

EARLY CRETACEOUS CONTINENTAL-SCALE SEDIMENT DISPERSAL: TOWARDS RESOLVING THE McMURRAY CONUNDRUM—DISCUSSION

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INTRODUCTION

Wahbi et al. (2025) addresses aspects of the oilsands-hosting McMurray Formation (Fm) in northeast Alberta, Canada. As one of the largest petroleum reservoirs on Earth, resolving the geology of the McMurray Fm has potentially wide-ranging economic implications, and so the interval has received significant research attention. As noted by Wahbi et al. (2025), differing interpretations of the McMurray Fm stem largely from varying assessments of the degree of marine influence, and this is commonly referred to as the “McMurray conundrum” (Gingras and Leckie 2017; Gingras et al. 2019). At its core, the McMurray conundrum describes the seemingly irreconcilable juxtaposition of: 1) fluvial architectures (point bars and channel belts) that are associated mainly with the C2 through A2 parasequences and some evidence that the regional parasequences were deposited in freshwater (terrestrial) environments; *versus* 2) the preservation of bioturbation in both sand beds and the mudstone layers that drape point bar surfaces (i.e., inclined heterolithic stratification) coupled with the minimal preservation of terrestrial strata (e.g., floodplain deposits, coal beds, and paleosols).

Channel thicknesses and point-bar architectures are well established from 3-D seismic images and cross sections (Hubbard et al. 2011; Labrecque et al. 2011; Musial et al. 2012; Durkin et al. 2017a, 2017b; Martinus et al. 2017; Brekke and Roenitz 2021) and from dip-meter and micro-imaging well logs (Brekke and Evoy 2001; Brekke and Couch 2011; Brekke 2015; Brekke et al. 2017; Brekke and Roenitz 2021). Geochemical studies of shells that are preserved sporadically in some regional parasequences indicate freshwater environments (Holdmen et al. 1997; Hasiuk et al. 2024), and dinosaur footprints and scroll bars have been reported from the tops of some point bars (Brekke 2015). In contrast, at the bed scale, extensive bioturbation in predominantly mudstone beds but also in sand beds is observed in many lateral-accretion deposits, with the style of bioturbation and its constituent trace fossils akin to estuarine point bars and not fluvial ones (Pemberton et al. 1982; Ranger and Pemberton 1992; Gingras et al. 2016; Shchepetkina et al. 2016; Gingras et al. 2019; La Croix et al. 2019, 2020). Moreover, terrestrial deposits such as paleosols and floodplain intervals that should have developed on all subaerially exposed surfaces and hence, should be widespread throughout the McMurray Fm if it accumulated in a terrestrial setting, are largely absent. Dinocyst assemblages in some McMurray point-bar deposits indicate mainly freshwater to slightly brackish water, with rare instances of a strong brackish-water influence (Hubbard et al. 2011; Dolby et al. 2013).

The degree of marine influence is important as mud-bed lengths and the proportion of mud in the channels increase from fluvial to estuarine settings (Burton and Wood 2013), and mud beds act as baffles to the vertical movement of injected steam needed to produce the bitumen. Additionally, in estuarine settings, extensive bioturbation in mudstone beds, especially where burrows are sand filled, may serve as conduits for the migration of steam through mudstone layers, thereby improving reservoir performance (Pemberton and Gingras 2005; La Croix et al. 2012).

Wahbi et al. (2025) present the results of three independent datasets to argue that the McMurray Fm comprises sediment laid down by a continental-scale drainage and that the deposits preserved in the oilsands region are not only fluvial but were deposited more than 1000 km from the paleoshoreline. However, in developing their interpretation, Wahbi et al. (2025) rely on a dataset that we consider insufficient, because it overlooks a substantial body of evidence that contradicts a fluvial model. Furthermore, the authors appear not to have incorporated considerations of time and stratigraphy, and once these elements are accounted for the notion that the entire McMurray Fm represents deposition along a continental-scale drainage becomes untenable.

QUESTIONABLE AND/OR LIMITED DATA

Wahbi et al. (2025) compare detrital-zircon (DZ) age spectra from across continental North America to the age spectra derived from DZ samples taken from the McMurray Sub-Basin (Wahbi et al. 2022) to argue for a continental-scale drainage. Their model builds upon previous DZ studies that introduced and refined the concept (Benyon et al. 2014; Blum and Pecha 2014). The application of DZ age spectra to the McMurray Fm and other Lower Cretaceous strata across North America has fundamentally shifted how the McMurray Fm is interpreted. However, as DZ analyses have become increasingly common in sedimentological and stratigraphic studies, higher-resolution datasets have demonstrated significant evidence of sediment recycling (e.g., Huang et al. 2022; Coutts et al. 2024; Dashtgard et al. 2025), and this introduces significant uncertainty into the interpretation of spatially low-density DZ datasets.

The North America-wide DZ dataset used by Wahbi et al. (2025) does appear to show evidence of northward routing of channels and mixing of multiple sources in the McMurray Sub-Basin; however, the scale of their inference is not supported by the scale of their dataset. The McMurray Fm sits directly on an angular unconformity that represents over 250 million years of

missing time (i.e., longer than the Mesozoic and Cenozoic combined; Alberta Geological Survey 2019). It is entirely possible that the DZs incorporated in the McMurray Fm derive from a recycled source or sources and do not represent mixing from primary sources. Consequently, the DZ data should be used as subordinate or supporting data for defining the scale of the drainage system rather than as a primary dataset.

Wahbi et al. (2025) also present isotope data from well-preserved gastropods in a carbonate-cemented zone that overlies a channel sequence (well 1AA/06-07-093-07W4). These data were originally published in Hasiuk et al. (2024). The shells preserve isotope signatures that indicate that the gastropods lived in freshwater, and this concurs with the geochemical findings of Holdmen et al. (1997). However, the single sample from Hasiuk et al. (2024) is derived from the A1 parasequence and is unassociated with the A2 channel fill that underlies it. Wahbi et al.'s Figure 13 shows no shell material in the mud-filled abandonment fill of the A2 channel. To use a single occurrence of freshwater gastropods deriving from genetically unrelated strata that overlies the channel belt and to claim that their freshwater origin is evidence that the entirety of the McMurray Fm was deposited in freshwater environments is misleading at best. Instead, what is surprising is that terrestrial strata, including freshwater gastropods, are not widespread at the top of or in most of the McMurray channel belts, which would be expected if they represent deposition more than 1000 km from the paleo-shoreline.

Wahbi et al. (2025) show photos of soil development, paleosols, pedogenic structures, and possible footprints in their Figure 14 (C to H); however, they do not provide well locations or depths for the cored intervals from which these photos are derived. Correspondingly, it is not possible to assess their relationship to the channel belts associated with the various McMurray parasequences, except to note that the structures are unrelated to the freshwater gastropods sampled in 1AA/06-07-093-07W4.

INCONSISTENT STRATIGRAPHY

The stratigraphic architecture of the McMurray Fm is well established, and has evolved from a simple lower–middle–upper subdivision (Carrigy 1963; Mossop and Flach 1983; Flach 1984) to the recognition of multiple parasequences in the equivalent of the middle and upper McMurray (Ranger and Pemberton 1997; AEUB 2003; Baniak and Kingsmith 2018; Horner et al. 2019a; Peng et al. 2022, 2024). The most recently accepted architecture defines C2, C1, B2, B1, A2, and A1 parasequences that together record overall net transgression (Château et al. 2020, 2021). An additional parasequence, C3, has also been proposed, although the sedimentologic basis for identifying it has not been established (Fig. 1; Peng et al. 2022; Durkin and Rinke-Hardekopf 2024; Peng et al. 2024). Wahbi et al. (2025) show a variant of the parasequences model in their Figure 2B, wherein they label the C valley fill (equivalent to the C1 and C2 parasequences) as the Middle McMurray and the B2 to A1 parasequences as the Upper McMurray (Fig. 1). They indicate that they mapped the architecture of “Middle McMurray” strata and focus their discussion around that interval (see their Figure 8 and Supplementary Data Files 1 and 2). However, it is unclear what stratigraphic framework Wahbi et al. (2025) chose to use because the surfaces mapped in the cross sections in the Supplementary Data files do not adhere to either the C3 to A1 parasequence stratigraphy (Fig. 1) or to what they define as the middle and upper McMurray Fm (their Fig. 2B). A comparison of the well-log map in Wahbi et al. (2025), their Figure 9, to the paleovalley map of Horner et al. (2019a) appears to indicate that Wahbi et al. (2025) focus entirely on the channel belt associated with the A2 parasequence. The A2 channel belt is also from where most 3-D seismic time slices of point bars are derived (Hubbard et al. 2011; Labrecque et al. 2011; Musial et al. 2012; Durkin et al. 2017a, 2017b; Hagstrom et al. 2019). Based on this, we assume that the majority, if not the entirety, of the dataset used by Wahbi et al. (2025) derives from the channel belt associated with the A2 parasequence, and that data from the five underlying parasequences of the middle and upper McMurray are either ignored or are treated as being part of the A2 channel

belt. Neither approach is suitable for proposing a generic model for the entire McMurray Fm.

MISSING DATA

As Wahbi et al. (2025) show, and has been pointed out in previous publications, the degree of bioturbation in point bars of the A2 channel belt is lower than it is in the other channel belts, although some bioturbation is present in most point-bar deposits in the A2 (Hubbard et al. 2011; La Croix et al. 2019; Hagstrom et al. 2023). The McMurray Fm, however, is not simply the A2 parasequence and its associated channel belt. There are six formally defined and one informally defined parasequences that overlie the lower McMurray Fm (Fig. 1), and point bars of a scale similar to that of the A2 channel belt have been imaged in the channel belt associated with the B2 parasequence (Brekke et al. 2017; Martinius et al. 2017; Brekke and Roenitz 2021). Channels and/or channel belts are also associated with most of the parasequences (AEUB 2003; Château et al. 2019; Horner et al. 2019a, 2019b; Weleschuk and Dashtgard 2019; Château et al. 2020, 2021). Many of the point-bar deposits associated with older parasequences are as thick as those in the A2 channel belt; however, they commonly exhibit significantly higher degrees of bioturbation (Fig. 2; Gingras et al. 2016; Shchepetkina et al. 2016). The intensities of bioturbation in these point bars differ fundamentally from those of any fluvial point bars described from modern rivers (Smith 1987; Smith et al. 2009; Hubbard et al. 2011; La Croix and Dashtgard 2014) or from the rock record (Gowland et al. 2018) including in the Alberta Basin (Hayes 1986; Zaitlin et al. 2002; Durkin et al. 2020). Alternatively, point bars that experience brackish-water conditions commonly show bioturbation intensities and trace-fossil diversities (Johnson and Dashtgard 2014; La Croix and Dashtgard 2015; La Croix et al. 2015; Fietz et al. 2021) similar to those of many McMurray point bars, and even preserve bioturbated mud beds overlying sand beds (inclined heterolithic stratification) as records of seasonal saltwater influx (Sisulak and Dashtgard 2012).

By seemingly overlooking the architecture and integrated sedimentological–ichnological characteristics of the channel belts associated with parasequences below the A2, Wahbi et al. (2025) advance an overly simplified model of the McMurray Fm—one that fails to account for most of the deposits that constitute the formation, including all parasequences and most channel belts.

THE IMPORTANCE OF STRATIGRAPHY AND TIME

The C3 to A2 parasequences and channel belts (Fig. 1) span six million years, and this time span is constrained by palynological biostratigraphy, and both absolute ages and high-probability maximum depositional ages derived from zircon preserved in ash beds (121 to 115 Ma; Rinke-Hardekopf et al. 2021, 2022; Fietz et al. 2023; Durkin and Rinke-Hardekopf 2024). Each parasequence is bounded at the base by a flooding surface, which is overlain by a mudstone that ichnologically appears to be of marine origin. The top of each parasequence is defined by a flooding surface. Paleosols are only rarely preserved at the top of parasequences, and when present they occur locally in isolated parts of the basin (Hein et al. 2000; Hein and Cotterill 2006; Hein et al. 2013; Baniak and Kingsmith 2018; Horner et al. 2019a; Château et al. 2020; Durkin and Rinke-Hardekopf 2024). As such, each parasequence must be considered to be genetically distinct from those overlying and underlying it, and the shoreline at the start of progradation of each parasequence must have been situated to the south of the McMurray Sub-Basin (AEUB 2003; Château et al. 2019; Weleschuk and Dashtgard 2019; Château et al. 2021).

Channel belts are associated with the tops of parasequences, but the scalloped margins of the belts (AEUB 2003; Horner et al. 2019a, 2019b; Hagstrom et al. 2023) and scale of the system indicate that the belts and parasequences were contemporaneous. Sediment trapping in terrestrial environments appears to have been minimal due to the very limited preservation of paleosols, coal, and floodplain deposits capping the parasequences, especially those outside of the channel belts. The implication of this is that most of the

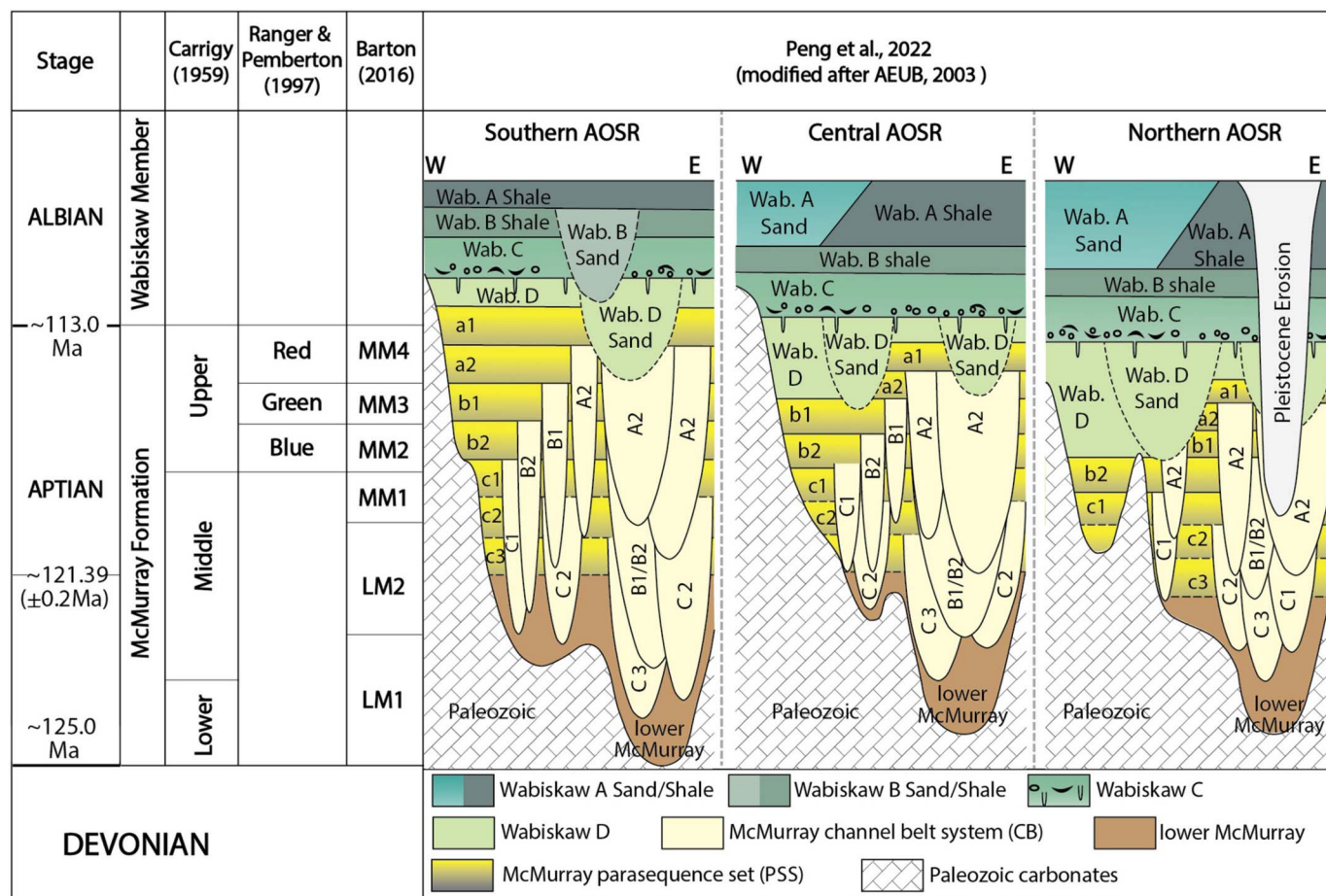


FIG. 1.—Chronostratigraphic chart for the McMurray Fm showing the basin-wide distribution of parasequences versus previously defined stratigraphic architectures. The chart is from Peng et al. (2024) and incorporates data from (AEUB 2003; Rinke-Hardekopf et al. 2019; Château et al. 2020; Peng et al. 2022; Rinke-Hardekopf et al. 2022). More recently, Durkin and Rinke-Hardekopf (2024) proposed that the top of the A2 channel belt is 115 Ma.

sediment delivered from the river must have reached the shoreline or been deposited in the adjacent marine basin. Additionally, the continental-scale drainage model advanced by Wahbi et al. (2025) and others (e.g., Blum and Pecha 2014; Durkin et al. 2017b; Horner et al. 2019a; Wahbi et al. 2022) is shown as being present in the McMurray Sub-Basin for the six million-year duration of deposition of the C3 through A2 parasequences (about one million years per parasequence; Rinke-Hardekopf et al. 2022; Durkin and Rinke-Hardekopf 2024).

The interpretation of a continental-scale drainage for the McMurray Fm is supported by the comparable channel widths, depths, and point-bar dimensions preserved in the A2 channel belt in the McMurray Fm and those measured in modern river systems. Point-bar dimensions in the McMurray Fm are especially comparable to the Mississippi River, albeit the interpreted McMurray drainage-basin area exceeds that of the Mississippi by a considerable margin. Using McMurray point-bar thicknesses (Hubbard et al. 2011; Musial et al. 2012; Durkin et al. 2017a; Brekke and Roenitz 2021) and the scaling relationships presented in Milliken et al. (2018), a 2–3 million km² drainage basin (i.e., Mississippi River drainage area) is a reasonable interpretation for the size of the McMurray Fm system. However, the McMurray Sub-Basin was a low-accommodation setting and the McMurray system was long lived. The combination of these factors makes the interpretation of a continental-scale drainage highly problematic.

Wahbi et al. (2025) reproduce maps from Wahbi et al. (2022) and Blum and Pecha (2014) that present the McMurray drainage extending over much of North America. Using Google Earth to calculate the area of the

drainage polygon, it exceeds seven million km². The scale of this drainage is over twice as large as the Mississippi River, three times that of the Paraná River, and about one million km² larger than the Amazon River basin (Orton and Reading 1993; Ludwig and Probst 1998; Water Resources Institute 2005; Blum and Roberts 2012; Durkin et al. 2017a; Wahbi and Blum 2023; Wahbi et al. 2025). The Mississippi River is the preferred analog for the McMurray Fm (Musial et al. 2012; Blum and Pecha 2014; Durkin et al. 2017b; Horner et al. 2019a; Wahbi et al. 2022, 2025), although Wahbi et al. (2025) also suggest that the river could have been the size of the Amazon River, whose drainage basin is almost as big as that proposed for the McMurray Fm. The Amazon River transports nearly five times as much sediment and ten times as much water as the Mississippi River (Milliman and Meade 1983; Orton and Reading 1993).

The Mississippi River delivers approximately 210 million tonnes of sediment each year (Milliman and Meade 1983; Hudson and Kesel 2000; Blum and Roberts 2012), and at least an equivalent amount of sediment would have been delivered through the McMurray paleo-drainage based on the apparent similarity in scale of the McMurray system with that of the Mississippi. However, while the Mississippi drains into the Gulf of Mexico, the McMurray drained into an epicontinental seaway that through the main oilsands-hosting fairway, at least, was about 15 m deep (the average thickness of C2 to A2 parasequences across the McMurray Sub-Basin) and about 100–150 km wide. We note that the lateral extent of the McMurray Sub-Basin is defined by the preservation of strata which are erosionally truncated to the northeast. The system could have been substantially larger

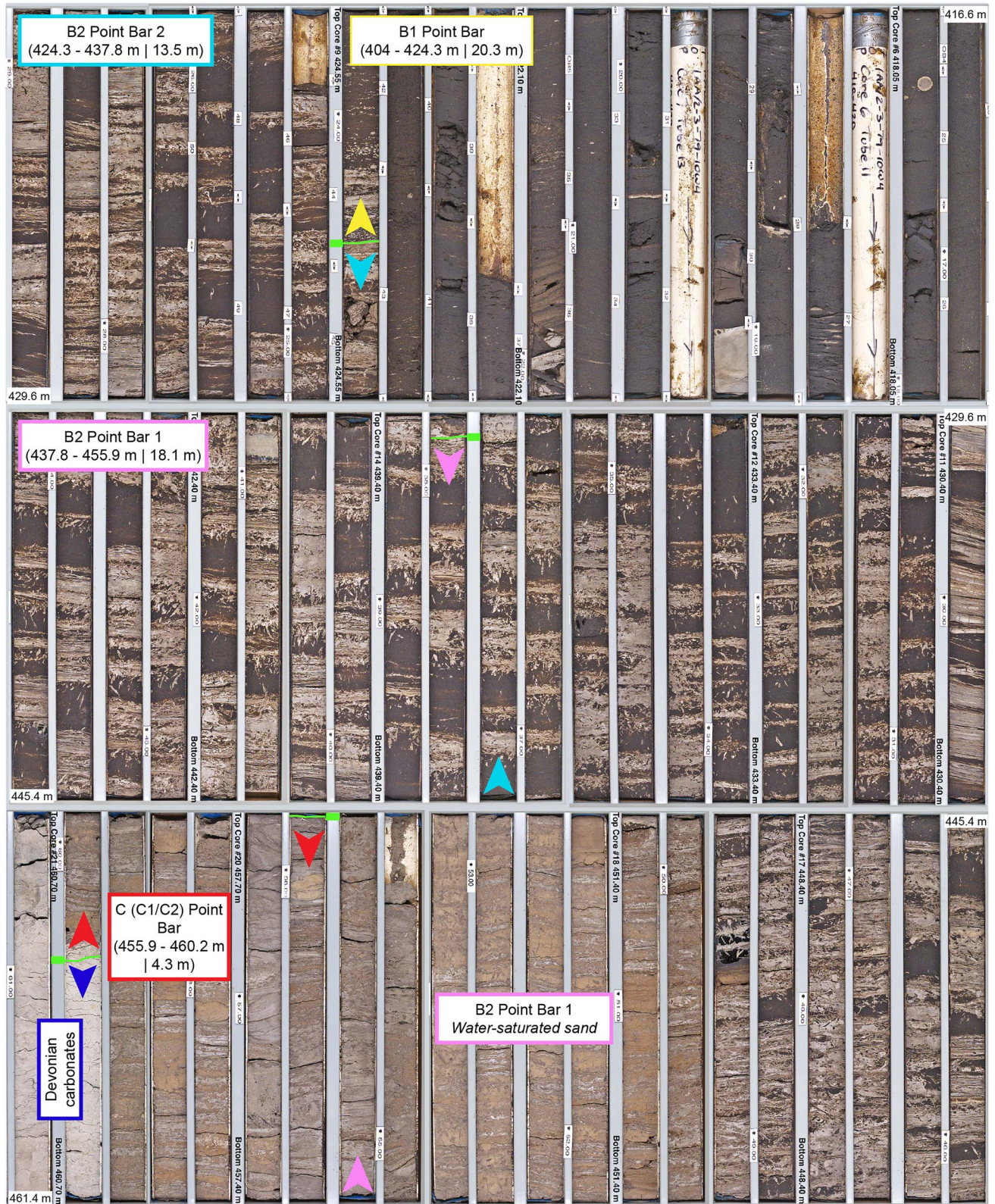


Fig. 2.—Cored succession through the oilsands-hosting McMurray Fm in the 1AA/02-03-079-10W4 well. The 42-m-thick succession from 404 to 456 m comprises stacked point bars that originate from the B1 and B2 parasequences (Brekke and Roenitz 2021). The B2 point bars are situated downstream but within the same point bars as the oilsands-producing Leismer Field. Note the extensive bioturbation (light brown vertical structures) that extend into underlying sand beds (dark brown due to oil saturation) throughout the entirety of all B2 point bars. This intensity of bioturbation is prevalent in most cored B2 and B1 point-bar successions in the Leismer area, wherein the point bars (B2 point bars 1 and 2 in the figure) reach up to 50 m thick (Brekke and Roenitz 2021). The bottom of the core succession is to the bottom left, and stratigraphic upwards is to the upper right (see depth markers).

(i.e., more areally extensive) than what is preserved, although this point is largely ignored by most workers.

The issue with the continental-scale drainage model is in reconciling sediment load, accommodation space, and time. To reiterate, the McMurray Sub-Basin is commonly shown to be about 100 km wide, and each parasequence in this low-accommodation setting is about 15 m thick. Sedimentation in terrestrial environments appears to be negligible, and the parasequences must preserve evidence of shoreline progradation resulting from sediment delivered from the continental-scale drainage. These criteria can be used to calculate the rate of shoreline progradation assuming the river system was the scale of the Mississippi River (delivered 210 million tonnes of sediment to the shoreline annually) and assuming that either all the sediment or 10% of the sediment was trapped at or near the shoreline.

Equation 1 is used to convert sediment load in tonnes to a sediment volume (V):

$$V = \frac{Q_s}{\rho_{Qtz} \cdot (1 - \phi)} \quad (1)$$

where, Q_s is the sediment discharge volume from the river (210 million tonnes), ρ_{Qtz} is the density of quartz (2.65 tonnes/m³) and ϕ is porosity. Porosity ranges from 30 to 33% in the McMurray Fm and we use 30% for simplicity. From Equation 1, the annual load of 210 million tonnes is equivalent to just over 113 million m³ of sediment (10% = 11.3 million m³).

The areal extent of the shallow marine region (A) adjacent to the McMurray shoreline can be calculated using estimated water depth (h), depositional slope (θ), and basin width (W ; Equation 2).

$$A = W \left(\frac{h}{\sin(\theta)} \right) \quad (2)$$

Water depth (from mean tide to maximum water depth) is derived from the typical thickness (15 m) of the C2 through A2 parasequences. Paleoslope is estimated at 0.3°. A 0.3° slope is reasonable for a tide-dominated shoreline to tidal flat (Short 1991; Masselink and Short 1993), which is the interpreted depositional environment for most of the preserved strata in the C2 through A2 parasequences (Baniak and Kingsmith 2018; Château et al. 2019; Weleschuk and Dashtgard 2019; Château et al. 2020). Basin width (W) is 100 km or 100,000 m. Using these values, Equation 2 indicates that the sloped shallow marine region would deepen over 2.9 km and the total area of the shallow marine region was about 286,500,000 m².

If the 113 million m³ of sediment were distributed evenly along the 286.5 million m² of seafloor, the whole shoreline would have aggraded by about 40 cm. If only 10% of the sediment was trapped at the shoreline, the shallow-marine extent of the basin would have aggraded by 4 cm.

The distance the shoreline prograded (P) annually based on the rate of sediment aggradation in the shallow marine realm can be calculated using Equation 3:

$$P = \frac{x}{\sin(\theta)} \quad (3)$$

where x is the thickness of the aggraded seafloor. An aggradation rate of 0.4 m per year would result in 76 m of shoreline progradation annually (10% = 7.6 m of progradation), or 76,000 km (10% = 7,600 km) every million years. A million years is the estimated time period represented by each of the C3 through A2 parasequences (six million years total). If the McMurray continental-scale drainage was indeed the size of the Amazon River (five times the sediment load), the amount of progradation would have been substantially higher. Even if the progradation rate was a fraction of the values calculated herein, most of the McMurray Sub-Basin would have been subaerially exposed throughout deposition of each parasequence, and thus soils and floodplains should be very well developed everywhere and in all parasequences. They are not.

Simply put, interpreting the channel belts associated with the C3 through A2 parasequences as recording deposition from a continental-scale drainage over the course of six million years and in a low-accommodation setting is highly problematic. Only by disregarding the stratigraphic architecture, the time represented by the McMurray Fm, and the facies constituting the parasequences can the channel belts be interpreted as purely terrestrial or fluvial. When time, stratigraphy, and facies are considered, the continental-scale drainage model is untenable.

CONCLUSIONS

In summary, while we appreciate Wahbi et al.'s use of modern analogs to address the McMurray conundrum, the sedimentary record is incomplete and the time-averaged record should not be interpreted to be directly equivalent to what we observe in modern systems (La Croix et al. 2019, 2020). The channel belts associated with most of the parasequences of the McMurray Fm (C2 to B1) have point bars with dimensions equivalent to those of the main A2 channel belt (the focus of Wahbi et al. 2025) but also preserve highly variable ichnological characteristics that depart markedly from those of any modern fluvial systems (Fig. 2). The preservation of highly bioturbated inclined heterolithic stratification on large point bars is inconsistent with a fluvial origin, and it remains unclear why such large point bars are highly bioturbated (i.e., the McMurray conundrum).

We also caution against the reliance on well-log signatures to map point-bar architectures. While well logs have proven useful in mapping the extent of parasequences (e.g., Ranger and Pemberton 1997; AEUB 2003; Horner et al. 2019a; Weleschuk and Dashtgard 2019; Château et al. 2021; Durkin and Rinke-Hardekopf 2024), their usefulness in resolving point-bar architectures is exceedingly limited (Brekke et al. 2017; La Croix et al. 2019, 2020; Brekke and Roenitz 2021). Spatial mapping using careful analysis of image logs coupled with the physical characteristics identified in cored successions is a far more reliable methodology (Brekke et al., 2017; Brekke and Roenitz, 2021).

Finally, the interpretation of a continental-scale drainage that persisted along the main axis of the McMurray Sub-Basin advanced by Wahbi et al. (2025) and others is highly problematic from a sedimentation perspective, especially in a low-accommodation setting such as the McMurray Sub-Basin. We contend that the McMurray Fm is substantially more complicated than Wahbi et al. (2025) propose and that other brackish-water and shallow-marine depositional environments unassociated with major river systems persisted throughout deposition of much of the C3 through A2 parasequences and their associated channel belts. Indeed, what is preserved in the McMurray Sub-Basin is an erosional remnant of a system that could have extended much farther to the east. It is also possible that the river system (and not necessarily a continental-scale drainage) that formed the A2 channel belt was present in the McMurray Sub-Basin only during deposition of the A2 parasequence and was situated there owing to the westward migration of the dissolution front of the underlying Prairie Evaporite (Broughton 2018). In this case, the assertion by Wahbi et al. (2025) that the *entire* McMurray Fm represents the deposits of a continental-scale drainage is further invalidated.

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