facies interpretation on the right: IHS commonly represent smaller-scale and amalgamated channel deposits. Modified after Mossop and Flach (1983), Lettley (2004).

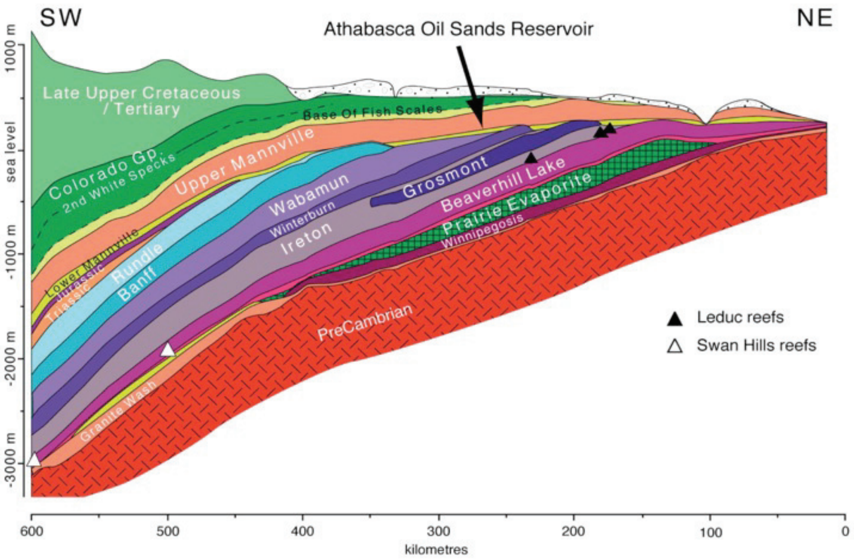


Fig. 5. Regional geology of the Athabasca Oil Sands. From Ranger, 1994.

Methods

- Analytical data was collected through detailed core logging of five wells from Devonian carbonates up to the Wabiskaw Member, if present. Core logging was accomplished using the software Apple Core © (Fig. 6).

- Data collected included sediment type, grain size, physical sedimentary structures and accessories, types of bed contacts, the identification of ichnofossils, bioturbation indices (Fig. 6), sedimentary facies and facies asscociations.
- The boxed cores, significant sedimentary and ichnological structures were photographed (Fig. 7-9).

Fig. 7. Core logging at the University of Alberta core facility.

Fig. 8. A boxed core picture. Well 15-8-95-8W4, boxes 24-25.

Fig. 9. A macrocore picture showing intensive bioturbation by *Gyrolithes*. Well 15-8-95-8W4, depth 44.0 m.

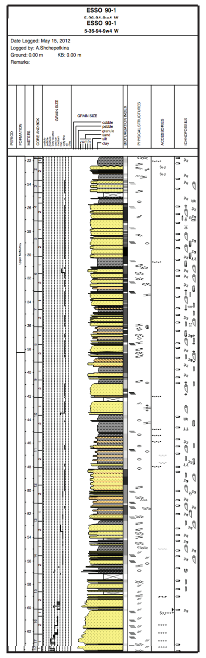


Fig. 6. A litholog of well 5-36-94-9W4 made in Apple Core © software.

- The data was processed for ichnofossil diversity, bioturbation index variation, and size-diversity index (SDI). SDI reveals the response of burrowing infauna to environmental stresses, particularly to salinity, indicating longitudinal trends in brackish water settings [8-10].

Research Rationale

- This research aims to refine and simplify the previously used terminology for tide-dominated estuaries, *e.g.*, different authors use a variety of terms to describe the same subenvironments within the Gironde Estuary, France (Fig. 10).

- Multiple subenvironments including "tidally-influenced fluvial" and "fluvio-tidal transition" zones are discernable in modern estuary studies by measuring the salinity and tidal currents distribution. These terms lack proper definition, but are embedded in the current scientific literature.

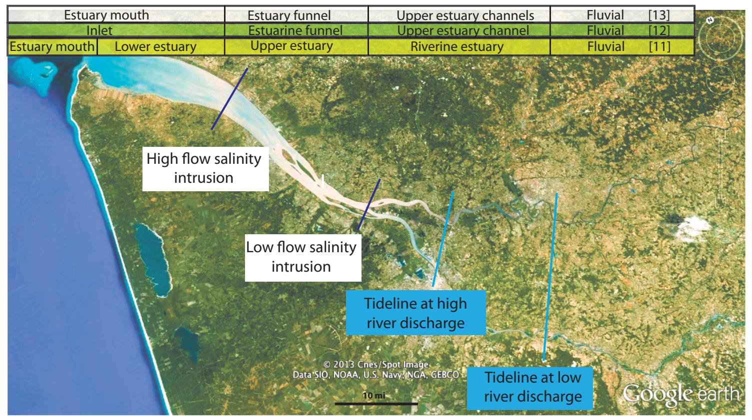


Fig. 10. Estuarine subenvironments based on literature review. Gironde Estuary, France.

- A precise level of estuarine subdivision cannot be achieved in studies of ancient deposits, *i.e.,* it is often impossible to observe any tidally-induced sedimentary structures in the limited core datasets, especially within the inner parts of the estuary.

- Existing estuarine models based on modern research are dissatisfying. There is a need to limit and implement terms which can be easily used while working with ancient strata and especially limited datasets (Fig. 11).

- The following subdivisions are suggested based on literature review and characterists observed in core (Table 1):

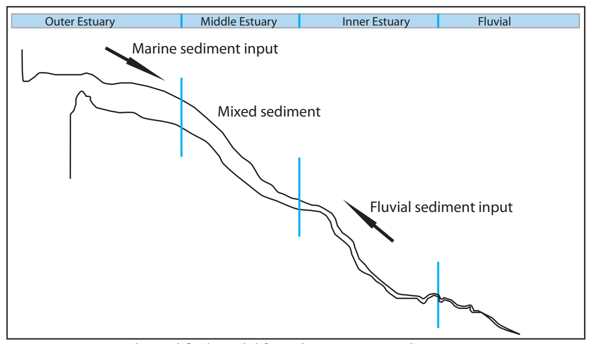


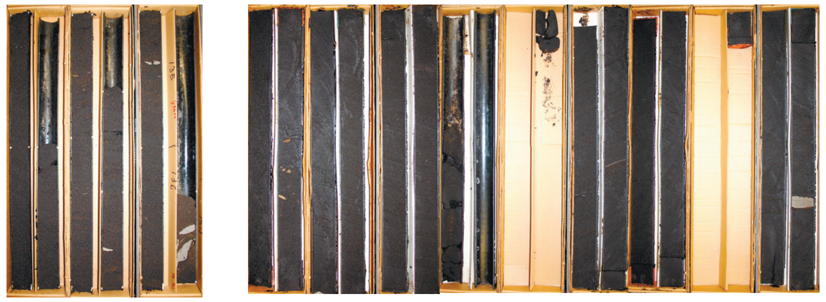
Fig. 11. A proposed simplified model for subenvironment division in an ancient tide-dominated estuary, based on a limited dataset.

Outer Estuary	Middle Estuary	Inner Estuary
• Marine sediments - the primary source • Landward bedload transport • Wide and deep channels • Constant marine salinities • Robust and diverse trace fossils • Strong tide and wave action • Inhibited preservation of biogenic activity	• Sediments from the fluvial and marine sources • Constant action of tides • Low to moderate tidal current velocities • Strongly heterolithic IHS deposits • Variable salinities (mainly mesohaline waters) • Extensive bioturbation • High preservation potential	• Sediments primarily from the fluvial source • Constantly modified by the tides • Net seaward sediment transport • Exceptional preservation of the tidal sedimen tary structures • IHS with rare, thin mud drapes • Freshwater and oligohaline waters • Rare bioturbation

Table 1. Characteristics of the subenvironments within the tide-dominated estuary.

Facies

- Four facies and three facies associations have been recognized within the given well dataset. The facies are: high- and low-angle cross stratified sand (F1), pervasively burrowed muddy sand (F2), inclined heterolithic sediments (F3), and soft-sediment deformed deposits (F4). The facies have been subdivided into subfacies.



Well 13-17-95-8W4. Boxes 45, 46, 48. Well 10-21-95-8W4. Boxes 32-38.

Facies 1

- High- and low-angle bedding, trough cross-stratification (TCS)
- Bioturbation: *Planolites*
- BI: 0 -1 (absent to sparse)
- Interpretation: lower point bar/ channel lag (inner to outer estuary)

Well 5-36-94-9W4. Boxes 12-13.

Facies 2

- Planar horizontal and wavy bedding
- Bioturbation: *Planolites, Skolithos, Cylindrichnus, Thalassinoides*
- BI: 5-6 (complete)
- Interpretation: intertidal flat (inner to middle estuary)

Well13-17-95-8W4. Boxes 19-21. Well 5-36-94-9W4. Boxes 16-17.

Facies 3a

- Low- and high angle, horizontal, wavy and lenticular bedding, TCS, ripple lamination
- Bioturbation: *Planolites, Cylindrichnus, Skolithos, Arenicolites, Palaeophycus*
- BI: 0 - 6 (absent to complete)
- Interpretation: lower –middle point bar (inner to middle estuary)

Well 14-20-94-8W4. Boxes 24-27. Well 5-36-94-9W4. Boxes 25-28.

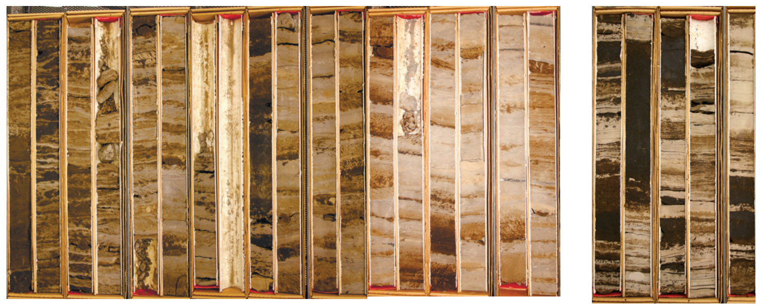
Facies 3b

- Structureless and laminated mud, low- and high-angle, lenticular and wavy bedding, current and combined flow ripples
- Bioturbation: *Planolites, Cylindrichnus, Arenicolites, Skolithos, Thalassinoides, Gyrolites*
- BI: 2-4 (rare to common)
- Interpretation: middle - upper point bar (inner to middle estuary)

Well 5-36-94-9W4. Boxes 29-32. Well 13-17-95-8W4. Boxes 55-58.

Facies 3c

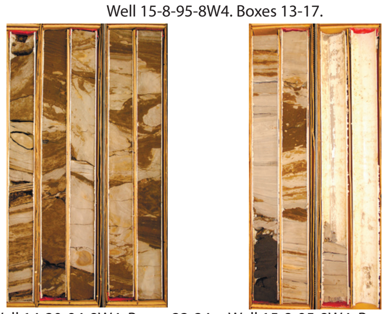
- Lenticular bedding, pin-head, low-angle and horizontal lamination, structureless mud and silt, current ripples, microfaults
- Bioturbation: *Planolites, Cylindrichnus, Thalassinoides, rhizoliths*
- BI: 0-2 (absent to rare)
- Interpretation: channel abandonment, intertidal muddy channel/creek



Well 15-8-95-8W4. Boxes 13-17. Well 14-20-94-8W4. Boxes 27-28.

Facies 3d

- Low- angle, horizontal, wavy and lenticular bedding, current ripples, convolute bedding
- Bioturbation: *Planolites, Cylindrichnus, Arenicolites, Skolithos, Thalassinoides*
- BI: 2-3 (low to moderate)
- Interpretation: upper point bar/intertidal flat/vertical accretion channel-fill (inner to middle estuary)



Well 14-20-94-8W4. Boxes 23-24. Well 15-8-95-8W4. Box 26.

Facies 4

- Structureless mud, low-angle, horizontal lamination, chaotic bedding, sand-filled cracks
- Bioturbation: *Planolites, Cylindrichnus, Palaeophycus*, mottled fabric
- BI: 0-6 (absent to complete)
- Interpretation: penecontemporaneous soft-sediment deformation of estuarine channel margins/ point bars (inner to middle estuary)

Facies Associations

- Facies Associations (FA) consist of a number of genetically related facies, combined together in a vertical succession [14-15].

- Three facies associations, describing different portions of the estuary, were denoted for the studied core dataset (Table 2).

Inner Estuary (FA 1)	Middle Estuary (FA 2)	Middle - Outer Estuary? (FA 3)
• F1 - F3a - F4 - F3a - F3b - F3d • F1 - F3a - F3c • F1 - F3c • F1- F3d - F3c • F3a - F3b • F3a - F3d	• F1- F3a - F3d • F1- F3d • F3a • F3a - F3b - F3d • F3a - F3d • F3b • F3b - F3a - F3d • F3b - F3d - F4 • F3b - F2 • F3b - F2 - F3d • F3d • F3d(*Gy*) - F3d	• F1 - F4 - F1 - F3b

Table 2. Genetically related facies, comprising Facies Associations.

Facies Association 1 - Inner Estuary

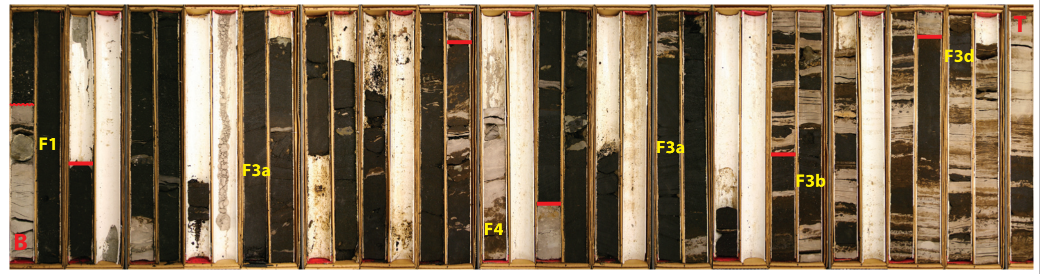


Fig. 12. Facies F1-F3a-F4-F3a-F3b-F3d comprising an inner estuary point bar succession. Well 14-20-94-8W4.

Facies Association 2 - Middle Estuary

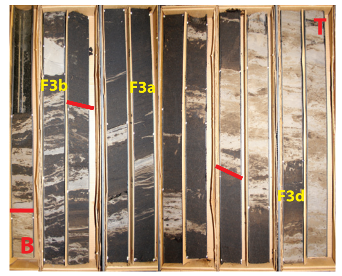


Fig. 13. Facies F3b-F3a-F3d comprising a middle estuary point bar succession. Well 13-17-95-8W4.

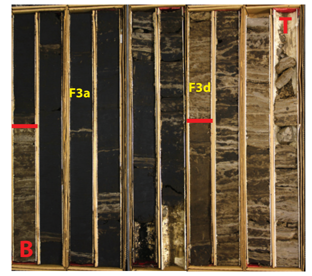


Fig. 14. Facies F3a-F3d comprising a middle estuary point bar succession. Well 15-8-95-8W4.

Facies Association 3 - Middle - Outer Estuary

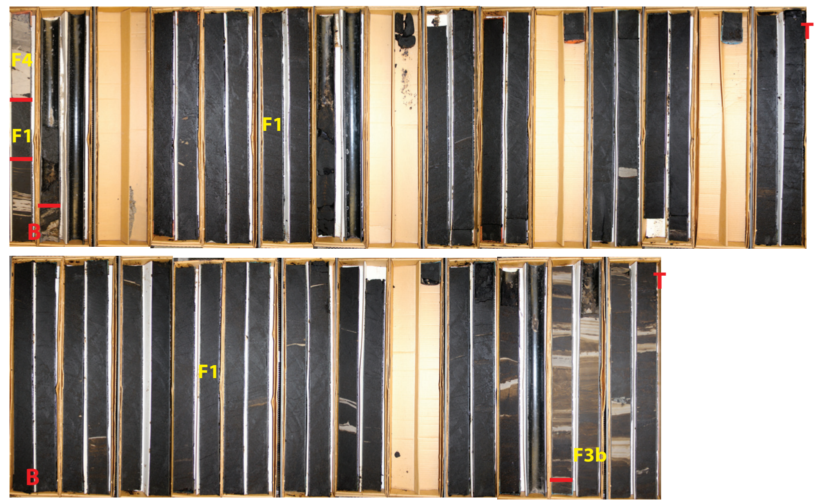


Fig. 15. Facies F1-F4-F1-F3b comprising a middle-outer estuary (?) point bar succession. Well 10-21-95-8W4.

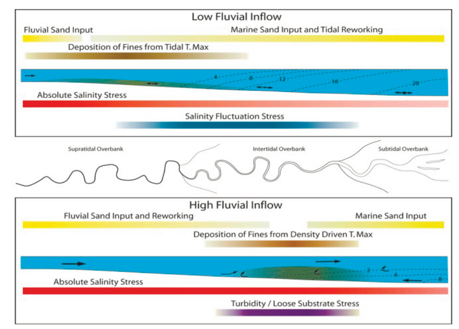


Fig. 16. Turbidity maximum displacement during low and high fluvial discharge within the tide-dominated estuary. From Lettley, 2004.

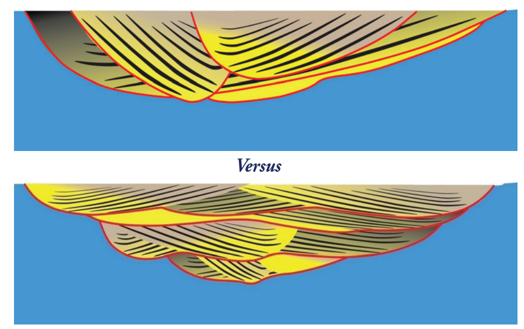


Fig. 17. IHS commonly represent smaller amalgamated channels. Their lateral correlation is not generally possible in the McMurray Formation.

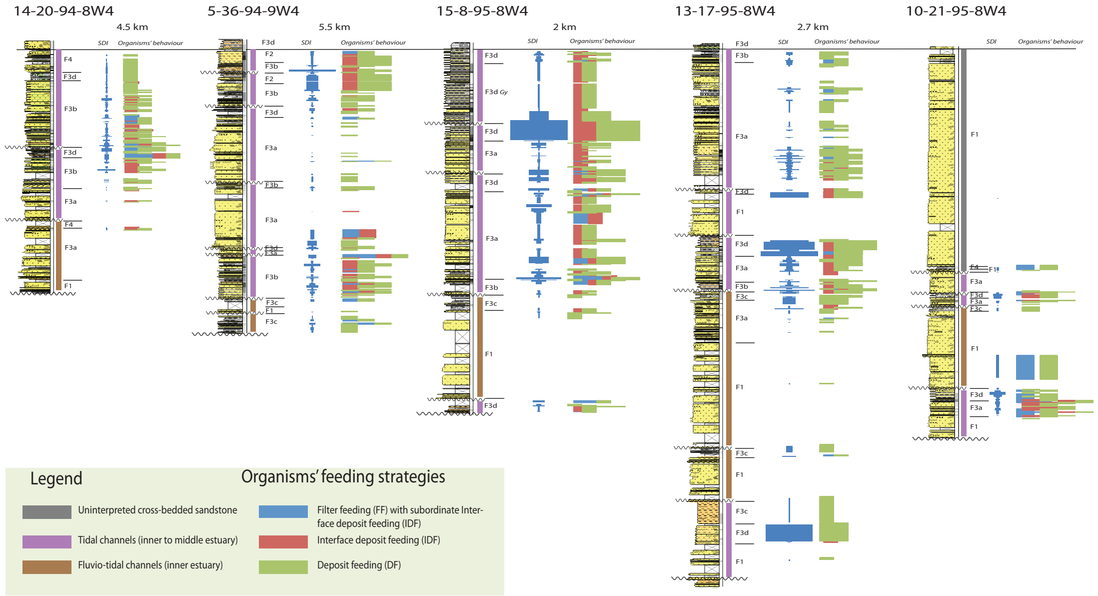


Fig 18. Lithologs with SDI and organisms' behaviour patterns.

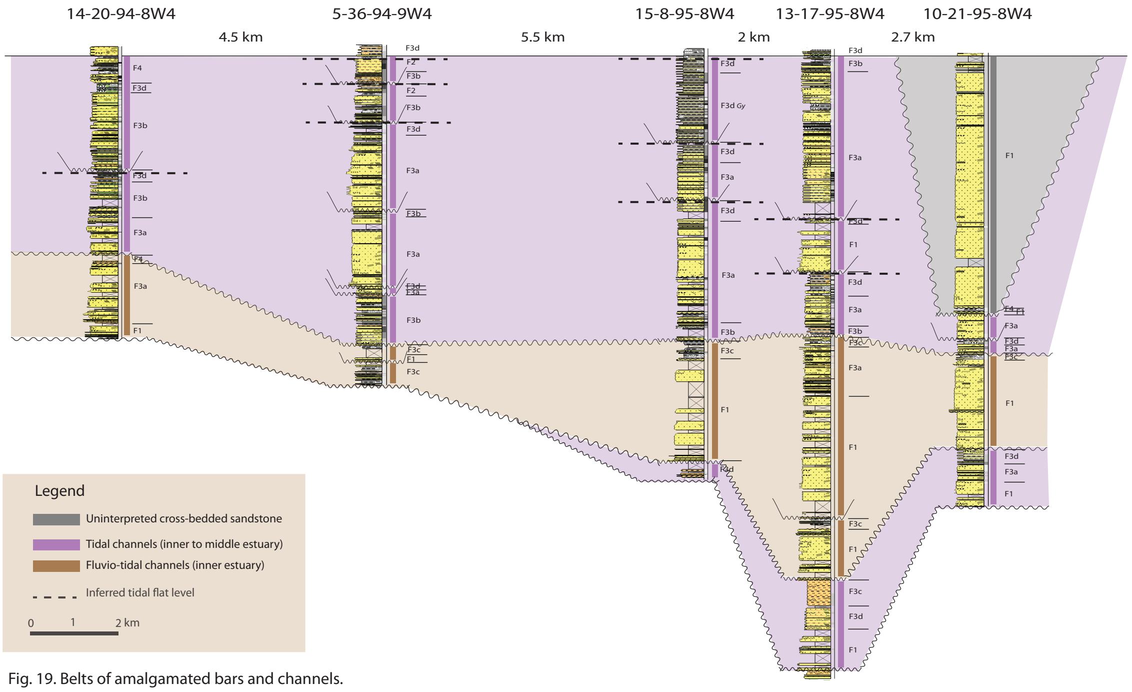


Fig. 19. Belts of amalgamated bars and channels.

Discussion

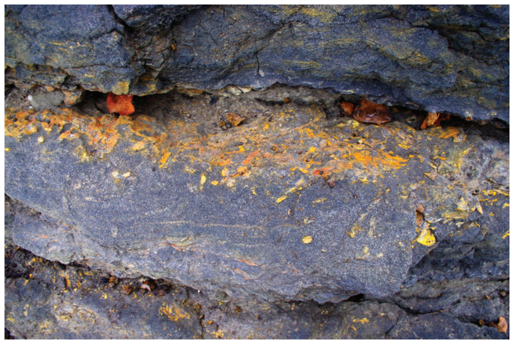


Fig. 20. A common trace fossil *Cylindrichnus*, oxidized, as appeared in outcrop studies. Near Fort McMurray, along the Athabasca River.

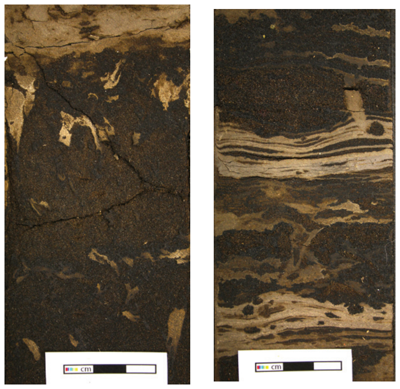


Fig. 21. A common trace fossil *Cylindrichnus* as appeared in core studies. Well 13-17-95-8W4, depth 47.89 m and 35.15 m.

Fig. 22. A channel incision with sand-dominated IHS deposits. Middle McMurray Formation. Near Fort McMurray, along the Athabasca River.

Fig. 23. IHS with various dips, comprising several channel incision events. Middle McMurray Formation. Near Fort McMurray, along the Athabasca River.

Conclusions

- The Lower Cretaceous middle McMurray Formation contains IHS deposits formed in a variety of estuarine subenvironments.
- Four major episodes of sea level change were identified.
- The case study shows that transgression during the McMurray deposition time was punctuated with periods of regression.
- Channels of different sizes and dimensions were identified during the core study.
- Correlation of individual channels is obstructed by complexity of the middle McMurray lateral relationships.
- Belts of amalgamated bars and channels can be traced along distances of several kilometers.
- A thick interval of cross-bedded sandstone was uninterpreted for the depositional environment. Primary sedimentary structures and negligible amounts of bioturbation solely by *Planolites* fail to help in the depositional environment interpretation. Further outcrop studies are needed for a more accurate interpretation.
- Tidal flat levels can be identified using primary sedimentary structures, lithology, high SDI values and multiple organisms' behaviour patterns.
- Tidal flat levels help approximate the stages of sea level rise and paleotidal range at a finer scale.

Acknowledgments

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Dr. Jenni Scott, myself and Dr. Murray Gingras at the McMurray Formation Amphitheater outcrop near Fort McMurray, AB, Canada.

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