

Sequence stratigraphic and sedimentological record of the McMurray and Wabiskaw depositional systems, Lower Cretaceous, Athabasca Oil Sands Area

Yang Peng¹, Stephen M. Hubbard¹, Cynthia A. Hagstrom¹, Sean C. Horner², Harrison K. Martin³, Dale A. Leckie¹, Cheryl Hodgson⁴, Per K. Pedersen¹

¹Department of Geoscience, University of Calgary, Canada

²Hudbay Minerals Inc., Canada

³Department of Earth and Atmospheric Sciences, Indiana University, USA

⁴Department of Earth Sciences, Simon Fraser University, Canada

Summary

The Lower Cretaceous McMurray-Wabiskaw stratigraphic interval in the Athabasca Oil Sands Region (AOSR) of northeastern Alberta contains the world's largest bitumen reserves (892 billion barrels). However, a comprehensive sequence stratigraphic model that encapsulates stratigraphic relationships and distribution of depositional environments across the entirety of the AOSR has been elusive. The McMurray Geology Consortium, a collaboration between researchers at the University of Calgary, University of Alberta, and Simon Fraser University, as well as 5 industry sponsors has been working to produce a unifying stratigraphic framework over the last six years across approximately more than 60,000 km².

The McMurray-Wabiskaw interval is within the Mannville Group, which is a 3rd-order depositional sequence (Cant, 1996) deposited mainly under the influence of a southward transgression of the Boreal Sea. The McMurray Formation was deposited during lowstand to early transgression, the Wabiskaw Member (Clearwater Formation) during transgression, and the overlying the Clearwater and Grand Rapid formations during highstand (cf. Jackson, 1984; Wightman et al., 1995; Cant, 1996; Wellner et al., 2018). Meanwhile, higher-order (4th order) sea-level fluctuations led to development of repeated packages of fluvial, valley fill and marginal marine deposits. The main objective of this study is to unravel the sequence stratigraphic details of the McMurray-Wabiskaw interval, providing context for the temporal and spatial record of the depositional systems.

Methods

Regional-scale stratigraphic mapping of the McMurray Formation and the overlying Wabiskaw Member (Clearwater Formation) was conducted across 60,000 km² in the AOSR (Township 69-104, Range 1-20 west of the 4th Meridian). A stratigraphic framework and detailed facies scheme for the McMurray Formation and Wabiskaw Member was constructed through the integration of ~20,000 wireline logs and more than 500 slabbed drill cores (Hagstrom, 2018; Horner et al., 2019; Martin et al., 2019). The stratigraphic framework builds on the widely used terminology first proposed by the AEUB (2003), which in itself leveraged a number of previous regional-scale observations (e.g., Ranger and Pemberton, 1997). Core observations were integrated with wireline data to calibrate log responses to lithofacies, and locally seismic data.

Results

McMurray Formation

At the onset of deposition during the late LST, small fluvial channels up to 150 m wide and 10 m deep developed directly above the sub-Cretaceous unconformity, emanating primarily from local catchments (Fig. 1; Benyon et al., 2016). In the northeastern portion of the AOSR, the Lower McMurray deposit is relatively thick (>20 m) with a thick coal seam at its top, which records an initial transgression of the Boreal Sea during a 4th order sea level rise (Rinke-Hardekopf et al., 2019).

Subsequently, punctuated relative sea-level fluctuations (100-300 kyr; 4th order) (Cant, 1996) resulted in deposition of widespread coarsening-upward deltaic packages across the AOSR (Château et al., 2019; Horner et al., 2019; Weleschuk et al., 2019). These are mapped as McMurray c3, c2, c1, b2, b1, a2, and a1 parasequence sets, which developed during phases of relatively sea level rises (Fig. 1). The parasequence sets (PS) (5-10 m thick) are commonly sandy and well-preserved over most of the southern AOSR. Distal, mudstone-dominated and coarsening-upwards succession are rarely preserved, owing to the low accommodation setting and the propensity of this basinward units to reworked during transgressive episodes. This stratigraphic architecture is distinct from overlying coarsening-upward units from the Clearwater to Grand Rapid period (Jackson, 1984; Cant, 1996; Pouderoux et al., 2016; Wellner et al., 2018), when relatively higher accommodation dominated. Parasequence sets from b2 to a1-2 become thinner and muddier upwards, reflecting retrogradation in response to the 3rd order rise in relative sea level.

Channel systems truncated and removed parasequence sets locally during 4th order sea level falls (cf. Horner et al., 2019), and a north-northwest-oriented drainage system developed in the eastern AOSR, which has been demonstrated to have been of continental scale (Blum and Pecha, 2014; Benyon et al., 2016). The trunk drainage system is composed of laterally amalgamated meander-belts (up to 50 km wide and 50 m thick) characterized by sandy cores and muddy, rugose edges that compare favorably to modern meander-belts (Durkin et al., 2018; Martin et al., 2019). The location of this trunk drainage system was strongly controlled by salt dissolution in underlying Paleozoic units (Broughton, 2015). The deeply incised meander-belt strata of the youngest A2 depositional system is well preserved, with a number of avulsion nodes in the central and northern AOSR revealing down-dip channel belt 10-30 km wide and 20-50 m thick. Martin et al. (2019) linked one such avulsion node to an upper tidal backwater position in the trunk channel, which is consistent with morphological observations of strata presented by Durkin et al. (2017).

Trunk channel systems were intersected by east-northeast flowing valley-constrained meander-belts tributaries up to 1-5 km wide and 50 m thick (e.g., McMurray C-B1; Horner et al., 2019). Both tributary and trunk channel segments are preserved for the McMurray C3-C1, B2-B1, A2 channel systems (Fig. 1). Only rather small remnants of McMurray C and B channel system deposits are locally preserved underlying A2 strata (Fig. 1). It is likely that channel belt strata and their associated shoreline systems in the McMurray C3-C1, B2-B1, and A2 channel systems generally migrated landwards as the relative sea level continued to rise during the overall 3rd order transgression.

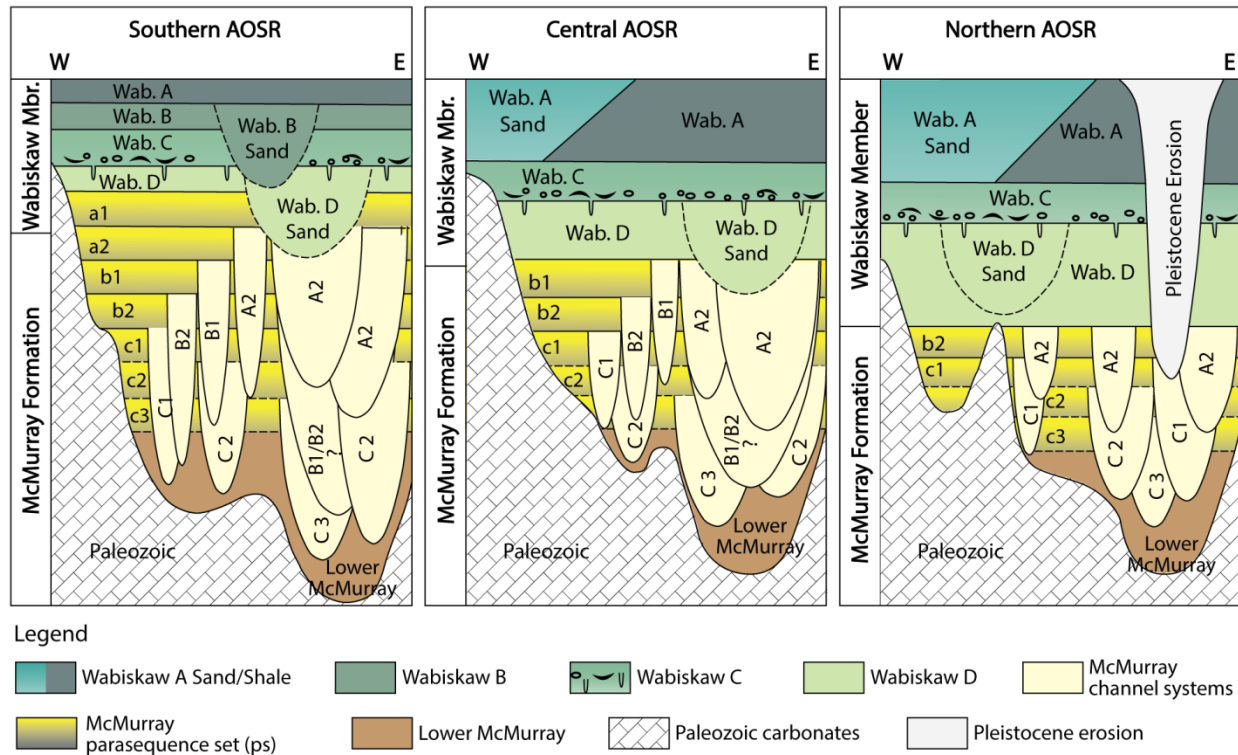


Figure 1. Stratigraphy of the McMurray-Wabiskaw interval in the southern (T69-T87), central (T88-T95), and northern (T96-104) AOSR in this study. The McMurray channel systems are generally named based on the regional parasequence sets from which they subtrend (i.e., B2 channel system subtrend from the top of the b2 PS). Towards the central and northern AOSR, a1, a2 and b1 PSs as well as uppermost parts of the A2 channel systems have been eroded and reworked, and the Wabiskaw Member overlies various units of the McMurray Formation. The McMurray strata are dominant in the southern AOSR, while the Wabiskaw strata become relatively thick in the central and northern AOSR.

Wabiskaw Member (Clearwater Formation)

As a result of relative sea level rise, transgressive shoreline systems developed, associated with the Wabiskaw Member (Fig. 1). The preliminary studied units of the Wabiskaw Member include the Wabiskaw D, Wabiskaw C, Wabiskaw B Sand, Wabiskaw A Sand as defined by Wightman et al. (1995).

The Wabiskaw D (2-30 m thick) is a sandy unit that sharply overlies the McMurray Formation (Fig. 1). The contact is recognized by an abrupt color change in mudstone from light grey to dark blue-grey (Wightman et al., 1995; AEUB, 2003). The Wabiskaw D exhibits a variety of depositional environments laterally, and it includes tide-dominated strata composed of tidally influenced channels and tidal sand bars, and open-coast tidal flats. The sharp contact between the localized Wabiskaw D and the McMurray interval is interpreted as a tidal ravinement surface

formed as estuaries progressively migrated landwards during transgression. NE-SW-oriented tidally influenced channels and sand bars are mainly located in the southeastern and northwestern AOSR (Fig. 1). The overlying Wabiskaw B Sand (10 to 40 m thick) shows similar tidal-influenced channel and tidal sand bar deposits, which developed only in the southeastern part of the study area (Fig. 1).

The Wabiskaw C (0.5-5 m thick) (Fig. 1) is characterized by glauconitic sandstones interbedded with siltstones and mudstones with a regionally extensive erosional base. The unit is intensely bioturbated by a trace fossil suite attributable to the *Glossifungites* ichnofacies (Fig. 1). Sandstones are characterized by hummocky/swaley cross stratification and wave ripples. In places, shell beds up to 0.6 m thick are locally preserved. The widespread erosional base of the Wabiskaw C is interpreted as a wave ravinement surface with its overlying strata representing the associated transgressive lag deposits. The Wabiskaw A Sand (5-25 m thick) (Fig. 1) overlies the Wabiskaw C, and is only present in the northwestern AOSR. It persists further west than the Wabiskaw D and B Sands. It shows a coarsening-upward trend with diverse trace fossils and represents the backstepping shoreface deposits.

Conclusions

The McMurray-Wabiskaw stratigraphic interval records deposition during the lowstand to transgressive system tracts under the influence of a southward transgression (3rd order) of the Boreal Sea superimposed with higher-order (4th order) sea-level fluctuations. The punctuated relative sea-level fluctuations during this overall transgression were associated with regional development of deltaic parasequence sets truncated by deeply incised channel systems during relative sea level falls. The Wabiskaw Member records transgressive shoreline systems, which includes tidally influenced channel sands, tidal sand bars, open-coast tidal flat, and backstepping shorefaces in the sandy units.

Acknowledgements

We thank Murray Gingras's research group (Qi Chen, Scott Melnyk, Eric Timmer, Derek Hayes) from the University of Alberta, and James MacEachern and Shahin Dashtgard's research group (Cheryl Hodgson, Chloe Chateau, Jonathan Broadbent, Lucian Rinke-Hardekopf, Zennon Weleschuk) from Simon Fraser University for providing stimulating discussion, stratigraphic data and core descriptions. We also acknowledge our industry sponsors BP, Cenovus, Husky, CNOOC, and Woodside for providing funding.

References

- Alberta Energy and Utilities Board, 2003. Athabasca Wabiskaw-McMurray regional geological study: Rep. 2003-A, 188 p. (CD-ROM).
- Benyon, C., Leier, A.L., Leckie, D.A., Hubbard, S.M. and Gehrels, G.E., 2016. Sandstone provenance and insights into the paleogeography of the McMurray Formation from detrital zircon geochronology, Athabasca Oil Sands, Canada. AAPG Bulletin, 100(2), pp.269-287.
- Blum, M. and Pecha, M., 2014. Mid-Cretaceous to Paleocene North American drainage reorganization from detrital zircons. Geology, 42(7), pp.607-610.
- Broughton, P.L., 2015. Syndepositional architecture of the northern Athabasca oil sands deposit, northeastern Alberta. Canadian Journal of Earth Sciences, 52(1), pp.21-50.

- Cant, D.J., 1996. Sedimentological and sequence stratigraphic organization of a foreland clastic wedge, Mannville Group, Western Canada Basin. *J. Sed. Res.*, 66, 1137–1147.
- Château, C.C., Dashtgard, S.E., MacEachern, J.A. and Hauck, T.E., 2019. Parasequence architecture in a low-accommodation setting, impact of syndepositional carbonate epikarstification, McMurray Formation, Alberta, Canada. *Marine and Petroleum Geology*, 104, pp.168-179.
- Durkin, P.R., Boyd, R.L., Hubbard, S.M., Shultz, A.W. and Blum, M.D., 2017. Three-dimensional reconstruction of meander-belt evolution, Cretaceous McMurray Formation, Alberta foreland basin, Canada. *Journal of Sedimentary Research*, 87(10), pp.1075-1099.
- Durkin, P.R., Hubbard, S.M., Holbrook, J. and Boyd, R., 2018. Evolution of fluvial meander-belt deposits and implications for the completeness of the stratigraphic record. *GSA Bulletin*, 130(5-6), pp.721-739.
- Hagstrom, C., 2018. Stratigraphic architecture and lithofacies distribution in meander belt deposits, South Saskatchewan River and Cretaceous McMurray Formation, Alberta. Unpublished Ph.D. Thesis, University of Calgary, Calgary, Ab.
- Horner, S.C., Hubbard, S.M., Martin, H.K., Hagstrom, C.A. and Leckie, D.A., 2019. The impact of Aptian glacio-eustasy on the stratigraphic architecture of the Athabasca Oil Sands, Alberta, Canada. *Sedimentology*, 66(5), pp.1600-1642.
- Jackson, P.C., 1984. Paleogeography of the Lower Cretaceous Mannville Group of western Canada. In: *Elmworth-Case Study of a Deep Basin Gas Field* (Ed. J.A. Masters), AAPG Mem., 38, 49–78.
- Martin, H.K., Hubbard, S.M., Hagstrom, C.A., Horner, S.C. and Durkin, P.R., 2019. Planform Recognition and Implications of a Cretaceous-age Continental-scale River Avulsion Node in the Western Interior Basin, Alberta, Canada. *Journal of Sedimentary Research*, 89(7), pp.610-628.
- Pouderoux, H., Coderre, A.B., Pedersen, P.K., Cronkwright, D.J. and Hein, F., 2016. Characterization, architecture and controls of Cold Lake marginal-marine oil sands: the Grand Rapids Formation (Upper Mannville) of east-central Alberta, Canada. *Bulletin of Canadian Petroleum Geology*, 64(2), pp.119-146.
- Ranger, M.J. and Pemberton, S.G., 1997. Elements of a stratigraphic framework for the McMurray Formation in south Athabasca area, Alberta. In: *Petroleum Geology of the Cretaceous Mannville Group, Western Canada* (Eds S.G. Pemberton and D.P. James), Canadian Society of Petroleum Geologists, Memoir 18, 375–391.
- Rinke-Hardekopf, L., Dashtgard, S.E. and MacEachern, J.A., 2019. Earliest Cretaceous Transgression of North America Recorded in Thick Coals: McMurray Sub-Basin, Canada. *International Journal of Coal Geology*, 204, pp.18-33.
- Weleschuk, Z.P., and Dashtgard, S.E., 2019. Evolution of an ancient (Lower Cretaceous) marginal-marine system from tide-dominated to wave-dominated deposition, McMurray Formation. *Sedimentology*, 66, p. 2354-2391.
- Wellner, R.W., Varban, B.L., Roca, X., Flaum, J.A., Stewart, E.K. and Blum, M.D., 2018. Simple is better when it comes to sequence stratigraphy: The Clearwater Formation of the Mannville Group reinterpreted using a genetic body approach. *AAPG Bulletin*, 102(3), pp.447-482.
- Wightman, D.M., Attalla, M.N., Wynne, D.A., Strobl, R.S., Berhane, H., Cotterill, D.K. and Berezniuk, T., 1995. Resource characterization of the McMurray/Wabiskaw deposit in the Athabasca oil sands area: A synthesis. Alberta Oil Sands Technology and Research Authority.