Salt tectonism and ichnozones of the Cretaceous McMurray Formation channel system

Paul L. Broughton
Broughton and Associates

Summary

A salt tectonism-saline seep model provides an alternative to the two widely accepted but irreconcilable depositional models for middle McMurray Formation of the Lower Cretaceous Athabasca Oil Sands deposit. Established interpretation of a fluvial axial channel belt system along the eastern Alberta Foreland Basin contrasts with the widely accepted interpretation as a 100s km long estuarine marine-fluvial transition zone setting characterized by brackish-water trace-fossil laden beds. The architecture of a highly sinuous fluvial meander channel-belt with bank-full depths of 30-40 m furthermore is not compatible with an estuary having a 10s m thick salt wedge extending 100s km upstream. This alternative salt tectonism model proposes that dissolution of the underlying 100 m thick Middle Devonian salt section occurred across 1000s of km² and resulted in voluminous saline seeps up-section into river channel fills of the middle McMurray Formation. Southward transgression by a Boreal Sea tongue terminated fluvial deposition of the lower McMurray Formation, and transported brackish-water larvae inland along the tide-impacted backwater length. This zoology was sustained along the fluvial channel belt by the saline seeps that elevated salinity levels in channel muds as the fluvial system dominance was reasserted. Brackish-water macroinvertebrates rapidly adapted to new terrestrial food sources in these fluvial channels, precluding the necessity for a salt wedge to have extended inland for 100s of km. This model is consistent with Quaternary saline seeps to surface, representing intermittent brine flows up-section since the Early Cretaceous.

Introduction

Mainstream interpretations of McMurray Formation depositional environment focus on the commercially important middle interval and follow either of two conflicting models: (1) accumulations of strongly fluvial channel fills typically with tide-impacted point bars (Hubbard et al., 2011; Durkin et al., 2016, 2017ab, 2018), or (2) brackish-water deposits of an estuary system that include a marine to fluvial transition zone extending inland for 100s of km (Gingras et al., 2016). These middle McMurray Formation channel fill sands and heterolithic beds include multi-cm to dm and m thick beds with invertebrate trace-fossils, mostly burrows and bioturbation intervals indicative of a brackish-water depositional environment.

The middle interval of the McMurray Formation has been widely interpreted as deposits accumulated along a strongly sinuous axial channel-belt characterised by looping meander architecture with multi-km long point bars, counter point bars and meander scrolling. This is comparable in channel morphology and scale to the modern Lower Mississippi River. The trace-fossil evidence suggests an estuary environment having a significantly lengthy marine to fluvial transition zone. However, this zoology is not consistent with a looping meander-belt river system with a 100s of km long tide-impacted backwater length and 10s m bank-full depths. Brackish-water fauna are commonplace in estuaries of both ancient and modern river systems, but not 100s of km inland of a highly sinuous and looping meander-belt fluvial system comparable to the Lower Mississippi River. Brackish-water colonies were established at various water depths and sediment fill levels along these channels, typically with burrowed beds at the upper reaches of 30-40 m thick point bars. They would necessarily require a 10s m thick salt wedge to have extended inland for 100s of km along the highly sinuous fluvial channel system, an unlikely occurrence for a giant river system at the scale of the Mississippi River. This is known as the “McMurray conundrum”.

Tectono-stratigraphic studies by Broughton (2013, 2015, 2016, 2017a-c, 2018a) interpreted salt removal patterns in the Middle Devonian substrate as exerting an overarching syndepositional control on the distribution of McMurray Formation strata. The salt tectonism model proposes that the zoology were responsive to saline seeps into the channel fills that emanated up-section from regional salt dissolution trends. The removal of 80-120 m of halite-dominated salt beds in Devonian substrate extended across 1000s of km². This interpretation provides insight into how brackish-water zoology would have extended for 100s km inland and successfully colonized 10s of m deep channels of a strongly fluvial river system without the necessity for transgression inland by a 10s of m thick salt wedge (Broughton, 2018b).

Impact of Salt Tectonism

The salt scarp is a 10-20 km wide trend that resulted from westward migration of the regional dissolution front in the shallow subsurface, 200 m below the sub-Cretaceous unconformity. This trend of partial salt removal, oriented N-NW, separates large areas of complete to mostly complete salt removal to the east from a largely undisturbed, 150-200 m thick, salt section to the west. Prior to McMurray Formation deposition, the salt scarp was oriented N-S. During McMurray Formation deposition, the southern length of the salt scarp southward of the Fort McMurray and lower Steepbank River remained relatively stable in contrast to the northern area where the regional dissolution front migrated westward. This resulted in a pivot area near Long Lake from which the arcuate sweep of the salt scarp migration westward occurred. South of Long Lake, the salt scarp was stable during McMurray Formation deposition, and dissolution events were volumetrically insufficient to have resulted in significant westward migration. In contrast, the salt scarp migration north of Long Lake was across the width of the overlying northern Athabasca deposit area resulted from removal of up to 100 m or more of salt section during deposition of the McMurray Formation. This salt scarp migration to the west-northwest resulted in the Bitumount Trough and the adjoined Central Collapse, regional scale collapse structures that combined as an unstable sub-Cretaceous unconformity surface (Broughton, 2013). This increasingly unstable depositional surface impacted the McMurray Formation channel architecture north of the lower Steepbank River and Steepbank mining district (Broughton, 2015).

Post-McMurray dissolution trends intermittently persisted into the Quaternary. Influxes of subglacial meltwater into the shallow subsurface came in contact with the salt scarp below the bituminous sands, altering the chemistry of the Middle-Upper Devonian and overlying McMurray Formation strata formation waters. The meltwater flow variously mixed with saline Devonian formation waters and dissolved salts derived from halite beds of the salt scarp. Saline seeps up-section permeated McMurray Formation strata and resulted in surface discharges as saline and brine springs that sourced saline lakes and permeated fenlands distributed along the Athabasca River Valley (Gue, 2012; Gue et al., 2015). These saline waters also seeped into channel bottom muds along the modern Athabasca River (Gibson et al., 2013), albeit not in quantity to significantly alter river water chemistry. As such, Quaternary dissolution trends were minor in comparison to Early Cretaceous removal of 80-120 m of salt section across 1000s of km², and were insufficient to impact the fauna and flora of the modern Athabasca River channel fills. Nonetheless, the geochemical trends of the Quaternary water samples largely coincide with older Early Cretaceous trends.

Middle McMurray Formation Ichnozone Distribution and Underlying Salt Removal Trends

The regional distributions of ichnozones (>5 m) across the northern Athabasca deposit area, northward of the lower Steepbank River and area of the type section, are consistent with the migration westward by underlying salt scarp and trailing areas of complete salt removal (Fig. 1). The cumulative thickness of trace-fossil laden beds recorded in each of the wells of the Athabasca deposit is mostly less than 2 m

(Broughton, 2018b). Only a minority of wells have fossil laden beds >5 m, and rarely to as much as 30-40 m. Some of the thickest trace-fossil beds occur far upstream to the south such as at Long Lake, where some isolated wells record 30-40 m thick intervals.

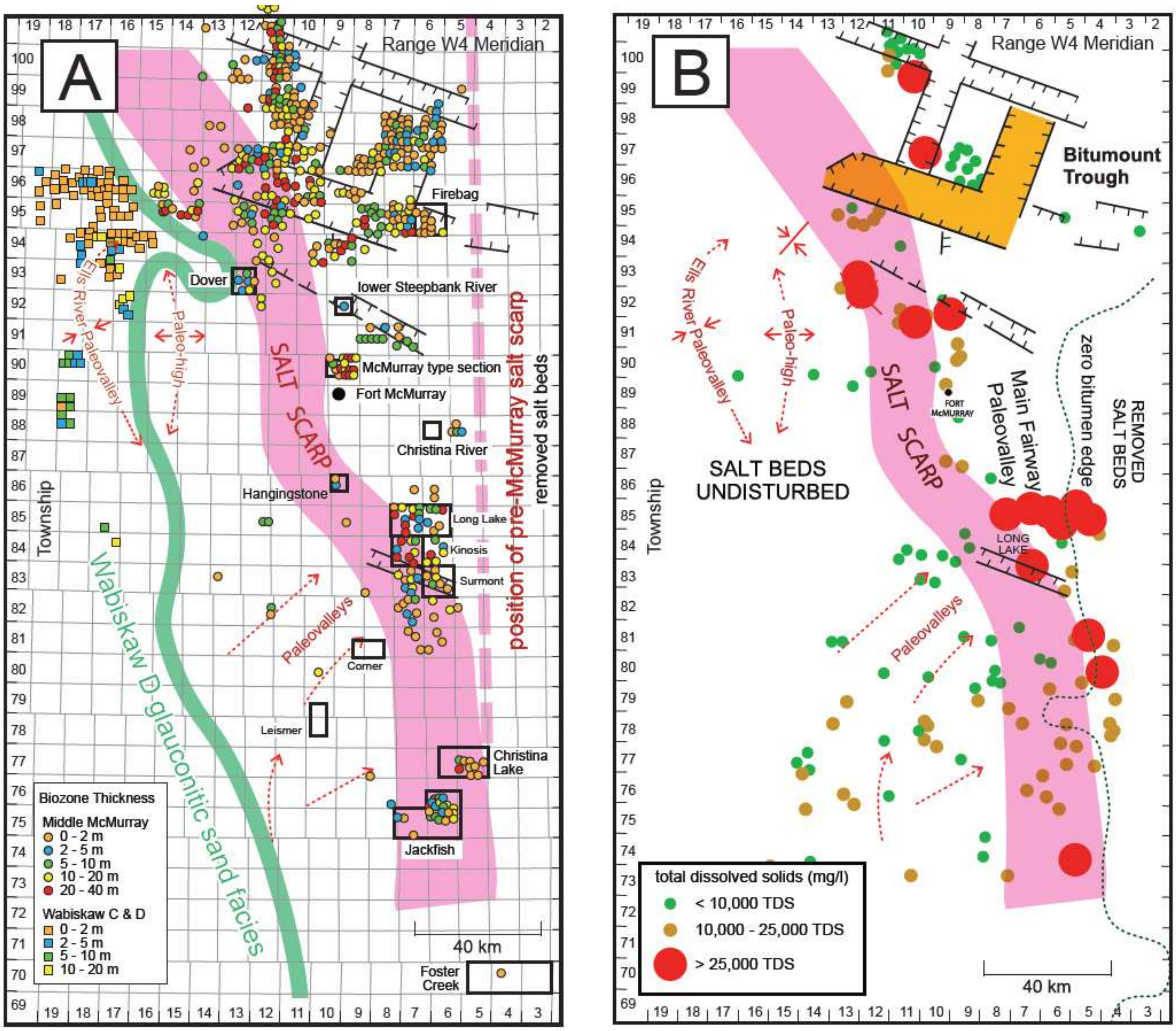

Figure 1. Distribution of brackish-water trace-fossil-laden beds in the middle McMurray Formation, consistent with elevated salinity trends resulting from saline seeps up-section as the salt scarp, 200 m below, migrated westward. The regional salt dissolution front, represented by the N-S-oriented salt scarp, pivoted to the NW from the area of Kinosis-Long Lake during deposition of the middle McMurray Formation. (A) The pattern of cumulative ichnozone thickness follows the trend of the underlying salt scarp and trailing salt removal area. A 200 km-long trend of ichnozones, including a sub-trend of very thick sites (20-40 m), extends from the Long Lake area to the western Bitumount Trough and further north to the preserved margin of the Athabasca deposit. This trend is consistent with elevated levels of T.D.S. in Quaternary saline waters, a modern analogue for saline seeps since deposition of the McMurray Formation. Modified from Broughton (2018b). (B) Measurements of Total Dissolved Solids in McMurray Formation water and saline seep samples. Regional distributions of elevated T.D.S measurements have a linear trend patterns oriented NW-SE that follow the underlying salt scarp and trailing edge, consistent with regional distribution of ichnozone thickness trends. T.D.S. patterns modified from Cowie (2013) and Cowie et al. (2015).

The distribution patterns of meters thick intervals of burrowed and bioturbated ichnozones are consistent with the regional salt removal patterns in Prairie Evaporite Formation underlying the Athabasca deposit (Fig. 1). During middle McMurray Formation deposition, the N-S orientation of the underlying salt scarp migrated to the NW with a pivot area located near Long Lake. This wedge-shaped sweep westward by the underlying migration of the salt dissolution front is consistent with the regional distribution patterns of thicker ichnozone intervals across the northern Athabasca deposit area. All sub-trends of moderate to very thick (5-40 m) ichnozone intervals overlying these salt removal areas have distribution patterns that parallel the eastern margin of the underlying salt scarp. There are often well sites with lesser thickness and concentration of trace-fossil beds above the only partial salt removal of the scarp compared to more extensive salt removal areas that trail the scarp migration westward below the northern Athabasca deposit area. In sharp contrast, markedly fewer and thinner fossil beds (0-2 m) are distributed across areas to the west of the Main Fairway and westward of the modern salt scarp position where the salt beds were largely undisturbed. A relatively narrow linear-curvilinear trend of thick trace-fossil beds extends for 200 km southward into the Long Lake-Kinosis area, representing a chain brackish-water oasis communities. This regional ichnozone trend parallels the eastern trailing margin of the dissolution front migration west-northwest, concurrent with overlying deposition of the middle McMurray Formation. The trend coincides with the migration of the salt scarp pivot to the northwest from the area of Long Lake-Surmont (Twp. 83-85). Distributions of thick to very thick ichnozone intervals, 10-40 m, are aligned north-south along Rge. 7-12 northward of Fort McMurray and coinciding with a major dissolution trend that paralleled the eastern margin of the salt scarp. There is a prominent 75 km long sub-trend with >20 m thick trace-fossil laden beds that is aligned at Rge. 11 and extends from Twp. 94 to 102, parallel to the eastern margin of the underlying salt scarp. At the southern end of this trend, a significant concentration of thick ichnozone sites occurs across the western Bitumount Trough, an area situated above the eastern margin of the salt scarp.

The ichnozone distribution patterns are patchy and geographically constrained southward of the lower Steepbank River trend into the Long Lake area and towards the southern reaches of the Athabasca deposit. They represent increasingly isolated oases of zoological communities. At Long Lake, a very thick ichnozone interval (>40 m) is located above the eastern margin of the underlying salt scarp, where this regional N-S oriented dissolution front pivoted westward during middle McMurray Formation deposition. Southward of the Long Lake-Kinosis-Surmont area, thinner ichnozone intervals, less than 5 m thick, are observed as far south as Twp. 75 into the Christina Lake and Jackfish SAGD operational areas. Otherwise the McMurray Formation channel deposits have only thin trace-fossil laden beds (<1 m), if at all. Extensive areas of McMurray Formation channel deposits to the south of the Long Lake-Surmont area are largely barren of trace-fossil beds. This paucity of observe ichnozone beds is consistent with minimal salt dissolution along the underlying salt scarp at the time of McMurray Formation deposition. Ichnozone intervals are nil to very thin to the west-southwest of the underlying salt scarp, albeit somewhat thicker along middle McMurray channel fills of tributary paleovalleys (Twp. 80-85, Rge. 8-12) that follow incipient salt removal trends to the west of the Main Paleovalley (Broughton, 2013).

Currently Accepted Paleogeographic and Deposition Models

Widely accepted depositional models for the middle McMurray Formation are: (1) accumulations along a strongly fluvial river system (Hubbard et al., 2011; Durkin et al., 2016, 2017ab, 2018); (2) estuary-related channel deposits (Gingras et al., 2016). These interpretations have resulted in contrasting and irreconcilable interpretations of the paleogeography.

(1) Fluvial channel belt model

Middle McMurray Formation strata accumulated along the axial channel-belt along the eastern margin of the Foreland Alberta Basin. This segment of the continental-scale river system, and elsewhere across the continental interior, was characterized by a fluvial architecture consisting of highly sinuous looping meanders with laterally accreting point bars and river meander scrolling (Fig. 2). The fluvial channel belt architecture is characterized by 30-40 m bank-full depths and similarly thick point bars accumulated along a low gradient long channel slope profile. This trunk and tributary system is consistent with a continental-scale drainage. The 3-6 km long and 20-30 m thick point bars are consistent with 10s of m bank-full channel depths. All of the fundamental types of fluvial meander-bend transformations are recognized, including expansion, translation, rotation and combinations thereof. These characteristics and the widespread distribution of counter-point bars and meander scrolls are fundamentally a fluvial architecture (Fig. 2), not estuarine, and consistent with channel-belt architecture of the Lower Mississippi River (Durkin et al., 2017ab, 2018).

The backwater length for the McMurray Formation axial channel system is unknown because the shoreline with the Boreal Sea northward of the Athabasca deposit has been eroded. The fluvial model of Blum and Jennings (2016ab) suggests that the preserved segment of the middle McMurray Formation channel system was likely situated along the boundary area between a mixed bedrock-alluvial valley sediment transfer range and the upstream limits of the paleovalley of the coastal plain. The highly sinuous meandering channel belt would have been located at the upstream limit to the length as impacted by sea-level influences. This would scale the now-eroded shoreline to be multiple 100s of km to the north and thereby result in a backwater length consistent with the modern analogue represented by the Mississippi River. With bank-full water depths of 30-40 m to as much as 60 m, the backwater reach can be 100s of km inland from the now-eroded shoreline, a distance of 400-600 km. Durkin et al. (2017ab) interpreted an up-section reduction in channel sinuosity consistent with reduced meander belt width, not unlike the Lower Mississippi River, as a result of landward migration of the backwater length responding to transgression of the Boreal Sea southward into the Alberta Foreland Basin.

In modern rivers, the increased extent to which brackish-water influxes extend inland from the river mouths are those with a wide low-to-high tide range or have deep channels facing onto the shoreline. This results in a salt wedge extending inland for a distance permitted by channel depth and floor gradient. The distribution of brackish-water fossils in middle McMurray Formation is enigmatic as it necessarily requires a 10s m thick salt wedge, as much as 40 m or more, to be consistent with the bank-full depths. This is not possible without obliteration of the highly sinuous looping meander architecture of a low gradient axial channel belt. In modern rivers, the extent inland by a brackish-water zone is constrained by the reach inland of the underlying salt wedge and does not extend further upstream along the backwater length. The reach upstream by a salt wedge constrains the similar length of the of the overlying brackish water zone invariably as a small percentage (10-15%) of the tidal length or the backwater length. Persistent brackish-water conditions linked to the southward advance of a salt wedge along a low gradient channel profile for 100s of km upstream from a river mouth are not physically possible as to dominate the upper part of a 30-60 m thick water column where bioturbated beds are prevalent. Because of salt wedge and fresh river water density segregation, a salt wedge would have to be more than 40 m thick to sustain brackish-water conditions for the zoology to survive across the upper surfaces of point bars. This is not possible along a highly sinuous meander-belt of an axial channel system whose channel architecture is distinctly fluvial. The distribution of brackish-water fossils at all levels of the 10s of meters deep channel fills along such a strongly sinuous channel belt is undisputed, but remains enigmatic.

(2) Estuary depositional model

Brackish-water trace-fossils are asserted as *prima facie* evidence that the middle McMurray Formation interval accumulated within an estuarine environment as the northward flowing river system across the continental interior approached the Boreal Sea. The channel fills along the Main Paleovalley fairway are characterized by a brackish-water, mostly low-diversity and diminutive ichno-fauna that represent colonization of km scale point bars and 10s m thick I.H.S. It is noteworthy that these burrowed and bioturbated beds are widely distributed along the upper reaches of the 10s m thick point bars and other channel fill sediments. The middle McMurray Formation deposits are interpreted as estuarine or a tidally

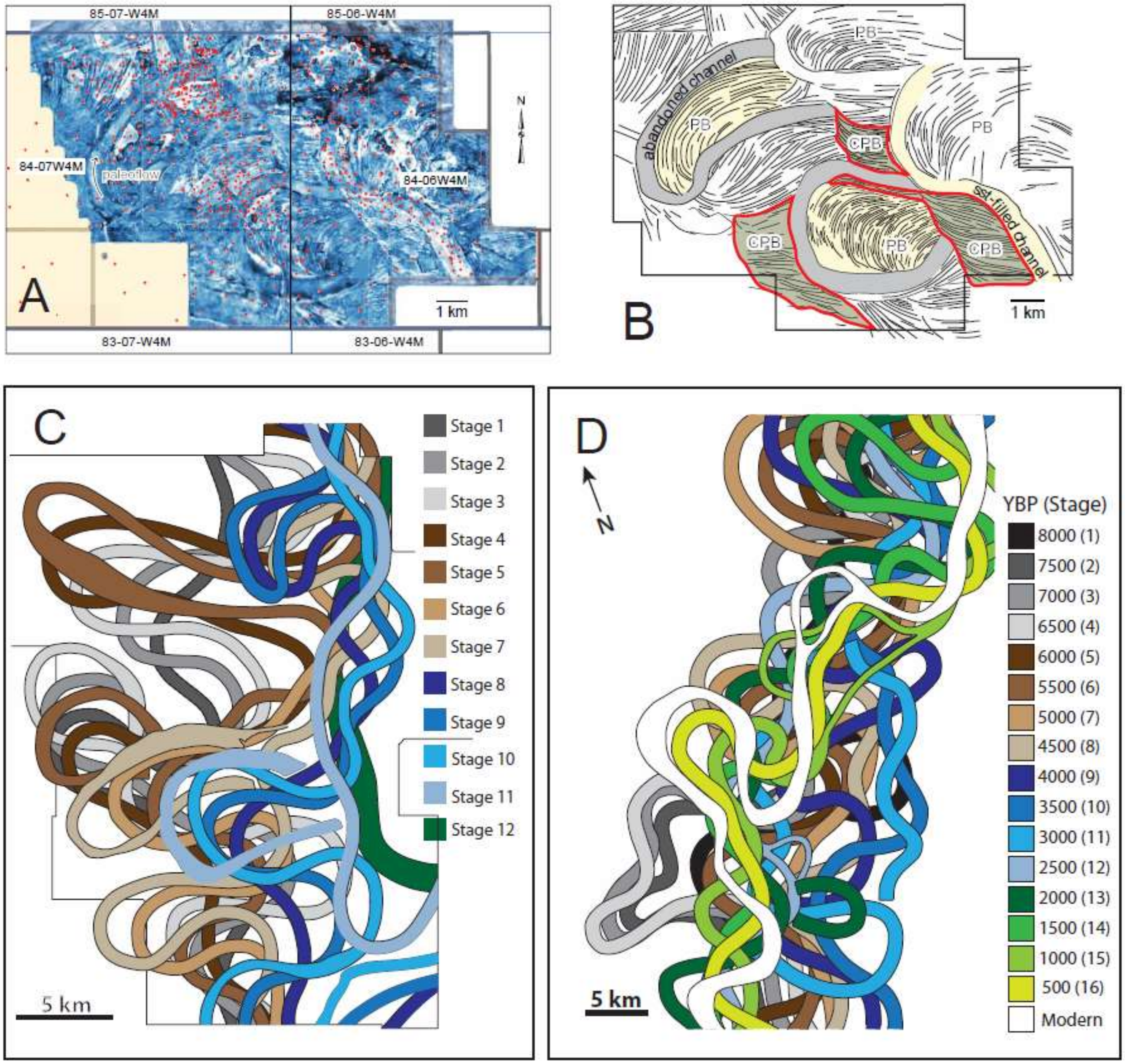

Figure 2. Seismic imaging and interpretation of fluvial channel-belt architecture. (A, B & C) Example of the sinuous loop meander river system at the Kinosis-Long Lake SAGD area (Twp. 84-85, Rge. 6-7W4M). Horizontal amplitude slice on 3D pre-stack migration 12 m below top of the middle McMurray Formation interval, and extending across the 15 km wide channel-belt. Interpretation of the reconstructed 5-6 km wide meandering paleochannels with point bars, counter point bars and meander scrolling. Image C represents a longer section of the McMurray channel-belt, illustrating the 12 sequential stages recognized. Modified from Hubbard et al. (2011); Durkin (2016), Durkin et al. (2017b, 2018). (D) Example of a meander-belt section of the Mississippi River near New Madrid, Missouri. The 8,000 year-long reconstruction of the channel pattern includes a trace every 500 years up to the present day. Modified from Holbrook et al. (2006), Durkin et al. (2018) and Broughton (2018b).

modulated estuarine-transition zone extending inland for 100s of km. This estuary model has been largely applied to areas of the Athabasca deposit northward of the lower Steepbank River outcrops near Fort McMurray, but also interpreted to include the south-central areas of the Athabasca deposit where the distribution of brackish-water trace-fossils are observed as far south as Twp. 75.

Strongly burrowed accumulations of finely grained heterolithic strata, consisting of laminated sand and mud intercalations or alternating beds, are dispersed inland for 100s of km, consistent with stages of sea-level rise and the possibly wide but unknown tidal range. This permitted a salt wedge to extend southward for 100s of km inland across most the Athabasca deposit area. The resulting estuarine environment with tide-impacted point bars permitted marine sourced larvae to establish colonies 100s km inland.

The distribution of brackish-water trace-fossils and areas barren of such zoological activity record the mixture of lesser and more elevated salinity presumed to be indicative of a brackish-water environment associated with estuarine paleogeography. Variations in activity level by brackish-water zoology were responses to the mixture of the salt wedge transgression inland with seasonal discharges levels by the river system. Stressed McMurray Formation fauna adapted to less saline conditions with diminutive body forms. During seasonal low flow river discharges into the estuary, the reduced sedimentation rates are consistent with increased tidal impact and the incursion of the salt wedge, permitting widespread colonization and intense burrowing activity on the more muddy beds of the upper point bar surfaces. Responses to such salinity level fluctuations were linked to the movements of the salt wedge inland with fluvial seasonality and tidal cyclicity controlling the inland distribution pattern of these colonies.

Impact of Salt Tectonism on Channel-belt Architecture

During middle McMurray Formation deposition, the northern length of the regional salt dissolution front, represented by the salt scarp, migrated W-NW, in contrast to a semi-stable segment between the area of the Lower Steepbank River southward to the vicinity of Long Lake-Kinosis, and a very stable length further to the south into the Jackfish area.

During deposition of the middle McMurray Formation, the highly sinuous axial channel-belt of the central and southern Athabasca deposit trended along low gradient channel floors. This was consistent with this segment of the salt scarp being quiescent below the Main Paleovalley fairway southward of the lower Steepbank River. Nevertheless, this relatively stable Devonian limestone floor of the McMurray Formation channels had been variously brecciated and fragmented prior to Aptian deposition. In contrast, the axial channel belt transitioned northward of the lower Steepbank River onto structurally unstable depositional surfaces responsive to concurrent salt dissolution tectonism. Rapid westward expansion of the salt removal area underlying the northern Athabasca deposit area resulted in development of the Bitumount Trough and the adjoined Central Collapse, together forming a regional fan-shaped or funnel-like structural configuration of the sub-Cretaceous unconformity surface flooring McMurray Formation channel network. This resulted in branching of the 10-20 km wide axial channel-belt into multiple 10s of km long subparallel tide-impacted fluvial distributary channels across a deltaic area (Broughton, 2016). Parallel syndepositional trends, typically 20 km long and 10s m thick, developed within the middle-upper intervals (Broughton, 2015, 2016).

Saline formation waters mixed with fresh meteoric groundwater resulted in brines that permeated the eroded Paleozoic stratigraphic column during the uplift of the foreland basin, further resulting in compaction driven flows up-section. Middle-Upper Devonian formations and lower McMurray Formation strata in salt removal areas above and eastward of the scarp were saturated with brackish water, eventually resulting in saline seeps to surface. The distribution of successful of brackish-water colonies are consistent with the widespread pattern of saline seeps into the middle McMurray Formation channel fills across the northern Athabasca deposit area, but also concentrated as 10s km longitudinal trends that coincide with westward migration positions of the underlying salt removal front (salt scarp).

The rate of salt removal is not known, nor is the total volume impacted during McMurray Formation deposition across various areas of the central and northern Athabasca deposit. Nonetheless, at least 100 m of salt section was removed concurrent with development of the Bitumount Trough and Central Collapse structures, in contrast to relatively minor amounts removed by dissolution responding to glacial meltwater influx into the shallow subsurface. It is also uncertain as to what percentage of this up-section saline flow would have been trapped within overlying McMurray Formation channel muds in contrast to leakage into the river system.

Salt Tectonism Impact on Distribution of Trace-fossils

During McMurray Formation deposition, saline seeps extensively but not uniformly altered the pore water chemistry of channel fill sediments distributed above the length of the salt scarp as the dissolution front migrated westward below the central and northern areas of the Athabasca deposit. More dispersed oases developed southward above more stable areas of the underlying scarp. Saline environments within the channel fill sand and muds were sufficient to sustain brackish-water zoology without any significant alteration of the voluminous river current flow above the sediment interface. Channel bottom muds would likely have inhibited leakage into the overlying currents. It is possible to maintain salinity levels within channel fills without similar salinity being established in the overlying river water column, partially because the channel floor muds functioned as partial seals ensuring continuation of the water density stratification. The salt tectonism model proposes that saline seeps, upwardly directed from the salt scarp 200 m below, migrated into permeable sandy point bars, altering the interstitial pore waters of the sand, and seeping into overlying heterolithic strata and laterally accumulated I.H.S. to sustain zoology colonies. Barren areas or short-lived colonies resulted from bypassed area with poorer permeability. This illustrates how a 20-30 m thick channel fill deposit with most of the multi-m thick vertical profile disrupted by strongly burrowed zones can be situated adjacent to a similar deposit nearly barren of trace-fossils or having a low level of bioturbation.

Sustained seeps in some areas in contrast to patchy distribution can explain varying dispersal patterns of trace-fossil assemblages. Elevated salinity levels would have been maintained for extended periods of time during seasonal discharge conditions or impacts by the tidal range, and be supportive of colonization by brackish-water organisms in dispersed oases along the seaward flow of the river system. There is little necessity for voluminous saline seeps into the channel muds to have significantly altered the chemistry of the river water above the interface with channel bottom sediment, nor would this have been possible for a river with a 30-40 m or more bank-full channel depth and voluminous discharge seaward.

Although dissolution events pre-dated the Cretaceous and were active during Aptian sedimentation, evidence suggests that seeps migrated up-section and reached the overlying channels only by the end of the lower McMurray Formation sedimentation and onset of the basal middle McMurray Formation deposition. Lower McMurray Formation channel fills lack brackish-water trace-fossils, except for sparse examples in the uppermost beds located north of the Bitumount Trough.

Quaternary Saline Seep Analogue

Water samples from the McMurray Formation show elevated dissolved solids and isotope ratios, which suggests that the Quaternary water chemistry is a modern analogue, albeit diluted, for saline chemistry trends intermittent since the Cretaceous. Dilution effects were significantly affected by glacial meltwater, but do not alter the regional pattern of the dissolution trends and remain consistent with salt removal patterns developed during McMurray Formation deposition and syndepositional trends. Saline flows emanated up-section from the salt scarp are interpreted as a process that may have been intermittent but nevertheless persistent from the Middle Jurassic-Early Cretaceous to the present day. Salt removal continued into the Quaternary and resulted in saline seeps that aligned sinkholes on the subglacial surface (Broughton, 2017ab).

Quaternary groundwater and surface water investigations have shown distinctive N-NW to S-SE oriented salinity trends across the northern Athabasca deposit area (Cowie, 2013; Cowie et al., 2014ab, 2015). These geochemical studies indicate patterns of elevated salinity in McMurray Formation water samples and saline seeps that discharge at surface, and form a longitudinal trend broadly from Twp. 78, Rge. 4 to the northwest into Twp. 100, Rge. 13, W4M (Fig. 1). These geochemical studies include measurements of river bed muds from the Athabasca River near the McMurray Formation type-section at Fort McMurray and northward for 10s of km. Saline groundwater discharges have been observed into fenlands and muskeg terrains along these river valleys.

The approximately linear trend of elevated T.D.S. values spatially coincides with: (1) the underlying salt removal areas that resulted from westward migration of the salt scarp concurrent with McMurray Formation deposition; and (2) patterns of very thick (10-40 m) brackish-water trace-fossil-laden beds (ichnozones). An example is the 10s km-long trend that extends along Twp. 91-102, Rge. 10-12 and continues to the south to more isolated sites such as at the area of the Long Lake-Kinosis SAGD project (Fig. 1). These trends indicate a strong spatial relationship between the colonization of organisms recorded as brackish-water trace-fossils and the sustained influx of upwardly directed saline water seeps into the McMurray Formation channel fills. The salt scarp trend that extends from south of lower Steepbank River into the Long Lake area was semi-stable during middle McMurray Formation deposition. The Long Lake-Kinosis area, where Aptian block displacements occurred, marks the pivot area for realignment of the regional dissolution front to a more northwestward direction. The area is characterized by strongly elevated saline seeps across a multi-township area. These voluminous seeps resulted in the highest T.D.S. measurements recorded for McMurray Formation strata. Brackish-water colonies were also established on trend as far south as Twp. 75-77 to the Christina Lake and Jackfish SAGD sites, but these were smaller and less diversified communities compared to those thriving across the northern Athabasca area.

This relationship was initiated during the Cretaceous during McMurray Formation deposition, but such similarly aligned post-Murray seepage sites were intermittently active into the Quaternary. Present-day saline seep trends date back to the Late Jurassic-Early Cretaceous, prior to and during deposition of the McMurray Formation. Early Cretaceous saline seeps would have been voluminous in response to the regionally extensive dissolution trends that removed as much as 100-120 m of salt section across 1000s of km^2 in the subsurface, in contrast to volumetrically minor modern groundwater seeps of the comparatively brief Quaternary time span. Hydrogeological processes that resulted in this extensive removal of salt beds during lower and middle-upper McMurray Formation deposition may be uncertain, but these regional dissolution events did occur, resulting in 10s of km-long syndepositional trends following collapse structures resulting from salt removal at depth (Broughton, 2015, 2016, 2017a, 2018ab).

Conclusions

This study presents definitive spatial relationship between salt dissolution trends and the distribution of thickened beds of brackish-water trace-fossils inferred by the Cretaceous-Quaternary saline seep-to-surface patterns. This relationship provides insight into how the otherwise enigmatic distribution of the brackish-water trace-fossils would be consistent with a strongly fluvial channel system. It illustrates the conceptual mechanism by which the distribution of the macro-crustacean and other brackish-water zoology colonies would have not have necessarily required a 30-40 m thick salt wedge during normal fluvial discharge, or thicker at flood stage. Sustained brackish-water colonies resulted as they rapidly adapted to the lower salinity environments in the channel fill muds by evolutionary adjustments in body fluid regulation and adaption to the new types of terrestrial food sources.

The salt tectonism model provides an alternative to the estuarine model with inherent saline depositional environments but problematic channel architecture, and to the axial channel model with fluvial channel patterns but lacking a conceptual basis to accommodate the widespread presence of brackish-water trace fossils.

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