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Early Cretaceous evolution of the McMurray Formation: A review toward a better understanding of the paleo-depositional system

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ABSTRACT

The Lower Cretaceous McMurray Formation of the Western Canada Sedimentary Basin has been the subject of numerous studies, with emphasis on its stratigraphic framework and sedimentological models. However, due to the stratigraphic complexity of the paleo-depositional system, which comprises fluvial and marginal-marine strata, it remains a challenging area of research. There is ongoing debate surrounding the depositional model of the most volumetrically significant and economically relevant units in the formation, with some suggesting that channel-belt deposits are predominantly fluvial in origin, while others argue that they are estuarine in origin, with some tidal influence. To gain insight into these issues, we present a comprehensive review of the McMurray Formation paleo-depositional system, focusing on three key aspects. First, we provide a detailed analysis of facies characteristics, including regional mapping results and trace fossil analysis. Second, we summarize the chronology of stratigraphic and depositional models developed for the McMurray Formation over the last 100 years. Third, we discuss the McMurray conundrum and present supporting information for the two widely accepted depositional models for the McMurray Formation channel-belt deposits. Proposed analogues and some of the associated critiques are discussed for each depositional model, and some future research directions are recommended. The complex nature of the McMurray Formation and the ongoing debates surrounding its depositional models emphasize the need for continued research and a multidisciplinary approach to better understand the McMurray paleo-depositional system.

1. Introduction

The Lower Cretaceous McMurray Formation is the primary reservoir interval in the Athabasca Oil Sands Region (AOSR), which comprises one of the world's largest petroleum reserves. The economic importance of this succession has led to the generation of an unparalleled volume of data, with 10,000 s of boreholes and extensive 3D seismic data coverage, combined with expansive outcrop along river valleys, all over a 60,000 km^2 area (Hein et al., 2013). These data reveal a stratigraphically complex amalgam of fluvial and marginal-marine strata, deposited on a topographically and diagenetically complex angular unconformity with underlying Devonian carbonates (e.g., Hein and Cotterill, 2006; Hein et al., 2013). Over the past ~100 years, several depositional models have been proposed for its most-productive deposits, which are generally associated with the informal 'middle member' of the McMurray Formation (Falconer, 1951; Carrigy, 1959, 1971; Stewart and MacCallum, 1978; Pemberton et al., 1982; Mossop and Flach, 1983; Ranger and Pemberton, 1988, 1992; Hubbard et al., 2011; Gingras et al., 2016; Durkin et al., 2017; Peng et al., 2022). However, despite the abundance of data and the importance of this deposit, there is no one universally accepted paleoenvironmental interpretation for it (e.g., La Croix et al., 2019; Durkin et al., 2020). The evolution of paleoenvironmental interpretations and the way in which the scientific community has incorporated new evidence from emerging technologies over time is a captivating example of the scientific method at work. A reflection on progress in understanding the McMurray Formation has the potential to

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guide efforts to understand analogous deposits that lack such abundant data (e.g., Triassic Chinle Formation, North America and Mungaroo Formation, offshore NW Australia; Trendell et al., 2012; Martin et al., 2018). Until now, a comprehensive review of literature and working theories for the McMurray Formation does not exist.

After nearly a century of study, two apparently incompatible interpretations have emerged as the prevailing theories for the middle McMurray member. A large body of work presents evidence for deposition in a tide-dominated estuary or its fluvial-tidal transition zone (FTTZ), largely based on the widespread presence of a brackish-water trace-fossil assemblage and prevalence of mudstone (e.g., Pemberton et al., 1982; Ranger and Pemberton, 1988, 1992; Gingras et al., 2016). Conversely, an equally large effort presents evidence for deposition in meandering fluvial-channel belts (e.g., Mossop, 1980a; Mossop and Flach, 1983; Flach and Mossop, 1985) comparable to those of the lower Mississippi River (Durkin et al., 2017; Horner et al., 2019a; Martin et al., 2019); this is primarily supported by large-scale sedimentary features (e.g., epsilon cross-beds, or inclined heterolithic strata) and fluvial

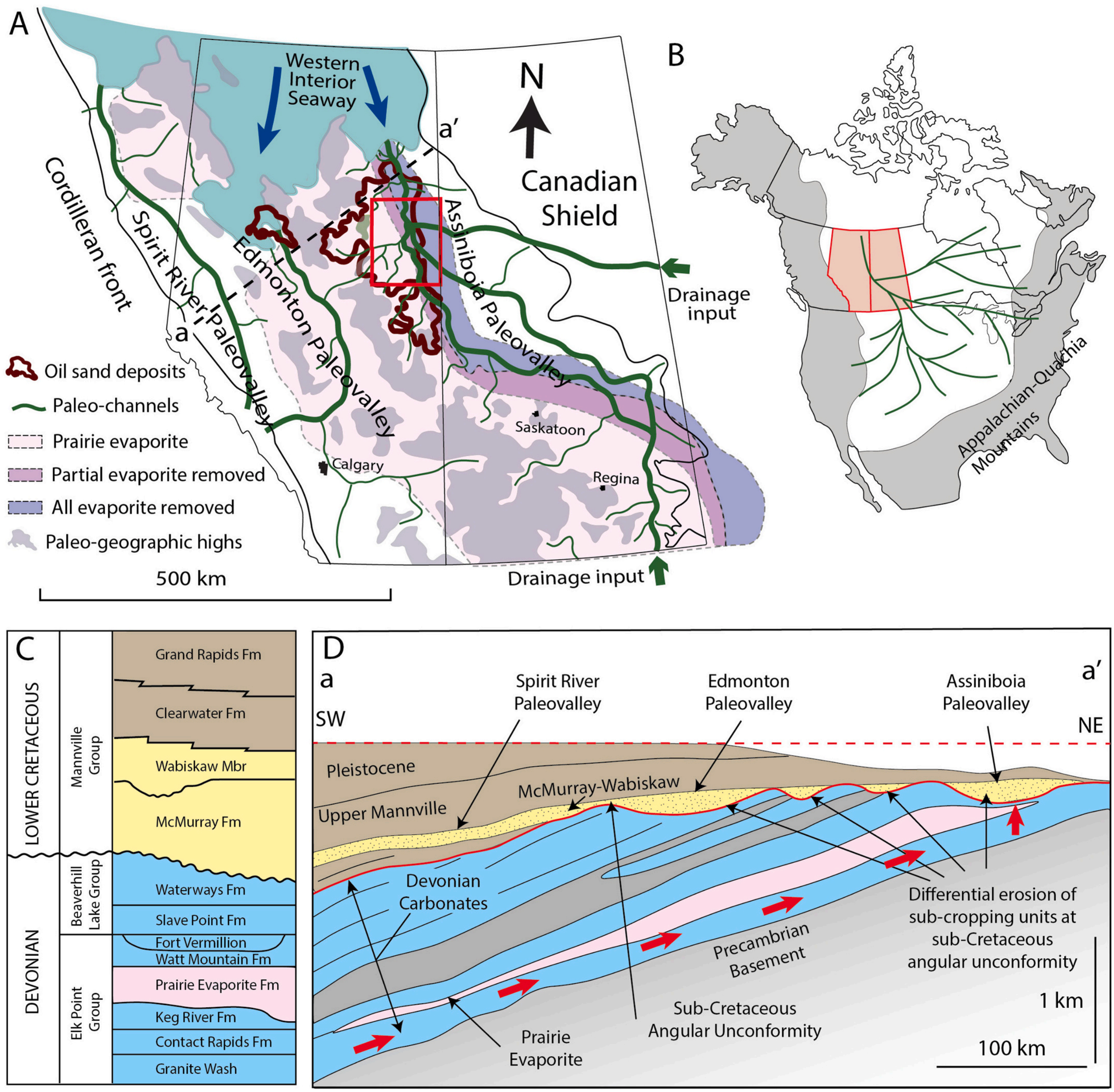


Fig. 1. (A) Paleogeographic map of the Early Cretaceous Western Canada Sedimentary Basin showing three paleovalleys and the distribution of the Prairie Evaporite removal zones (modified from Durkin et al., 2017, Broughton, 2018 and Wahbi et al., 2023). Red box shows the study area. (B) Drainge reconstruction of a continental-scale river that flowed northward through the Assiniboia paleovalley during the Early Cretaceous (modified from Blum and Pecha, 2014). (C) Stratigraphic column for the eastern Athabasca Oil Sands Region (modified from Broughton, 2013). (D) Schematic cross section (a-a') across the Western Canada Foreland Basin showing Paleozoic carbonates and Mesozoic siliciclastics separated by the sub-Cretaceous unconformity (modified from Ranger, 1994 and Benyon et al., 2016). Strata tilt to the southwest and deep basin aquifer water flowed updip to the northeast, as indicated by red arrows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

geomorphology revealed in extensive 3-D seismic data (Smith et al., 2009; Hubbard et al., 2011; Labrecque et al., 2011; Durkin et al., 2017). Attempts to reconcile or bridge these conflicting interpretations have yet to satisfy all observations (e.g., Blum, 2017; Gingras and Leckie, 2017). Complicating the issue further, researchers have also argued that dissolution of underlying Devonian evaporite strata and related tectonism influenced deposition of the McMurray Formation and this has provided a unique facet to paleoenvironmental interpretations (Ranger and Pemberton, 1988; Broughton, 2013, 2018). The apparent incompatibility between these prevailing interpretations is referred to as the 'McMurray conundrum' (Blum, 2017).

A better understanding of the McMurray Formation paleodepositional system will facilitate hydrocarbon production, reconstruct the geological history and evolution of this crucial interval of the Western Canada Sedimentary Basin, and provide insight to the paleodepositional systems of other, data-limited formations around the world. The goal of this study is to synthesize previous research efforts and to identify directions for advancement of robust sedimentological and stratigraphic models for the McMurray Formation. Specific research objectives are to (1) document detailed facies characteristics and present new regional mapping results; (2) summarize the chronology of stratigraphic and depositional models developed for the McMurray Formation over the last 100 years; (3) review supporting evidence and critiques for the two prevailing depositional models of the McMurray conundrum, including proposed depositional analogues; and (4) recommend future research directions. Through this comprehensive review and contribution of new data, we present the arguments to the broad geoscientific community and envision a unified effort moving forward to unravel the enigmatic paleoenvironment of the McMurray Formation.

2. Geologic setting

The Western Canada Sedimentary Basin (WCSB), which hosts sediments of the McMurray Formation, is a northwest-southeast-oriented basin that preserves stratigraphic records of two major tectonostratigraphic phases (Leckie and Smith, 1992). From the Paleozoic to Triassic, the basin was dominantly characterized as a passive continental margin, with an extensive record of carbonate sedimentation (Thompson et al., 1987; Price, 1990). The Elk Point Group and Beaverhill Lake Group are the primary Devonian units in the study area. In the Elk Point Group, an important paleogeographical element is the Prairie Evaporate Formation, which contains an accumulation of thick halite and other evaporite minerals (Meijer Drees, 1994; Rogers, 2017) (Fig. 1). During the Late Jurassic to Eocene, a northwest-southeast-oriented foreland basin developed due to the growth and denudation of the Canadian Cordillera (Price, 1990; Leckie and Smith, 1992; Stockmal et al., 1992) (Fig. 1). Orogenic processes during the formation of the Canadian Cordillera led to the formation of the foreland basin, which rests on a sub-Jurassic/sub-Cretaceous angular unconformity, with progressively older units exposed along the surface eastward, away from the mountain front (Fig. 1D).

The basin-wide sub-Cretaceous unconformity (SCU) exhibits up to 80 m of paleotopographic relief (Cant, 1996; Ranger and Pemberton, 1997; Miles et al., 2012). This relief was controlled by differential erosion and dissolution of the underlying Devonian strata (Hauck et al., 2017). Subaerial exposure along the eastern basin margin along the unconformity resulted in karst formation within carbonate strata and significant halite dissolution as water flowed into the Prairie Evaporite Formation (Hauck et al., 2017). Extensive salt removal along the eastern margin of the WCSB resulted in a 1000-km-long and 150-kw-wide salt dissolution trend that influenced the subsequent deposition of the Cretaceous Mannville Group, of which the McMurray Formation is part (Fig. 1A).

The structure of the SCU shows three orogen-parallel, northwest-southeast-trending paleovalleys (i.e., Spirit River, Edmonton, and Assiniboia) that were cut and infilled by rivers that flowed to the north and northwest into the southward-transgressing Boreal Sea (Jackson, 1984; Cant and Stockmal, 1989; Hein et al., 2013; Rinke-Hardekopf et al., 2019) (Fig. 1A). Overall, the strata of the Mannville Group represent a third-order transgressive-regressive sequence deposited during the Early Cretaceous (Cant and Abrahamson, 1996; Deschamps et al., 2017).

The McMurray Formation is the oldest unit of the Mannville Group in the Assiniboia paleovalley, and it is thickest (up to 120 m) east of the salt scarp zone where the SCU has relatively high paleotopographic relief (Nardin et al., 2013; Hauck et al., 2017; Peng et al., 2022) (Fig. 2). To the west of the salt scarp, several southwest to northeast oriented tributary paleovalleys join the main trunk paleovalley (Fig. 2). It is important to note that the unconformity encapsulates >200 Myr of erosion and/or non-deposition, and the areas subject to surface modification would have varied over that time.

The McMurray Formation is up to 120 m thick where sediment infilled lows on the SCU, thinning onto paleotopographic highs to the west (Fig. 2B). The eastern margin of the region is less constrained due to a lack of data. The McMurray Formation exhibits a regional dip to the southwest. In the southern AOSR, the McMurray Formation is >300 m deep; at Fort McMurray, Alberta the formation intersects the surface where outcrops along modern river valleys and mining are prevalent (Alberta Energy Regulator, 2023). Further north (~T96, Fig. 2) and to the east, the McMurray Formation is top truncated by glacial erosion and overlain by associated Pleistocene sediments (Andriashek and Atkinson, 2007). The down-dip equivalent to the McMurray Formation north of T104 has been almost entirely removed by glaciation, which contributes significantly to the difficulty of paleogeographical interpretations.

3. Stratigraphy and sedimentology of McMurray Formation

The McMurray Formation was originally subdivided into three informal lithostratigraphic units: the lower McMurray, dominated by non-marine deposits (e.g., fluvial, floodplain, lacustrine); the middle McMurray, dominated by estuarine or fluvial point-bar deposits; and the upper McMurray, dominated by marginal-marine deposits (Carrigy, 1959; Stewart and MacCallum, 1978) (Fig. 3). This traditional lithostratigraphic subdivision of the McMurray Formation has limitations due, in part, to highly complex cut-and-fill processes. Regional-scale approaches by Ranger and Pemberton (1997), Alberta Energy and Utilities Board (2003), and Hein and Cotterill (2006) provided key observations, including the delineation of regionally correlatable units bounded by marine flooding surfaces toward the top of the formation (i.e., parasequence sets of Ranger and Pemberton, 1997) and cross-cutting channel systems that stratigraphically originate from a series of flooding surfaces (i.e., valleys of the Alberta Energy and Utilities Board, 2003). These studies demonstrated incision of upper McMurray member strata by middle McMurray member channel belts, resulting in the middle units being demonstrably younger than numerous upper units (Ranger and Pemberton, 1997; Alberta Energy and Utilities Board, 2003; Hein and Cotterill, 2006). For this reason, the traditional lithostratigraphic subdivisions are no longer tenable and their use going forward is not recommended (Château et al., 2019; Horner et al., 2019a; Hagstrom et al., 2023).

The regional stratigraphic framework has been largely confirmed and expanded upon recently (Timmer, 2018; Hayes, 2018; Hagstrom 2018; Broadbent, 2019; Château et al., 2019, 2021; Horner et al., 2019a; Martin et al., 2019; Rinke-Hardekopf et al., 2019; Weleschuk and Dashtgard, 2019). The most up-to-date stratigraphic framework was presented in Peng et al. (2022), which included the spatial distribution of the McMurray Formation and details of the overlying Wabiskaw Member of the Clearwater Formation. The review herein will adhere to the framework presented in Fig. 3, where regional parasequence sets (PSS) are incised by channel belts (CB) that are named based on the flooding surface from which they subtend. The term CB here captures a

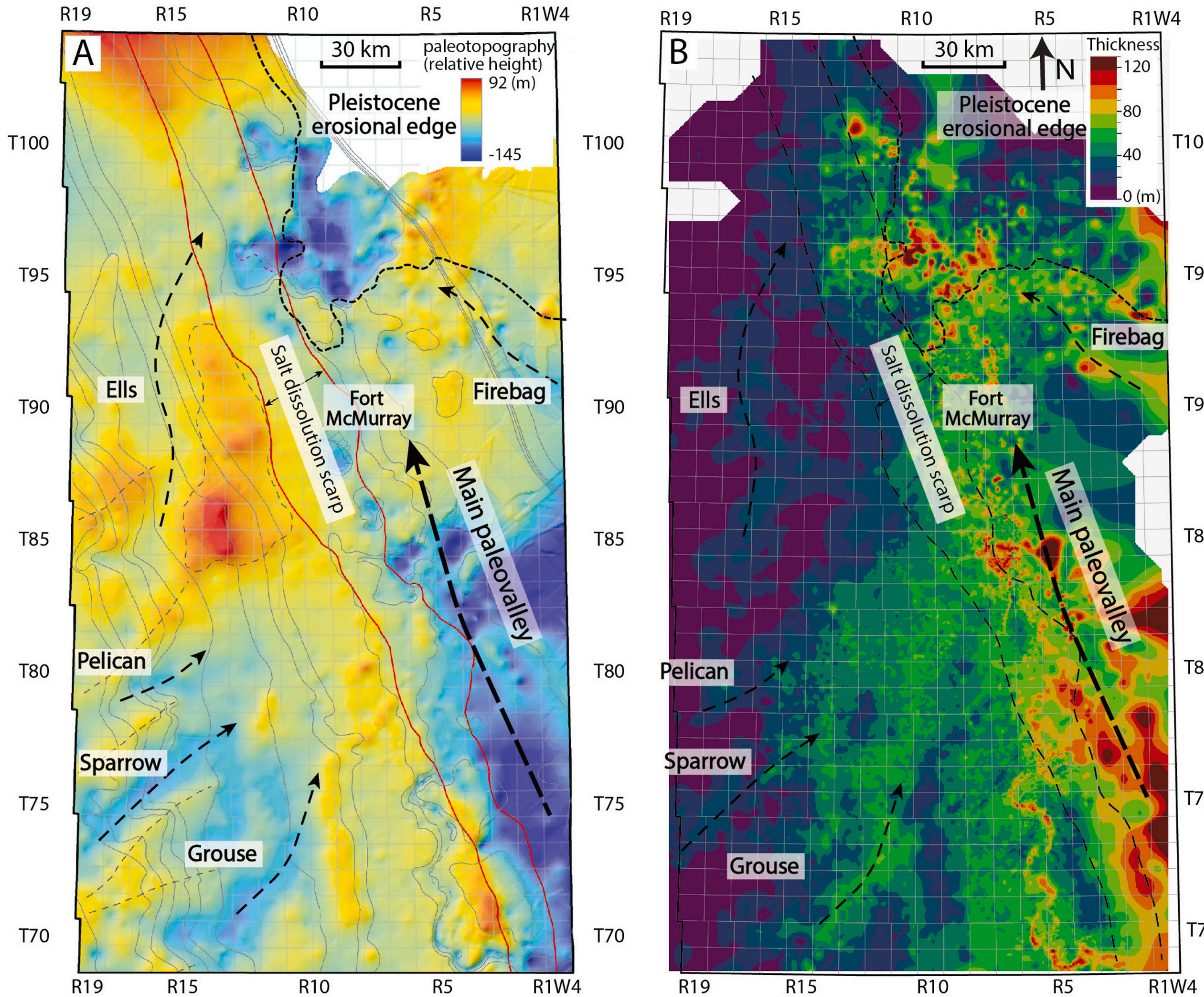


Fig. 2. (A) Reconstructed paleotopography of the sub-Cretaceous unconformity (modified from Hauck et al., 2017). (B) Isopach map of the McMurray Formation. Note that the main paleovalley distributed along the salt dissolution scarp with several secondary paleovalleys (Grouse, Sparrow, Pelican, Ells, and Firebag) trending northeast or northwest toward it.

range of architectural-element types from single-story channel-belt deposit to channel-belt-complex (Miall, 2014) comprised of multiple, laterally- or vertically-stacked channel-belt deposits (e.g., Hagstrom et al., 2023). Not shown on Fig. 3 but distinct from CB's, are smaller-scale (i.e. < 10 m thick) distributary channel-fill deposits contained within PSS (e.g., Baniak and Kingsmith, 2018; Château et al., 2021).

The stratigraphic framework has largely been applied along strike (i.e. east – west; Fig. 3), but it is not without its limitations in the depositional dip orientation. The transgressive surfaces that demarcate boundaries between PSSs are inherently diachronous; however, along strike they are practically isochronous, formed during southward transgression of the Boreal Sea (Ranger and Pemberton, 1997; Barson et al., 2001). The PSSs are interpreted as packages of genetically related strata formed during fourth-order sea-level highstands (Peng et al., 2022). Along depositional dip, which for the AOSR is approximately 300 km south to north, the existing framework suggests that each PSS can be correlated over these distances (e.g., Horner et al., 2019b). Recent work has demonstrated that each package is comprised of smaller-order parasequences separated by flooding surfaces, thus forming parasequence 'sets' (Van Wagoner et al., 1990). The parasequences are thin and shingle basinward (i.e. progradational) such that a PSS at any location may only be comprised of a single coarsening upward parasequence (Peng et al., 2022). A benefit of this framework is that CBs can be relatively dated based on the presence or absence of a PSS above, and therefore it can be determined from which PSS the CBs subtend (Peng et al., 2022; Hagstrom et al., 2023).

Isochronous surfaces are below the resolution available in the dataset, but recent identification and dating of reworked volcanic ash has provided coarse geochronologic constraints on the stratigraphic framework. At the top of the informal lower McMurray member, a regionally-correlatable interval characterized by coals and paleosols contains volcanic ash (Rinke-Hardekopf et al., 2019, 2022; Fietz et al., 2023). Maximum depositional ages derived from reworked volcanic ash sampled at two separate locations has dated this horizon to ~121 Ma (Rinke-Hardekopf et al., 2019; Fietz et al., 2023). The agreement between these ages established a widespread chronostratigraphic surface that provides a high-confidence age for initiation of PSS and CB deposition (Fietz et al., 2023). An additional volcanic ash from the Firebag tributary has been dated to ~115 Ma and was attributed to the top of the b1 PSS (Rinke-Hardekopf et al., 2022). However, the exact stratigraphic position has been alternatively proposed as the top of the a2 PSS/A2 CB.

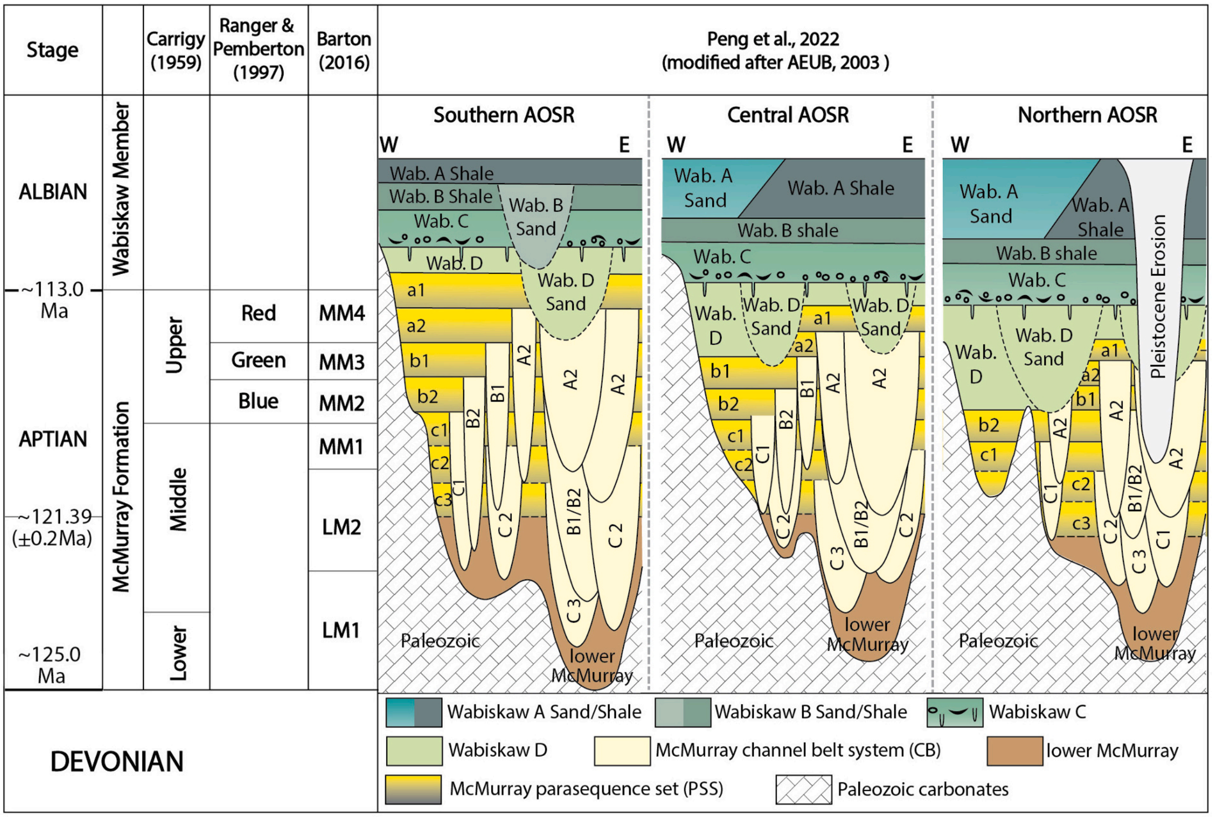


Fig. 3. Stratigraphy of the McMurray-Wabiskaw interval in the southern (Townships 69–87), central (Townships 88–95), and northern (Townships 96–104) Athabasca Oil Sands Region with previous stratigraphic nomenclature for reference (Peng et al., 2022). Ages are from Rinke-Hardekopf et al. (2019) and Fietz et al. (2023).

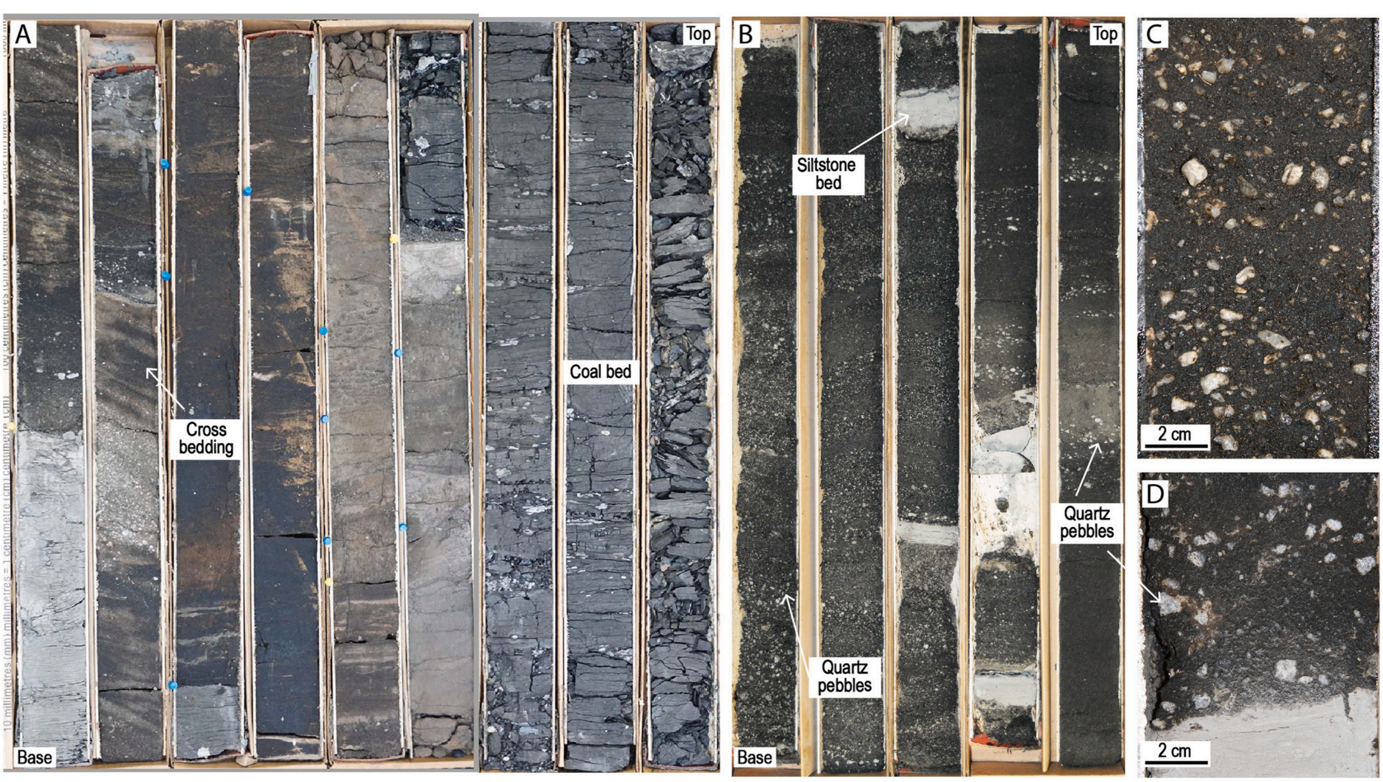


Fig. 4. Lower McMurray facies. (A) A fining-upward succession of cross-bedded sandstones changing upward into mudstones capped by a thick coal. (B) Cross-bedded sandstone with abundant quartz pebbles. (C) and (D) Detailed views of quartz pebbles. Core boxes are 75 cm long.

The following section describes the sedimentology of the McMurray Formation in three sections: i) the lower McMurray member, defined as the interval from the SCU to the aforementioned ash-bearing coal and paleosol horizon (Rinke-Hardekopf et al., 2019; Fietz et al., 2023) beneath the first 'c' PSS; ii) the regionally-correlatable parasequence sets (PSS) c3 through a1; and iii) the channelized units subtending from each PSS. Although the review herein utilizes this stratigraphic framework, it also acknowledges the potential for improvement going forward.

3.1. The lower McMurray member

The lower McMurray member name has been retained in the stratigraphic framework but received less attention due, in part, to its variable distribution and lack of reservoir potential. The member is the basal unit of the McMurray Formation commonly characterized by one- to-two fining-upward successions (3 to 30 m total thick) of cross-bedded sandstone grading upward into mudstone-dominated intervals. The sandstones are characterized by coarse sand with quartz granules and pebbles, which are noticeably coarser (Fig. 4B-D) than those in overlying CBs. Total unit thickness is typically <10 m, but it can be up to 60 m thick in topographic lows on the SCU, where pre- and/or *syn*-depositional salt-dissolution collapse occurred (Broughton, 2015; Hauck et al., 2017). The succession is commonly capped by coals and paleosols (Fig. 4). Thick (>10 m) coals are present at the top of the member in the Firebag Tributary of the northeastern Athabasca Oil Sands Region (AOSR) (Rinke-Hardekopf et al., 2019). Continental trace fossils such as *Naktodemasis* and *Taenidium* are present in this unit (Harris et al., 2016).

The lower McMurray has been widely interpreted to be deposited by purely fluvial, low-sinuosity to braided rivers (Carrigy, 1959; Mossop and Flach, 1983; Nardin et al., 2013; Barton et al., 2017), largely attributed to drainage off of the adjacent Canadian Shield (Benyon et al., 2016). The general distribution of thick strata along the main paleovalley was cited as evidence to suggest that the salt-dissolution collapse might have influenced the development of fluvial channels during the lower McMurray Formation (Barton et al., 2017; Broughton, 2018). The thick coals in the Firebag Tributary have been interpreted as recording the initial transgression of the Boreal Sea (Rinke-Hardekopf et al., 2019). Overall, the paleoenvironments recorded in the lower McMurray have not been the subject of extensive debate. A consensus of meandering or braided fluvial channels with associated floodplain and lacustrine deposits has been reached (e.g., Hein et al., 2013; Barton et al., 2017).

3.2. Regional parasequence sets

The regional parasequence sets are characterized by upward-coarsening units of silty mudstone overlain by interbedded mudstone and wave-rippled and/or low-angle cross-stratified sandstone that is variably capped by rooted mudstone and coal (Fig. 5) (Baniak and Kingsmith, 2018; Château et al., 2019; Horner et al., 2019b; Weleschuk and Dashtgard, 2019; Peng et al., 2022; Hagstrom et al., 2023). These units are 2 to 15 m thick and are sparsely to abundantly bioturbated. The trace-fossil assemblage typically comprises *Skolithos, Arenicolite, Planolites*, *Teichichnus, Chondrites*, *Palaeophycus*, *Asterosoma*, *Fugichnia,* and *Diplocraterion* (Ranger and Pemberton, 1992).

The coarsening-upward units are interpreted as parasequences deposited in wave-influenced deltas, bayhead deltas, and shorefaces that prograded in a protected bay setting (Caplan and Ranger, 2001; Baniak and Kingsmith, 2018; Weleschuk and Dashtgard, 2019; Peng et al., 2022; Hagstrom et al., 2023). The low-angle cross bedding is interpreted as poorly developed hummocky/swaley cross stratification (HCS/SCS), suggesting storm influence in the basin was minimal.

Up to seven upper McMurray parasequence sets (PSSs) (i.e., McMurray c3, c2, c1, b2, b1, a2, a1) are mappable within the basin

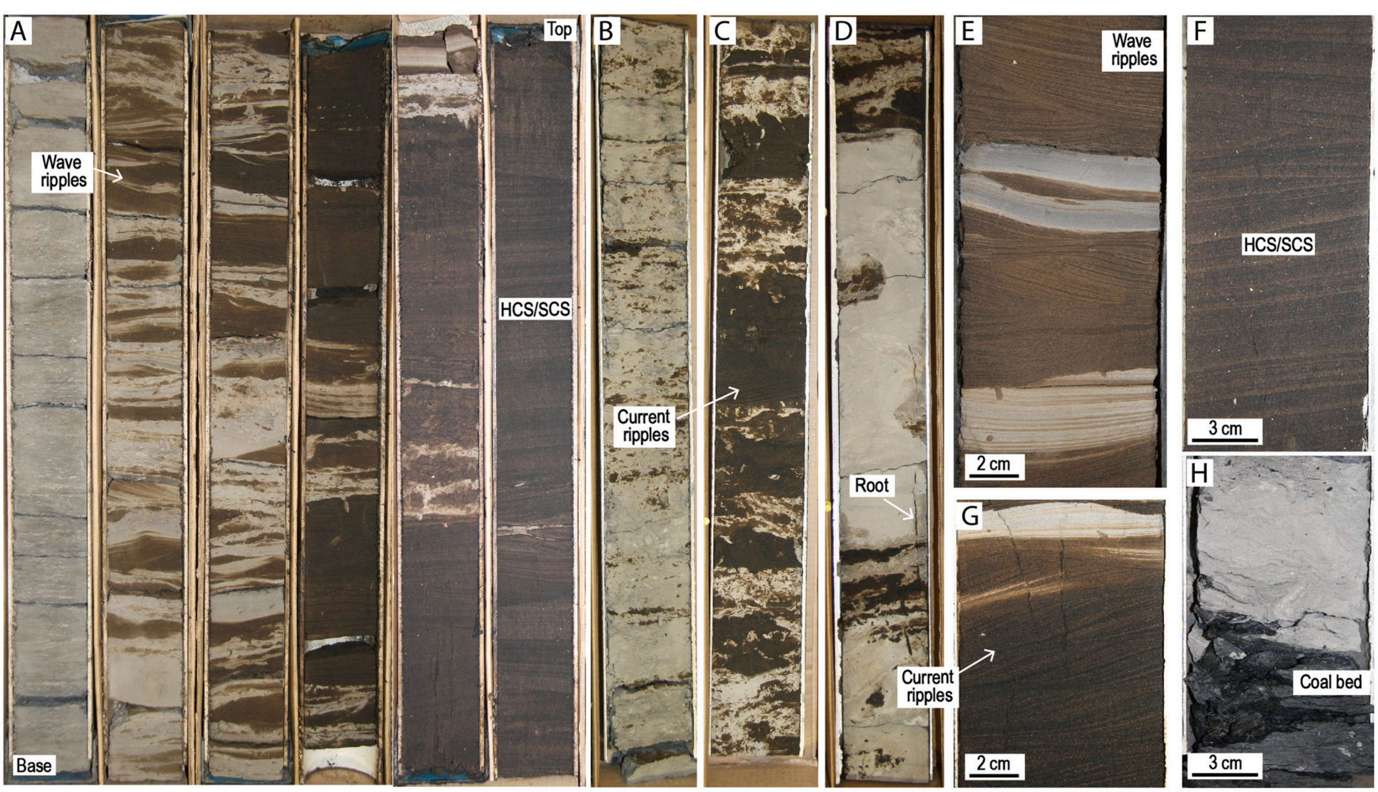


Fig. 5. McMurray PSS facies. (A) A coarsening-upward (CU) succession showing a transtion from bioturbated mudstone, through interbedded siltstone and wave-rippled sandstone to thin hummocky/swaley cross-stratified (HCS/SCS) sandstone. (B) Bioturbated mudstones. (C) Highly biotubated upper facies in a coarsening-upward succession. (D) Mudstone-dominated beds with roots. (E) Wave-rippled sandstones interbedded with mudstone beds. (F) Thin HCS/SCS sandstone. (G) Current-rippled sandstone. (H) A coal bed at the top of a coarsening-upward succession. Core boxes are 75 cm long.

(Château et al., 2019; Hagstrom, 2019; Peng et al., 2022). They likely prograded across the basin during fourth-order sea-level highstands (100–300 kyr) (Cant, 1996; Peng et al., 2022). In general, the PSSs are well preserved west of the main paleovalley trend (Fig. 2), where they were not eroded by CBs. The c3, c2, and c1 PSSs are locally present in the tributary paleovalleys (e.g., Ells, Pelican and Sparrow paleovalleys) (Château et al., 2021; Peng et al., 2022; Hodgson, 2023). The b2 and b1 PSSs are mainly distributed in Townships 69–85 between Ranges 1–15 and are characterized by northwest-southeast-oriented thickness trend (Fig. 6B, C). Toward the northern region, they are rarely preserved due to subsequent erosion associated with McMurray Formation channel belt or Wabiskaw Member shoreline migration processes (Fig. 6). Sandstone-dominated deposits of the a2 PSS are centered on Township 80, Range 7 (Fig. 6D). The a1 PSS is thin and only preserved in scattered pockets.

3.3. Channel-belt and channel-belt-complex deposits

Channel belt strata are characterized by fining-upward packages consisting of erosionally based, trough-to-tabular cross-bedded sandstones with mudstone-clasts breccia, grading upward into strata characterized by inclined heterolithic strata (IHS) and overlain by mudstones (Fig. 7). Inclined heterolithic strata can be sandstone-dominated (i.e., sandstone beds make up >50% of the succession), often in the lower portion, or siltstone-dominated (i.e., sandstone beds make up <50% of the succession), often in the upper part. Coals, paleosols and rooted mudstones are relatively rare, but present locally in interfluve areas (Baniak and Kingsmith, 2018; Horner et al., 2019b; Peng et al., 2022). Bioturbation in cross-bedded sandstones is absent to sparse (BI 0–1). By contrast, units with IHS display a low-diversity and variably abundant (BI 0–5) assemblage typically associated with one or more of *Cylindrichnus*, *Planolites*, *Skolithos*, *Teichichnus*, *Gyrolithes*, and/or *Chondrites*. The uppermost mudstone beds typically exhibit rare bioturbation (BI 0–1).

Channel-belt deposits (i.e., C3, C2, C1, B2, B1, A2 CB) can be mapped at multiple stratigraphic levels in the northwest-trending main paleovalley and its tributaries (Fig. 3). McMurray C3, C2, C1, B2, and B1 channel belts are well preserved in the tributary valleys; we interpret that they are typically not identifiable within the main paleovalley because they were removed as a result of incision by younger channel belts. The B2 and B1 channel belts are up to 5 km wide and, on average, 30–35 m thick (Horner et al., 2019a, 2019b; Hagstrom et al., 2023). The

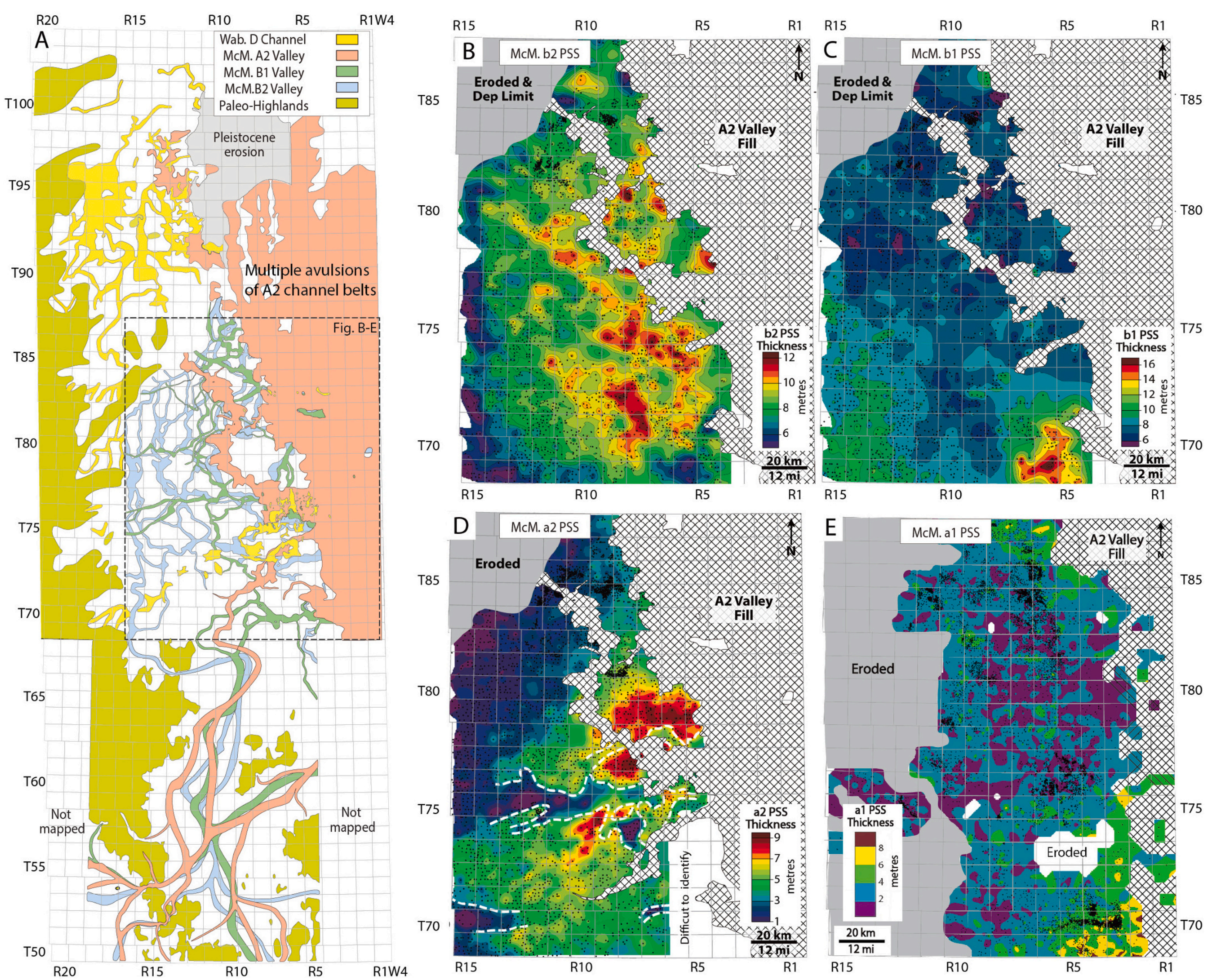


Fig. 6. (A) Map showing distribution of the McMurray B2, B1, A2 channel belts. Note that the eastern edge of the A2 CB was difficult to delineate due to a lack of well control. The mapping results south of T69 were based on less wells compared to those in the northern area. (B) Isopach map of McMurray b2 PSS. (C) Isopach map of McMurray b1 PSS. (D) Isopach map of McMurray a2 PSS. (E) Isopach map of McMurray a1 PSS.

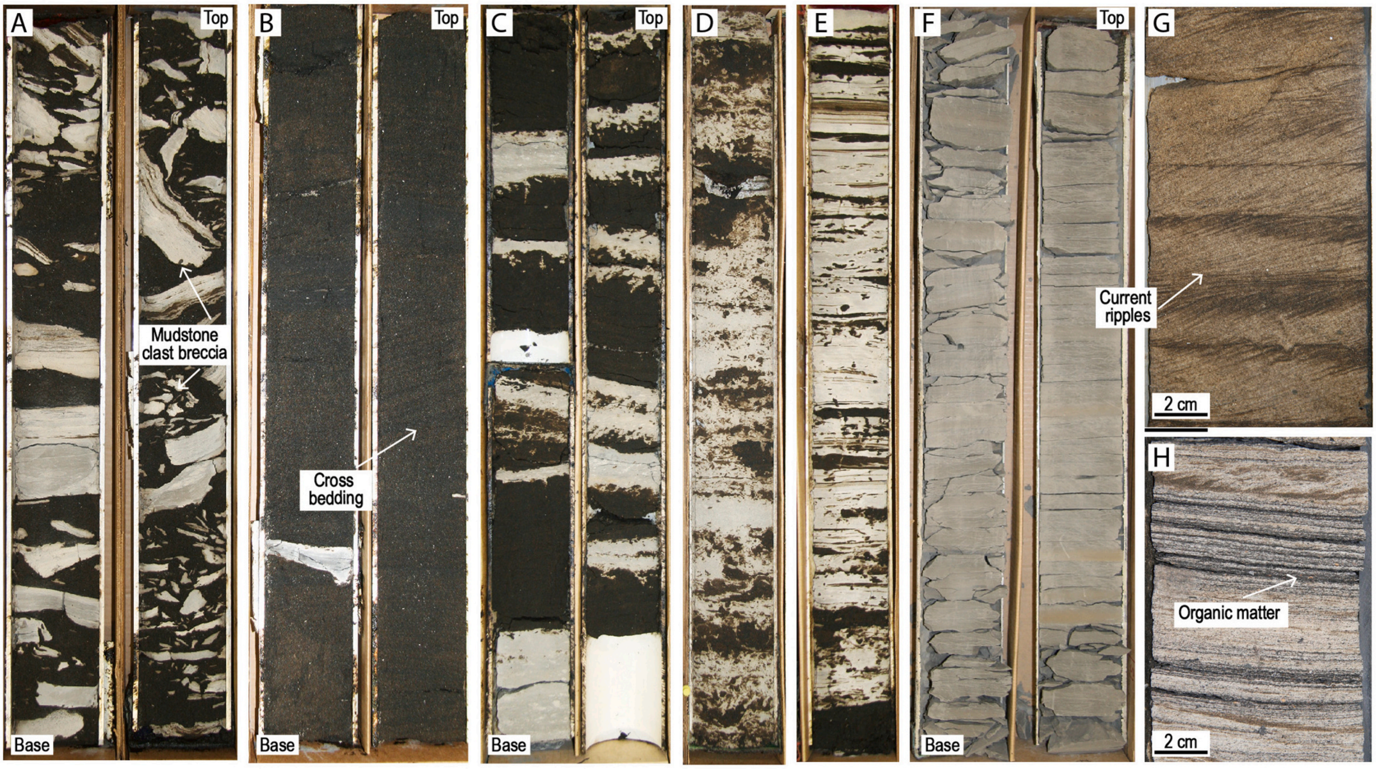


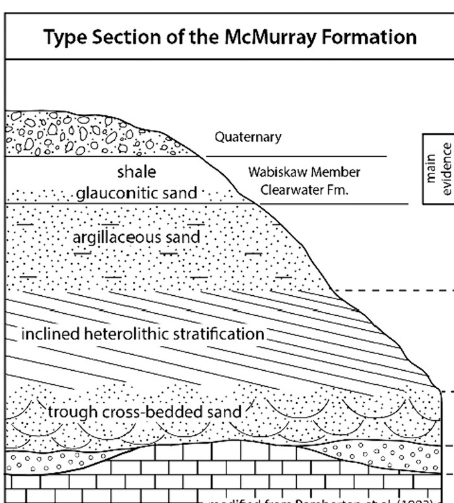
Fig. 7. McMurray CB facies. (A) Mudstone-clast breccia, which is commonly present at the base of the CB deposits. (B) Cross-bedded sandstone. (C) Bioturbated, sandstone-dominated inclined heterolithic strata (IHS). (D) and (E) Bioturbated, siltstone-dominated IHS. (F) Thick mudstones with no bioturbation. (G) Current-rippled sandstone. (H) Climbing current ripples and organic-rich laminae. Core boxes are 75 cm long.

composite McMurray A2 channel belt is mainly present in the main paleovalley (Fig. 6A), where it is up to 50 km wide and has an average thickness of 48 m (Hagstrom et al., 2023).

The paleoenvironment of McMurray Formation CBs, particularly the A2 CB, has been the subject of much debate and is the focus of the McMurray conundrum. We expand on this in the following section.

4. Evolution of paleoenvironmental interpretations

Over the last ~100 years, the origin of McMurray Formation sediments has been widely speculated upon. From initial mining operations to recent subsurface bitumen extraction, the contribution of new types of data have driven an evolution of paleoenvironmental interpretations (Fig. 8). The new scientific questions that arise, along with the iterative refining of models, is a captivating example of application of the



Timeline of Previous Work (~100 years)

	McLearn (1917)	Carrigy (1959)	Carrigy (1971)	Stewart & MacCallum (1978)	Mossop (1980)	Pemberton et al. (1982)	Mossop & Flach (1983)	Ranger & Pemberton (1988; 1992; 1997)	Wightman & Pemberton (1997)	Hubbard et al. (2011)	Blum & Pecha (2014)	Gingras et al. (2016)	Durkin et al. (2017; 2020)
main evidence	-lithology	-lithology	-outcrop architecture	-outcrop -sed.	-outcrop arch.	-trace fossils -palyn. -sed.	-accretion & paleoflow data	-trace fossils -sed.	-outcrop -trace fossils -sed.	-3D seismic -sed. -palyn.	-detrital zircons	-trace fossils -sed.	-3D seismic -sed.
	McMurray Formation	upper	Gilbert-type delta: delta topsets	marine	n/a	marine (low-energy beach)	n/a; floodplain	brackish shoreface	brackish bay	n/a	n/a	brackish-to-marine shoreline	marine shoreline
		middle	Gilbert-type delta: delta front foresets; n/a	estuarine	large, deep, meander-ing fluvial or upper estuarine channels	large channels, brackish, proximal to the shoreline	point bars of large fluvial drainage on coastal plain	estuarine point bars; turbidity maximum zone	estuarine point bars; sub-tidal sand bars	large, tidally-influenced fluvial meander belt	fluvial; continen-tal-scale drainage system	brackish-water channel sands & tidal flats; estuarine	fluvial meander-belt; upper backwater zone; 100s km from shoreline
		lower		fluvial	n/a	n/a	n/a	fluvial	fluvial	n/a	n/a	fresh/brackish	n/a
Waterways Fm. (Devonian)													

Fig. 8. McMurray Formation type section and ~ 100-year timeline of interpretations. The type section is based on outcrop along the Athabasca River. The timeline from left to right is oldest to youngest publications. The selected publication listed is the leading article for each interpretation but many are supported by additional studies indicated by letters (a) through (i) and are listed here: (a) Nelson and Glaister, 1978; (b) Mossop, 1980b; (c) Flach, 1977, 1984; Flach and Mossop, 1985; (d) Ranger and Pemberton, 1988, 1992; (e) Ranger and Gingras, 2003; Lettley, 2004; Ranger et al., 2008; (f) Smith et al., 2009; Musial et al., 2012; (g) Benyon et al., 2014; (h) Harris et al., 2016; Shchepetkina et al., 2016; (i) Horner et al., 2019a; Martin et al., 2019; Durkin et al., 2020.

scientific method.

The earliest paleoenvironmental interpretations of the McMurray Formation were formulated in the 1930s through 1950s, which suggested that deposition took place under strong currents (Sproule, 1938) that may have been fluviatile (Ells, 1930). An Athabasca Oil Sands Conference in 1951 that focused on the accumulation of oil in the McMurray Formation saw several theories emerge. Falconer (1951) was the first to propose that the lower-middle-upper succession represents a transition from fluvial to deltaic/estuarine to marine conditions. Others envisioned shoreline lagoonal conditions with contemporary accumulation of heavy oil (Hume, 1951; Link, 1951; Sproule, 1951), and broad floodplain or coastal lowland environments (Kidd, 1951).

Following an informal subdivisions of the formation stratigraphy (see Section 3; Carrigy, 1959), Carrigy (1971) interpreted outcrop observations of large (>30 m thick) inclined packages of bedded sandstone and mudstone as Gilbert-type delta-front deposits. Further investigation into the inclined sandstone and mudstone packages led researchers to interpret the middle McMurray member as estuarine due to grain-size distributions, heterolithic bedding, and primary sedimentary structures cited as evidence for tidal processes (Stewart and MacCallum, 1978). Shortly thereafter, building on previous work, (Flach, 1977) and Mossop (1980a) suggested deposition in large (>1000 m wide), deep (up to 45 m) fluvial or estuarine channels. In 1982, Pemberton et al. documented bioturbation comprised of diminutive and low diversity trace fossils comparable to those in modern brackish-water settings and interpreted that the depositional setting was proximal to the paleoshoreline. Further analysis of the thick packages of inclined-bedding showed that the dip directions of inclined beds were oriented perpendicular to paleoflow measurements from dune-cross-stratified sandstone; this relationship lead to the first interpretation of point-bar deposition, which was attributed to fluvial meander belt processes in a coastal plain setting (Mossop and Flach, 1983; Flach and Mossop, 1985). Following on the trace-fossil work, Ranger and Pemberton (1992) then focused on the sedimentology in cores and interpreted the point-bar-dominated channel fills as estuarine based on the prevalence of mudstone in the inclined heterolithic stratification (IHS) (i.e. inclined bedded sandstone and mudstone). The mudstone was interpreted to be evidence for clay flocculation in brackish water and deposition in the turbidity maximum zone of the estuary, which agreed with ichnological assemblage interpretations (e.g., Pemberton et al., 1982).

The estuarine interpretation largely persisted over the next 20 years, until 3D seismic data was published that revealed large point-bar and abandoned channel-fill deposits (Smith et al., 2009; Hubbard et al., 2011; Labrecque et al., 2011) consistent with the paleochannel reconstructions and fluvial interpretations of Mossop and Flach (1983). Researchers attempted to reconcile the fluvial geomorphology with the brackish-water ichnology and minor palynological component by interpreting the paleoenvironment as a tidally-influenced river, comparable to that of the modern Sittang River in Myanmar (Hubbard et al., 2011). Furthermore, detrital zircon data from channel sandstones supported a large, continental-scale drainage area for the McMurray Formation (Benyon et al., 2014; Blum and Pecha, 2014) and additional 3D seismic data led researchers to make comparisons with the upper backwater zone of the lower Mississippi River (Durkin et al., 2017; Martin et al., 2019). The latter fluvial channel-belt interpretations implied deposition landward of the saltwater wedge (e.g., Durkin et al., 2020). In response to many fluvial-focused interpretations, Gingras et al. (2016) re-affirmed the significance of trace-fossil evidence and stated that fluvial channel interpretations were not tenable. At this point the 'conundrum' was born (e.g., Blum and Jennings, 2016; Blum, 2017; Gingras and Leckie, 2017).

5. McMurray conundrum

The McMurray conundrum acknowledges the apparent incompatibility of a brackish-water interpretation of the trace fossil assemblage (e.g., Gingras et al., 2016) and a fluvial channel belt interpretation of the geomorphologic elements explicitly imaged in seismic data (e.g., Durkin et al., 2017). The trace fossil interpretation implies deposition seaward of the saltwater wedge (i.e, brackish water) (Gingras et al., 2016), whereas the geomorphology implies deposition landward of this zone, and potentially quite far landward beyond the limit of tidal influence (Durkin et al., 2017). In large-catchment depositional systems, distances between these zones are typically 100 s of kilometers (Gugliotta et al., 2016). Characteristics of the CBs that are generally agreed upon include the continental-scale drainage area interpreted from detrital zircon data (e.g., Benyon et al., 2014; Blum and Pecha, 2014) and the scale of point bars and channel features (e.g., Hubbard et al., 2011). The debate has centered around the depositional environment of these features and the following will summarize the two prevailing models and their critiques.

It is important to acknowledge the spatial and temporal expanse of McMurray Formation CBs. With an along-dip length of >300 km and a temporal duration of at least 6 Ma, the observations made are not always placed in equivalent context. With a depositional system of the magnitude of that in the McMurray Formation, and the complex history of innumerable cut-and-fill events, interpretations of the paleogeographic setting are dogged by: (1) the reality that both fluvial through to tidal-fluvial sub-environments are plausibly associated with any given CB; and (2) not all detailed observations are from known stratigraphic intervals, meaning the observations of different workers are not a part of the same CB. Indeed, the recognition of various genetically distinct channel-belts only goes back to the 1990's (e.g., Ranger and Pemberton, 1997), many researchers were reluctant to use these stratigraphic frameworks since their identification (e.g., Crerar and Arnott, 2007; Barton, 2016; Wahbi et al., 2023), and in many areas the top of the formation is not preserved such that observations of the McMurray cannot be placed in context of mapped CBs (e.g., Peng et al., 2022).

5.1. *Estuarine fluvial-tidal channel model*

The estuarine fluvial-tidal channel model for McMurray CBs asserts that deposition of inclined heterolithic stratification on point bars occurred under brackish-water conditions with varying tidal influence, which has been interpreted as an estuarine environment or its fluvial-tidal transition zone (e.g., Gingras et al., 2016; La Croix et al., 2019). The model is primarily driven by interpretations of the trace-fossil assemblage, but also supported by evidence for tidal processes in physical sedimentary structures and the presence of brackish-water palynomorphs (e.g., dinoflagellate cysts) (Pemberton et al., 1982; Ranger and Pemberton, 1988, 1992; Martinius et al., 2015; Hein and Dolby, 2018), which will be summarized herein.

5.1.1. *Supporting evidence*

5.1.1.1. Biogenic Structures. The bioturbation in CBs is characterized by a general upward-increasing trend of bioturbation intensity and/or diversity with markedly diminutive burrow size (1–3 cm long) and variable burrowing styles (Fig. 9)(Gingras et al., 2016). The basal, channelized deposits that are comprised of mudstone-clast breccias and thick cross-bedded sandstones typically exhibit no trace fossils. In places, the cross-bedded sandstones have sporadically and unevenly distributed trace fossil suites (BI 0–2) that can include *Cylindrichnus*, *Gyrolithes, Planolites*, *Skolithos*, *Teichichnus* and/or *fugichnia*. The most significantly bioturbated interval is the IHS, in which siltstone-dominated IHS is more intensely bioturbated (BI 3–5) than sandstone-dominated IHS (BI 0–2) (Fig. 10). Some IHS intervals display no to rare bioturbation even when they have same sand/mud ratio as other intensely bioturbated IHS intervals (Fig. 10A). The uppermost mudstone-dominated interval, which was interpreted as mainly abandoned-channel fills, typically exhibits no or few trace fossil (Fig. 7F)

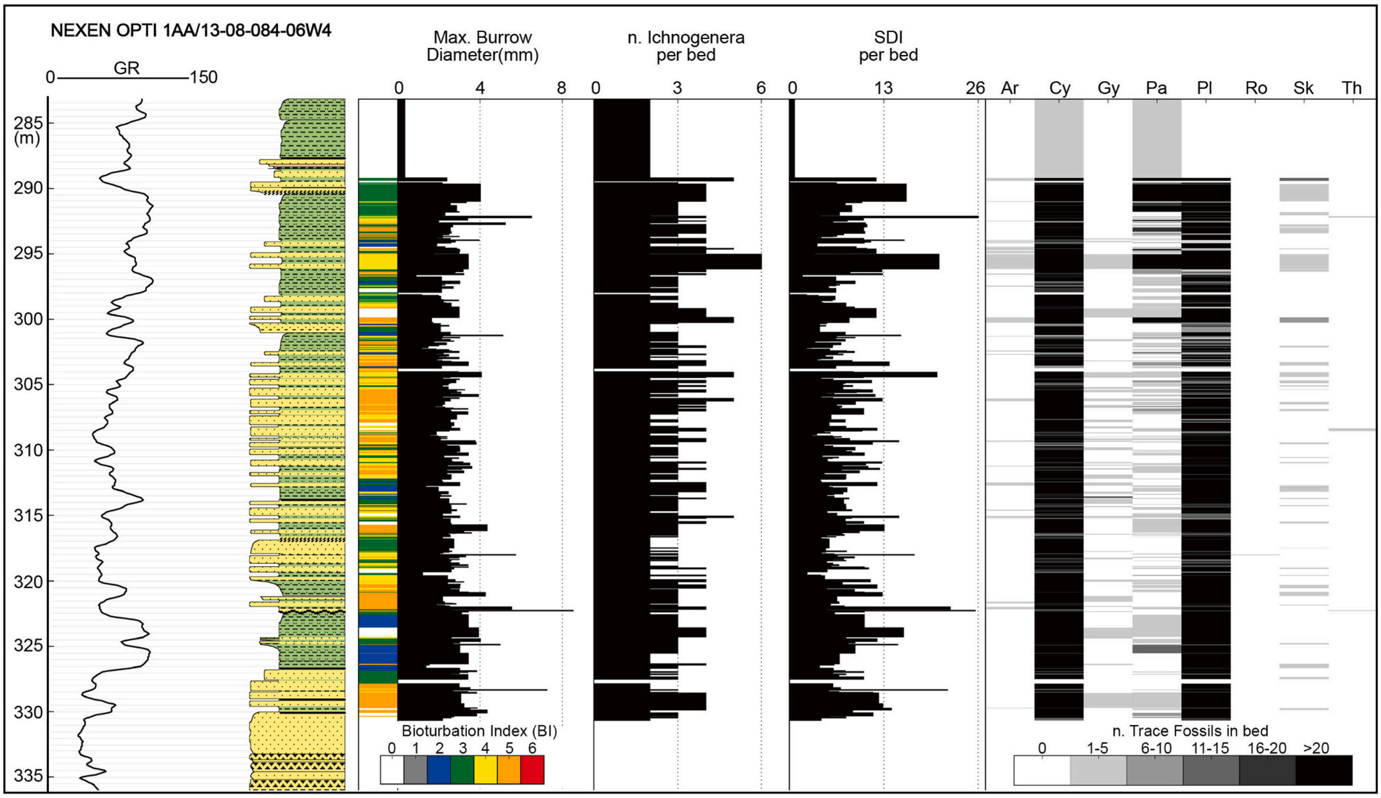


Fig. 9. Gamma-ray log, lithology, and ichnological characteristics of a large point bar (from Gingras et al., 2016). Note the general diminutive burrow size and dominantly two trace-fossil species in most intervals.

with only rare burrows in thin heterolithic beds (Hubbard et al., 2011).

IHS displays variable bioturbation styles that can be generally summarized as: (i) *Planolites*-dominated with subordinate *Teichichnus* and/or *Cylindrichnus*, (ii) *Cylindrichnus*-dominated with rare *Skolithos* and *Planolites*, and (iii) monospecific assemblages of *Gyrolithes* (Gingras et al., 2016). The *Planolites*-dominated type mainly occurs in thinly interbedded sandstones and siltstones (mm- to cm-scale bedding thickness) (Fig. 10A). The *Cylindrichnus*-dominated (Fig. 10B,C,F,H,I) and *Gyrolithes*-dominated (Fig. 10G) types developed in thicker sandstone beds (sand proportions >30–50%). In particular, the *Cylindrichnus* and *Gyrolithes* occur exclusively at the interface between the sandstone and mudstone beds. The burrowing style, described as 'top-down' bioturbation (Jablonski and Dalrymple, 2016), shows a high concentration of burrows penetrating down from overlying siltstone beds into the uppermost parts of sandstone beds (Fig. 10). Most of these burrows are vertically or slightly oblique in one direction (Fig. 10). Intervals of colonized sandstones and mudstones are commonly capped by massive, unborrowed mudstones (Fig. 10).

Absent to sporadically distributed bioturbation in the cross-bedded sandstones is likely due to high migration and deposition rates of dune-scale bedforms (MacEachern and Gingras, 2007; Gingras et al., 2011; Sisulak and Dashtgard, 2012) in the channel bottom and lower parts of point bars. The absence of trace fossils in the abandoned channel fills is interpreted as an indication of a stressed environment for organisms, potentially due to poor connection to the open marine environment (Crerar and Arnott, 2007).

The diminutive, low-diversity trace fossil suite is interpreted to imply exceptional physico-chemical stress in the depositional environment, where only opportunistic trophic generalists adapted and colonized (Pemberton et al., 1982; Gingras et al., 2011; Hubbard et al., 2011; Shchepetkina et al., 2016). The randomly distributed *Planolites* in thin siltstone beds is interpreted to suggest a relatively low sedimentation rates such that infauna colonization was well developed. The 'top-down' burrowing of the organisms that formed *Cylindrichnus* and *Gyrolithes* (dwelling burrows) are interpreted to be formed by biological reworking of the fine-grained sediment down into the previously deposited sand beds (Jablonski and Dalrymple, 2016) during extended periods of low energy (Sisulak and Dashtgard, 2012). These mud-filled burrows and overlying mudstones have been interpreted to suggest that the infaunal organisms were smothered when their burrows were filled with mud (Ranger and Pemberton, 1992). Locally pervasive burrows in both sandstone and mudstone indicate the sedimentation rates were low (Gingras et al., 2016) and the saline conditions probably persisted.

5.1.1.2. Palynology. The palynological assemblages in the McMurray CBs were characterized by dominant terrestrial gymnosperm pollen and trilete spores with a small portion of brackish and marine dinocysts and acritarchs (Hubbard et al., 2011; Hein and Dolby, 2018). The gymnosperm pollen (e.g., *Alisporites* sp., *Podocarpidites* sp.) and trilete spores (e.g., *Appendicisporites* sp.) are generally associated with well-drained upland and flood-plain areas, respectively (Singh, 1964). The identified dinocysts (e.g., *Muderongia* sp., *Nyktericysta* sp., and *Balmula* sp.), which represent brackish-water forms, and acritarchs (e.g., *Classopollis* sp.) are indicative of marine environments (Demchuk et al., 2007). The presence of the brackish and marine palynomorphs could be due to marine influence, which supports the estuarine fluvial-tidal channel model for the McMurray CBs (Hubbard et al., 2011; Musial et al., 2012; Hein and Dolby, 2018), or recycling from the regional PSSs and/or underlying Paleozoic strata during channel incision (Horner et al., 2019b).

5.1.1.3. Physical structures. In addition to its ichnological characteristics, researchers have argued that the McMurray CBs have tide-generated sedimentary structures (Wightman and Pemberton, 1997; Barton, 2016; Gingras et al., 2016; Timmer et al., 2016). Current ripples oriented up-slope on lower foreset of cross beds, as well as organic-matter drapes, were observed at High Hill River (Wightman and

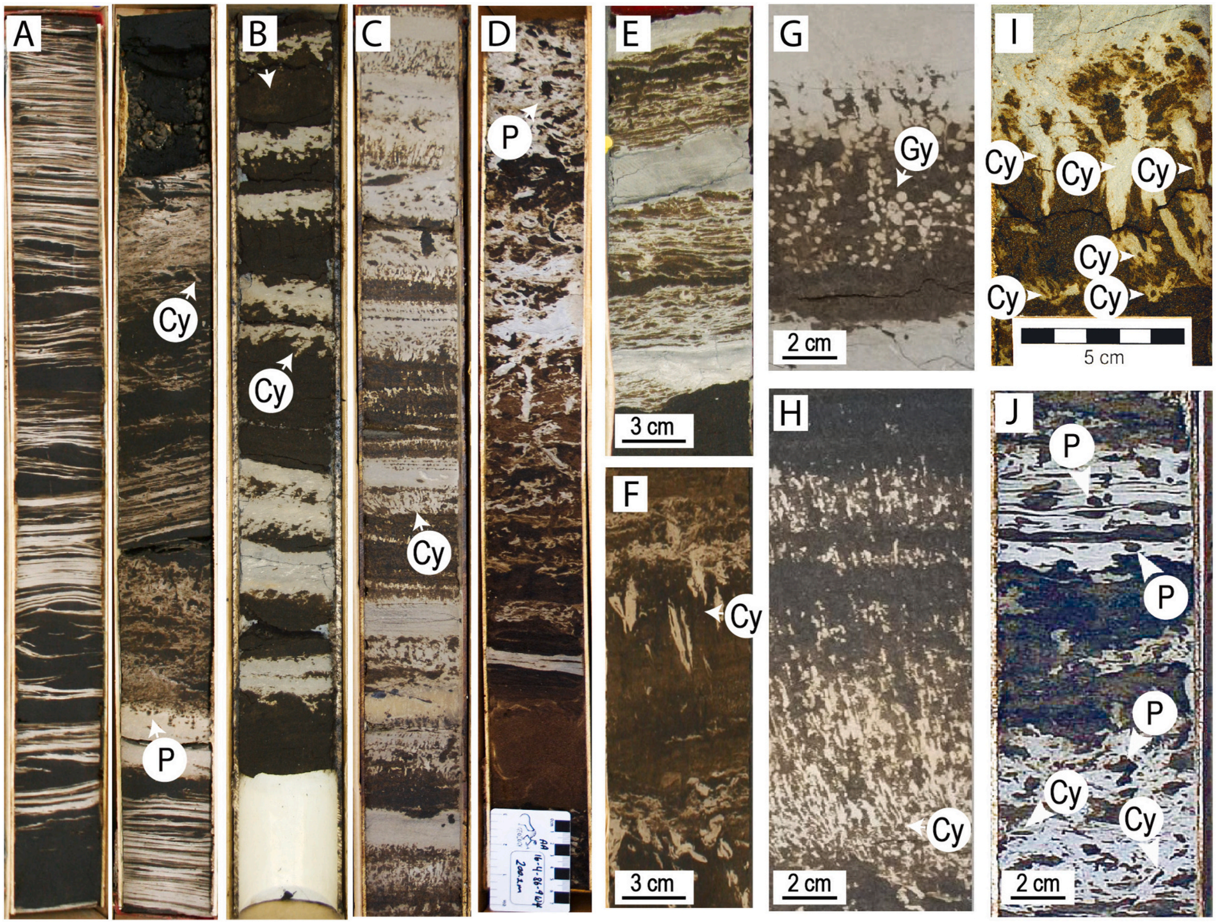


Fig. 10. Examples of bioturbated IHS in the McMurray CB deposits (figs. I and J are modified from Gingras et al., 2016).

Pemberton, 1997) and Christina River outcrop sections (Fig. 11) (Martinius et al., 2015). Well-developed trough-cross-stratified beds are exposed with backflow ripples and organic-matter-rich bottomsets that exhibit cyclic variation in thickness at the Christina River outcrop (Fig. 11). Cross beds in the dune strata exhibit alternation of thicker and finer bundles of laminae (Musial et al., 2012). Trough or planar tabular bedding is commonly observed with opposing dipping beds (Musial et al., 2012; Chen et al., 2022).

The current ripples that climbed up the foreset slope have been interpreted as the product of the subordinate tidal flow (Wightman and Pemberton, 1997). The backflow ripples in the thick bottomset layers have been interpreted as strong vortex ripples when fluvial flow strength reduced and tidal retardation increased (Martinius et al., 2015). The cyclic variation in organic-matter concentration and bottomset thickness (Fig. 11) were interpreted to suggest a superimposed tidal modulation upon predominantly fluvial conditions within the fluvial-tidal transition zone (Martinius et al., 2015). The alternating thicker and thinner cross beds in the McMurray CBs has been interpreted as tidal bundles deposited due to semidiurnal neap-spring tidal periodicity (Timmer et al., 2016), whereas others have claimed that they were likely attributed to seasonal flow variations in climate (Labrecque et al., 2011) due to the lack of clear tidal rhythm (Jablonski and Dalrymple, 2016; Chen et al., 2022). Bedform foresets with apparent opposing dips observed in the McMurray Formation (e.g., Barton, 2016) have been alternatively interpreted to represent variably oriented dunes (Hein et al., 2001) or core rotation during slabbing processes (Chen et al., 2022) rather than sedimentary structures of distinctly tidal origin (cf. Dalrymple and Choi, 2007; Peng et al., 2018).

5.1.2. *Depositional settings and analogues*

Based on trace-fossil assemblages, the McMurray CBs have commonly been attributed to tide-dominated estuary environments (Ranger and Pemberton, 1988, 1992; Wightman and Pemberton, 1997; Nardin et al., 2005; Crerar and Arnott, 2007; Peacock, 2010; Barton, 2016; Gingras et al., 2016; Timmer et al., 2016; Chen et al., 2022). The cross-bedded sandstones and IHS beds have been interpreted as the deposits of dune-scale migrating bedforms that were subject to variations in bedform migration rates, depositional energy, and salinity (Gingras et al., 2016). The cross-bedded sandstones were interpreted to occur in the lower part of inner-estuarine point bars (Wightman and Pemberton, 1997; Chen et al., 2022). The paucity or sporadic distribution of bioturbation in cross-bedded sandstones was likely due to rapid sedimentation and highly mobile substrates that organisms were not able to inhabit (Gingras et al., 2016; Chen et al., 2022). The sandstone-dominated IHS was interpreted as deposits in the lower to middle part of laterally accreting estuarine point bars (Stewart and MacCallum, 1978; Pemberton et al., 1982; Smith, 1988, 1989; Ranger and Pemberton, 1997; Wightman and Pemberton, 1997). The sandstone and silty mudstone beds were interpreted to be deposited during high fluvial discharge and tide-dominated low base-flow periods, respectively (Chen et al., 2022). Mudstone-dominated IHS, which has gentle dipping to horizontal bedding, were interpreted to represent the upper point bar or intertidal flat deposits (Wightman and Pemberton, 1997; Barton, 2016; Gingras et al., 2016; Chen et al., 2022). The upward increase in mudstone content and bioturbation intensity were interpreted to reflect a transition from point bars to intertidal flats (Gingras et al., 2016). Besides this, the mudstone-dominated IHS has also been interpreted as muddy point bars deposited within the turbidity maximum zone of the estuary (Ranger and Pemberton, 1992; Wightman and Pemberton,

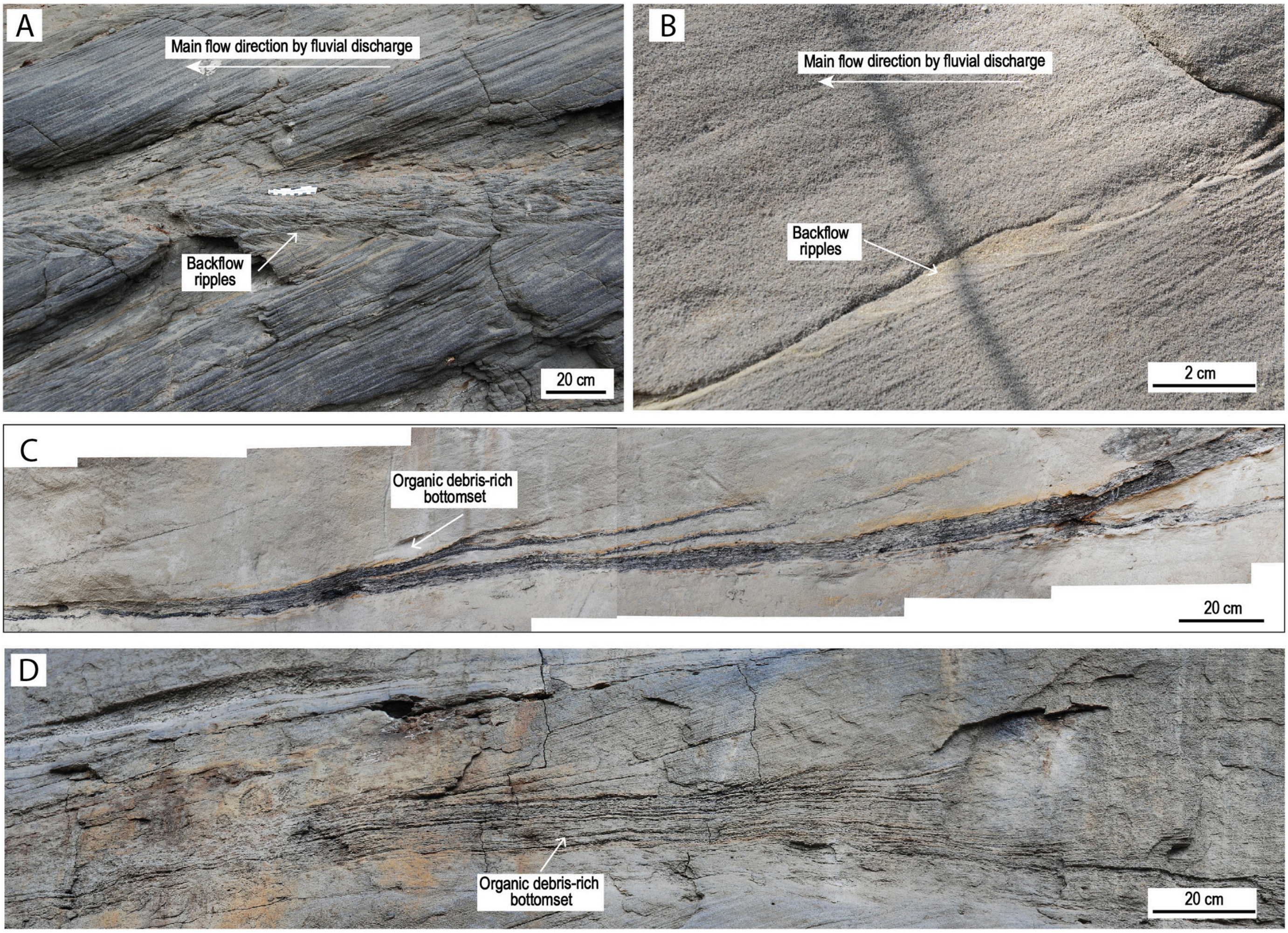


Fig. 11. Backflow ripples and organic debris-rich bottoms from outcrops along the Christina River (modified from Martinius et al., 2015). (A) Backflow ripples developed in the bottomsets of point bar deposits. (B) A small backflow ripple preserved in the foreset. (C) and (D) Bottomsets of the point bars showing abundant organic matter concentration.

1997).

Other workers have suggested the McMurray CBs were developed in the FTTZ (Hubbard et al., 2011; Musial et al., 2012; Martinius et al., 2015; Jablonski and Dalrymple, 2016) located landward of an estuary (Dalrymple and Choi, 2007; Shchepetkina et al., 2019). The bioturbated IHS was interpreted as tidally influenced point-bar deposits in meandering channels developed in a brackish-water, or periodically brackish-water environment (Musial et al., 2012). Jablonski and Dalrymple (2016) argued the IHS in the McMurray CBs along the Steepbank River was likely situated in a relatively landward position within the fluvial-tidal transition zone. The alternations between sandstone and mudstone beds in IHS were interpreted as the result of seasonal or annual variations in fluvial discharge. The sandstone beds and the mudstone beds were interpreted to be deposited during river floods and inter-flood periods, respectively. The presence of intense bioturbation in mudstone beds and thin sandstone beds, and abundant trace fossils subtending into underlying sandstone beds were interpreted to suggest tidally influenced brackish-water conditions occurred during low-flow stages (Jablonski and Dalrymple, 2016).

The FTTZ of the Sittang River estuary of Myanmar in Southeast Asia has been proposed as an analogue to the McMurray CBs (Hubbard et al., 2011)(Fig. 12). The tidal range at the Sittang River estuary mouth is macrotidal (4–7 m) with tides intruding the estuary at least 75–100 km from the tide-dominated estuary mouth (Hubbard et al., 2011; Choi et al., 2020). In the FTTZ, the planform morphological characteristics and depositional elements, such as point bars, counter point bars, and oxbow lakes, resemble those of the McMurray A2 channels. However, a main problem of using the Sittang River as an analogue is that the drainage system is significantly smaller (the river is 420 km long with a discharge of 1542 m^3s^{-1}) (Van Rest, 2015) compared to the McMurray system (continental-scale river with an estimated discharge of 20,700–23,000m^3s^{-1}) (Horner et al., 2019a). Unfortunately, bed-scale studies of the Sittang River are rare.

5.2. *Fluvial channel-belt model*

The fluvial channel-belt model has several variants that range from deposition in tidally-influenced fluvial channels (e.g., Hubbard et al., 2011; Musial et al., 2012) to deposition in the upper backwater zone with little to no tidal influence (e.g., Blum, 2017; Durkin et al., 2017, 2020; Horner et al., 2019a; Martin et al., 2019). These models are primarily based on seismic geomorphology of large-scale point bars and abandoned channels that compose wide, laterally amalgamated channel-belt deposits of the A2 CB (Fig. 13F). Additional evidence includes mapped extent of CBs (Horner et al., 2019a; Martin et al., 2019; Peng et al., 2022) and physical sedimentary structures (Durkin et al., 2017), which will be summarized herein.

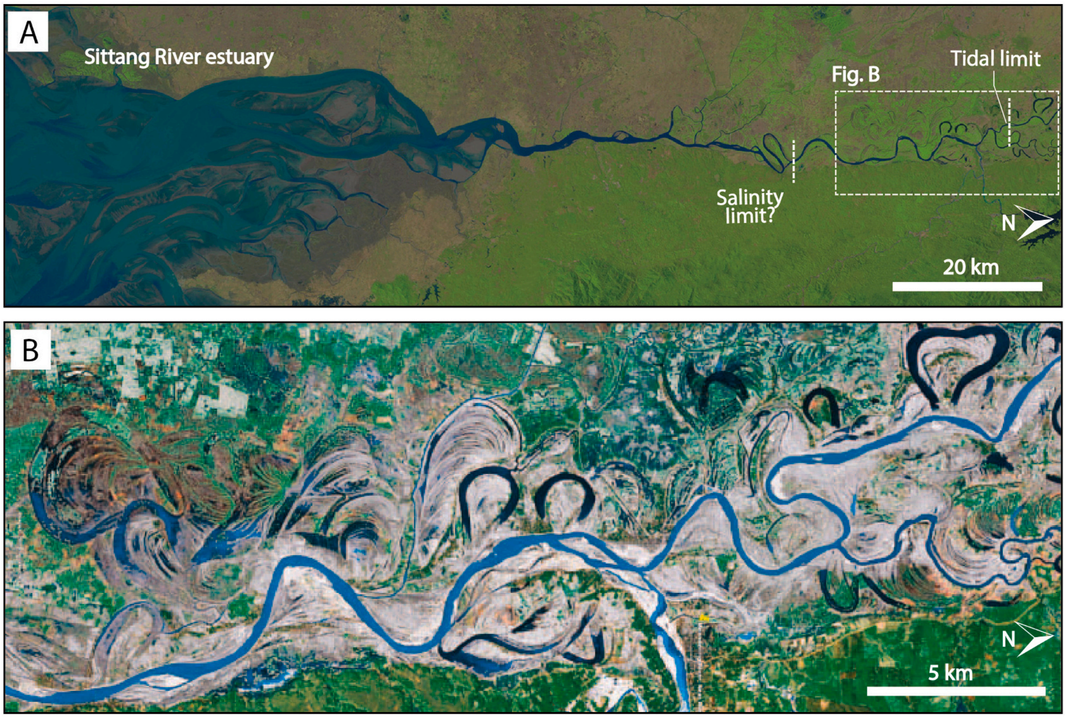


Fig. 12. (A) The Sittang River estuary located in Myanmar, Southeast Asia (modified from Choi et al., 2020). (B) Tide-influenced fluvial architecture which was considered analogous to the McMurray CBs (from Hubbard et al., 2011).

5.2.1. Supporting evidence

5.2.1.1. Seismic geomorphology. The primary supporting evidence for a fluvial channel-belt model is the geomorphology of depositional elements revealed in 3D seismic data of A2 CBs (Fig. 13) (e.g., Smith et al., 2009; Hubbard et al., 2011; Musial et al., 2012; Moreton and Carter, 2015; Durkin et al., 2017; Hagstrom et al., 2023). These planform perspectives were the first unequivocal evidence for the scale of the point-bar and abandoned-channel deposits, originally hypothesized by Mossop (1980a) and others, as well as the width of laterally amalgamated channel belts (>20 km; e.g., Durkin et al., 2017). The abandoned channel (i.e. oxbow-lake) fills are an average of ~880 m in width, which is used as an approximation of paleobankfull width of the active channel at time of deposition (Horner et al., 2019a). Seismic cross sections, borehole data from channel fills, and estimations from adjacent point-bar deposit thickness reveal an average paleobankfull channel depth of 40 m (Durkin et al., 2017; Horner et al., 2019a). From these dimensions, slope estimates, and grain size data, maximum bankfull paleodischarge has been estimated at 15,000 m^3s^{-1}, which is consistent with large meandering river systems (e.g., lower Mississippi River, USA; Parana River, Argentina; McKenzie River, Canada, and Peace River, Canada) (Musial et al., 2012). However, the scale of the river channel is not diagnostic of a fluvial environment, as there are many large tidally-dominated, brackish-water estuarine channels (e.g., Sittang River, Myanmar). The argument for a fluvial environment is built on the evidence for extensive meander-bend migration that constructed wide, laterally amalgamated channel-belt deposits (e.g., Blum, 2017; Durkin et al., 2017, 2020).

Studies quantifying meander-bend migration rates of large meandering fluvial systems entering a marine basin demonstrate a peak at or slightly basinward of the backwater zone (i.e. the point where the river channel goes below sea level) and a substantial decrease to very low rates of migration through the saltwater incursion zone (Hudson and Kessel, 2000; Blum, 2017; Durkin et al., 2020). This is driven by variations in flow velocity and sediment transport as rivers enter the backwater zone, resulting in net deposition in the upper backwater zone and net erosion and sediment transport in the lower backwater zone (Nittrouer et al., 2012). As a result, fluvial channel belts are characterized by a decrease in channel-belt width-to-thickness (or active-channel-to-channel-belt width-to-thickness) ratio basinward through the backwater reach (Blum et al., 2013; Fernandes et al., 2016). Therefore, wide, laterally amalgamated channel-belt deposits are not constructed near the shoreline (Blum, 2017; Durkin et al., 2017, 2020). Rather, due to low migration rates, channels near the shoreline will avulse before constructing wide channel belts with many meander bend cutoffs, akin to those revealed in 3D seismic data (e.g., Durkin et al., 2020). The width-to-thickness ratio of channel-belt deposits in the McMurray A2 CB (Fig. 13) are consistent with measurements from upper backwater zones of large meandering river systems, >100 km landward of the salinity limit (Blum, 2017; Durkin et al., 2017, 2020). The paleoenvironment interpreted from channel-belt width-to-thickness ratios is further supported by physical sedimentary structures and the mapped extent of the A2 CB.

5.2.1.2. Physical sedimentology. The sedimentology of the McMurray CBs is also consistent with the fluvial channel-belt model (e.g., Durkin et al., 2020). Upward-fining successions from erosionally-based trough-cross-stratified sandstone to IHS overlain by horizontal mudstone is consistent with fluvial point-bar deposition (e.g., Allen, 1965). Measurements from cross-stratified sandstone document a unidirectional paleoflow that exhibits a perpendicular relationship with IHS dip direction (e.g., Mossop and Flach, 1983; Hubbard et al., 2011; Durkin et al., 2017; Hayes et al., 2018). The thickness of point-bar successions is consistent with abandoned channel dimensions measured in 3D seismic data, confirming their genetic relation. The decimeter-scale alterations of sandstone and mudstone that compose IHS have been interpreted to represent seasonal fluctuations in river discharge (e.g., Jablonski and Dalrymple, 2016). IHS is also common in many ancient and modern fluvial point bar deposits (e.g., Thomas et al., 1987; Gowland et al., 2018; Durkin et al., 2018; Clift et al., 2019; Mayo et al., 2023), despite the tendency to cite IHS as evidence for tidal influence (e.g., Ranger and Pemberton, 1992; Shanley et al., 1992; Corbett et al., 2011). Widespread

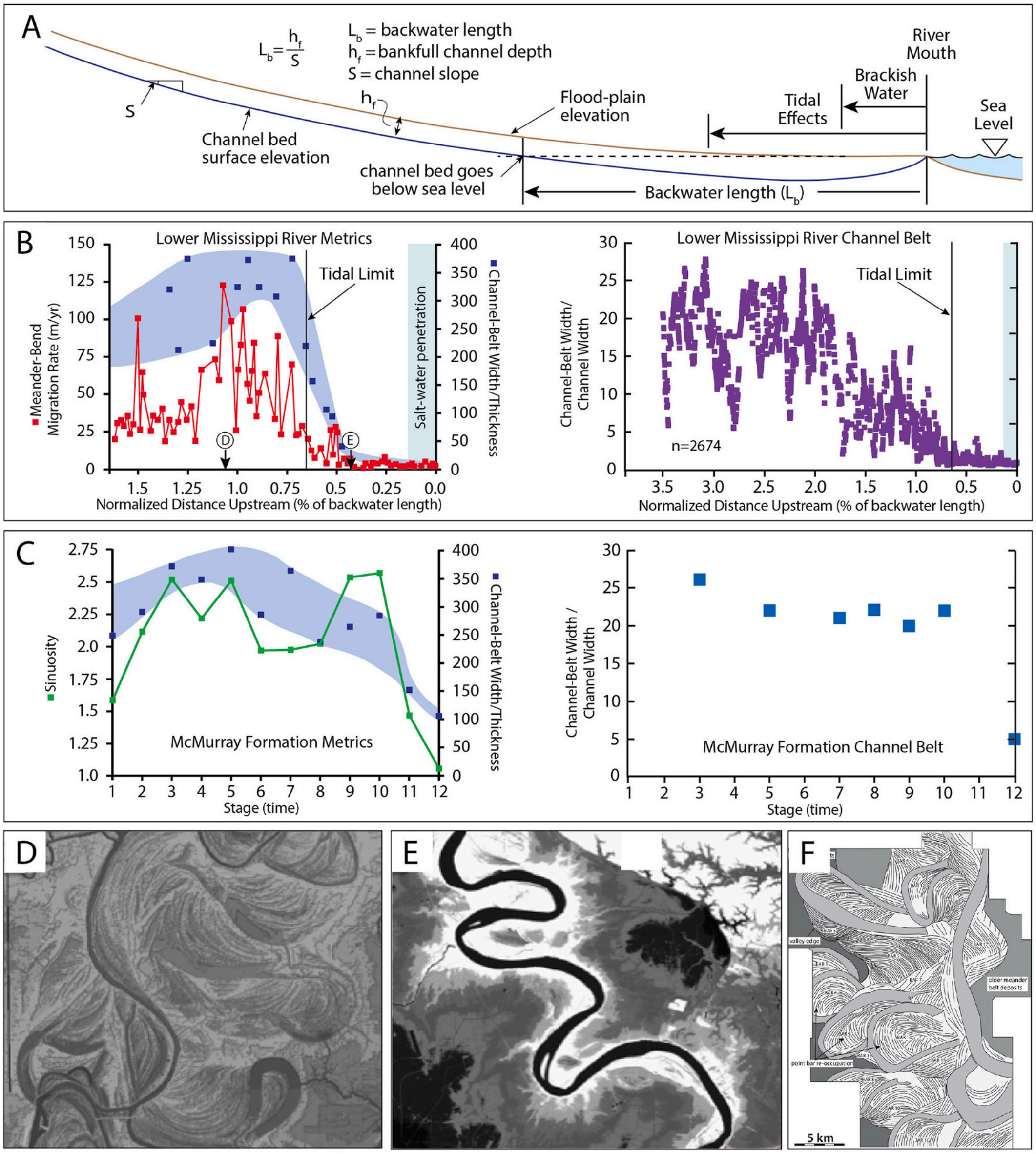


Fig. 13. (A) Generic fluvial profiles showing zones of brackish water, tidal effect, and backwater length (from Blum et al., 2013). (B) Meander-bend migration rates, channel-belt width/thickness, and channel-belt width/channel width compared to normalized distance (represented as a percentage of the backwater length) for the lower Mississippi River (from Blum et al., 2013; Fernandes et al., 2016). (C) Sinuosity, channel-belt width/thickness, and channel-belt width/channel width over stages (time) of the McMurray A2 CBs (from Durkin et al., 2017). Note that paleochannel evolution stages (stage 1 represents the oldest) were reconstructed and associated morphometric parameters were measured based on the seismic data. (D) Channel-belt planform of the Mississippi River within the upper limits of the backwater reach from LIDAR (from Bentley Sr et al., 2016). (E) Channel-belt planform of the Mississippi River within the backwater reach (from Bentley Sr et al., 2016). (F) Line tracing of the McMurray A2 CB platform (from Durkin et al., 2018).

unidirectional paleoflow measurements and evidence for extensive lateral accretion of meander bends are diagnostic of dominantly fluvial processes.

Point bars and counter point bars have been identified in the McMurray CBs (Smith et al., 2009; Hubbard et al., 2011; Durkin et al., 2017). In the point-bar deposits from seismic time slices and cross sections, accretion packages are separated by intra-point-bar erosion surfaces (also termed as discontinuity surfaces) as results of expansion, extension, translation and rotation of a meander bend (Hagstrom et al., 2019). Such accretion packages with variable lithology and evidence for intra-point-bar erosion are commonly observed in the ancient record and modern river systems (Ghinassi et al., 2014; Durkin et al., 2015; Hagstrom et al., 2019). Counter point bars, which are siltstone-dominated with concave scroll patterns in plan view (Smith et al., 2009; Hubbard et al., 2011), were deposited on convex banks of meander bends. This depositional pattern is caused primarily by the down-valley migration of meanders because lateral accretion and expansion are restricted as rivers encounter resistant muddy sediments (Smith et al., 2009; Durkin et al., 2017). The down-valley migration or translation of meander bends was well documented in north or north-west oriented valleys. More than 75% of IHS in the counter-point-bar and point-bar deposits from outcrop and subsurface dip paleo-basinward to the north and northwest (Fustic et al., 2012). This down-valley translation in the McMurray Formation is morphologically similar to those in numerous modern rivers, such as the Peace River of Canada (Smith et al., 2009, 2011), the Athabasca River of Canada (Smith et al., 2011), the Sittang River of Myanmar (Hubbard et al., 2011), and the Kolyma River of Russia (Fustic et al., 2012).

5.2.1.3. Regional mapping. Regional mapping efforts have delineated the extent of McMurray CBs over a 300 km basinward transect from south (township 69) to north (township ~100) (Fig. 6). The A2 CB is the largest channel-belt system documented, has been the focus of most seismic geomorphology studies (e.g., Hubbard et al., 2011; Durkin et al., 2017; Hagstrom et al., 2023), and forms the main reservoir interval in many large steam-assisted gravity drainage (SAGD) production projects. The A2 CB is arguably the best-constrained channel-belt system globally, with over 1000 km^2 of published 3D seismic time-slice data and 1000s of boreholes. Therefore, the A2 CB has been used as the main evidence for a fluvial channel-belt model due to the amount of data available and mapped extent. Studies of the A2 CB demonstrate consistent characteristics along its length, including point-bar sedimentology and channel scale (Horner et al., 2019a; Martin et al., 2019; Durkin et al., 2020; Hagstrom et al., 2023) as well as ichnology (cf. La Croix et al., 2019). The physical mapped extent of a 300-km-long channel belt system implies that for any time-equivalent channel belt, deposition in the south would be *at least* 300 km from its genetic paleoshoreline. Although tidal influence can extend 100 s of kilometers inland, it has not been demonstrated that brackish water conditions can extend this far up a system of this scale (i.e. continental-scale river).

5.2.2. Depositional settings and analogue

Drainage area and discharge estimates (Musial et al., 2012; Horner et al., 2019a), as well as provenance studies (Benyon et al., 2014, 2016; Blum and Pecha, 2014) have suggested that the McMurray CBs likely represent a continental-scale drainage system, comparable to the Mississippi River. Discharge rates estimated by Horner et al. (2019a) (20,700–23,000 m^3s^{-1}) are consistent with those calculated by Musial et al. (2012) (15,000 m^3s^{-1}) and Bhattacharya et al. (2016) (17,000–34,000 m^3s^{-1}). These estimations are comparable to that of the modern Mississippi River (18,000 m^3s^{-1}). The drainage area for the McMurray A2 channel system, between 1.7×10^6 km^2 and 2.0×10^6 km^2 (compared to 2.9×10^6 km^2 of the Mississippi River) was interpreted to suggest that the A2 trunk system was occupied by a continental-scale drainage network (Horner et al., 2019a). Moreover, detrital zircon studies also support that the Lower Cretaceous McMurray CB deposits were likely sourced from long-lived, continental-scale drainage systems extending to the Appalachian Mountains in the southeastern United States, the Sevier fold-and-thrust belt in the southeastern United States, and the Canadian Shield in eastern Canada (Benyon et al., 2014, 2016; Blum and Pecha, 2014; Wahbi et al., 2023).

Based on its geomorphologic characteristics, which are similar to those of the lower Mississippi River, the McMurray A2 CB was interpreted to be deposited in the upper reaches of the backwater zone (Durkin et al., 2017; Martin et al., 2019). For example, the meander-bed migration rates in the McMurray A2 CB and lower Mississippi River are

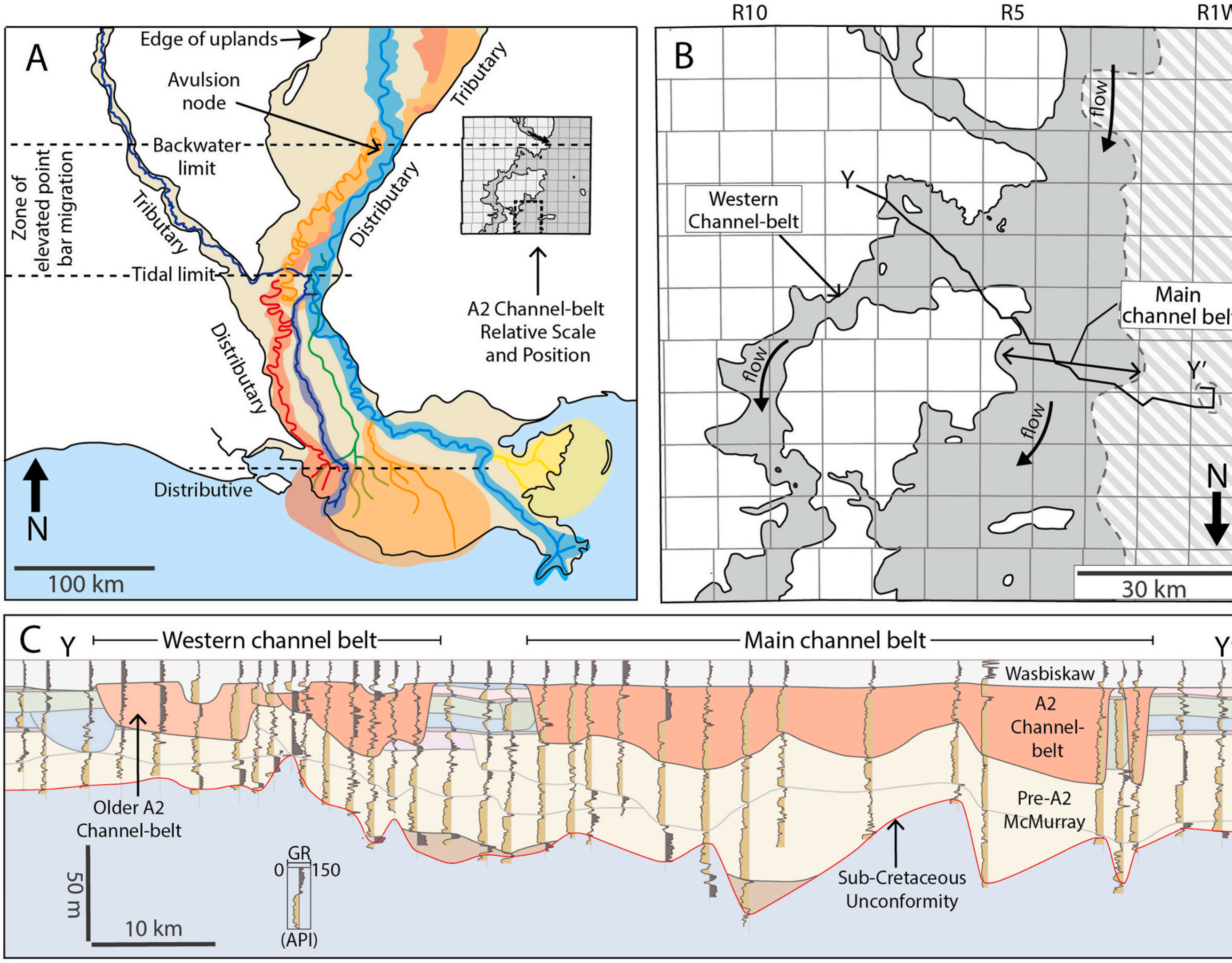


Fig. 14. A comparison of a large-scale avulsion of the lower Mississippi River to an avulsion of the McMurray A2 CB (From Martin et al., 2019). (A) A map of the lower Mississippi River CBs illustrating the location of an avulsion node coinciding with its backwater limit, with [B] inset to-scale. (B) *Re*-oriented map of the McMurray A2 CB shows a similar avulsion node, which was interpreted to be the result of backwater influence. (C) Stratigraphic cross section (line of section shown in [B]) illustrating the main CB and the avulsed CB to the west.

30–65 m/yr and 45 m/yr, respectively (Hudson and Kessel, 2000; Musial et al., 2012). Meander-belt-width to thickness ratios of the McMurray channels are >400, similar to ratios of channels located between 500 and 900 km upstream from the Mississippi River mouth (Durkin et al., 2017) (Fig. 13B, C). Channel-belt-width to channel-width ratios in the McMurray Formation exhibit high values (i.e., 20–25), which are comparable to those in the lower Mississippi River (Fig. 13B, C). In addition, a large channel-belt-scale avulsion in the McMurray A2 CB was documented and interpreted as the stratigraphic product of backwater effects (Martin et al., 2019). New mapping result of this study reveal several avulsions of the McMurray A2 channel belts farther in the north (Fig. 6A). The scale and platform geometry are comparable to the avulsion node located downstream of the backwater limit of the Mississippi River (Fig. 14). The meander-belt characteristics have been interpreted to suggest that the meander belt was not located in close proximity to its shoreline (Durkin et al., 2017). Later-stage A2 channels are more deeply incised and less sinuous, with decreased channel-belt-width to thickness ratios; this was interpreted to record a landward migration of the paleo-backwater zone during the overall transgression of the Boreal Sea (Durkin et al., 2017).

5.3. Critiques of paleo-depositional models

5.3.1. Estuarine models

As part of the McMurray conundrum debate, researchers have demonstrated observations that appear in contradiction to the estuarine models, including but not limited to, channel and channel-belt dimensions, vertical distribution of bioturbation, and position of the paleoshoreline. Horner et al. (2019a) demonstrated the constant width of abandoned-channel fills over a 40 km basinward segment of time-equivalent channel-belt deposits (Fig. 15). According to Leuven et al. (2018), the tidal limit in rivers entering estuaries is coincident with an exponential increase in channel width basinward (Fig. 15C). Therefore, Horner et al. (2019a) concluded that the consistent abandoned channel width suggested deposition landward of the tidal limit. The saltwater limit (i.e. extent of brackish water conditions) is a fraction of the tidal limit (Gugliotta et al., 2016), and only penetrates upstream during periods of low fluvial discharge. Additionally, if freshwater river discharge

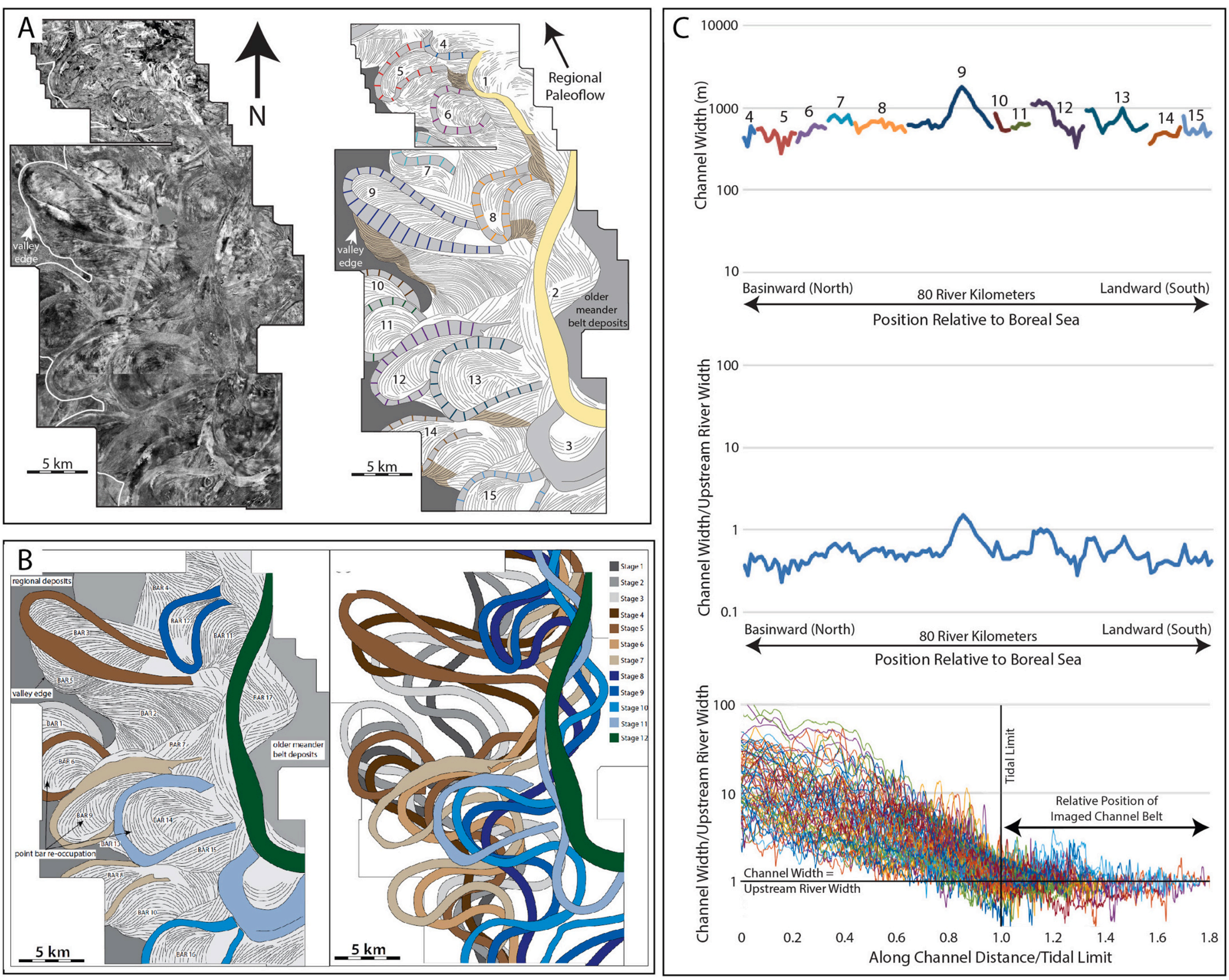


Fig. 15. (A) Seismic time slices and interpreted line tracing of the McMurray CB deposits (from Horner et al., 2019a). (B) Line traces of the lower two-thirds of the seismic image from fig. A showing meander-belt elements and reconstructed evolutional stages of meandering belts (from Durkin et al., 2018). (C) Channel width profiles of the McMurray A2 meandering belt (from Horner et al., 2019a); channel-width profile is normalized to the upstream width of the Mississippi River (i.e., 1200 m) (from Horner et al., 2019a), and the along-channel width profiles through the FTTZ of modern tidally influenced rivers (from Leuven et al., 2018). Note that the channel width and normalized channel width do not significantly increase downstream, indicating that the channel belt is possibly located in the upstream of the estuary's tidal limit.

was low to zero, brackish conditions would only exist in the lowermost reaches of the system and upstream bar deposits would be subaerially exposed (Blum, 2017). Therefore, Blum (2017) questioned the mechanism for pervasive bioturbation over the full thickness of bar deposits over a ~ 200 km basinward transect (e.g., Lettley et al., 2007). This would imply bar deposition always occurred within a few kilometers of the shoreline without subsequent fluvial channel reworking during shoreline regression (Blum, 2017).

Lastly, Durkin et al. (2020) critiqued a FTTZ interpretation because previous work has not demonstrated evidence of a basinward transition (cf. La Croix et al., 2019). Many modern studies of the FTTZ show morphological, sedimentological, and ichnological changes coincident with the basinward transition from fresh to brackish to marine conditions (Blum et al., 2013; La Croix et al., 2015; Fernandes et al., 2016; Gugliotta et al., 2016). Durkin et al. (2020) noted consistent morphological (e.g., channel-belt width-to-thickness ratios) and ichnological (i.e. trace-fossil diversity) trends over a 145-km basinward transect of time-equivalent channel-belt deposits. Durkin et al. (2020) asserted that it cannot be a *transition* zone if characteristics of the channel-belts do not change (i.e. transition), and they concluded that deposition must have occurred under relatively comparable conditions from south to north. Lines of evidence that challenge the estuarine models are consistent with evidence presented in favor of a fluvial channel-belt model.

5.3.2. Fluvial model

The principal critique of the fluvial channel-belt model is the inability to explain the origin of the trace fossil assemblage (Gingras et al., 2016). Although the brackish-water trace fossil model (Howard et al., 1975) was first developed in application to the McMurray Formation (Pemberton et al., 1982), it has been replicated in other locations and periods of geologic history with less contention regarding the depositional setting (e.g., Gingras et al., 1999; Buatois et al., 2005, 2010; Hovikoski et al., 2007; MacEachern and Gingras, 2007). Freshwater trace fossils (e.g. *Naktodemasis, Taenidium*) have been identified locally in the McMurray Formation (Harris et al., 2016), but studies have yet to demonstrate a chronostratigraphic equivalence to deposits characterized by a brackish-water trace fossil assemblage (cf. La Croix et al., 2019). More broadly, freshwater fluvial channel ichnology, when present, is dominated by meniscate ichnogenera formed by insects including *Taenidium, Naktodemasis, Scoyenia*, or *Beaconites* (e.g., La Croix et al., 2015; Gingras et al., 2016), while unlined *Skolithos*, *Planolites* and *Cylindrichnus* have also been documented (Gowland et al., 2018). Therefore, the fluvial model cannot explain the presence of lined *Skolithos* and *Cylindrichnus* using a modern or ancient fluvial analogue.

Other critiques of the fluvial model include the presence of marine palynomorphs (e.g., dinoflagellate cysts) in IHS mudstones (Hubbard et al., 2011). The tidally-influenced model of Hubbard et al. (2011) attempted to reconcile this observation, but more recent mapping efforts of the A2 CB summarized above challenge this model. The brackish water zone of the Sittang River is characterized by a ~ 10 km segment of large meanders, including one large meander cut-off (Hubbard et al., 2011); however, this does not explain over 300 km of channel-belt deposits with a brackish-water trace fossil assemblage (e.g., A2 CB; Fig. 6A). Even if deposition always occurred in this limited zone that meets all criteria, subsequent regression would cause reworking by updip fluvial zones as they move basinward. These trends should be observable and consistent with cross-cutting relationships but have not been demonstrated. A more thorough study of IHS mudstone palynology is warranted and should also include investigation of possible reworking of palynomorphs from eroded PSSs (Horner et al., 2019b).

Another critique of the fluvial model is that the channel-belt deposits are not time equivalent and their geomorphology is not comparable to satellite-image perspectives of modern channel belts (La Croix et al., 2020), but this claim has yet to be further investigated or substantiated.

5.4. Impact of underlying salt dissolution

The dissolution of the Prairie Evaporite Formation has been considered a potential factor contributing to the presence of brackish-water trace fossils in the McMurray CBs. Broughton (2018) and Hein and Dolby (2018) proposed that the removal of salt in the underlying Devonian strata led to saline seeps moving upward into fluvial channels at volumes large enough to sustain brackish-water faunal communities. Quantitative analysis of trace-fossil distribution exhibits that moderate to very thick (5–40 m) ichnozones (i.e., cumulative thickness of ichnofossil-laden beds) are located parallel to the eastern margin of the underlying salt scarp within the significant salt-dissolution zone (Fig. 16) (Broughton, 2018). The resulting fracture systems were interpreted as conduits for saline water to move between the Prairie Evaporite Formation and McMurray Formation hydraulic systems (Broughton, 2013, 2018; Cowie, 2013). Broughton (2018) identified a 22 m thick zone of heavily burrowed beds near a sinkhole collapse-subsidence structure, whereas thin bioturbated intervals (0–3 m) are located more distant from the collapse structures. Additionally, Broughton (2018) proposed that the saline migration pathway could have been influenced by stratigraphic architecture of point bars to some extent. For example, a thick IHS interval with heavily bioturbated zones is located adjacent to rarely bioturbated IHS strata (Broughton, 2018). Saline seeps possibly migrated into the channel-bottom sand and laterally into the associated IHS with no communication with other adjacent deposits. The variable bioturbation in different intervals of point-bar deposits is interpreted as a result of periodic salt-water seepage.

This model remains untested in terms of modeling volumes of salt dissolution, saline seep discharge, and mixing with freshwater in fluvial channels. Moreover, the theory lacks a mechanism for the larvae of marine organisms to be transported landward, potentially 100 s of kilometers, into fluvial environments. In the brackish-water trace fossil model (e.g., Pemberton et al., 1982; La Croix et al., 2015), larvae from the marine end of the system are advected landward by the flood tide (e.g., Staton et al., 2014; Gingras et al., 2016), which also brings saltwater that mixes with the fresh river water, resulting in the brackish water portion of the FTTZ. Any theory proposed that interprets the trace fossil assemblage as indicative of brackish water conditions must also explain the transport mechanism of marine-derived larvae (Shchepetkina et al., 2016).

Apart from the bioturbation, the salt dissolution and tectonism likely influenced the development and morphology of the McMurray A2 CB system in the northern part of the study area. The location of multiple McMurray A2 CBs corresponds to a funnel-shaped structural configuration formed by the Bitumount Trough and adjoined Central Collapse due to the concurrent salt-dissolution tectonism (Fig. 6). Alternatively, the development of these multiple channel belts could be due to backwater effects, which were similarly interpreted to have caused a large channel-belt-scale avulsion in the McMurray A2 channel belt 100 km upstream (Martin et al., 2019). At some locations (e.g., North Mine of the Steepbank River), dissolution along the salt scarp not only led to collapse and rotation of overlying McMurray CBs strata, but also resulted in over-thickened McMurray CB deposition (Broughton, 2015).

It has been increasingly documented that underlying salt tectonism impacted lower McMurray and regional parasequence set deposition (Ranger and Pemberton, 1997; Broughton, 2015; Barton et al., 2017; Baniak and Kingsmith, 2018; Broughton, 2018; Château et al., 2019). In the Bitumount Trough (10 s of km long), lower McMurray channels exhibit low sinuosity with elongate, linear sand trends (1–3 km long) oriented northwest-southeast and northeast-southwest. These deposits are characterized by thick sandstone (up to 80 m thick) passing upward into muddy and coaly floodplain deposits (5–60 m thick)(Broughton, 2015). The channels exhibit a lattice-like network that was interpreted to be the result of tilted surfaces of the Devonian fault blocks (Broughton, 2013, 2015) likely corresponding to differential subsidence caused by removal of the underlying salt beds (Barton et al., 2017).

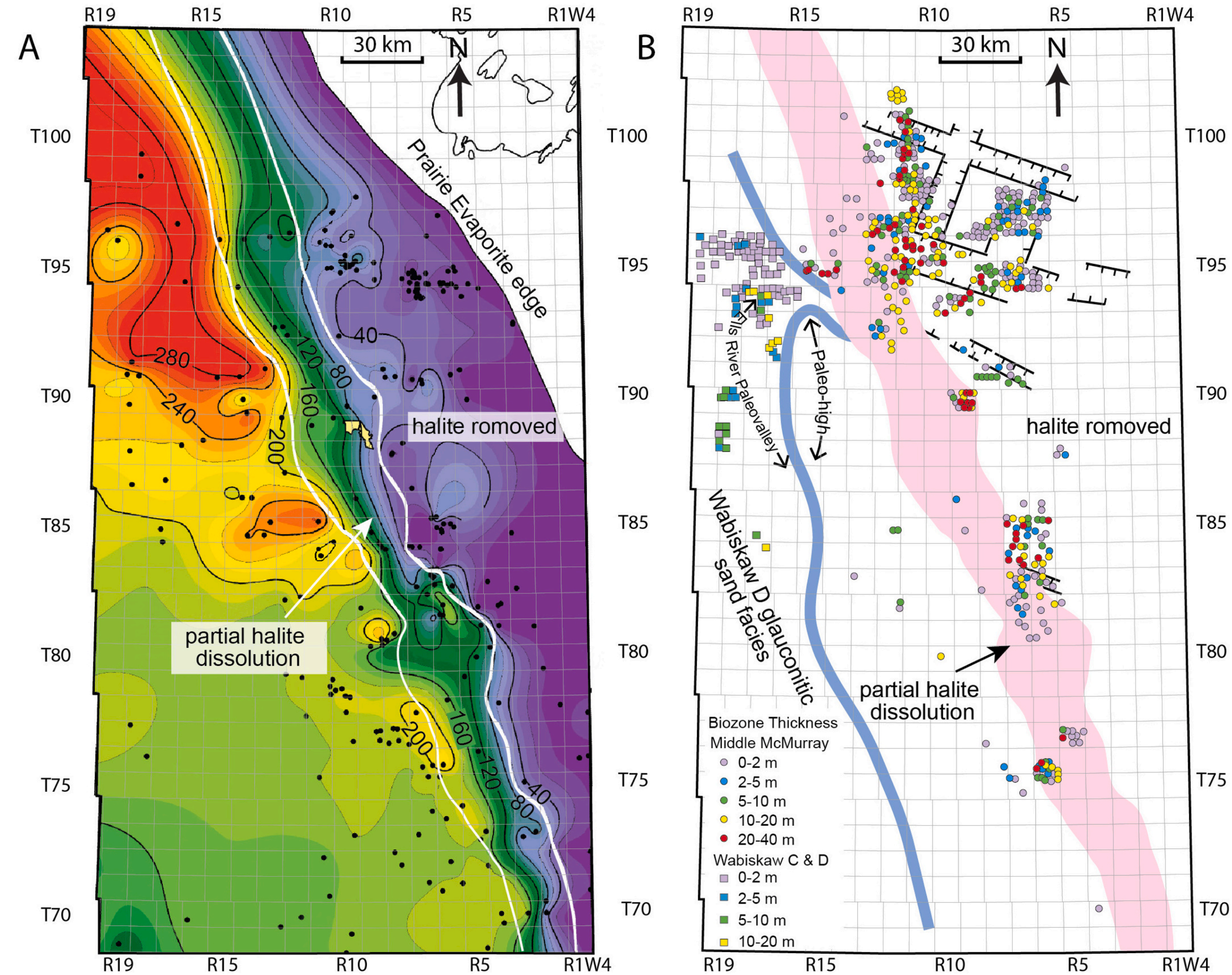


Fig. 16. (A) Isopach map (expressed in meters) of the Prairie Evaporite Formation showing zones of halite romoval and partial halite dissolution to the east (from Hauck et al., 2017). (B) Distribution of cumulative thickness for bed containing trace fossils in the McMurray CBs (Broughton, 2018). The zone of the relatively thick trace-fossil beds follows the trend of underlying halite removal and partial dissolution areas in fig. A.

Baniak and Kingsmith (2018) proposed that the salt dissolution and the resulting topographic low caused the distributary channels to change direction and incise into previously deposited upper McMurray parasequence sets toward the northeast in the southeastern area (T73–76 and R4–7 W4M). It has been interpreted that syndepositional epikarst processes likely influenced the deposition of deltaic parasequences in the tributary paleovalley to the southwest, as evidenced by overthickening strata and associated soft-sediment deformed beds (Château et al., 2019).

6. Future directions

Given the existing challenges associated with different paleogeographic interpretations of the McMurray Formation (Fig. 17), we outline opportunities for potentially resolving issues and further enhancing our understanding of the paleo-depositional system. Although detailed sedimentologic, stratigraphic, paleontological, and geochronological data are always invaluable for delineating and developing a resource play, we posit that these types of data are now expansive, and new information is not likely necessary for solving the McMurray conundrum. Instead, vast data are likely best leveraged for approaches that have yet to be applied to the basin. With the development of more robust Earth-systems models (e.g., Voinov et al., 2010; Tessler et al., 2018; Tucker et al., 2022), paleo-landscape modeling, for example, is a logical way to generate new perspectives, or rather, a baseline for reframing and answering long outstanding questions about the McMurray Formation depositional system. We posit three considerations about the paleogeographic setting that could be explored through modeling.

Sediment supply – Researchers have proposed that the McMurray system represents a continental-scale river with high sediment supply (e.g., Musial et al., 2012; Blum and Pecha, 2014; Horner et al., 2019a). The poor preservation of original sedimentary structures as a result of extensive bioturbation and the prevalence of evidence for wave processes in the interpreted fourth-order highstand deltas could indicate a more modest sediment supply (e.g., b2, a2, a1 PSSs) (Fig. 5). If the McMurray system resembles the lower Mississippi River, the high sediment supply would have promoted rapid progradation of fluvial channels and associated deltas, and this likely resulted in a more complete preservation of sedimentary structures with insufficient time for biogenic reworking of the deposits (Bhattacharya et al., 2020; Peng et al., 2020), although one could argue that bioturbated intervals were possibly developed during the low-flow conditions (e.g., Jablonski and

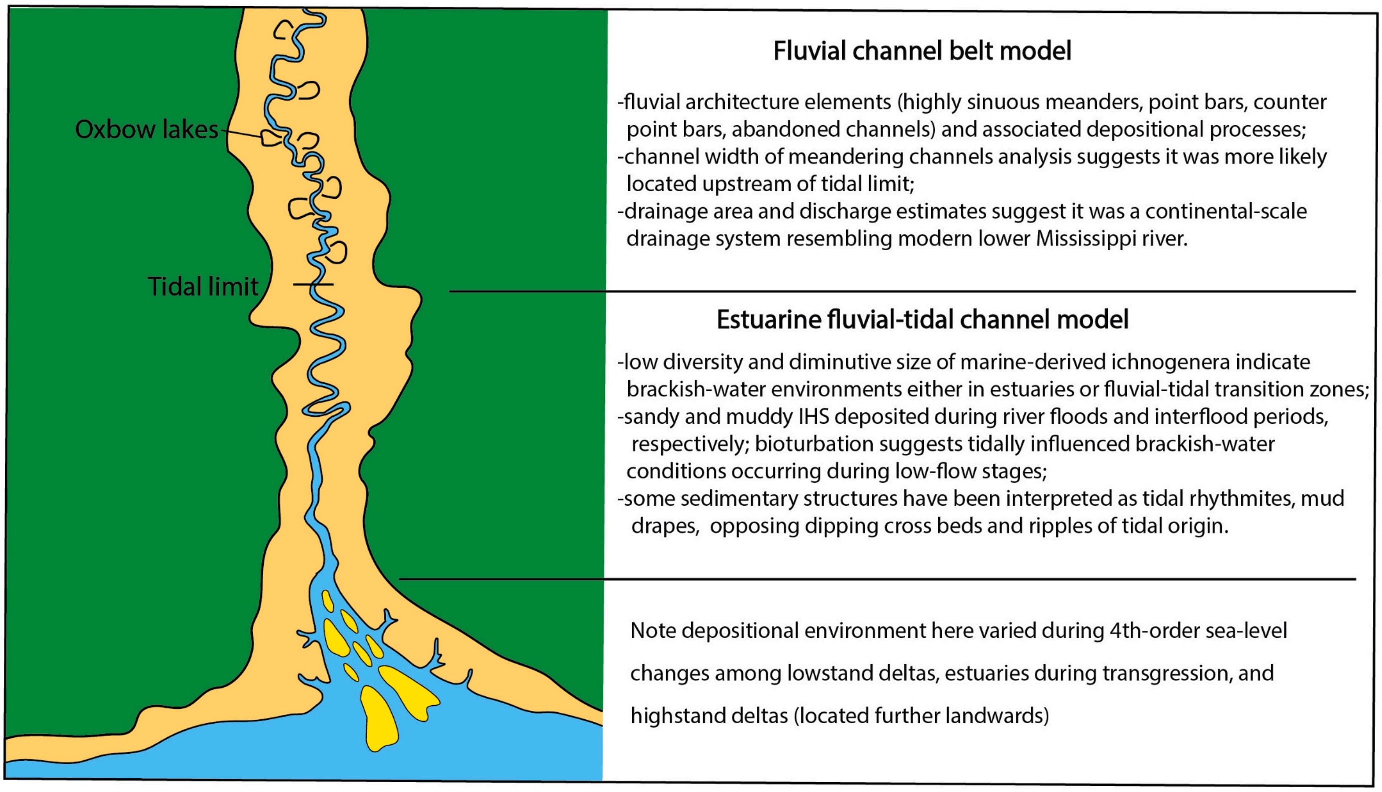


Fig. 17. Summary of the two constrasting depositional models for the McMurray Formation with supporting evidence.

Dalrymple, 2016). Within the McMurray Formation (interpreted as the lowstand and transgressive system tracts of a third-order sequence), prograding deltas should have formed during the fourth-order lowstand of sea levels, but they were presumably eradicated by Quaternary glacial processes to the north of the study area. The only preserved deltas in the study areas are the upper McMurray parasequence sets interpreted as fourth-order highstand deltas, and they host abundant wave ripples and HCS/SCS in most intervals. The prevalence of evidence for wave processes over fluvial processes suggests the sediment supply was not high at least during the fourth-order highstands.

Sea-level fluctuation – Even if the McMurray Formation was a high-sediment-supply system, it is still questionable whether the sea-level rises during the short-lived transgressive stages were able to cause such a high sediment-supply system to move landward over such a long distance (at least 700 km) (Christopher, 1997). The fourth-order highstand deltas (b2-a1 PSSs) preserved in the study area suggest the fourth-order sea-level rises would have forced the system to move landward across the study area (Peng et al., 2022; Hagstrom et al., 2023). Such rapid landward migration of the shorelines during each fourth-order sea-level rise was interpreted as a consequence of the low-gradient setting (Peng et al., 2022). Additionally, the nearly ubiquitous absence of vegetated scroll bars and well-developed floodplains with pedogenic alternation (Gingras et al., 2016) also suggest that it was not likely a high-accommodation and high-gradient setting. However, the interplay among the sediment supply, basin gradient, and sea-level changes needs to be tested by integrating numerical and/or experimental models with data from the McMurray Formation or other similar systems.

Infaunal influence of salt tectonism - The hypothesized influence of the underlying salt tectonism and dissolution on brackish-water nature of McMurray depositional systems need to be further tested.

7. Conclusions

This study presents a detailed and updated characterization of facies and their associated distributions within the Cretaceous McMurray Formation in the Western Canada Sedimentary Basin based on regional mapping. The lower McMurray interval is characterized by fining-upward successions of cross-bedded sandstone, transitioning into mudstone-dominated intervals, interpreted as small local braided rivers. The McMurray CBs and regional PSSs are diachronous, and they are interpreted to comprise multiple successions of deltaic strata that are vertically and laterally juxtaposed with valley-fill deposits, representing several progradation and retrogradation cycles of a drainage system during fourth-order sea-level fluctuations. The McMurray CBs have been interpreted to be either in fluvial or fluvial-tidal origin, and they are primarily preserved in several tributary and trunk paleovalleys. The PSSs have been interpreted to represent wave-dominated or wave-influenced deltas and bayhead deltas, deposited during fourth-order highstands. The conundrum of the McMurray CBs arises due to the presence of brackish-water bioturbation within seismically resolvable fluvial-style meandering-belt deposits. The estuarine fluvial-tidal channel model is supported by evidence from the highly intensive biogenic structures, mixed of terrestrial-brackish-marine palynomorphs and some possible sedimentary structures. However, some observations are in contradiction to the estuarine models. For instance, river channels entering estuaries tend to exhibit an exponential increase in channel width basinward, but McMurray channel width is constant over a 40 km basinward segment of time-equivalent channel-belt deposits, suggesting deposition landward of the tidal limit. Additionally, McMurray CBs show consistent morphological and ichnological trends over a 145-km basinward transect of time-equivalent channel-belt deposits without any obvious basinward transition from fresh to brackish to marine conditions in a FTTZ. The fluvial channel-belt model is supported by the evidence for geomorphic characteristics, such as extensive meander-bend migration, as well as sedimentological characteristics and regional mapping results. But the presence of trace fossil assemblage and brackish to marine palynomorph is inexplicable for the fluvial channel-belt model. Although several modern analogues have been proposed for the McMurray CB system, finding a suitable analogue is challenging due to the unique requirement of a low-accommodation and gradient setting, as well as the salt dissolution underlying the drainage system.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

The authors do not have permission to share data.

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