Description and Interpretation of Coarsening-Upward Cycles in the McMurray Formation, Northeastern Alberta: Preliminary Results

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ABSTRACT

The McMurray Formation in the Athabasca bitumen accumulation region of northeastern Alberta exhibits some of the most complex lithofacies variations within the Western Canada Sedimentary Basin. Refinements to depositional models are necessary, and a greater comprehension of internal stratigraphic architecture of the formation is required. Such an improvement in understanding of the stratigraphic framework of the McMurray Formation could aid in the determination of occurrence and distribution of reservoir facies at both a lease and reservoir scale. This information could ultimately improve cost savings regarding the drilling strategy associated with various subsurface SAGD projects.

A new sequence stratigraphic framework for the McMurray Formation was proposed by Ranger (1994). He identified a number of laterally correlatable sequences. We focus on some of the sedimentological details associated with these sequences and try to develop environmental interpretations based on core examination from Townships 79 and 80, Range 7W4. A series of stacked coarsening-upward cycles (representing the highstand systems tract of sequences) has been identified within the Lower Cretaceous McMurray Formation of northeastern Alberta. These coarsening-upward cycles are interpreted to represent progradation of mixed wave/fluvial-influenced bayhead deltas into a partially-closed, brackish inland seaway.

INTRODUCTION

Until recently, the internal stratigraphic architecture of the McMurray Formation had been poorly understood. Some researchers, however, (*e.g.;* Nelson and Glaister, 1978; Ranger, 1994; Ranger and Pemberton, 1997) have successfully commenced to unravel the stratigraphic complexity of the McMurray Formation through the recognition of some geologically significant and correlatable stratigraphic surfaces. These surfaces comprise argillaceous units that can be correlated for several sections and bound cleaning/coarsening-upward cycles. Such coarsening-upward cycles in the McMurray Formation have rarely been documented in current literature, and yet are not uncommon in wells or cores. It is of paramount importance that the genesis of these coarsening-upward cycles be fully comprehended, and their genetic relationship to the more *typical* channel facies of the McMurray Formation be understood (Ranger *et. al.,* 1994; Ranger and Pemberton, 1997). A better understanding of the genesis and geometry of these cycles will allow for an improved understanding of the McMurray stratigraphic architecture, and may aid in the spatial prediction of reservoir quality sands required for SAGD projects. In this abstract, we focus on the core description and interpretation of lithofacies encountered in coarsening-upward cycles from the McMurray Formation.

METHODS

Four cores and 30 well-logs from the McMurray Formation were examined from Townships 79 and 80, Range 7W4 (Fig. 1). Lithofacies descriptions involved the examination of the sediment texture, mineralogy, bedding thickness and nature of contacts, colour, fluid type, body fossils, trace fossils, sedimentary structures and cement. Sandstone and shale samples have been extracted for palynological analysis. This data will be used in conjunction with the ichnological and physical sedimentological data to reconstruct the environment of deposition.

SEDIMENTOLOGICAL RESULTS

Coarsening-upward cycles are more commonly preserved towards the top of the McMurray Formation, where two or more vertically-stacked cycles may be present (Fig. 2). The uppermost cycle can sometimes be traced for several townships, but more typically the lateral extent varies from 1 to 5 kms. These cycles vary from 1 to 10.5 metres in thickness; the thickest cycle commonly occurring at the top of the McMurray Formation.

Each cycle exhibits a coarsening- and cleaning-upward trend (Fig. 2). The occurrence and thickness of sandstone beds increases upwards as does bitumen saturation and grain size. Fully developed cycles are composed of three lithofacies (A, B and C; Table 1). Each lithofacies exhibits a successively greater proportion of sand. Cycles commence with bioturbated mudstones of Lithofacies A which grade upward into interbedded sandstone and mudstone of Lithofacies B which finally passes up into sandstones of Lithofacies C. Poorly-developed cycles consist of lithofacies A and B only. Cycles are typically bounded above and below by laterally correlatable dark-grey laminated shale or paleosol horizons. Such horizons may be traced for up to several sections. The base of cycles can be sharp and can overly a variety of lithologies ranging from shale to sandstone. In one instance, a *Glossifungites* surface has been identified at the base of a cycle where heavily bioturbated silty-shales abruptly overly laminated clayshales (Fig. 3).

Lithofacies A: Cycles typically commence with a light-grey silty-shale (mudstone) which is heavily bioturbated forming a low diversity/very high density ichnofossil suite. The traces are mostly very small *Planolites* and *Teichichnus* which reflect grazing and deposit feeding strategies (Fig. 3a; Table 1).

Interpretation: Ichnofossil suites resulting from brackish water faunal communities tend to constitute a distinctive pattern resulting from the stress of low and/or fluctuating salinities. Diversity is low due partly to a low diversity of faunal species, but mostly due to a limited range of feeding (trophic) activity. Fluctuating conditions encourage colonisation by trophic generalists resulting in simple structures rather than the more complex structures left by specialised feeding strategies. One consequence of this is a mixed *Skolithos-Cruziana* ichnofacies. Fluctuating environmental conditions encourage population by opportunistic species which reproduce rapidly and gregariously. The predominance of juveniles, as well as the advantages provided by a small surface area when exposed to the ionic stresses of low salinity, typically correspond to brackish trace fossil forms that are dominantly diminutive in size. Although diversity may be low, the individual ichnofossil forms are typically abundant due to aggressive, opportunistic colonisation combined with a lack of competition. Lithofacies A displays the typical characteristics of these features, and supports the brackish, estuarine interpretation of these sediments. Furthermore, the high degree of bioturbation together with the mud to silt size particles, indicates that the sedimentation rate was low.

Lithofacies B: Sand and silt content tends to increase upward whereas clay content and bioturbation intensity decreases upward (Figs. 2, 3a and 4a; Table 1). Sandstone is very fine-grained and forms thin (2-4 cm thick) beds towards the base of the lithofacies. These beds are sharp-based, and exhibit low-angle inclined parallel-laminated to oscillation ripple cross-laminated sedimentary structures. Frequency of occurrence of sandstone beds and bed thickness increases upward with values ranging from 8 to 15 cm. These sandstone beds are sharp-based and exhibit low-angle inclined parallel-lamination, or horizontal, parallel-lamination and grade up into interlaminated sandstone and mudshale beds forming combined-flow asymmetrical ripple lamination and finally into laminated medium-grey clayshale, 1 to 8 cms thick. In places, tops of clayshale beds exhibit 1-2 cm long synaeresis cracks that are infilled with sandstone from the overlying sand bed. Rare *Planolites* trace fossils are restricted to the interlaminated sandstone-shale portion of each unit. There are intervals of the lithofacies with no thick-bedded, parallel-laminated sandstone beds. These intervals are dominated by thinly-interbedded sandstones and mudshales reflecting oscillation ripple cross-laminated features with a higher content of synaeresis cracks in the mudshales.

Interpretation: Towards the base of Lithofacies B, the sharp-based, thin-bedded, sandstone beds, exhibiting parallel-laminated structures that grade up into combined-flow ripple lamination, were deposited from a decelerating unidirectional current superimposed on background oscillatory currents. Background oscillatory currents are thought to have been formed by wind-induced waves. Continued current deceleration resulted in mud settling out of suspension and blanketing the sand. The low abundance of bioturbation indicates that either the water column was of very low salinity (affected by recurring unidirectional currents of freshwater origin) or that there was a high clay sedimentation rate. The presence of synaeresis cracks suggests that salinity levels may have fluctuated somewhat. Intervals of thinly-bedded sandstone and mudshale with oscillation ripple cross-lamination were deposited from oscillatory background currents influenced by wind-induced waves.

The ichnofossil suite of Lithofacies B has an extremely low diversity, typically monospecific, and constitutes very simple structures. The ichnofossil suite is almost exclusively a *Cruziana* ichnofacies. There never appears to be a mixed *Skolithos-Cruziana* ichnofacies present. These characteristics are at the opposite pole from any fully marine ichnofacies, indicative of some extreme stress in the environment. This stress may be anticipated to be very low salinities, rapid deposition and/or extreme turbidity (probably associated with rapid deposition). The presence of synaeresis cracks suggests episodic salinity fluctuations. The synaeresis cracks are almost invariably present in clayshales that are completely barren of ichnofossils. The cracks typically originate from the top of a cycle and are overlain by the somewhat more bioturbated, sand and inter-laminated sand and mudshale. The barren clayshales containing the synaeresis cracks probably represent quiet conditions in a low salinity, or even freshwater environment. In a brackish environment with regularly fluctuating salinity (i.e. tidal cycles), interstitial water within a few centimetres of the sediment-water interface tends to be uniform but skewed towards marine values, a feature that serves to buffer the infaunal organisms against rapid salinity fluctuations. In the case of the synaeresis-cracked clayshales, the apparent lack of an infaunal community suggests that the normal interstitial salinity was extremely low, and therefore that the overlying water column was of extremely low salinity or fresh. Compared to Lithofacies A, this lithofacies indicates slightly less brackish water conditions.

Lithofacies C: Towards the top of each coarsening-upward cycle, sandstone beds range from 10 to 150 cms in thickness. The sandstone beds gradually coarsen-upward from lower-fine grained at the base of the lithofacies to medium-grained at the top. Most beds are sharp-based, and typically display horizontal to low-angle inclined parallel-lamination with rare fugichnia, which pass upward into combined-flow ripple cross-lamination and rare oscillation ripple cross-lamination (Figs. 3b and 4; Table 1). Occasionally, the parallel-lamination forms diverging laminae that display subtle upward increases and decreases in angle of dip. These structures are interpreted as hummocky cross-stratification. The sandstone beds grade or pass sharply up into medium-grey laminated shales with rare *Planolites* traces and synaeresis cracks. In certain parts of the lithofacies, thick-bedded, parallel-laminated sandstones are separated by intervals of thin-bedded, oscillation cross-laminated sandstone and clayshale with rare synaeresis cracks. Toward the top of the lithofacies sandstones sometimes exhibit small-scale trough cross-bedding and gently-inclined, parallel-laminations with internal discontinuity surfaces. The latter sedimentary structures are interpreted as swash cross-stratification. Rare *Skolithos* and *Cylindrichnus* traces occur within this lithofacies.

Interpretation: Decelerating unidirectional currents appear to have been the dominant process responsible for forming the sharp-based, thick-bedded, parallel-laminated sandstone beds of Lithofacies C. Hummocky cross-stratified structures developed within these sandstone beds may indicate a component of oscillatory flow associated with the unidirectional currents. The upward transition from parallel-lamination to combine-flow ripple cross-stratification and oscillation ripple cross-stratification reflects a deceleration of the unidirectional current, but sustained reworking of sediments by oscillatory currents (wind-induced waves). The overlying shale is laminated with rare *Planolites* traces and synaeresis cracks. The few traces and synaeresis cracks further indicate that the clay sediments were deposited under a fresh-to-brackish water mass. Rare *Skolithos* and *Cylindrichnus* traces in sandstone beds exhibit characteristics of a *Skolithos* ichnofacies. These traces indicate the presence of organisms with suspension feeding strategies that are accustomed to high-energy environments and shifting sandy substrates. Toward the top of the lithofacies, parallel-laminated sandstone beds are very thick, or are separated by very thin shale beds, and produce amalgamated sand-on-sand beds. These beds represent the most proximal currents which were erosive, removing the upper part of each upward-fining unit. The shale beds are eroded and removed or preserved as mud-filled vertical trace fossils forming concealed bed junctions (Fig. 3b). Swash cross-stratification is also present in these uppermost sands. It indicates high-energy levels resulting from wave-dominated background processes. Lower down in the lithofacies, the presence of thin interbedded sandstone and clayshale with oscillation ripple cross-stratification indicates deposition by background oscillatory wave processes.

INTERPRETATION

The general upward increase in grain-size, decrease in mudstone content and progressive change in style of sedimentary structures indicates the progradation of a sandstone body. The vertical arrangement of lithofacies A through C represents the superposition of proximal on distal environments. The bioturbated silty-shales at the base of each cycle (Lithofacies A), indicate that the sediment body prograded into a brackish water body below fairweather wave base as evidenced by the high-density/low-diversity opportunistic trace fossil suite. The increase in occurrence and thickness of sharp-based, parallel-laminated sandstone beds reflects the progressive increase in intensity of freshwater flood-derived currents over time. These currents are thought to have been dominantly freshwater in composition as they would make environmental conditions very difficult, if not intolerable, even for the most opportunistic organisms. The presence of wave-induced oscillation ripples and swash cross-stratified sands within lithofacies B and C indicates an influence from background wave-dominated processes. The cycles are herein tentatively interpreted as mixed fluvial-wave-dominated bayhead deltas that prograded into a brackish bay. The synaeresis-cracked clayshales may represent the bayhead delta above the salt wedge. The bayhead delta would only be exposed to marine water during periods of low fluvial flow, during storm surges, periods of extreme high spring tides or perhaps during post-storm oscillation of the salt wedge.

CONCLUSIONS

Several coarsening-upward cycles have been recognised in the McMurray Formation of northeastern Alberta. These cycles are bounded by correlatable shale horizons. It is thought that these cycles may represent a mode of background sedimentation within the McMurray Formation. Lateral continuity of these cycles is poor, as younger incised channels tend to rework and replace them with thick sandstone successions. The preservation potential of these coarsening-upward cycles increases upward in the McMurray Formation; the uppermost cycle being the most laterally extensive of all cycles so far recognised in this study area.

By analysing and recognising subtle variations in physical and biological signatures comprising coarsening-upward cycles, it may be possible in the future to refine and improve the palaeogeographic and geological model of the McMurray Formation in northeastern Alberta. More work is required to better delineate the lateral extent and correlation of these coarsening-upward cycles, their facies relationships, and their stratigraphic association with channel deposits.

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ACKNOWLEDGEMENTS

Jean-Loup Rubino is thanked for his comments on the sedimentology of the McMurray Formation. Iskander Umar provided stratigraphic picks for figure 2. The Core Research Centre is thanked for its continued high-calibre and efficient service. We also acknowledge TotalFinaElf S.A. for permitting us to present this information.

Lithofacies	Lithology	Sedimentary Structures	Trace Fossil Abundance	Trace Fossil Genera	Process Sedimentology	Environmental Interpretation
A	Light-grey silty-shale	None preserved	high	*Planolites, Teichichnus*	Slow sedimentation, brackish-water conditions	Prodelta (?)
B	Thin bedded, very fine-grained sandstone, Interlaminated sandstone and mudshale	Parallel-lamination, combine-flow cross lamination, oscillation ripple cross-lamination, synaeresis cracks	moderate	*Planolites*	Decelerating, unidirectional currents (freshwater distal flood events); oscillatory currents	Wave-dominated Distal Delta Front
C	Thick-bedded, upper fine grained sandstone	Parallel-lamination, cross-bedding, swash cross-stratification, hummock cross-stratification, oscillation ripple-cross lamination, synaeresis cracks	low	*Cylindrichnus, Skolithos*	Decelerating, unidirectional currents (freshwater proximal flood events); oscillatory currents	Wave-dominated Proximal Delta Front

Table 1. Lithofacies comprising coarsening-upward cycles of the McMurray Formation, northeastern Alberta.

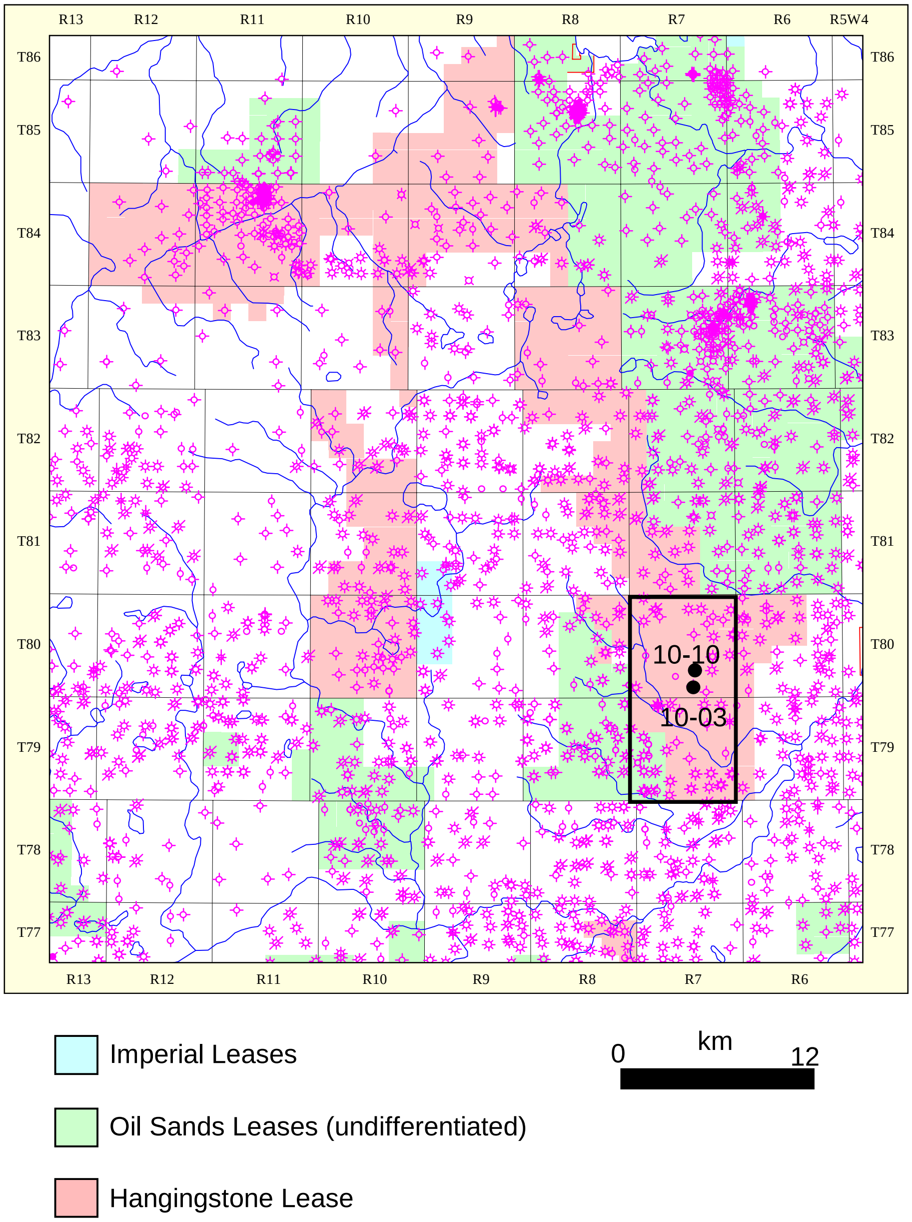


Figure 1. Location map of study area and 2 cores described in this abstract.

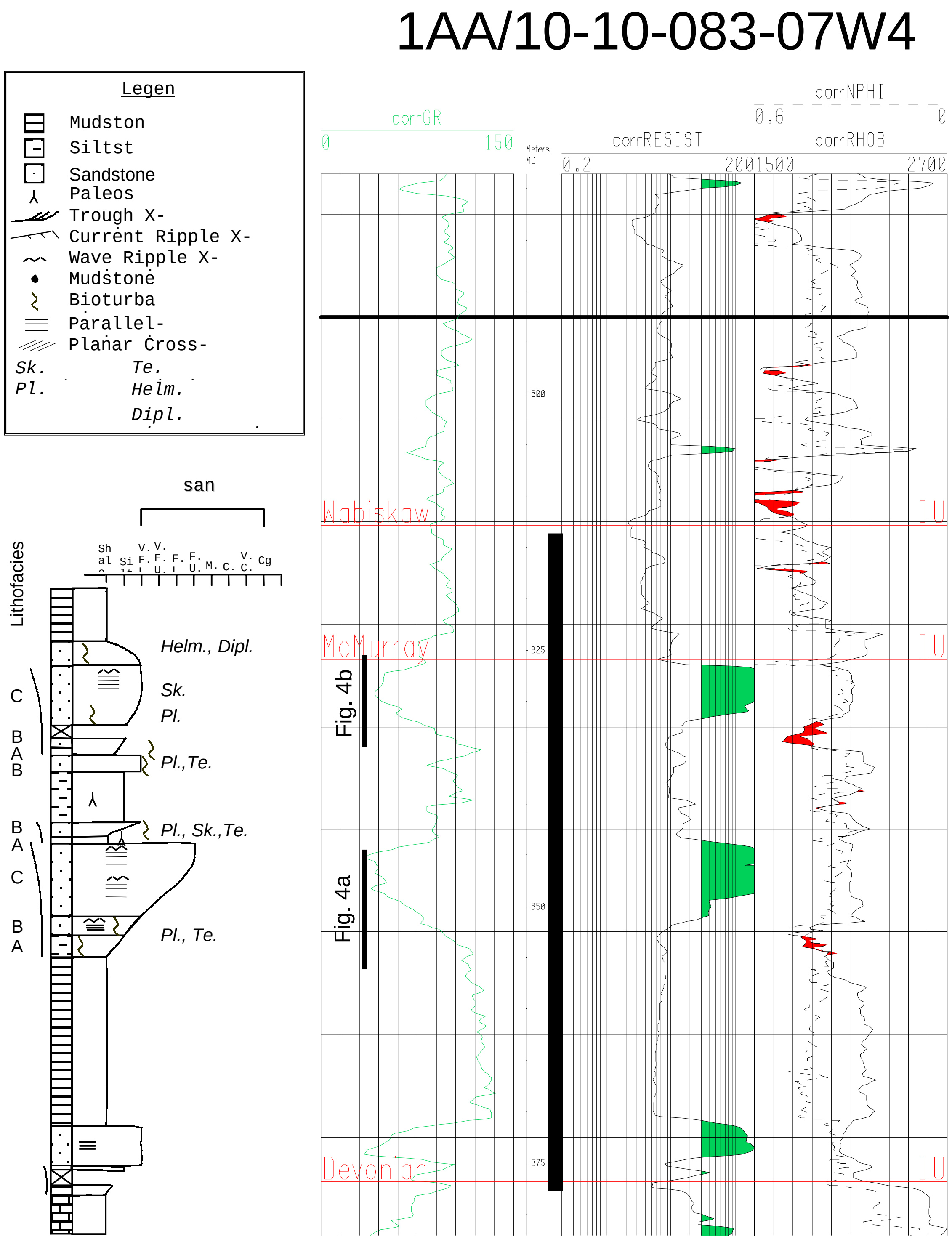
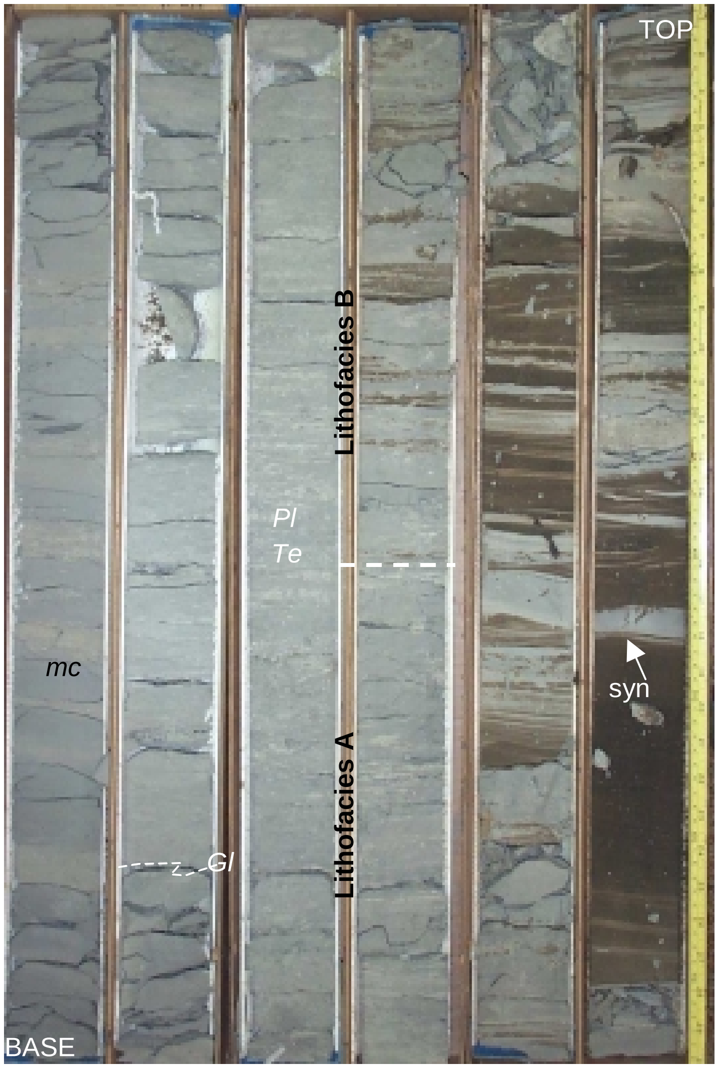
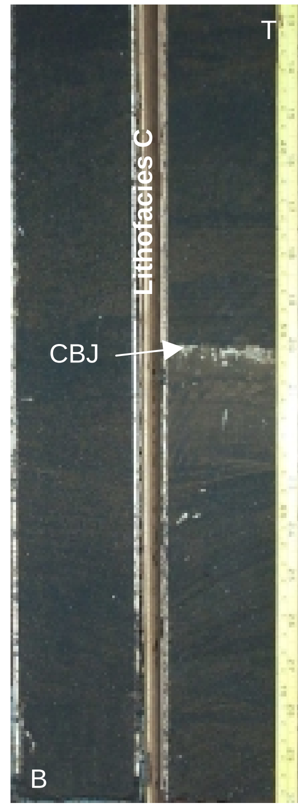


Figure 2. Type well-log and core description of coarsening-upward cycles. Solid green on deep resistivity refers to highly bitumen-saturated sandstones (long black bar indicates core interval; short black bars correspond to core intervals for figures 4a and 4b; formation picks courtesy Iskander Umar). Note, in this well, upper coarsening-upward cycle only partially preserved below basal Wabiskaw erosion surface. Measured true vertical depth in metres (well 1AA/10-10-080-07W4).



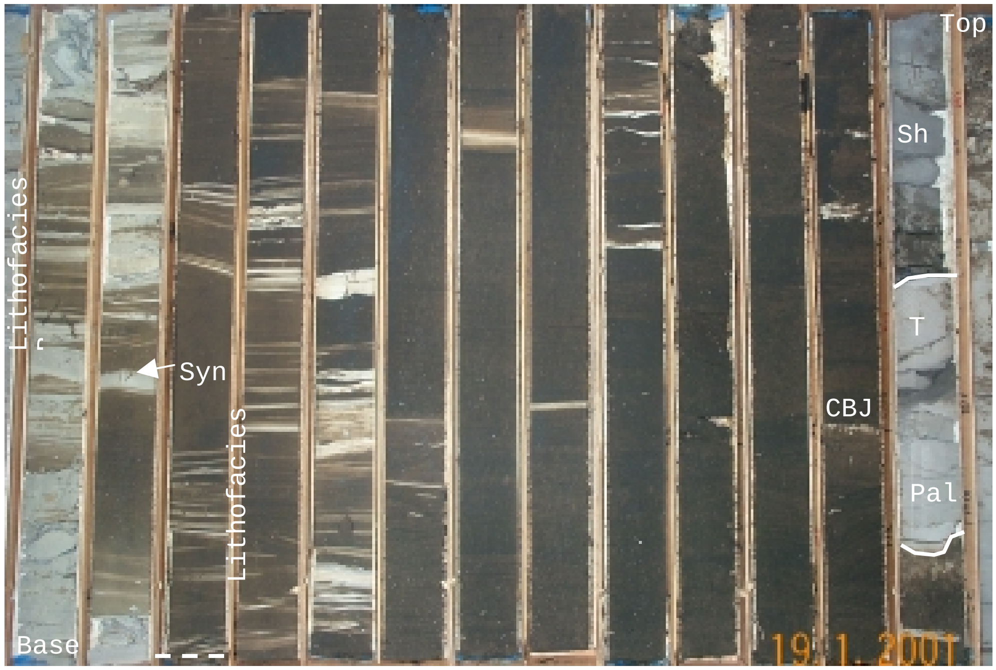
A



B

Figure 3. Core photographs of lower and upper parts of a coarsening-upward cycle (entire cycle illustrated in Fig. 4a). **A.** Core photograph of the lower part of a coarsening upward cycle exhibiting lithofacies A and B. The base of the coarsening-upward cycle commences with a *Glossifungites* surface. (*Planolites* (*Pl*.); *Teichichnus* (*Te*.); Synaeresis cracks (syn); *Glossifungites* surface (*Gl.*); massive claystone (mc)). (10-10-080-07W4, interval 354.5 to 344.00 metres; core box 75 cms long); **B**. Core photograph illustrating the upper part of the same coarsening-upward cycle (Lithofacies C) showing two thick-bedded bitumen-saturated sandstone units delimited by a concealed bed junction (CBJ) of mud-filled traces. The upper sandstone bed has a sharp, erosive base which planes off the mudstone bed (10-10-080-07W4, 374.8 metres; length of core 44 cms).

A.



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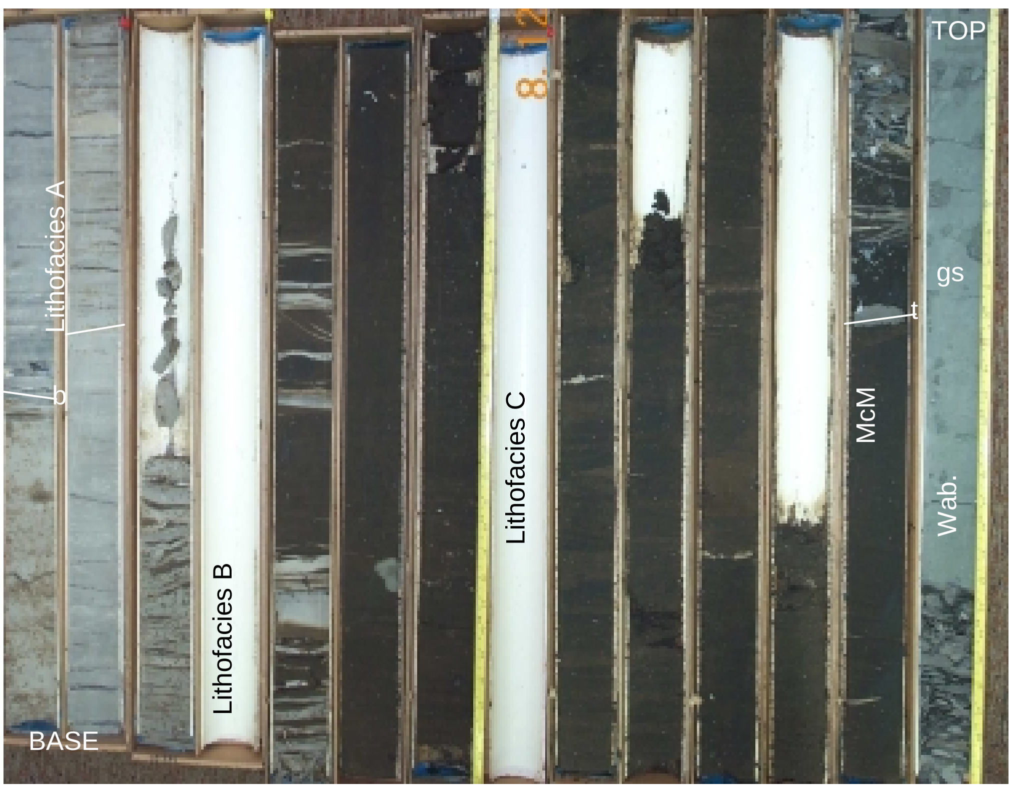

Figure 4. Core photographs illustrating coarsening-upward cycles of the McMurray Formation (core boxes 75 cms long). **A.** Lower coarsening-upward cycle (concealed bed junction (CBJ); paleosol (Pal); bioturbated, dark-grey shale (Sh); synaeresis cracks (syn); top of cycle (T); well 10-10-080-07W4, interval 354.5 to 344.00 m); **B.** Upper coarsening-upward cycle. An erosion surface at the McMurray/Wabiskaw contact results in incomplete preservation of the top of this cycle (Base of cycle (b); top of cycle (t); McMurray (McM); Wabiskaw (Wab.); bioturbated glauconitic sandstone (gs); well 10-10-080-07W4, 334.80-326.00 m).