Canadian Journal of Earth Sciences
Revue canadienne des sciences de la Terre

Alignment of fluvio-tidal point bars in the middle McMurray Formation: implications for structural architecture of the Lower Cretaceous Athabasca Oil Sands Deposit, northern Alberta

Journal:	<i>Canadian Journal of Earth Sciences</i>
Manuscript ID	cjes-2015-0137.R1
Manuscript Type:	Article
Date Submitted by the Author:	21-Jan-2016
Complete List of Authors:	Broughton, Paul; Chevron Canada, Oil Sands
Keyword:	McMurray Formation, Athabasca Oil Sands Deposit, salt dissolution, fluvio-tidal channels

**Alignment of fluvio-tidal point bars in the middle McMurray Formation:
implications for structural architecture of the Lower Cretaceous Athabasca
Oil Sands Deposit, northern Alberta**

Paul L. Broughton

Chevron Canada Resources

500-5th Avenue, S.W.

Calgary, Alberta T2P 0L7

email: broughton@shawcable.com

Abstract

The northern Athabasca Oil Sands Deposit accumulated on sub-Cretaceous structure partially configured by multi-stage pre-Cretaceous salt dissolutions in Prairie Evaporite (Middle Devonian) substrate that continued concurrent with deposition of McMurray Formation (Aptian) strata. Dissolution fronts only 250 m below advanced along NW- and NE-oriented fracture-fault lineaments that coalesced into larger salt removal areas. This structural grain was transmitted to the overlying dissected Upper Devonian karst topography draped by lower McMurray braided rivers along a lattice-like channel network. The dominant NW structural grain continued during middle McMurray deposition with fluvial-estuarine point bars aligned along subparallel tidal channels. Regional salt removal fronts concurrent with middle McMurray deposition migrated north of the Bitumount Trough, resulting in the 200 km² central collapse. The northern Athabasca Deposit area was configured as a funnel-shaped lower estuary structure consisting of aligned Upper Devonian-lower McMurray fault block terraces that stepped down northward into the central collapse. Sinuous river channels of the upper estuary, constrained along stable substrate of the main paleovalley, flowed northward onto the unstable floor of this funnel-form lower estuary. The main paleovalley fairway branched into multiple 10s of km long sub-parallel fluvio-estuarine tidal channels aligned parallel to the NW structural grain. Sand transport fairways cascaded over the step down terraces and permitted aggradations of overlying fluvio-tidal point bars to accumulate into giant commercially attractive sand complexes. The internal architecture of these 10s of meters thick sand deposits included deposit-wide erosion surfaces resulting from cycles of collapse-subsidence, stabilized substrate and erosion, and renewed subsidence and aggradation.

Key Words

McMurray Formation, Athabasca Oil Sands Deposit, salt dissolution, tidal channels, bitumen sand.

1.0 Introduction

The 45,000 km² Athabasca Oil Sands Deposit is the largest and economically most important of several Lower Cretaceous bitumen-cemented sand reservoirs accumulated across northern Alberta (Fig. 1). The structural-stratigraphic traps accumulated oil that migrated from Devonian source rocks to the southwest (Hein and Marsh 2008; Berbesi et al. 2012; Adams et al. 2013). The trillion barrel bitumen resource is hosted by McMurray Formation (Aptian) point bar complexes, 20-80 m thick, and locally by thinned (<5 m) sand beds of the overlying Wabiskaw Member, Clearwater Formation (Albian). McMurray sand complexes accumulated as deposits by fluvial braided rivers (lower), fluvio-estuarine point bars (middle), and marginal marine parasequences (upper). The McMurray strata accumulated unconformably on an Upper Devonian limestone karst paleo-topography. The stratigraphy and sedimentology of the multi-km long middle McMurray sand deposits have been interpreted as large tide-influenced fluvial point bars up to 3-5 km long and 10-50 m thick by Smith et al. (2009), Hubbard et al. (2011), Labrecque et al. (2011a, 2011b), Hein (2015) and references therein. These studies are mostly the result of studies made tens of kilometres south of the study area, south of Fort McMurray.

Sands were transported along a fairway northward for 300 km towards the Boreal Sea (Fig. 2). The point bars accumulated along highly sinuous rivers channels that formed the upper estuary, southward of the Fort McMurray and classic exposures along the Steepbank River, and were emplaced over a relatively stable substrate of Upper Devonian limestone. These channels were configured with multi-km diameter looped meanders (Fig. 3) that are considered comparable to the scale of Mississippi River channels (Holbrook 2014).

This current research proposes that the highly meandering upper estuary fluvial river channels dissipated northward onto the lower delta plain, northward of the classic exposures along the Steepbank River (Fig. 2B). Multiple fluvio-tidal channels that formed were dispersed across a structurally configured lower estuary funnel which includes the study area (Figs. 1 and 2). This article proposes that the over-thickened middle McMurray bitumen sand deposits are giant fluvio-tidal point bar sand deposits with alignments at

least partially influenced by structural trends in the Devonian substrate consistent with concurrent removal of salt beds. The present research interprets the large point bars distributed across the study area as accumulations along multiple sub-parallel curvilinear fluvio-tidal channels. This tectono-stratigraphic architecture differs from controls on the distribution of point bars across more structurally stable areas of the upper estuary to the south.

This present model continues earlier studies by Broughton (2013a, 2015) that the northern area of the Athabasca Deposit accumulated channel deposits across a semi- to unstable substrate of Upper Devonian fault blocks concurrent with lower and upper McMurray deposition. The wider stratigraphic application is proposed for the middle McMurray deposits across a broadened lower estuary funnel, and that this structuration at least partially impacted the distribution, orientation and internal architectures of the fluvio-tidal point bars.

The tectono-stratigraphic architectural models used to interpret the morphogenesis and distribution of the middle and undifferentiated middle-upper McMurray sand bars have been controversial because of conflicting data sets related to the role of sea-level fluctuations and the extent to which concurrent regional salt collapse impacted the *regional* McMurray tectono-stratigraphic framework. One model proposes that fluvio-estuarine point bars accumulated along deeply incised valleys that resulted from sea-level drops followed by rapid rebounds possibly linked to a Late Aptian global sea-level fall (*sensu* Maurer et al. 2013; Bover-Arnal et al. 2014), although not all point bar models draw a relationship to deeply incised valleys (*sensu* Labrecque et al. 2011a). This resulted in continuous, uninterrupted, channel fills with point bar complexes accumulated as clean point bar sands that fine upward and pass laterally into sandy inclined heterolithic beds (I.H.S.) that were covered over by mud-dominated I.H.S. beds (Flach and Mossop 1985; Hein and Langenberg 2003; Larter et al. 2008; Fustic et al. 2012; Hein et al. 2013). This model has been countered by viewpoints that clean sand bars are genetically separate from overlying heterolithic beds, and do not represent continuous sedimentation (Ranger and Gingras 2006, 2010; Musial et al. 2012), but accumulated as transgressive and regressive cyclic packages separated by erosion surfaces that may or may not be obscured, and distributed along prograded shallow channels entrenched along a relatively stable coast. These stacked parasequences prograded northward towards the Boreal Sea. Sea-level continuously rose during McMurray deposition, but the impact of fluctuations during this otherwise persistent rise on depositional processes was limited to 3-8 m thick intervals accumulated along overlying shallow channel networks. This parasequence model interprets the formation of extraordinarily large sand complexes as stacked channel bars that scoured the underlying heterolithic beds. This resulted in tens of metres thick sand complexes that did not necessarily fill older deeply incised valleys. Both of

these models consider the more limited impact of underlying salt dissolution collapse-subsidence on concurrent but *localized* deposition sites.

A third architectural model asserts that regional salt dissolution trends in the underlying Middle Devonian halite hypogene karst resulted in collapse-induced syndepositional trends that exerted an overarching control on the distribution of McMurray sand deposits. This Broughton (2015) model proposed that underlying regional salt dissolution patterns were the dominant control on the lower and upper, but not middle, McMurray deposits across the northern Athabasca area. This earlier syndepositional model suggested that salt removal was relatively subdued during intervening middle interval deposition, and had an uncertain but probably minimal impact on aggradations of multi-km long commercially important sand deposits. In contrast to this earlier work, this present research describes the distribution of multi-km long bitumen saturated sand complexes accumulated during the middle McMurray interval as having been impacted partially to significantly by underlying salt tectonics to a significantly greater extent than previously appreciated. This research proposes a more unified tectono-stratigraphic architectural model that interprets salt collapse controls as having a continual control on distribution of McMurray deposition for all three stratigraphic intervals that supplemented other processes across the northern Athabasca Deposit. It links salt removal induced structural controls on the economically attractive middle McMurray sand bars to the tectono-stratigraphic distribution patterns observable for the lower and upper intervals.

2.0 Study area and database

Thick bitumen saturated sand complexes (>10 m) variously combined into trends that collectively constitute the economically attractive Athabasca Oil Sands Deposit (Fig. 2A). There are two bitumen mining districts aligned along McMurray fills of multi-km long troughs that extend southeastward on the sub-Cretaceous structure (Figs. 2B and 4). The Steepbank River mining district, 5-10 km south of the study area, includes: Suncor Millennium (1), Steepbank (2), Base (3) and North (4) Mines. The mines within the study area are aligned along the fill of the Bitumount Trough: Imperial Oil Kearn Lake (5), Shell Canada Jackpine (6) and Muskeg River (7), Syncrude Aurora North (8) and Canadian Natural Resources Horizon (9). These bitumen sand deposits are commercially exploited by large open pit mining operations where the overburden is sufficiently thin (<75 m) and burial of the bitumen saturated beds is less than 150 m. Bitumen sand deposits south and southwest of the mining districts are buried to up to 400 m depths and suitable for *in situ* thermal recovery operations (SAGD).

The mine exposures have provide observational evidence of fault block movements, intra-deposit erosion surfaces, channel cuts and accretion trends, breccia-sinkhole collapses and other tectono-stratigraphic relationships exposed along the multi-km long mine benches. The thousands of cores cut by exploration and development wells, outcrop exposures along the Athabasca River Valley, and mine cuts have provide a voluminous data base for the geologic studies of the McMurray Formation, such as those by Wightman et al. (1995), Langenberg et al. (2002), Ranger and Gingras (2001, 2003, 2006, 2010), Smith et al. (2009), Hubbard et al. (2011), Musial et al. (2012), Nardin et al. (2013), and Broughton (2013a, 2015).

This study has a data base consisting of 30,000 wells, most of which have cored intervals that penetrated the McMurray Formation strata in advance of the mining operations, and to evaluate more deeply buried beds suitable for thermal SAGD operations that enable bitumen to flow to surface. The distribution of wells in active mine operation areas such as the study area have drill spacing with 100-200 m centers and 200-400 m for areas anticipated for future pit expansions.

The author mapped the McMurray Formation strata during the 10 year period of 2005-2015. Correlations were made for approximately 20,000 wells across the study area, and another 10,000 wells across the remaining area of the Athabasca Deposit. Cores from more than 3,000 wells were examined, including over 1,000 from wells within the study area. Photographic digital images of core slab surfaces were examined from an additional 4,000 wells within the study area. More than 90% of the wells drilled within the bitumen leases that site the Aurora North, Muskeg River and Jackpine Mines have cored intervals examined by the author. Approximately 20-30% of the wells drilled elsewhere across the study area have publically available cores, and most (>75%) of these were also examined.

The cored intervals illustrated for this article have dark, blackened, color due to very strong bitumen saturations often obscure bedding and other depositional features. These digital images have been altered by rebalancing the color saturation and contrast to improve clarity of the bed forms. The often very heavy bitumen staining throughout the middle McMurray sands penetrated by this extensive subsurface core data set affects observations of small cm scale sedimentary structures, compared to weathered outcrop surfaces along the river cuts. This disadvantage is offset by the ability to ascertain a more complete understanding of the subsurface dimensionality at the 100s of metres to multi-km scales.

Sand trend maps were created using bulk weight bitumen percentage cutoffs, which is standard practice in the oil sands industry. A bulk weight percentage (BWB) of bitumen of the rock mass combines multiple reservoir rock properties such as porosity, water saturation, shale volume, grain density, etc. Cutoffs for

economic bitumen ore grade are generally considered a minimum of BWB>6-7%. Bitumen sand with 10% BWB is equivalent to sand having 32-34% porosity. The upper range for bitumen saturation is 14-16% BWB. Maps using bitumen grade cutoffs are nearly identical at all scales to maps created without this parameter, excepting where bottom water is present in some structural lows filled by lower McMurray beds.

The pattern of fault traces across the study area, particularly those that define the V-shaped Bitumount Trough are based on a data set including the voluminous well control, often spaced only 100 m apart that have evidence for tens of metres of vertical displacement across a few hundred metre wide distances, and can be reliably correlated from well to well along multi-km linear traces on the sub-Cretaceous structure. Regardless, this may be regarded as largely interpretive since continuous 3D seismic coverage across tens to hundreds of km², and focused into the sub-Cretaceous, is mostly unavailable or not available to the author. This has resulted in differing structural models that interpret the style of faulting, or lack thereof, applicable to the study area and is further discussed below.

3.0 Geologic setting

The Alberta Basin area of the Western Canadian Sedimentary Basin developed as the foreland basin of the Canadian Rockies. The regional tectono-stratigraphic framework changed when lithospheric loading of the fragmented passive continental margin evolved into a Middle Jurassic foreland basin. The fold and thrust fault belt developed as the deformation front advanced eastward during the Cordilleran orogeny (Leckie and Smith 1992). The basin filled with mostly Middle to Late Jurassic and Early Cretaceous clastics shed from the eroding Cordillera (Leckie 1986; Cant 1988; Pana et al. 2001). The northeastern Alberta Basin was uplifted, and no beds representing this post-Devonian to pre-Aptian hiatus accumulated across the study area (Figs. 4 and 5). The resulting Upper Devonian limestone karst topography was covered by fluvial and fluvio-estuarine sand deposits of the McMurray Formation (Aptian).

Hydrogeologic models interpret the regional dissolution of the Middle Devonian hypogene salt karst underlying the Athabasca Deposit and configuration of the sub-Cretaceous structure floor of the deposit to have resulted from formation waters that flowed northeastward up-structure along Middle-Upper Devonian strata towards and into the study area (Garven 1985; Connolly et al. 1990; Anderson and Knapp 1993; Bachu and Underschultz 1993; Bachu 1995, 1999; Anderson and Hinds 1997; Amfort et al. 2001; Michael et al. 2003; Grasby and Chen 2005; Hein et al. 2013; Hein 2015).

3.1 Tectono-stratigraphy

Structural reconfigurations resulting from post-burial salt removal patterns within the Prairie Evaporite basin were extensively controlled by the Rocky Mountain tectonism and development of the fold and thrust belt located along the British Columbia-Alberta Provincial Boundary concurrent with evolution of the Western Canadian Sedimentary Basin (WCSB) to the east. The Cordilleran fold and thrust fault belt developed as the deformation front advanced eastward. Northeastern Alberta was uplifted by the Late Jurassic tectonism concurrent with the deepening of the Deep Basin trough as the WCSB deformed across western Alberta. This tectonism and associated ancestral movements broadly configured the Prairie Evaporite Basin into structural domains eastward of the Rocky Mountain foothills: (1) the uplifted eastern limb of the Alberta Basin across central and northeastern Alberta, and (2) the northern rim of the Williston Basin across southern Saskatchewan, northeast of the central Montana Uplift (Parker 1967; LeFever and LeFever 2005).

Tectonostratigraphic and paleogeographic models formulated during the last couple of decades suggest that major regional controls on development of hypogene aquifers that controlled widespread salt removal patterns in the WCSB were linked to continental scale tectonism (Garven 1989; Leach et al. 2001). Burial-uplift cycles induced deep seated aquifer flows that refigured areas of the Middle Devonian salt basin during the Late Devonian-Carboniferous (Antler) and Late Cretaceous-Paleogene (Laramide) mountain building compressions with the creation the Pangea supercontinent and subsequent fragmentation that separated North and Central America from Europe and Western Africa. Tectonic events associated with the Antler orogeny lasted from the Late Devonian into the Carboniferous with the creation of the ancestral Rocky Mountains. This was followed by the Columbian orogeny that resulted in regional uplift during the Late Jurassic to Early Cretaceous, and culminated with the Laramide build of the Rocky Mountains from the Late Cretaceous into the Paleogene.

Columbian-Laramide compressional tectonism events and associated foreland uplift resulted in significant hydrogeologic controls on the eastward flow of deep seated aquifers in the Deep Basin areas that paralleled the eastern fold and thrust belt of the emergent Rocky Mountains. This hydraulic head provided the westward drive for deep seated aquifer flows from elevated mountainous areas into areas with lower topographic relief to the east, and controlled the flows of expelled connate waters as deeply buried sediments compacted with continued sedimentary loading (Garven and Freeze 1984; Garven 1989). The Roncott Platform-Hummingbird Trough in southern Saskatchewan, for example, records this multi-stage collapse history during the Late Devonian and Carboniferous (Antler) and the Jurassic-Cretaceous

(Columbian-Laramide). Other dissolution events include the impact by Pleistocene glacial loading and unloading.

Devonian strata represent almost all of the preserved Paleozoic succession below the Athabasca Oil Sands Deposit. The thinned Paleozoic interval was a consequence of both surface erosion, resulting in Upper Devonian limestone karst topography, and subsurface removal of 100-150 m thick salt beds accumulated in the Prairie Evaporite (Middle Devonian) buried evaporite basin. Salt dissolution induced collapse-subsidence of the overlying Upper Devonian strata is widely recognized as being largely responsible for reconfiguration of the sub-Cretaceous structure (Ranger and Gingras 2001, 2006, 2010; Ranger 2010; Hein et al. 2013; Broughton 2015). This configuration of the sub-Cretaceous structure was concurrent with increased surface erosion of the Upper Devonian limestone beds to the northeast as the area uplifted and tilted, resulting in regional subcrop of Waterways Formation strata across the study area (Figs. 5-7). Laramide tectonics further modified the regional sub-Cretaceous structure with a low ($\sim 2^\circ$) tilt to the southwest. Joint dissected and folded strata with low amplitudes (<10 m) and km-long wavelengths modified some Upper Devonian limestone beds, such as those exposed along the Athabasca River Valley (Pana 2002).

The Prairie Evaporite (Middle Devonian) salt basin extends across most of Western Canada (De Mille et al. 1964; Holter 1969; Broughton 1977; Irvine et al. 1978; Williams 1984; McTavish and Vigrass 1987; Meijer Drees 1994). Halite salt beds up to 250 m thick accumulated along the basin axis from south-central Saskatchewan westward into central Alberta. For example, undisturbed halite beds, 150-200 m thick, were penetrated by stratigraphic test wells located 20 km southwest of the study area. Halite beds are 40% to as much as 90% of the overall thickness with the remainder consisting of anhydrite, dolostone and calcareous mud beds (Meijer Drees 1994; Grobe 2000).

The northern area of the Athabasca Deposit and easternmost margin of the Cold Lake Deposit (Fig. 1) overlie a segment of the 1,000 km long and 150 km wide salt dissolution-collapse trend developed along the eastern margin of the Prairie Evaporite salt basin (Meijer Drees 1994; Ford 1997). Broughton (2013a) and Barton et al. (2014) calculated the regional thickness of the removed salt beds in the Bitumount Trough to have been at least 80-100 m, probably more, which is comparable to the pre-erosion thickness projected by regional scale mapping by Meijer Drees (1994). This is also consistent with the 80-100 m depths of deeper sinkholes located across the Upper Devonian paleo-topography northeast of the Bitumount Trough (Broughton 2013a). Thinned salt bed also draped Keg River mounds and were subsequently removed. There is no observational evidence in any cored intervals of the Middle Devonian

strata for halokinesis, doming, turtle structures or other indications of plastic salt flow. Salt removal resulting in post-burial thinning is attributable to dissolution only (Broughton 2013a).

3.2 Structural models applicable to the northern Athabasca Deposit

It is widely accepted that salt dissolution subsidence-collapse in the underlying Prairie Evaporite reconfigured the overlying pre-Cretaceous paleo-topography (Flach and Mossop 1985; Wightman and Pemberton 1997; Hein and Cotterill 2006, 2007; Ranger and Gingras 2001, 2006, 2010; Schneider et al. 2012; Hein et al. 2013). Salt removal episodes in the Prairie Evaporite substrate, both pre-Aptian and concurrent with McMurray strata deposition, were responsible for the valley and ridge reconfiguration of the Upper Devonian hypogene karst topography onto which sands of the lower McMurray interval accumulated along karst valley lows (Broughton 2013a, 2015).

Salt dissolution in the subsurface only 200-250 m below was probably a near continuous process characterized by multi-stage phases with substantial salt removal that mostly commenced during the Middle Jurassic in the Athabasca area, but to a lesser extent as early as the Late Devonian. Significant successive salt removal collapses were episodic: (1) Middle Jurassic to Early Cretaceous, pre-Aptian, uplift that removed substantial thicknesses of halite salt; (2) several episodic stages concurrent lower, middle and upper McMurray interval depositions (Broughton 2015); (3) during the Quaternary when proglacial melt waters invaded the Devonian karst aquifer and permitted under-saturated waters to rejuvenate dissolution (Stoakes et al. 2014a, 2014b).

Salt removal continued throughout the Cretaceous with significant dissolution stages during deposition of the lower and upper McMurray beds (Mahood et al. 2012; Broughton 2013a, 2015; Stoakes et al. 2014a, 2014b). These dissolution events are recorded by observations of fault block rotations with stratal onlaps, breccia pipes and sinkholes (Broughton 2013a, 2015; Barton et al. 2014). The dissolution continues into the present day, although to a lesser extent, resulting in widespread saline seeps to the surface along the Athabasca River Valley (Gibson et al. 2013; Gue et al. 2015). Elsewhere, there were earlier salt removal stages that were significant were often earlier, such during the Late Devonian and Mississippian dissolution-collapses eastward across southern Saskatchewan especially along the margins of the Roncott Platform (Broughton 1977).

Structural interpretations vary on the spatiotemporal rates of regional salt removal patterns across the study area and result in conflicting structural models. A tectonic model interpreted by Schneider et al.

(2014) suggests that slower regional salt removal resulted in undulations and low sinuosity folds of the Upper Devonian limestone beds, and induced multi-km long monocline-like structural flexures that dip towards the central depression across the central study area. In contrast, the Broughton (2015) model suggests that multi-staged salt dissolution episodes resulted in fault-bound bench-like terraces along the rim of the central depression that stair step-down northward of the Bitumount Trough (Figs. 4A, 7 and 8). It is also possible, if not probable, that the combined effect of both models is applicable to the study area, and this is presented as a new interpretation, Model 3, below:

Model 1. Regional salt removal patterns induced fault bound troughs and resulted in chains of collapsed Upper Devonian fault blocks that exerted an overarching architectural control on the configuration of the sub-Cretaceous structure and result in formation of multi-km long syndepositional trends in the overlying McMurray strata (Broughton 2015). Deep rooted faults that cross-cut Upper Devonian, McMurray (Aptian) and overlying Clearwater (Albian) strata have been partially exposed by cut benches in all of the mines of both mining districts, and is interpreted as the general case for all of the partial to largely complete salt removal patterns in the Middle Devonian subsurface (Fig. 2B). The fault lineaments mapped on the sub-Cretaceous structure represent traces linked to differentially subsided fault blocks that extend upward into the overlying Cretaceous cover exposed in mine cuts (Broughton 2015) and 2D seismic profiles (Barton et al. 2014).

Model 2. This model interprets large areas of salt removal to have been a gradual process that resulted in gentle warping of the Upper Devonian limestone beds into large amplitude flexures (Dufresne et al. 1994; Nikols 1996; Schneider 2011; Schneider et al. 2012). These regional scale salt removal pattern caused large scale monocline folds of the Upper Devonian substrate that reconfigured the sub-Cretaceous structure. The impact was largely confined to multi-km scale curvilinear monocline folds. This model does not accept the existence of multi-km long near linear trough boundary faults. Regional cataclysmic collapses did not occur regionally, in contrast to gradual bed warping across tens to thousands of km², other than isolated sinkhole collapses. This structural viewpoint has been advanced by studies of the Alberta Geological Survey (Schneider and Grobe 2013; Schneider et al. 2014), based on interpretations of the well control and on observations of scattered outcrop exposures of Devonian and Cretaceous beds along the Athabasca River Valley. The exposures of Upper Devonian limestone strata have gently folded beds with 100s m to km scale wavelengths with fault offsets.

Model 3. A reinterpretation of the structural framework for this study combines aspects of the above two models with the recognition that the displacements in the Devonian substrate may be interpreted as

338 closely spaced en-echelon fault splinters that result in the appearance of linear traces on the sub-
339 Cretaceous structure as defined by the often densely distributed well control. A well-defined linearity
340 resulting from steep structural offsets is at the level of the sub-Cretaceous structure along the southern
341 boundary of the western Bitumount Trough. This is designed as lineament A with tens of metres of
342 vertical throw (Figs. 2 and 4). Northward, the traces designated as lineament B and eastward as
343 lineaments C and D are less well defined, and probably do represent aligned fault arrays. These are likely
344 en-echelon displacements of splinter fault blocks that collectively partitioned of the displacement, such as
345 those described in mine cuts by Broughton (2015), in contrast to a single vertical fault with a linear
346 surface trace. This re-evaluation of the earlier Broughton (2015) model would be consistent with
347 structural displacements of Upper Devonian strata by en-echelon fault arrays above an advancing
348 dissolution front in the salt beds. Similarly, wider spaced fault block splinters, en-echelon, would also
349 result in the appearance of a monocline-like fold as they splinter and segmented the limestone beds in the
350 Upper Devonian substrate. Such as structural style would be applicable to the Bitumount Trough and the
351 central collapse area, and consistent with formation of structural step-downs into the central collapse area
352 as the salt dissolution front migrated that northward of the Bitumount Trough.

353
354 There is a widespread distribution of collapse breccia in the Upper Devonian substrate that resulted from
355 multi-stage dissolution phases linked to major trough faults that extend vertically upward from the Middle
356 Devonian to dissect the Upper Devonian paleo-topography and subsequently cross-cut McMurray strata.
357 This resulted in widespread distribution of collapse breccia throughout the Upper Devonian interval
358 (Broughton 2013a), and observations of km-scale rotated and tilted McMurray fault blocks such as those
359 exposed in mines of the Bitumount Trough and the Steepbank River mining districts. Examples of these
360 excavated fault blocks exposed in multi-km long mine cut benches are illustrated by Broughton (2015).
361 The widespread breccia patterns described by Broughton (2013a) suggest that the en-echelon fault model
362 characterized the Devonian substrate as response to pre-Cretaceous salt removal, resulting in regional
363 troughs on the sub-Cretaceous structure. However, fewer of these near vertical Upper Devonian faults
364 were active concurrent with McMurray deposition, and resulted in km scale fault blocks of McMurray
365 strata bounded by individual vertical fault planes distributed above a fault fragmented and brecciated
366 Upper Devonian substrate that down warped into the central collapse area.

367
368 **3.4 Regional sub-Cretaceous structure flooring McMurray strata**

369
370 The regional sub-Cretaceous structure along the western Bitumount Trough floor and large areas of the
371 central collapse were interpreted by Broughton (2015) to have been partially to extensively reconfigured

by salt removal in the substrate concurrent with McMurray deposition in addition to earlier pre-Cretaceous events. Cross-section A-A' illustrates the impact of regional surface erosion combined with salt removal in the subsurface during the prolonged pre-Cretaceous hiatus, resulting from uplift of the area now covered by the Athabasca Deposit (Fig. 5). Most of the Upper Devonian strata younger than the Waterways Formation were removed from areas overlying and eastward of the salt scarp (Fig. 5B). The area of the eastern Trough, however, was probably a well-defined pre-Cretaceous structure commensurate with most but not all of the salt substrate removed during the Middle Jurassic to pre-Aptian Columbian tectonism, and initial dissolution episodes possibly as early as the Late Devonian (Stoakes 2014a, 2014b).

The several largest salt removal-collapse regional features that configured this sub-Cretaceous structure are: (1) the 300 km long main paleovalley trunk that paralleled the underlying eastern margin of the salt scarp; (2) the 50 km long V-shaped Bitumount Trough, and (3) the 200 km² central collapse area (Figs. 6 and 7).

1. Main paleovalley. This curvilinear trunk channel on the sub-Cretaceous structure overlies the length of the salt scarp eastern margin, which demarcates the westernmost migration front across the salt removal area, 200-250 m below in the Middle Devonian substrate. The main paleovalley intersects the V-join of the western and eastern Bitumount Trough segments on pre-Cretaceous structure. It was the dominant lower McMurray fairway for transport of voluminous detritus northward towards the Boreal Sea, probably from eroded Jurassic strata southeast of the Athabasca Deposit (Ranger and Gingras 2001, 2006, 2010), and mixed with additional detritus from far-reaching eastward sources implying continental scale transport pathways (Benyon et al. 2014; Blum and Pecha 2014).

Broughton (2015) discusses the probability that the main paleovalley parallel to the eastern margin of the salt scarp was a rejuvenated bedrock river valley at least as old as the Middle Jurassic, if not older. The northward flow of such an ancestral bedrock river along the ancestral main paleovalley was entrenched over extensive collapse breccia trends in the Upper Devonian strata contiguous with eastern edge of the underlying salt scarp (Broughton 2013a).

2. Bitumount Trough. The structure of the floor underlying the northern Athabasca Deposit is dominated by the 50 km long V-shaped Bitumount Trough (Keith et al. 1990; Wightman and Pemberton 1993; Broughton 2013a; Wozniwicz et al. 2014). Broughton (2013a, 2015) interpreted this V-shaped sub-Cretaceous structure as consisting of a pair of orthogonally aligned salt dissolution collapse troughs configured by the salt removal patterns 200 m below. The Trough provided accommodation space for up

to 75 m thick sand dominated intervals accumulated and preserved during deposition of the lower McMurray Formation. The western Trough segment extends to the southeast between a pair of parallel fault lineaments (arrays of en-echelon fault traces) with 20-50 m throws on the sub-Cretaceous structure (lineaments A and B, Figs. 2B, 4B and 6). The structural style and precise mapping of the trace pathways on the sub-Cretaceous structure has been uncertain and reliant on often dense well control with only limited seismic data. The eastern Trough trends to the northeast as discontinuous segmented or aligned shorter lineaments, designed C and D. The Trough and its lower McMurray fill were mostly covered by middle McMurray deposits, but segments of the V-shaped Trough and areas continued to subside during deposition of middle McMurray strata.

Lower McMurray strata up to 75 m thick accumulated across the northern Athabasca Deposit in the accommodation space created by tens of km long Bitumount Trough that cross-cut the sub-Cretaceous structure. Only thin intervals (<10 m) of lower McMurray strata have been preserved beyond the confines of the Trough. These fluvial deposits have been widely interpreted as medium to coarse gravely sand bars deposited by braided rivers that pass upwardly into heterolithic floodplain deposits (Wightman et al. 1995; Hein et al. 2000, 2001; Ranger and Gingras 2001, 2006; Hein and Cotterill 2006; Nardin et al. 2010; Hein et al. 2013; Hein 2015). Broughton (2015) documents the evidence for interpreting structural collapse-related controls on lower McMurray deposition trends resulting in NW-SE and NE-SW oriented sand deposition trends.

3. Central collapse area. The central collapse area accumulated an overly thickened middle and upper McMurray beds concurrent with salt removal in the substrate (Broughton 2015). This 200 km² structural depression deepened as the underlying salt dissolution fronts migrated northward of the Bitumount Trough (Figs. 4 and 7). The salt removal front is interpreted to have advanced northward from the Deep Trough and resulted in bench-like terraces on the sub-Cretaceous structure that stair step down into the central collapse low. Some benches aligned parallel to multi-km long NW and NE oriented horst block ridges on the sub-Cretaceous structure that resulted from thinned salt beds draped over elongated curvilinear Keg River mounds (Figs. 8B). Significant and widespread downwarping of this regional depression probably commenced during the middle interval. Although the Bitumount Trough was the dominant lower McMurray structural event, the central collapse to the north was the main structuration associated with the middle and upper McMurray intervals. Collectively, they defined the shape of the estuary funnel on the sub-Cretaceous structure prevalent by the time of middle McMurray deposition.

The various shapes of this funnel-like sub-Cretaceous structure evolved throughout McMurray deposition, initially as the Bitumount Trough during the lower interval and a more fully developed funnel form during the middle-upper interval with deepened central collapse area. These salt removal induced configurations of the sub-Cretaceous structure resulted in the formation of a funnel-like accommodation space for the distribution of middle McMurray fluvio-estuarine deposits (Fig. 2B). This widening of the accommodation space, linked to the northwest migration of the salt scarp margin, resulting in the funnel-like estuarine paleogeography with the classic exposures along the Steepbank River area located near at the southernmost neck pinch-point terminus. Structural configuration of the floor of this funnel-like area was enhanced by semi-stable to unstable substrate alignments by differentially subsided fault blocks aligned as a northwestward structural grain. Movements along the sub-Cretaceous floor of the structure were interpreted by Broughton (2015) to have exerted at least a partial to a dominant control the distribution of lower and upper McMurray deposits, resulting in regional trends oriented to the NW and to the NE. This research interprets the distribution of middle McMurray deposits to have been similarly impacted by this tectono-stratigraphic framework, discussed below.

4.0 Middle McMurray sand distribution across the northern Athabasca Deposit

Maps of the middle McMurray interval indicate that the sandy geobodies distributed across the northern Athabasca Deposit vary from less than 10 m to as much 80 m thick (Fig. 9). The distribution and geometric configuration of these tens of km² sand deposits used a relatively clean higher quality reservoir map criteria such as >10% bitumen weight. Use of more inclusive bitumen quality map criteria, such as >6% bitumen weight, results in a continuous bitumen sand platform across most of the northern Athabasca Deposit area. Cleaner multi-metre thick sand bar complexes (BWB>10%) have constrained these distribution patterns and indicate well-defined elongated linear geometries similar to dimensions of larger scale point bar deposits. This alignment of large scale sand deposits along parallel trends differs from the overall distribution of point bars accumulated along the fluvial dominated upper estuary to the south, which was constrained by the considerably narrower fairway of the Main Valley.

Most of these deposits are interpreted to have elongated geometric forms and distribution patterns consistent with collinearly aligned aggradations along NW-SE oriented trends. The distribution patterns for these numerous multi-km² deposits accumulated along channel-like fairways, each 10-30 km in length, arranged as sub-parallel trends across the width of the estuarine funnel-like area on the sub-

Cretaceous structure (Fig. 2B). These NW-SE alignments were consistent with configurations of the sub-Cretaceous structure, and regionally corresponded to salt removal trends (Fig. 9):

1. Parallel channels trends above the salt scarp. Middle McMurray sand deposits accumulated across the western study area above the 10 km wide buried salt scarp, Ranges 9-10, and further to the west (Figs. 4B and 8B). These large sand deposits accumulated as multi-km long point bars that were collinearly aligned NW-SE along multiple sub-parallel trends having increased linearity over the 10 km wide buried salt scarp underlying the western Bitumount Trough. These trends also parallel NW-SE oriented structures consistent with chains of differentially subsided Upper Devonian fault blocks and horst block trends elongated on thinned salt deposits overlying multi-km long linear Keg River mounds. This distribution pattern dominates the western half of the study area (western Fig. 9B). Examples of a large sand accumulations above the dissected margins of an underlying salt platform and contiguous Keg River reef mounds are the multi-km long deposits excavated by the adjacent Muskeg River-Aurora North Mines and the sand deposit excavated at the Jackpine Mine site (Fig. 8).

Interpretation. The geometry and distribution patterns of the large middle McMurray sand deposits accumulated across the study area suggest that these larger scale point bars accumulated along multiple fluvio-tidal channel systems that developed above NW-oriented lineaments in the Devonian substrate along the western reaches of the widened estuarine funnel (Fig. 9). These tidal impacted clastic transport fairways represent the transition from a constrained single channel of the Main Valley to an estuary funnel area underpinned by multiple parallel or sub-parallel structural trends following the structural grain responses to underlying fault block collapse trends on the sub-Cretaceous floor. Pre-existing and concurrent reconfigurations of the sub-Cretaceous structure below McMurray deposition resulted in multiple structurally oriented sub-parallel fluvio-tidal fairways that branched outward northward across the width of the funnel from the constrained main paleovalley fairway trend. The elongated fluvio-tidal point bars sand deposits aligned along these NW-oriented fairways were similarly aligned to the NW-SE.

The structural configuration of the 10 km wide salt scarp was interpreted by Broughton (2013a, 2015) as a mosaic of cross-cutting dissolution trends oriented mostly NW-SE but also SW-NE along fault-like lineaments interpreted as en-echelon offsets that would have been consistent with migration of the dissolution-collapse front. This structural grain dominated the configuration of the larger features on the sub-Cretaceous structure such as the boundaries and the mosaic of km-scale fault blocks flooring the Bitumount Trough (see Broughton 2013a). Westward, beyond the recognized influence of the underlying salt removal patterns, there is less evidence for the morphogenesis of a similarly aligned NW and NE

regional structural grain and a more random distribution of smaller middle McMurray bitumen saturated sand deposits. Otherwise, the large point bar deposits accumulated along extensive paleovalleys on the sub-Cretaceous structure that joined the main paleovalley fairway. These tens of km long northeast oriented valley trends on the Upper Devonian paleotopography formed over incipient linear dissolution trends westward of the salt scarp across large areas underlying the Athabasca Deposit. They occur as far west as the Ells River paleovalley where incipient dissolution-collapse was observed by Broughton (2013b). Many SAGD operations have been located along middle McMurray strata that filled these valleys (see Fig. 2B).

2. Structural step down aggradation sites overlying salt removal areas. Areas eastward of the salt scarp were variously impacted by multi-staged salt removal and resulting collapse-subsidence of the overlying Upper Devonian and lower McMurray strata. The northern reaches of the Bitumount Trough and the central collapse dominated reconfigurations of the sub-Cretaceous structure, partially concurrent with middle McMurray deposition. Regionally significant sand transport fairways developed over these structural trends and controlled the distribution and alignment of multi-km long sand deposits. These deposits overly thickened at sites that responded to concurrent regional down warping of the central collapse area (Fig. 2B). For example, tens of km long and multi-km wide sand transport fairways trended northward down-structure towards and into the central collapse low. The multi-km scale sand deposits, aligned along these fairways into the central collapse area, accumulated above bench-like breaks in the underlying sub-Cretaceous and lower McMurray structural levels (Figs. 4 and 9). The sand deposit at the Jackpine Mine site is an example of such a deposit on a step-down bench.

Interpretation. Large sand aggradation sites collinearly aligned along fairways that trended over structural benches that stair stepped down into the central collapse low. These step downs resulted from collapse-subsidence trends of Upper Devonian fault blocks that aligned with the northward migration fronts in the underlying salt dissolution pattern resulting in the central collapse area. Some of the Upper Devonian block alignments were partially configured by NW or NE orientated, multi-km long, Keg River mounds responsible for linear horst-like ridges on the sub-Cretaceous structure.

The regional scale Firebag fairway, also termed a mega-channel trend, extends from beyond the southeast corner of the map area, across the eastern Trough and turns northward at the site of the Jackpine Mine and continues into the structural lows of the central collapse. This mega-channel sand transport fairway cascaded over the structural benches developed along the southern margin of the central collapse depression on the buried sub-Cretaceous and underlying lower McMurray structures northward of the

Bitumount Trough (Fig. 9B). Favored sites for accumulation and stabilizing large point bar complexes were above these structural step downs. This linkage between the distribution of large sand deposits and the underlying pattern of salt removal across the central collapse/westward embayment of the salt scarp margin was a strong control that impacted the distribution of giant point bar complexes across the central and eastern half of the study area (Fig. 9B).

The tens of km long sand complex straddling the adjacent Muskeg River-Aurora North Mines and the Jackpine Mine sites are examples of a complex that drapes over structurally higher substrate impacted by partial salt removal, and continued to thicken as the deposition site steps down over differentially subsided substrate with increased salt removal below. The structural conditions for the Jackpine and Aurora North sand deposits resulted in multiple stacked point bars that stacked within the accommodation space are further described below to illustrate the significant impact of such structural terracing on the internal architecture of these sand deposits.

3. Northern reaches of the estuary funnel. Smaller middle McMurray sand bars, similarly oriented NW-SE, distributed across the northern study area as 1-3 km long and 10-20 m thick deposits. Their NW-SE orientations are oblique to the shallow structuration of the N-S oriented salt removal trend. They accumulated over a northward oriented salt removal trend and corresponding low on the sub-Cretaceous structure, located between remnants of the mostly eroded main paleovalley to the east and the poorly defined salt scarp to the west (Fig. 9A). The overall preserved trend has a northward, seaward, fairway orientation probable represents a remnant of the main paleovalley trunk that was extensively eroded by glaciation across large areas northward of the central collapse. No McMurray strata has been preserved eastward of these sand bars (Fig. 9A).

Cored interval from wells scattered across the area of Figure 9A typically have deposits of fine sand with faint ripple laminated stratification and frequently observed intervals of small (<1 cm) mud clasts and mudstone clast breccia deposits up to 20 cm thick. A typical profile consists of a mostly homogenous fine grain sand interval, 10-20 m thick, with basal facies including mudstone breccia. These beds pass upwardly to I.H.S. beds, 10-20 m thick with 5-10° dips, and include 1-3 m thick mud-plug intervals from abandoned channel fills. Overlying this sand dominated succession are mud dominated heterolithic facies usually represented by alternating decimeters thick beds of thin fine grain sand and mud, which pass upwards into cm thick laminated mud and sand beds similar to tidal mud flat deposits. These deposits are often overlain by fine heterolithic sands including more distinctly marine-influenced deposits with larger *Asterosoma*. These uppermost facies of the middle McMurray interval are overlain unconformably by an

upper McMurray deposit consisting of 3-5 m thick coarse sand beds with trough cross-stratified beds (Fig. 9A).

Interpretation. The distribution area of these smaller middle McMurray sand bars northward of the central collapse area are interpreted accumulations along distributary channels across the lower deltaic plain preserved from erosion as a remnant of areas more proximal to the estuary funnel mouth. Their sedimentology suggests a distinct fluvial influence, and the distribution pattern suggests a networks of smaller fluvio-tidal point bars along cross-cutting distributary channels (Fig. 9A). This area may represent the western margin of the broader lower deltaic area, and that the larger channel deposits eastward towards the main channel trend of the main paleovalley were eroded and not preserved because of glaciation.

The trace fossils of this area and westward are often characterized by anomalously large burrow traces (Fig. 10). Their distribution patterns and geometries are suggestive of elongated shallow marine-impacted sand bars, possibly comparable to the northwest Athabasca area described by Broughton (2013b) as having accumulated marine equivalent facies during middle-upper upper McMurray intervals. However, these northernmost study area deposits are distinctly fluvial and do not include glauconitic facies similar to the deposits at Ells River to the west (Broughton 2013b). The sedimentology of these deposits along the northernmost margin of the Athabasca Deposit is not fully understood at this time. Future work on this area is a promising because the area has been proposed as a future site of bitumen mining operations (Fort Hills).

5.0 Estuary funnel point bars: transition from fluvial to fluvio-tidal architecture

The northward flowing river drainage down structure seaward along the Main Valley fairway towards the Boreal Sea transitioned from a fluvial-dominant but tide-influenced upper estuary towards and into an increasingly tidal and near-marine influenced lower estuary funnel area that accumulated fluvio-tidal point bar sand deposits (Fig. 9). The funnel-like geometry on the sub-Cretaceous structure across the study area, resulting from the greater westward migration of the underlying salt scarp dissolution front for the region northward of the Steepbank River and Christina River outcrop areas. This resulted in a broad regional low on the sub-Cretaceous structure dominated by the accommodation space created initially by the Bitumount Trough and later by the central collapse depression (Fig. 2B).

607
608 This structural funnel-like area flooring the middle McMurray deposits is interpreted as representing a
609 lower estuary during the middle Murray interval and accumulated deposits of tidal impacted fluvio-tidal
610 point bars. Exposures of the middle McMurray point bars along the Steepbank and Christina Rivers are
611 sites located at the southern end of this broad funnel-shaped structural area that coincided with the
612 northwestward shift by the underlying salt scarp. This resulted in an inshore tidal zone across this lower
613 estuarine funnel characterized by multiple channel deposit trends that are elongated and curvilinear, in
614 contrast to the highly sinuous meandering channel network of the upper estuary.

615
616 Sedimentologic studies of middle McMurray beds exposed along the Steepbank River (Musial et al.
617 2012) and the Christina River (Martinius et al. 2015) areas, approximately 10-15 km south of the
618 Bitumount Trough (Fig. 2B), indicate depositional processes attributable to this transition from fluvial
619 point bar deposits with tidal impacts to fluvio-tidal point bars. There is a mixture of sedimentary
620 structures indicative of mixed tidal and fluvial conditions or transitional between for the southern funnel
621 areas immediately to south of the study area, i.e. exposures along the Steepbank and Christina Rivers.
622 This implies that areas northward across the study area would have increasingly stronger tidal influences
623 commensurate with encroachment of the Boreal Sea and increased influence of marine conditions
624 responding to southward encroachments by the Boreal Sea. These areas differ from locations further to
625 the south such as at Long Lake (Labrecque et al. 2011a) and Surmont (Boyd et al. 2014) where multi-km
626 scale fluvial point bar deposits accumulated within the fluvial dominated upper estuary have evidence for
627 subdued tidal impacts during deposition.

628
629 Sedimentologic processes during middle McMurray deposition at sites across this southern end of the
630 funnel-like structural area (Twps. 91-92, Fig. 2) have been interpreted by Musial et al. (2012, 2013),
631 Strobl et al. 2013, Martinus et al. (2015), and Jablonski and Dalrymple (2015) as tide impacted fluvio-
632 estuarine sub-tidal point bar deposits. The sedimentary structures have evidence of unidirectional current
633 flow and clastic transport along the trajectory of channels, and were modified by counter
634 northward/southward flood and ebb flows of tidal currents. The lower point bars exposed along the
635 Christina River Valley also include transitions into subaqueous dunes having bimodal thickness
636 distributions accumulated within the lower reaches the channel fills (Martinius et al. 2015). There,
637 foresets oriented to the southwest (202°) with average dip angles of 25° are associated with bottom sets of
638 the point bar sands having planar and tabular cross-stratified bed sets with intervals dominated by ripple
639 laminated stratification. When the fluvial dominance waned and tidal forces exerted greater control, the
640 resulting backflow ripples climbed the slip faces and passed into the dune foresets impacted by strong

flow vortices. The ripples indicate a flow direction opposite to the main fluvial flow and no co-current flow ripples were preserved. Reactivation surfaces become increasingly evident with the increased tidal influence, and resulted in rapid and thick aggradation. These fluvio-tidal basal bed deposits were covered over by I.H.S. as the thickest depositional unit, which may or may not display evidence of tidal double mud drapes (c.f. Visser 1980; Nio and Yang 1991).

Similar tidal point bars modified with dune deposits are increasingly observed northward across the study area. However, these linked point bar-dune deposits are difficult to reliably discern using only cored intervals, but are exposed across the northern study area along the cut banks of the northern Athabasca River Valley. Figure 11(A) illustrates an example of a dune complex exposed in an outcrop located along the northern reaches of the Athabasca River Valley, where it transects the central collapse area of the lower estuary funnel across the central study area. In this example, a ripple laminated bed separates the truncated planar-laminar foreset/bottomset of a dune from planar foreset/toeset of the overlying dune. The southward dips of the bottom set beds are 12-15° (M. Ranger, personal communication, 2014). A second example is illustrated by Figure 11(B). This dune is located in basal middle McMurray beds exposed along the Ells River 1 km west of the confluence with the Athabasca River at the western margin of the Muskeg River Mine lease. They have tops that are usually truncated, and may represent compound dune structures (M. Gingras, personal communication, 2015).

The point bar sand deposits across the study area also host mud couplets that are generally attributable to impact by tidal processes (Fig. 12). Various types of channel sand bar architectures (fluvial point bar, tidal bar, subaqueous tidal dune, etc.) may or may not have structures that record tidal influences, such as double mud drapes that have been interpreted as diurnal or semi-diurnal mud couplets (*sensu* Friedman and Chakraborty 2006; Martinius and van den Berg 2011). The I.H.S. intervals associated with point bar sand deposits within the study area have an increased concentration of these tidal mud couplets, compared to similar point bar deposit exposures along the Steepbank and Christina Rivers, and appear to be more prevalent compared to fluvial dominated point bars further to the south as fills along the main paleovalley.

The southern study area has numerous sites in the subsurface that accumulated multi-km scale fluvio-tidal point bar deposits similar to those located near the southern reaches of the estuary funnel such as those examples exposed along the Steepbank and Christina River cut banks. However, these multi-km scale point bar sand deposits of the study area have differing internal architectures that suggests correspondence to the increasingly unstable substrate northward across the study area floored by the Bitumount Trough

and central collapse areas that structurally underpinned the increased accommodation space created across the central and northern estuarine funnel.

Changes in the ichnology of the middle McMurray deposits northward across the study area are further evidence for increased impact by tidal processes of the estuary funnel, compared to deposits at the southern neck of the funnel along the Steepbank and Christina Rivers, and other located to the south along the Main Valley and tributaries. The study area ichnofauna assemblage has a similarly narrow diversity represented by *Planolites*, *Skolithos*, *Cylindrichnus*, *Asterosoma*, *Chondrites*, *Gyrolithes*, *Teichichnus*, *Thalassinoides*. The size range of these burrows is mostly at the 1-3 cm scale in cored intervals recovered from the southern study area and southward into the Steepbank River and Christina River areas and further southward in deposits accumulated as middle McMurray fills of the main paleovalley. This constrained diversity, sometimes mono-species, and diminutive sizes contrast with some forms that display rapidly increased size seaward across the central and northern reaches of the study area and northwestward of the main paleovalley towards the Ell River area (Broughton 2013b). Although this is without significant changes in ichno-diversity, there is an increased prevalence of many remarkably robust species. *Teichichnus* burrow lengths are observed up to 40 cm, and *Rosella* burrows as large as 15 cm (Fig. 10A-D). The robustness of these individuals are interpreted to signify greater impact by increasingly stronger tidal processes dominating over fluvial processes as responses to pronounced shifting sands northward of the Bitumount Trough and central collapse areas.

The northernmost study area, especially regions such as Township 99-101 (Fig. 9A), significantly northward of the central collapse area has middle McMurray sand bar deposits, probably situated in more proximal to shallow marine sites fronting the southward advances by the Boreal Sea. These sand bars are overlain by muddy intervals with very large *Asterosoma* (Fig. 10E), indicative of distinctly more marine environments that would be associated with the northernmost reaches of the estuarine funnel, in contrast to the fluvio-tidal deposits across the southern study area.

6.0 Fluvio-tidal point bar aggradations on unstable substrate: case studies from the Muskeg River-Aurora North and Jackpine Mines

Morphogenesis and internal architecture of two large fluvio-tidal point bar complexes are illustrated from the sites of the Muskeg River/Aurora North Mines and Jackpine Mine sites are described as case studies.

These reference examples illustrate structural step down controls on distribution, geometric configuration and internal architectures that resulted from aggradation onto unstable substrate.

6.1 Case 1: point bar architecture of the sand complex at Aurora North-Muskeg River Mines

A multi-km long and 10s of km² point bar sand complex, oriented NW-SE, extends from northern Twp. 95, Rge. 10 on the lease of the Muskeg River Mine northwestward into the southern area of Twp. 96, Rge. 10 across the lease area of the Aurora North Mine (Fig. 9B). This area is above the unstable substrate underlying the eastern end of the Deep Trough extending along the northern margin of the Bitumount Trough. The southern end of this 20 km long sand deposit at the site of the Muskeg River Mine overlies an elevated area on the sub-Cretaceous structure above the salt scarp margin and a large buried reef mound within the Keg River substrate (Fig. 8). The middle and undifferentiated middle-upper McMurray sand deposit thickens northward over a structural step down developed along the northern margin of the western Bitumount Trough and across the northern margin of the underlying Keg River mound towards and into the southernmost margin of the central collapse. Differentially subsiding substrate increased by 20-30 m or more locally at the eastern end of the Deep Trough (Fig. 4A) and 10s of metres into further northward into the central collapse area. The preserved thickness of the point bar sand complex increases by up to 50% onto the lease area of the Aurora North Mine. The entire McMurray interval was strongly bitumen saturated.

Bench cut profiles oriented east-west transect the McMurray intervals accumulated at the site of the Aurora North Mine to depths up to 80-100 m (Fig. 13). These step cut benches, 3-4 km wide and 16-20 m high, transect the overly thickened central area (40-60 m) of this point bar complex in the Aurora North Mine. Similar step cut benches transect the southern areas of the sand complex within the adjacent Muskeg River Mine. For example, the profiles of the Aurora North Mine illustrated by Figure 13 consists of a 20 m thick lower interval, 40 m thick middle interval and a relatively thinned 5-10 m thick upper interval. Similar cut benches in the Muskeg River Mine are illustrated by Figure 14.

These bench cuts into the Aurora North sand deposit transect the full width of the middle McMurray complex and reveal an internal organization consisting of least two, and variously preserved remnants of a third, overlying horizontal intervals, each representing a partially eroded point bar surface. Each of these accretion bed intervals within the middle McMurray interval are separated by a planar erosion surface that

extends laterally, sub-horizontally, for the multi-km width of the central sand deposit accumulated across structural step down lower areas into the central Aurora North Mine (Fig. 13). The erosion surfaces do not extend southward up structure into the area of the Muskeg River Mine deposit. The erosional surfaces at the upper surface boundary for each of the overlying point bars extend laterally across the width and most of the length of the complex. Such surfaces may be obscured locally and the stratigraphic position may be interpretive for sand-on-sand contacts when having only log profiles data.

The exposed mine cuts indeed indicate that the horizontal erosion surfaces persist laterally. These well-defined erosion surfaces within the middle McMurray interval truncate internal structures of each overlying point bar deposit, such as channel fills, reactivation surfaces and sand dominated lateral accretion surfaces. This stacking of two or three 10-20 m thick point bars, each bounded by a laterally extensive erosion surface, resulted in an unusually large middle interval point bar aggradation complex sited over the structural step down along the northern reaches of the western Bitumount Trough into the southern margin of the Deep Trough/central collapse area.

The stacked lateral/forward accreting point bar sand deposits and internally down cutting channel fills that accumulated as the central sand complex were disconformably covered over by a 20-25 m thick muddy I.H.S. interval (Fig. 13A). There is no apparent gradually fining upward vertical profile for the middle interval sand complex. This up-section transition to this overlying muddy interval was abrupt across a sharply defined unconformable contact. The middle McMurray interval at the Aurora North site was covered by a relatively thin upper McMurray heterolithic sand, mostly less than 10 m thick, where preserved below Clearwater or absent because of glacial scour and Holocene deposition. This contrasts with the upper McMurray interval elsewhere that may thicken to 10s of metres across central collapse area (Broughton 2015).

Multiple channel cut and fill structures excavate into each of the several overlying sub-horizontal lateral/forward (northwestward) accretion deposit. The two or three intervals consisting of overlying middle McMurray point bars have lateral accretion beds with bed dips less than 10-15°, and were each cut into by 100-150 m wide and relatively shallow (<15 m) channels with northward flow directions. These channels appear to be irregularly spaced along the E-W transects. They represent as much as 30-40% of a strike or dip section profiles. Figures 13B and 13C are representative east-west oriented bench cut profiles of the McMurray succession westward of the vertical profile illustrated by Figure 13A. They display similar channel cuts into the dip section that are modestly oblique to the overall northwestward strike-length of the deposit. Each channel fill was truncated above by the lateral continuity of the inter-point bar

erosion surface. The late stage fills of all of these concave upward channels all consist of very fine sand. No mud-plug filled abandoned channels have been observed, unlike smaller mud plug channel fills cross-cut by Muskeg River operations to the south. Evidence for these late stage mud-plug abandonments, however, may have been eroded.

The 15-20 m thick accretion beds of each point bar interval dip modestly northwestward (10-15°). The bases of the concave upward channel cuts do not extend downward for the entire thickness of the intervals and do not reach the next complex-wide erosion surface below. The preserved portions of the channel fills are typically 12-14 m thick, suggesting cut bank heights of at least 12 m. The concave upward channel fills are laterally traceable for approximately 100-150 m, resulting a constrained 1/10 to 1/12 depth/width ratios for all of the channels. The geometries and fill architectures of the channels repeat consistently within each point bar layer and between each of these 2 or 3 stacked bar intervals.

The general flow direction for these intra-bar channels is to the northwest parallel to the strike-length of the deposit. Within each of the larger depositional intervals, channel flow directions vary little from the overall northward direction. Dips are up to 15-20° for the forward accreting deposits. However, there is only partial preservation of each channel below the pervasive inter-bar (intra-complex) erosion surfaces. Partially preserved remnants of meander bend scrolling below these complex wide erosion surfaces have been mostly truncated by local erosion-reactivation surfaces that dip up to 40-60° (Fig. 13B), and onlap the channel deposits (*sensu* Durkin et al. 2015). Rotation of the overlying channel direction along the channel bend configuration locally shifts paleo-flow direction and orientation of the concave upward channel fills (*sensu* Smith et al. 2009; Hubbard et al. 2011; Labreque et al. 2011a), but eventually overall N-NW paleo-flows re-establish.

The internal architecture of the thickened middle area of this large fluvio-tidal point bar complex at the site of the Aurora North Mine changes southward up-structure towards the southern margins of the complex where it has been partially exhumed by the Muskeg River Mine (Fig. 14). The middle McMurray interval is thinner, averaging 20-25 m, although it is as much as 50 m thick across very small areas of a km². This southern extension of the point bar complex consists of laterally continuous horizontal beds disrupted by markedly smaller channels only 5-10 high and 20-30 m wide, some of which may be mud plugged upon abandonment (Fustic 2007). These sub-horizontal middle McMurray interval beds are continuous beds but pass eastward and westward into sandy I.H.S. beds with steep dips (20-45°) (Fig. 14). These steeply dipping lateral accretion bed are not characteristic of the thicker central area of the complex to the north where east-west lateral accretions were more constrained or even contained by

the confining structuration imposed by differential subsidence at the eastern margin area of the Deep Trough onto the area of the Aurora North Mine (Fig. 4). Significantly, internally pervasive intra-complex erosion surfaces that truncate the channels or the lateral accretion surfaces are not observed southward up structure into the area of the Muskeg River Mine.

6.1.1 Interpretation and discussion

The overlying erosion surfaces within the large sand complex were responses to multi-stage differential subsidence within the Devonian substrate that impacted the internal architecture of the point bar sand complex. This tectono-stratigraphic framework enhanced vertical aggradation and constrained lateral accretion along narrow areas mirroring the substrate instability. The tens of km long and multi-km wide fluvio-tidal sand dominated point bar complex was covered over by vertically by muddy I.H.S. aggradation, but the lateral accretion deposits were sand-dominated, and not muddy. Prior to late stage cessation of the expanding accommodation space, muddy fines were mostly transported northward of the complex and probably winnowed by fluvio-tidal processes. This resulted in extensive accumulations of muddy laminated heterolithic facies commonly associated with tidal mud flats. These deposits accumulated laterally between dominantly sand aggradation sites throughout the study area.

Each of the multiple overlying point bar accretion deposits were terminated by an extensive erosion surface. The preserved remnants of these channel complexes are thinner than those associated with the multi-km scale fluvial point bars at Long Lake and to south. For example at the Surmont SAGD property, the average channel depths are significantly greater (30-50 m), and the internal bar geometries show lateral accretion surfaces up to 35 m with dip angles of 5-15° (Boyd et al. 2014).

The east-west transects across each of the 2 or 3 point bar sand intervals expose 4 or 5 northward oriented channels cuts. The multiple intersections of these channel cuts indicate a channel system with compound tidal bar fills capable of rapid lateral migration by multiple coeval avulsive channels that flowed northward. The channel network organization does not represent a single channel with a highly convoluted meandering pathway that migrated across the multi-km width of the deposition surface and necessitated multi-km scale meander loops. This interpretation confirms earlier preliminary studies by Nardin et al. (2010).

The underlying lower McMurray strata excavated by the Aurora North Mine accumulated along a braided river channel system (Nardin et al. 2010). This lower McMurray channel organization at the Aurora North

Mine, and elsewhere across the Bitumount Trough, has been interpreted by Broughton (2015) as a footprint on the reticulate dissected Devonian substrate. This paleotopography directed impacted the organization of the overlying lower McMurray deposits, and partially impacted the distribution pattern of the overlying middle interval sand deposits. Although they are two distinct depositional systems, the braided river overlain by avulsive channel deposits were structurally linked.

This interval architecture of this large bar complex is a composite of tens of km long and several km wide layers cut into by a channel network established prior to and truncated by the successive complex-wide erosion events. This suggests a channel network flow system that repeatedly reasserted itself after each erosion but sustained overall aggradation, although multi-staged and pulsate. These successive erosion surfaces across the entire surface of the complex probably resulted from a temporary cessation and then resumption of the sediment supply into the area in balance with accommodation space linked to intermittent pulses in the underlying salt dissolution induced subsidence. During deposition of this middle McMurray interval, the southern margin of the central collapse area (Aurora North Mine) continued to detach and subside northward of the western Bitumount Trough (Muskeg River). This is interpreted by Broughton (2015) to have been a consequence of the dissolution front below the northern margin of the western Bitumount Trough migration northward from the Deep Trough during the middle McMurray period with stages of regional down warping into the central collapse area.

The differential subsidence resulting in concurrent reconfiguration of the sub-Cretaceous structure and the impact on the overlying deposition surface is consistent with the transition in the architecture from the area of the Muskeg River Mine northward, where the channels are small and non-avulsion, northward down valley into the increasingly thicker aggradation at the site of the Aurora North Mine, and change from semi-stable to unstable substrate as the underlying salt dissolution front below the Deep Trough migrated northward. Southward, large scale, 20-30 m high, lateral accretion beds with steep bed dips (30-45°) were more consistent with deposition across a lesser unstable substrate and more analogous to the fluvial deposits of the upper estuary (i.e. Long Lake and Surmont). However, the transition northward over the unstable substrate constrained this east-west lateral migration and enhanced vertical aggradation above the increasing accommodation space tied to pulses of differential subsidence. This resulted in point bar architectures with larger down cutting channels terminated by successive erosion surfaces as the underlying differential subsidence in the Devonian substrate stalled and then ceased, inviting erosional conditions. Several of these cycles stacking of stacking overlying, erosion bound, point bars resulted in a larger sand complex, prior to prolonged cessation and covering over by late middle McMurray muddy I.H.S. beds.

6.2 Case 2: point bar architecture of the Jackpine Mine deposit

The Jackpine Mine is the site of one of the largest sand complexes accumulated in the northern Athabasca Deposit. The 25 km² deposit is 8-10 km long, 3-4 km wide, and 10-40 m thick (Fig. 15A). It has a modified T-shape geometry consisting of a thick SE-NW oriented sand trend attached to a narrower and thinner SE trending deposit (Fig. 15A). The deposit consists of stacked point bars aligned parallel above a structural bench oriented to the northeast in the sub-Cretaceous structure. This bench-like step down structure consists of a northeast oriented chain of horst blocks on the sub-Cretaceous structure that follows a multi-km long linear reef build in the underlying Keg River (Fig. 8B). Cross-sections D-D', E-E' and F-F' illustrate stratigraphic profiles transecting this deposit (Figs. 15-18; traces located on Figs. 4B and 15D). Dip meter readings, lithofacies and sedimentary structures are illustrated by cored intervals on the two E-W and one N-S cross-sections.

Many, if not most, of this and other large sand accumulation sites across the study area commenced aggradations at the basal middle McMurray level over small sags, 10s to 100s of metres across, on the underlying Upper Devonian structure. These vertical sags above Upper Devonian fault blocks were transmitted upwards to the overlying lower McMurray structure prior to and concurrent with onset of middle McMurray deposition as opportunistic depocenters for incipient aggradation. Some sites developed over compacted breccia pipes, resulting in shallow depressions at the deposition surface. At the Jackpine Mine sand deposit, for example, a 20-25 m sag on the Upper Devonian structure (Fig. 15B) was transmitted up-section as a 10-15 m sag at the base of the middle McMurray structure (Fig. 15C). This Devonian-lower McMurray breccia pipe sag was penetrated by the Shell Canada SH04-1574 well located at 1AA/16-23-95-09W4M (Fig. 18, cross-section F-F'). The pipe at the site initiated a shallow depression that focused aggradation and helped to constrain extensive lateral migration beyond the width of the structural bench.

The Jackpine point bar sand complex is interpreted to consist of two stacked point bars (Facies A and B) that were covered over by a thicker upper point bar with very steep dip beds (Facies C) (cross-section E-E', Fig. 17).

There are four overlying lithofacies recognized in most well log profiles and cored intervals that penetrate this Jackpine deposit. The sandy facies were very strongly bitumen saturated.

(Stratal bottom)

Facies A. The fine to medium grained sand, often with bioturbated and mottled fabrics mixed with planar cross-stratified beds. This sand deposit is overlain by muddy heterolithic beds across most areas of the Jackpine complex, but locally the muddy upper interval has been eroded at the disconformable contact with overlying Facies B, especially across structurally high areas (Fig. 17, core 3). Overall, the deposit is more heterolithic compared to overlying bar deposit (Facies B). The 10-30° dips are dominated by unidirectional N-NW azimuths of the accretion surfaces. Scattered mud chips from reworked muddy accretion surfaces are more widespread within this lower of the two basal point bars (Fig. 17, cross-section E-E', cores 3 and 6; Fig. 18, cross-section F-F', core 2). The homogeneous sand beds, and those with faint stratification enhanced trains of scattered very small mud chips, pass latterly into muddy heterolithic beds. The thicker alternating sand and mud beds at the decimetre scale often incorporate ripple cross-stratified sand with mud drapes (Fig. 18, core 7). These pass latterly into parallel stratified beds, 1-2 m thick, consisting of cm-scale fine grain sand beds covered by silt laminae (Fig. 17, core 3). Reactivation surfaces are observed with trains of very small mud clasts (Fig. 18, core 7).

Interpretation: This 5-10 m thick sand deposit with heterolithic intervals is the lower of two basal point bars, but latterly constrained to the width of the step down structure on the northwest margin of the protruding fault blocks. It is characterized by multiple cm to decimetre thick layers of mudstone clasts. The structurally higher areas of the deposit accumulated medium grain beds that were more homogeneous (Fig. 17, core 6) that transition down-structure to the northwest into sands with increasing mud content and steeper dips.

----- *erosion surface* -----

Facies B. The deposit is mostly represented by a medium to coarse grain sand, 5-10 m thick. It is often homogeneous with only faint indications of bedding. Pronounced bed surfaces are characterized by variously dispersed gravel lags accumulated against and draping over structural relief on the Devonian fault blocks (Fig. 16, cross-section D-D', core 8). There is a wide range of NW and SE oriented dips recording trough cross-stratification (5-60°) (Fig. 18, cross-section F-F', core 1). The planar bed sets are usually very faint. Ripple stratification and trough cross-stratification are evident in some cored intervals of the deposit (Fig. 16, core 8).

Interpretation: The deposit represents the upper of two basal point bars that can be traced laterally across the area of the Jackpine deposit. It accumulated above more heterolithic facies of the lower point bar (Facies A).

Facies B/C. Heterolithic beds, 1-2 m thick, consisting of fine to medium grain sand deposits were emplaced between B and C sand facies. The deposit is bounded above by an overlying erosion surface onto which Facies C accumulated. The interval is characterized by muddy, burrowed and bioturbated zones and lenses of medium-coarse sand (Fig. 18, cross-section F-F', core 6). Some of the sand beds have relatively homogeneous textures with only faint indications of bedding surfaces. The ichno-fauna is sparse with low diversity, mostly represented by *Cylindrichnus* and unrecognizable clay-filled burrow fragments. The interval has been largely eroded, but a more complete interval has been preserved in localized areas. An example is the lowermost decimetres of core 6 (Fig. 18), where the muddy to sandy heterolithic facies hosts a more diversified assemblage including *Conichnus*, *Cylindrichnus*, *Skolithos* and *Chondrites*.

Interpretation: The deposit represents heterolithic topset beds of overlying the basal interval consisting of two overlying point bars (Facies B). These topset beds, mostly but not completely eroded, were covered by the unconformable aggradation of the thicker upper point bar (Facies C).

----- *erosion surface* -----

Facies C. This interval, 10-30 m thick, consists mostly of medium grain sand beds accumulated over and on the step down structure fronting the northwest margin of the SW-NE oriented structural high consisting of protruding Upper Devonian fault blocks. The sand beds have faint to distinct planar cross-stratification to the NW and SE that are often steep and often near vertical (5-80° dips), but pass to the northwest into beds with very low dips (5-10°) (Fig. 18, cross-section F-F', cores 4 and 5). The dips are low in beds accumulated above the structural high, but rapidly increase to 40-80° off-structure onto the step down northwest margins of tilted fault blocks (Fig. 16, cross-section D-D', cores 1-2, 4-7; Fig. 18, cross-section F-F', cores 4-6). The cross-stratified beds have dispersed reactivation surfaces onto which cm thick trains of small mud clasts or pebble trains accumulated. These reactivation surfaces are dispersed in the vertical profile at 1-2 m intervals. Evidence of tidal impact on depositional processes consists of preserved mud couplets, such as those observed in core 7, Figure 16. This facies passes laterally to the northwest into muddy heterolithic deposits (Facies D).

Interpretation: This upper point bar, tens of metre thick, consists of moderate to overly steep dipping accretion surfaces of steep dipping I.H.S. The deposit accumulated on the erosion surface that extends across the two overlying thinner point bars in the substrate (Faces A and B). This deposit may also include dune deposits similar to those exposed a few kilometres to the northwest along the northern Athabasca River Valley (Fig. 9), and have similarities to the point bar/dune bed complexes described by Martinius et al. (2015) at exposures along the Christina River to the south. Such dune foresets would partially account for bidirectional dip meter reading to the NW and SE. However, dune depositions can be difficult to confirm with only the use of cored intervals, in contrast to multi-metre wide outcrop exposures. The bench cuts at the Jackpine Mine expose sand intervals that are so strongly bitumen saturated that it has not been possible to readily differentiate larger multi-metre wide depositional structures such as transition dune beds. Nevertheless, some dip meter readings would suggest their deposition.

Facies D. The mud dominated facies is mostly represented in log profiles and cored intervals by alternating heterolithic beds consisting of laminated muds and beds of fine grained sands with sub-horizontal to low bed dips (5-15°) (Fig. 17, cross-section E-E', cores 7 and 8; Fig. 18, cross-section F-F', core 3, 9 and 10). These muddy deposits were overlain by 1-3 m thick upper McMurray beds consisting of medium grain sand with wavy clay drape fabrics, but often eroded (Fig. 18, cross-section F-F', core 3).

Interpretation: The interval consists of laminated mud alternating with and silt and fine sand grain heterolithic deposits similar to tidal mud flat deposits that accumulated off structure to the northwest of the overlying point bars. The interval accumulate laterally to the upper point bar (Facies C) with an abrupt transition boundary and minimal inter-bedding resulting from aggradation of the point bar above the structural step down that constrained lateral migration.

(Stratal top)

Overview. Facies A and B represent two overlying point bars, each 10 m thick, and covered over by the B/C heterolithic facies. This A/B coupled basal bar succession is distinct from the thicker upper point bar (Facies C). The Jackpine deposit represents persistence of the fluvio-tidal depositional environment northward into the estuarine funnel concurrent with extensive regional salt removal in the substrate.

The Jackpine sand complex site was positioned over a bench-like step down on the sub-Cretaceous and lower McMurray structures (Fig. 15, B and C). The area was one of the many stair step downs formed

1011 concurrent with McMurray deposition along the southern rim of the central collapse (Figs. 8B). At the
1012 Jackpine site, this structural step down initiated movement earlier during lower McMurray deposition.
1013 This reconfiguration on the sub-Cretaceous structure resulted in accommodation space for overly
1014 thickened lower McMurray beds (>75 m) accumulated along the northwest front of the collapse-rotated
1015 Upper Devonian fault blocks. The structural reconfiguration resulted from alignment of a horst-like trend
1016 of Upper Devonian blocks over a multi-km long elongated Keg River mound in the substrate following
1017 partial removal of the flanking and draping salt beds. Salt removal continued during middle McMurray
1018 deposition, resulting in collapse-subsidence and rotation of the Upper Devonian fault block substrate and
1019 beds with near vertical dip meter readings. This renewed collapse-rotation-subsidence was mostly
1020 concurrent with deposition of the overly thickened upper point bar. There was sufficient relief on the
1021 deposition surface and resulting accommodation space to have constrained extensive lateral accretion to
1022 the northwest. This, and further block tilting resulted in relatively steep accretion bed dips as the sand
1023 transport to the northwest cascaded over the fault block high and overly thickened above the step down
1024 structure. The point bars banked against and covered remaining protrusions by the Upper Devonian fault
1025 blocks. This resulted in a T-shaped geometric configuration by the deposit. The sand complex passes
1026 northwestward into stratigraphically equivalent muddy heterolithic beds dispersed between this deposit
1027 and the next aggradation site above a step-down terrace further to the northwest. Distinctly muddier
1028 heterolithic deposits were transported further to the northwest down structure and accumulated along the
1029 outer margins of the deposit.

1030
1031 This and other large sand deposits include evidence of tidal mud couplets with the implication that this
1032 and other similar sand deposit sites were to some extent mobilized southward by tidal processes and
1033 enhance southward banking against back walls of the step down structures. Direct evidence for strong
1034 tidal activity, such as widespread mud couplets, are not observed to be associated with the pair of basal
1035 point bars, but the erosion surface on B/C interval suggests a break in this depositional framework. The
1036 overlying upper point bar (Facies C) with steep dipping sandy I.H.S., possibly including dune beds,
1037 indicate a change in the depositional environment that directly impacted configuration and internal
1038 architecture of the sand complex linked to structural instability in the substrate.

1039
1040 Issues remain as to the spatio-temporal continuity of the erosion surface at the base of Facies C in the
1041 Jackpine deposit to one of the intra-point bar erosional surfaces associated with the Aurora North Mine
1042 sand complex to the northwest. Pulses of differential subsidence may have been coordinated as the
1043 regional dissolution front migrated northward of the Bitumount Trough, and resulted in a more
1044 widespread intra-middle McMurray erosion surfaces than previously considered.

7.0 Discussion: transition from upper to lower estuary distribution of point bars

7.1 Lower estuary: point bar aggradation and stair stepping down structures

Middle McMurray deposits responded to a range of substrate instabilities linked to regional structural configuration trends such as: (1) deposition overlying continued dissection of the salt scarp, including the western Bitumount Trough, and (2) pervasive salt removal that embayed the scarp and resulted in the regional down warping that resulted in the central collapse area northward of the Bitumount Trough. These structural domains were at least partially responsible for the geometric configuration of a broad, structurally lower, funnel-like form on the sub-Cretaceous structure. This is interpreted as the lower estuary funnel-like area northward of the upper estuary represented by the main paleovalley.

This structural instability in the substrate across the study area during middle McMurray deposition at least partially impacted the distribution patterns of large point bar sand deposits, modified their geometric configurations and their internal architectures. Sub-parallel fluvio-tidal channels, 10-30 km long, accumulated multi-km long point bars aligned parallel to NW-SE trends in the underlying lower McMurray lattice-like drainage pattern across the Bitumount Trough floor, as described by Broughton (2015). These trends were superimposed on the salt dissolution-impacted reticulate dissection patterns on the post-Upper Devonian karst paleo-topography. Reconfiguration of the sub-Cretaceous structure above multiple staged dissection patterns in the salt platform and remnants of previously eroded areas resulted in a series of differentially subsided fault blocks and step-down bench-like terraces across the study area towards and into the central collapse area northward of the Bitumount Trough.

The most significant structuring during middle McMurray deposition across the study area was concurrent subsidence-collapse of the central depression area that reconfigured the sub-Cretaceous structure as fault block-aligned benches that stair step down northward of the Bitumount Trough. This concurrent with extensive salt scarp dissections that resulted in widespread fault block collapse-rotations throughout the Steepbank Mining district southward of the study area (Broughton, 2015). This regional structuration during middle McMurray deposition is interpreted to have controlled the spatial distribution of major sand transport fairways northward along the underlying NW oriented structural grain, and redirected their pathways as cascades over these underlying structural benches down structure towards

and into the central collapse area. This resulted in collinear alignment of the larger sand complexes, consisting of stacked fluvio-tidal point bars, at aggradation sites located above increased accommodation space created by differentially subsided chains of Devonian/lower McMurray fault blocks in the substrate. Larger point bar sand complexes developed into giant commercially attractive deposits at the more structurally impacted aggradation sites. The instability of the northward stair stepping down structures directly controlled the elongated geometry of the deposits and impacted the intra-point bar architecture.

Reconfigurations of the buried sub-Cretaceous structure during depositions of middle interval beds were concurrent with reorganization of the northward sediment transport system directed along two major fairways that converged at the V-join of the eastern and western Bitumount Trough segments: (1) continued but diminished transport northward along the main paleovalley that overprinted the ancestral, pre-Cretaceous, bedrock river channel previously established as the main conduit for lower McMurray clastic transport northward towards the Boreal Sea; (2) a newly established or increased profile of a middle interval fairway that transported clastics to the NW across the southeastern study area. This “Firebag fairway” transported clastics northward diagonally across the mostly buried eastern Bitumount Trough, but turned more towards the central collapse down structure in the area of Trough V-join at the site of the Jackpine Mine (and the Aurora North site to the northwest), and continued into the central collapse (Fig. 19). This Firebag fairway cascaded over the underlying fault bound structural terraces into the central collapse area, resulting in point bar aggradations banked along the high back walls of these structural step downs. There was much as 30-40 m local relief in the underlying sub-Cretaceous and lower McMurray structures that stabilized the deposit from dispersal further northward by the banking against the high walls of the step downs (Figs. 12 and 20).

Stratigraphic differentiation of middle and upper intervals along these fairways was often obscured by rapid aggradation concurrent with the underlying collapse-subsidence. Broughton (2015) discusses the various log profile and textural variations or sedimentary fabrics used to differentiate middle and upper McMurray intervals, and define the undifferentiated middle-upper succession. It is generally recognized that the middle McMurray interval is a fining-up stratal succession overlain by the upper interval consisting of correlative coarsening upward beds, often several stacked parasequences that locally coalesced into 10-30 m thick coarsening upward sandy geobodies (Broughton 2015). Definitive upper McMurray beds are characterized by a multitude of wave form clay drapes resulting from the influence of increased marine-influenced wavy dominated bay conditions that transgressed southward. Cross-section G-G', Figure 21, illustrates differentiated middle and upper strata, off-channel, that pass laterally into an appreciably thicker in-channel interval of undifferentiated middle-upper strata. The strata penetrated by

the westernmost off-channel well at 1AC/01-07-96-10W4M site are heterolithic with clearly differentiated middle and upper McMurray intervals (Fig. 21). The next well to the east, 1AA/07-08-96-10W4M, is located along the outer margin of a mega-channel fairway. It also penetrated clearly differentiated strata with fining-up beds (middle interval) covered by coarsening-up beds (upper interval). The laterally equivalent middle-upper stratigraphic interval penetrated by two mid-channel wells at 1AC/11-09-96-10W4M and 1AD/06-10-96-10W4M consists of overly thickened, but undifferentiated, sand beds accumulated along sag-aggradation sites on the underlying sub-Cretaceous structure.

7.2 Transition northward into aligned fluvio-tidal point bars of the lower estuary

The impact of the regional structure concurrent with middle McMurray deposition across the lower estuarine funnel, including the study area differs from the morphogenesis of point bars further to the south towards and into the upper estuary. This is partially related to the structural stability of the Devonian substrate underlying the sand transport fairways northward. The classic reference area for large multi-km long point bar deposits accumulated above mostly stable substrate is the subsurface SAGD project at Long Lake (Smith et al. 2009; Hubbard et al. 2011), and fluvial point bars exhumed by mining operations near Steepbank River confluence with the Athabasca River Valley (Labrecque et al. 2011a).

These upper estuary fluvial channels developed over relatively stable Devonian limestone substrate that permitted large scale highly sinuous channels to meander, resulting in fluvial point bar along the multi-km diameter meandering channel loops characterized by broad lateral accretion scrolling point bar I.H.S. deposits accumulated as the channel loops transitioned downstream, subsequently abandoned and mud plugged (Hubbard et al. 2011). An example of this is illustrated by a 3D seismic imaging of a horizontal time slice of the middle McMurray interval across a 12 km wide area near the SAGD project at Long Lake (Fig. 3), located along the main paleovalley trunk to the southward of the study area. The sinuous mud plugged abandoned channels are 400-500 m wide. The exceptionally large scale of these laterally accreting point bars offset to these abandoned mud-plug filled channels suggests a fluvial channel system with multi-km scale sinuous meanders possibly analogous to the modern Mississippi River (see Holbrook 2014). Accordingly, the reaches of this continental scale drainage basin branched far beyond the Alberta Basin (Mossop and Flach 1983; Miall et al. 2008), perhaps as far as Appalachia as suggested by provenance studies on detrital zircon grains (Benyon et al. 2014).

The multi-km long and tens of metre thick point bar deposits accumulated within the upper estuary, tens of kilometres to the south of the study area, were not collinearly aligned. Their distribution was controlled by variously overlapping and complexly cross-cutting sinuous fluvial channels geographically constrained by the structurally low width of the 10-12 km wide floodplain across the main paleovalley fairway. The deposits were impacted by tidal processes, but only to a minor extent, resulting in the apparently erratic dispersal of tide-influenced fabrics such as diurnal mud couplets. Nonetheless, the deposits also have elevated salinity indicators suggested by the ichno-fauna (Ranger and Gingras 2001, 2006, 2010; Hubbard et al. 2011; Musial et al. 2012, 2013; Nardin et al. 2010, 2013, Jablonski and Dalrymple 2015).

The upper estuary channel deposit architecture, characterized by these multi-km wide looped meander channels meandering across the stable substrate transitioned down structure northward into multiple linear trends. They trended along structural grain oriented to the northwest within the relatively unstable substrate flooring the widened estuary funnel. As a result, transport by the main fairway directed along the paleovalley trunk transitioned northward by branching outward across the widened structural funnel into numerous sub-parallel aligned curvilinear fairways. These accumulated multi-km scale fluvio-tidal point bar complexes that were collinearly aligned along these sub-parallel fairways that flowed N-NW towards the encroaching Boreal Sea. These 10s of km long fairways coursed over stair-stepping down structures that became favored aggradation sites that directly impacted the external geometry and the internal architecture of the fluvio-tidal point bars. The transition from the upper estuary regime northward into the lower estuary funnel probably occurred near the exposures along the Steepbank River, an area coinciding with the neck of the southern funnel, although such a transition may have been very gradual across a larger area.

The large sand complexes of this lower estuary have internal architectures characterized by sand complex-wide erosion surfaces that bound each of the stacked point bars and terminate intra-bar channels as responses to intermittent movements by the unstable substrate. This intra-bar architecture is not characteristic of giant upper estuary point bars accumulated over stable surfaces to the south of the funnel. Both types of deposits, nevertheless, have smaller scale erosion/reactivation surfaces induced by shifting channel orientations by down channel lateral accretion.

8.0 Conclusions

Towards a unified McMurray tectono-stratigraphic architecture

The unusually low 1:2 thickness ratio of removed halite salt beds to overlying strata resulted in sharply defined dissolution-collapse controls that regionally responded to removal of 100 m or more thick salt beds across areas covered by only 200-250 m of overlying strata. The resulting structural patterns created by migration of the salt dissolution fronts exerted a significant control on the distribution and alignment of McMurray point bars oriented and elongated to the northwest and to the northeast. The regional salt dissolution collapse-induced syndepositional architecture across the northern Athabasca Deposit links the morphogenesis of lower and middle-upper interval McMurray point bar deposits into a unified tectono-stratigraphic framework. The spatiotemporal links to salt dissolution patterns in the Middle Devonian substrate are interpreted as depositional alignments paralleling instability trends in the substrate across the northern Athabasca area. The distribution of the larger multi-km long sand deposits often paralleled the structural grain in the pre-Cretaceous substrate oriented to the NW and secondarily to the NE that exerted a variable but often pronounced structural impact on depositional trends within the three McMurray intervals.

During the lower McMurray interval, coalesced fluvial sand bar aggradations along cross-cutting linear channel segments aligned as 2-5 km long linear point bars oriented NW-SE and NE-SW. This lattice-like pattern of the braided river channel network was configured by the mosaic pattern of differentially subsided fault blocks that induced a reticulated karst paleo-topography on the dissected Upper Devonian depositional surface. Depositions along the lattice-like braided channel network stabilized vertical aggradation of the lower McMurray point bars and constrained lateral accretions. Accumulations of heterolithic deposits were distributed mostly as over bank deposits along the outer channel margins. The largest lower McMurray sand complex developed as a 25 km long and 30-70 m thick syndepositional trend along the northern margin of the western Trough. It was a response to concurrent collapse of a 25 km long linear chain of Upper Devonian fault blocks, designated as the Deep Trough. This regional structuration on the lower McMurray paleo-topography was linked to the underlying salt removal patterns, and possibly related to deeper patterns resulting from displaced Precambrian blocks as the craton deformed below the WCSB, although unambiguous direct evidence for this tectonic relationship is lacking. The impact of this structural framework is interpreted to have continued upwards into middle and upper McMurray deposition patterns as the dissolution fronts advanced and expanded along the cross-cutting fracture/fault-lineament patterns in the underlying salt beds.

By middle McMurray deposition, reconfiguration northward of the sub-Cretaceous structure enhanced the transition from a relatively narrow fluvial dominated river trunk channel fairway constrained along the main paleovalley to rapidly expand northward by branching into multiple sub-parallel channels aligned

parallel to the NW-oriented structural grain in the Devonian substrate and parallel tectono-stratigraphic trends in the lower McMurray interval. The subsidence-collapse of the sub-Cretaceous structure underlying the northern Athabasca Deposit resulted in broadly widening the lower deltaic plain. The estuary funnel extended across and beyond the accommodation space on the sub-Cretaceous structure created by the combined Bitumount Trough and central collapse structures as the underlying salt scarp trend migrated further to the northwest.

Middle McMurray fluvial point bars, 10-50 m thick, dominate the stratigraphic architecture of the upper estuary deposits, south of the study area, where the highly sinuous river channels with several km wide looped meanders were distributed across the main paleovalley floodplain. Northward, this highly sinuous intertwining channel system dissipated into multiple parallel tidal channels positioned across the widened estuarine funnel. These 10-30 km long tidal channels oriented sub-parallel to the NW-SE orientations of sand bar trends in the lower McMurray, which overprinted structural lineaments in the Devonian substrate. Subsidence by the Devonian-lower McMurray substrate resumed as the salt dissolution front below the northern Bitumount Trough migrated northward and impacted the orientation and distribution of parallel fluvio-tidal fairways during middle-upper McMurray depositions. Middle McMurray tidal channel-like sand transport fairways distributed across this lower estuary funnel are interpreted to have followed the NW-SE oriented structural grain established earlier by underlying chains of Upper Devonian fault blocks that differentially subsided along multi-km long linear trends. The removal of salt beds underlying the central collapse area during the middle-upper intervals resulted in sand transport fairways that coursed northward over these step down structures, where aggradations were favored and resulted in overlying fluvio-tidal point bars. This tectono-stratigraphic pattern resulted in collinearly aligned giant sand complexes that are commercially attractive.

The sedimentological architecture of these middle McMurray sand complexes consisting of overlying fluvio-tidal point bars was at least partially impacted by shifts in accommodation space availability in balance with sand supply. Erosion surfaces between successive point bar aggradations within the giant sand complex resulted when the episodic substrate subsidence large ceased and was out of balance with sediment supply. These tectonic controlled fluvio-tidal processes across the lower estuary of the northern Athabasca Deposit markedly contrast with the fluvial dominated point bars distributed to southward of the study area.

9.0 Acknowledgements

This research into the tectono-stratigraphy of the northern Athabasca Oil Sands Deposit was sponsored by Chevron Canada Resources, Calgary for evaluation of the spatiotemporal changes in the bitumen sand complexes. The Bitumount Trough study area includes the Aurora North-Muskeg River Mines and the Jackpine Mine. The overall project was sponsored by the joint venture of Shell Canada (operator), Chevron Canada and Marathon Canada. The author appreciates access granted by these companies to the thousands of well logs, digital core images and bitumen analyses made available for this study, and permissions to publish the research. The seismic time slice at the Long Lake SAGD project (Fig. 3A) was adapted with permission from Hubbard et al. (2011) and Labrecque et al. (2011b). Images from the Aurora North and Muskeg River Mines cut faces were kindly provided by Dr. M. Ranger. Images of dune beds exposed in middle McMurray outcrops were kindly supplied by M. Ranger and M. Gingras (Fig. 11). The author acknowledges and appreciates critical review of the manuscript by A. W. Martinus, Statoil, Trondheim, and by anonymous reviews, whose commentaries considerably improved the organization and clarity of the manuscript.

References

- Adams, J., Larter, S., Bennett, B., Huang, H., Westrich, J., and Van Kruisdijk, C. 2013. Dynamic interplay of oil mining, charge timing, and biodegradation in forming the Alberta oil sands: insights from geologic modeling and biogeochemistry. *In Heavy-Oil and Oil-Sand Petroleum Systems in Alberta and Beyond. Edited by F. Hein, D. Leckie, S. Larter, and J. Suter. American Association of Petroleum Geologists, Studies in Geology 64, pp. 23-102.*
- Amfort, S., Bachu, S., and Bentley, L. 2001. Regional-scale hydrogeology of the Upper Devonian sedimentary succession, south-central Alberta Basin, Canada. *American Association of Petroleum Geologists Bulletin*, **85**: 637-660.
- Anderson, N., and Hinds, R. 1997. Glacial loading and unloading: A possible cause of rock salt dissolution in the Western Canada Basin. *Carbonates and Evaporites*, **12**: 43-52.
- Anderson, N., and Knapp, R. 1993. An overview of some of the large scale mechanisms of salt dissolution in western Canada. *Geophysics*, **58**: 1375-1387.

- 1278 Bachu, S., and Underschultz, J. 1993. Hydrogeology of formation waters, northeastern Alberta. American
1279 Association of Petroleum Geologists Bulletin, **77**: 1745-1768.
1280
- 1281 Bachu, S. 1995. Synthesis and model of formation-water flow, Alberta Basin, Canada. American Association
1282 of Petroleum Geologists Bulletin, **79**: 1159-1178.
1283
- 1284 Bachu, S. 1999. Flow systems in the Alberta Basin: Patterns, types and driving mechanisms. Bulletin of
1285 Canadian Petroleum Geology, **47**: 455-474.
1286
- 1287 Barton, M., Porter, I., and Mahood, R. 2014. Impact of the Prairie Evaporite dissolution collapse on
1288 McMurray stratigraphy and deposition patterns, Shell Albian Sands Lease 13, northeast Alberta
1289 (abstract). Canadian Society of Petroleum Geologists, 2014 GeoConvention, Calgary.
1290
- 1291 Benyon, C., Leier, A., Leckie, D., Webb, A., Hubbard, S., and Gehrels, G. 2014. Province of the
1292 Cretaceous Athabasca Oil Sands, Canada: Implications for continental-scale sediment transport. Journal
1293 of Sedimentary Research, **84**: 136-143.
1294
- 1295 Berbesi, L., Di Primio, R., Anka, Z., Horsfield, B., and Higley, D. 2012. Source rock contributions to the
1296 Lower Cretaceous heavy oil accumulations in Alberta: A basin modelling study. American Association of
1297 Petroleum Geologists Bulletin, **96**: 1211-1234.
1298
- 1299 Blum, M., and Pecha, M. 2014 Mid-Cretaceous to Paleocene North American drainage reorganization
1300 from detrital zircons. Geology, **42**: 607-610.
1301
- 1302 Boyd, R., Shultz, A., Durkin, P., Suter, J., Carmichael, P., Schroeder, R., Barbosa-Ortiz, W., Sanchez-Phelps,
1303 C. and Cardozo, L. 2014. Tidal-fluvial sedimentology and stratigraphy of the McMurray Formation in the
1304 Surmont area of the Athabasca Oil Sands (abstract). Oil Sands & Heavy Oil Symposium: A Local to Global
1305 Multidisciplinary Collaboration. AAPG and CSPG, October 14-16, 2014, Calgary.
1306
- 1307 Bover-Arnal, T., Salas, R., Guimerà, J., and Moreno-Bedmar, J. 2014. Deep incision in an Aptian
1308 carbonate succession indicates major sea-level fall in the Cretaceous. Sedimentology, **61**: 1558-1593.
1309
- 1310 Broughton, P. L. 1977. Origin of coal basins by salt solution. Nature, **270**: 420-423.
1311

- 1312 Broughton, P. L. 2013a. Devonian salt dissolution-collapse breccias flooring the Cretaceous Athabasca oil
1313 sands deposit and development of lower McMurray Formation sinkholes, northern Alberta Basin,
1314 Western Canada. *Sedimentary Geology*, **283**: 57-82.
1315
- 1316 Broughton, P. L. 2013b. Depositional setting and oil sands reservoir characterization of giant longitudinal
1317 sandbars at Ells River: marginal marine facies of the McMurray Formation, northern Alberta Basin,
1318 Canada. *In Heavy-Oil and Oil-Sand Petroleum Systems in Alberta and Beyond. Edited by F. Hein, D.*
1319 *Leckie, S. Larter and J. Suter. American Association of Petroleum Geologists, Studies in Geology 64, pp.*
1320 *313-357.*
1321
- 1322 Broughton, P. L. 2015. Syndepositional architecture of the northern Athabasca Oil Sands Deposit,
1323 northeastern Alberta. *Canadian Journal of Earth Sciences*, **52**: 21-50. DOI: 10.1139/cjes-2014-0021.
1324
- 1325 Cant, D. 1988. Regional structure and development of the Peace River Arch, Alberta: A Paleozoic failed-
1326 rift system? *Bulletin of Canadian Petroleum Geology*, **36**: 284-295.
1327
- 1328 Connolly, C., Walter, L., Baadsgaard, H., and Longstaffe, F. 1990. Origin and evolution of formation waters,
1329 Alberta Basin, Western Canada Sedimentary Basin: II, Isotope systematic and water mixing. *Applied*
1330 *Geochemistry*, **5**: 397-413.
1331
- 1332 De Mille, G., Shouldice, J., and Nelson, H. 1964. Collapse structures related to evaporites of the Prairie
1333 Formation, Saskatchewan. *Bulletin of Geological Society of America*, **75**: 307-316.
1334
- 1335 Dufresne, M., Henderson, B., Fenton, M., Pawlowicz, J., and Richardson, R. 1994. The mineral deposits
1336 potential of the Marguerite River and Fort McKay areas, northeast Alberta (NTS 74). Alberta Research
1337 Council, Alberta Geological Survey, Open File Report 1994-09, 128 p.
1338
- 1339 Durkin, P.R., Hubbard, S., Boyd, R., and Leckie, D. 2015. Stratigraphic expression of intra-point bar
1340 erosion rotation. *Journal of Sedimentary Research*, **85**: 1238-1257.
1341
- 1342 Flach, P., and Mossop, G. 1985. Depositional environments of Lower Cretaceous McMurray Formation,
1343 Athabasca oil sands, Alberta. *American Association of Petroleum Geologists Bulletin*, **69**: 1195-1207.
1344
- 1345 Ford, D. 1997. Principal features of evaporite karst in Canada. *Carbonates and Evaporites*, **12**: 15-23.

- 1346
1347 Friedman, G., and Chakraborty, C. 2006. Interpretation of tidal bundles: two reasons for a paradigm shift.
1348 Carbonates and Evaporites, **21**: 170-175.
1349
- 1350 Fustic, M. 2007. Stratigraphic dip analysis – a novel application for detailed geological modeling of point
1351 bars, and predicting bitumen grade, McMurray Formation, Muskeg River Mine, northeast Alberta.
1352 National Resources Research, **16**: 31-43.
1353
- 1354 Fustic, M., Hubbard, S., Spencer, R., Smith, D., Leckie, D., and Bennett, B. 2012. Recognition of down-
1355 valley translation in tidally influenced meandering fluvial deposits, Athabasca Oil Sands (Cretaceous),
1356 Alberta, Canada. Marine and Petroleum Geology, **29**: 219-232.
1357
- 1358 Garven G, and Freeze R. A. 1984. Theoretical analysis of the role of groundwater flow in the genesis of
1359 stratabound ore deposits, 2, Quantitative results. American Journal of Science, **284**: 1125-1174.
1360
- 1361 Garven, G. 1985. The role of regional fluid flow in the genesis of the Pine Point Deposit, Western Canada
1362 Sedimentary Basin. Economic Geology, **80**: 307-324.
1363
- 1364 Garven, G. 1989. A hydrogeological model for the formation of the giant oil sands deposits of the
1365 Western Canada sedimentary basin. American Journal of Science, **289**: 105-166.
1366
- 1367 Gibson, J., Fennell, J., Birks, S., Yi, Y., Moncur, M., Hansen, B., and Jasechko, S. 2013. Evidence of
1368 discharging saline formation water to the Athabasca River in the oil sands mining region, northern Alberta.
1369 Canadian Journal of Earth Sciences, **50**: 1244-1257.
1370
- 1371 Grasby, S., and Chen, Z. 2005. Subglacial recharge in the Western Canada Sedimentary Basin - impact of
1372 Pleistocene glaciations on basin hydrodynamics. Geological Society of America Bulletin, **117**: 500-514.
1373
- 1374 Grobe, M. 2000. Distribution and thickness of salt within the Devonian Elk Point Group, Western Canada
1375 Sedimentary Basin. Alberta Energy and Utilities Board, Alberta Geological Survey, Earth Sciences
1376 Report 2000-02, 12 p.
1377
- 1378 Gue, A., Mayer, B., and Grasby, S. 2015. Origin and geochemistry of saline spring waters in the
1379 Athabasca oil sands region, Alberta, Canada. Applied Geochemistry, **61**: 132-145.

- 1380
1381 Hein, F., Cotterill, D., and Berhane, H. 2000. Atlas of lithofacies of the McMurray Formation, Athabasca
1382 oil sands deposit, northeastern Alberta: surface and subsurface. Alberta Geological Survey, Earth Science
1383 Report 200-07, 217 p.
1384
- 1385 Hein, F., Langenberg, C., Kidston, C., Berhane, H., and Berezniuk, T. 2001. A comprehensive field guide
1386 for facies characterization of the Athabasca oil sands, northeast Alberta. Alberta Energy Utilities Board,
1387 Special Report 13, 415 p.
1388
- 1389 Hein, F., and Langenberg, C. 2003. Reply to discussion of seismic modeling of fluvial-estuarine deposits
1390 in the Athabasca oil sands, Steepbank River area, northeast Alberta. Bulletin of Canadian Petroleum
1391 Geology, **51**: 354-366.
1392
- 1393 Hein, F., and Cotterill, D. 2006. The Athabasca oil sands - A regional geological perspective, Fort
1394 McMurray area, Alberta, Canada. National Resources Research Council, **15**: 85-102.
1395
- 1396 Hein, F., and Cotterill, D. 2007. Field guide: Regional sedimentology and processes of deposition of the
1397 Athabasca oil sands, northeast Alberta. Alberta Energy and Utilities Board/Alberta Geological Survey,
1398 EUB/AGS Geo-Note 2006-04 CD, 157 p.
1399
- 1400 Hein, F., and Marsh, R. 2008. Regional geologic framework, depositional models and resource estimates
1401 of the oil sands of Alberta, Canada. 2008 World Heavy Oil Congress, Edmonton, Alberta, Proceedings
1402 Paper 2008-320, 9 p.
1403
- 1404 Hein, F., Dolby, G., and Fairgrieve, B. 2013. A regional geologic framework for the Athabasca oil sands,
1405 northeastern Alberta, Canada. *In* Heavy-Oil and Oil-Sand Petroleum Systems in Alberta and Beyond.
1406 *Edited by* F. Hein, D. Leckie, S. Larter, and J. Suter. American Association of Petroleum Geologists,
1407 Studies in Geology 64, pp. 207-250.
1408
- 1409 Hein, F. 2015. The Cretaceous McMurray oil sands, Alberta, Canada: A world-class, tidally influenced
1410 fluvial-estuarine system – An Alberta government perspective. Developments in Sedimentology, Elsevier,
1411 **68**: 561-621.
1412

- 1413 Holbrook, J. 2014. Connectivity within and between channel-belt reservoirs: A Mississippi River analog
1414 for the McMurray Oil Sands. Abstracts, Oil Sands and Heavy Oil Symposium: A Local to Global
1415 Multidisciplinary Collaboration, 2014, Calgary, Canadian Society of Petroleum Geologists and American
1416 Association of Petroleum Geologists.
1417
- 1418 Holter, M. 1969. Middle Devonian Prairie Evaporite of Saskatchewan. Saskatchewan Department of
1419 Mineral Resources, Report 123, 134 p.
1420
- 1421 Hubbard, S., Smith, D., Nielsen, H., Leckie, D., Fustic, M., Spencer, R., and Bloom, L. 2011. Seismic
1422 geomorphology and sedimentology of a tidally influenced river deposit, Lower Cretaceous Athabasca oil
1423 sands, Alberta, Canada. American Association of Petroleum Geologists Bulletin, **95**: 1123-1145.
1424
- 1425 Irvine, J., Whitaker, S., and Broughton, P.L. 1978. Coal resources of southern Saskatchewan: A model for
1426 evaluation methodology. Geological Survey of Canada, Economic Geology Report 30; Saskatchewan
1427 Department of Mineral Resources, Report 209; Saskatchewan Research Council Report 20, v. 1, 150 p.
1428 and 78 p. microfiche; v. 2 Atlas, 56 plates.
1429
- 1430 Jablonski, B., and Dalrymple, R. 2015. Recognition of strong seasonality and climatic cyclicity in an
1431 ancient, fluvially dominated, tidally influenced point bar: Middle McMurray Formation, Lower Steepbank
1432 River, north-eastern Alberta, Canada. Sedimentology, 34 p. doi: 10.1111/sed.12228
1433
- 1434 Keith, D., MacGillivray, J., Wightman, D., Bell, D., Bereznik, T., and Berhane, H. 1990. Resource
1435 characterization of the McMurray/Wabiskaw deposit in the Athabasca central region of northeastern
1436 Alberta. AOSTRA Technical Publication, Series 7, 63 p.
1437
- 1438 Labrecque, P., Hubbard, S., Jensen, J., and Nielsen, H. 2011a. Sedimentology and stratigraphic
1439 architecture of a point bar deposit, Lower Cretaceous McMurray Formation, Canada. Bulletin of
1440 Canadian Petroleum Geology, **59**: 147-171.
1441
- 1442 Labrecque, P., Jensen, J., and Hubbard, S. 2011b. Cyclicity in Lower Cretaceous point bar deposits with
1443 implications for reservoir characterization, Athabasca Oil Sands, Alberta, Canada. Sedimentary Geology,
1444 **242**: 18-33.
1445

- 1446 Langenberg, C., Hein, F., Lawton, D., and Cunningham, J. 2002. Seismic modeling of fluvial-estuarine
1447 deposits in the Athabasca oil sands using ray-tracing techniques, Steepbank River area, northeastern
1448 Alberta. *Bulletin of Canadian Petroleum Geology*, **50**: 178-204.
- 1449
- 1450 Larter, S., Adams, J., Gates, I., Bennett, B., and Huang, H. 2008. The origin, prediction and impact of oil
1451 viscosity heterogeneity on the production characteristics of tar sand and heavy oil reservoirs. *Journal of*
1452 *Canadian Petroleum Technology*, **47**: 52-61.
- 1453
- 1454 Leach, D. L., Bradley, D., Lewchuk, M. T., Symons, D. T. A., de Marsily, G., and Brannon, J. 2001.
1455 Mississippi Valley-type lead-zinc deposits through geological time: implications from recent age dating.
1456 *Mineralium Deposita*, **36**: 711-740.
- 1457
- 1458 Leckie, D. 1986. Rates, controls and sand-body geometries of transgressive-regressive cycles: Cretaceous
1459 Moosebar and Gates Formations, British Columbia. *American Association of Petroleum Geologists*
1460 *Bulletin*, **70**: 516-535.
- 1461
- 1462 Leckie, D., and Smith, D. 1992. Regional setting, evolution, and depositional cycles of the Western
1463 Canada Foreland Basin. *In* *Foreland Basins and Fold Belts. Edited by R. Macqueen and D. Leckie.*
1464 *American Association of Petroleum Geologists, Memoir 55*, pp. 9-46.
- 1465
- 1466 LeFever, J. A., and LeFever, R. D. 2005. Salts in the Williston Basin, North Dakota. *North Dakota*
1467 *Geological Survey, Report of Investigations 103*, 41 p.
- 1468
- 1469 McTavish, G., and Vigrass, L. 1987. Salt dissolution and tectonics, south-central Saskatchewan.
1470 *Saskatchewan Geological Society, Williston Basin Symposia Proceedings*, pp. 157-168.
- 1471
- 1472 Mahood, R., Verhoef, M. and Stoakes, F. 2012. Paleozoic stratigraphic framework beneath the Muskeg
1473 River Mine (Twp 95, Rge 9-10): Controls and constraints on present day hydrogeology (abstract).
1474 *Canadian Society of Petroleum Geologists, 2012 GeoConvention, Calgary.*
- 1475
- 1476 Martinius, A. W., and van den Berg, J. H. 2011. Atlas of sedimentary structures in estuarine and tidally-
1477 influenced river deposits of the Holocene Rhine-Meuse-Scheldt system: Their application to the
1478 interpretation of analogous outcrop and subsurface depositional systems. Eagle Publications, Houlten,
1479 The Netherlands. ISBN: 978-90-73834-11-8.

- 1480
- 1481 Martinius, A. W., Jablonski, B.V. W., Fustic, M., Strobl, R., and Van den Berg, J. H. 2015. Fluvial to
1482 tidal transition zone facies in the McMurray Formation (Christina River, Alberta, Canada), with emphasis
1483 on the reflection of flow intensity in bottomset architecture. *In* *Developments in Sedimentology* 68, pp.
1484 445-480.
- 1485
- 1486 Maurer, F., van Buchem, F., Eberli, G., Pierson, B., Raven, M., Larsen, P., Al-Husseini, M., and Vincent,
1487 B. 2013. Late Aptian long-lived glacio-eustatic lowstand recorded on the Arabian Plate. *Terra Nova*, **25**:
1488 87-94.
- 1489
- 1490 Meijer Drees, N. 1994. Devonian Elk Point Group of the Western Canada Sedimentary Basin. *In*
1491 *Geological Atlas of the Western Canada Sedimentary Basin. Edited by G. Mossop and I. Shetsen.*
1492 *Canadian Society of Petroleum Geologists, Alberta Research Council*, pp. 129-147.
- 1493
- 1494 Miall, A., Catuneanu, O., and Vakarelow, B., Post, R. 2008. The Western Interior Basin. *In* *The*
1495 *Sedimentary Basins of the United States and Canada. Edited by A. Miall. The Sedimentary Basins of the*
1496 *World, Elsevier, Amsterdam*, 5, pp. 329-362.
- 1497
- 1498 Michael, K., Machel, H., and Bachu, S. 2003. New insights into the origin and migration of brines in deep
1499 Devonian aquifers, Alberta, Canada. *Journal of Geochemical Exploration*, **80**: 193-219.
- 1500
- 1501 Mossop, G., and Flach, P. 1983. Deep channel sedimentation in the Lower Cretaceous McMurray
1502 Formation, Athabasca Oil Sands, Alberta. *Sedimentology*, **30**: 493-509.
- 1503
- 1504 Musial, G., Reynaud, J-Y., Gingras, M., Fenies, H., Labourdette, R., and Parize, O. 2012. Subsurface and
1505 outcrop characterization of large tidally influenced point bars of the Cretaceous McMurray Formation
1506 (Alberta, Canada). *Sedimentary Geology*, **279**: 156-172.
- 1507
- 1508 Musial, G., Labourdette, R., Franco, J., and Reynaud, J. 2013. Modeling of a tide-influenced point-bar
1509 heterogeneity distribution and impacts on steam assisted gravity drainage production: example from
1510 Steepbank River, McMurray Formation, Canada. *In* *Heavy-Oil and Oil-Sand Petroleum Systems in*
1511 *Alberta and Beyond. Edited by F. Hein, D. Leckie, S. Larter, and J. Suter. American Association of*
1512 *Petroleum Geologists, Studies in Geology* 64, pp. 545-564.
- 1513

- 1514 Nardin, T., Carter, B., and Bassey, N. 2010. Braided river and avulsive depositional systems in the
1515 McMurray Formation–LIDAR and subsurface data integration at Syncrude’s Aurora North Mine
1516 (abstract). American Association of Petroleum Geologists, Conference, Calgary, Alberta, AAPG Search
1517 and Discovery Article 30143.
- 1518
- 1519 Nardin, T., Feldman, H., and Carter, B. 2013. Stratigraphic architecture of a large-scale point-bar
1520 complex in the McMurray Formation: Syncrude’s Mildred lake Mine, Alberta, Canada. *In* Heavy-Oil and
1521 Oil-Sand Petroleum Systems in Alberta and Beyond. *Edited by* F. Hein, D. Leckie, S. Larter and J. Suter.
1522 American Association of Petroleum Geologists, Studies in Geology 64, pp. 273-312.
- 1523
- 1524 Nikols, D. J. 1996. Assessment report: Fort MacKay property, 1996. Alberta Geological Survey, Mineral
1525 Assessment Report 19960008, 34 p.
- 1526
- 1527 Nio, S. D., and Yang, C. 1991. Diagnostic attributes of tidal deposits: a review. *In* Clastic Tidal
1528 Sedimentology. *Edited by* D. G. Smith. Canadian Society for Petroleum Geologists, Memoir 16, pp. 3–27.
- 1529
- 1530 Pana, D., Waters, J., and Grobe, M. 2001. GIS compilation of structural elements in northern Alberta.
1531 Alberta Energy and Utilities Board and Alberta Geological Survey, Earth Sciences Report 2001-01, 60 p.
- 1532
- 1533 Pana, D. 2002. Structural control of lead-zinc mineralization in carbonate sequences of northern Alberta:
1534 a contribution to the carbonate-hosted Pb-Zn (MVT) targeted geoscience initiative. Alberta Geological
1535 Survey, Geo-Note 2002-15, 32 p.
- 1536
- 1537 Parker, J. M. 1967. Salt solution and subsidence structures, Wyoming, North Dakota and Montana.
1538 American Association of Petroleum Geologists Bulletin, **51**: 1929-1947.
- 1539
- 1540 Ranger, M., and Gingras, M. 2001. Geology of the Athabasca oil sands: Field guide and overview.
1541 Canadian Society of Petroleum Geology, 2001 GeoConvention, Calgary, 132 p.
- 1542
- 1543 Ranger, M., and Gingras, M. 2003. Discussion of Langenberg, C.W., Hein, F.J., Lawton, D.W., and
1544 Cunningham, J., 2002, Seismic modeling of fluvial-estuarine deposits in the Athabasca oil sands using
1545 ray-tracing techniques, Steepbank River area, northeastern Alberta. Bulletin of Canadian Petroleum
1546 Geology, **51**: 347-353.
- 1547

- 1548 Ranger, M., and Gingras, M. 2006. Geology of the Athabasca oil sands: Field guide and overview.
1549 Canadian Society of Petroleum Geology, 2006 GeoConvention, Calgary, 120 p.
1550
- 1551 Ranger, M., and Gingras, M. 2010. Geology of the Athabasca oil sands: Field guide and overview.
1552 Canadian Society of Petroleum Geology, 2010 GeoConvention, Calgary, 125 p.
1553
- 1554 Ranger, M. 2010. Working hypotheses for McMurray Formation stratigraphy: Focusing the search for
1555 modern analogues (abstract). Canadian Society of Petroleum Geologists, 2010 GeoConvention, Calgary.
1556
- 1557 Schneider, C. 2011. Effects of Prairie Formation salt dissolution on the overlying Waterways Formation
1558 in northeastern Alberta (abstract). Canadian Society of Petroleum Geology, 2011 GeoConvention,
1559 Calgary.
1560
- 1561 Schneider, C., Mei, S., and Huag, K. 2012. Beneath the oil sands: Stratigraphy and structural features of
1562 the Devonian of northeast Alberta (abstract). Canadian Society of Petroleum Geology, 2012
1563 GeoConvention, Calgary.
1564
- 1565 Schneider, C., and Grobe, M. 2013. Regional cross-sections of Devonian stratigraphy in northeastern
1566 Alberta (NTS 74D, E). Alberta Geological Survey, Open File Report 2013-05, 25p.
1567
- 1568 Schneider, C., Mei, S., Haug, K., and Grobe, M. 2014. The sub-Cretaceous unconformity and the
1569 Devonian subcrop in the Athabasca Oil Sands area, Townships 87-99, Ranges 1-13, West of Fourth
1570 Meridian. Alberta Energy Resources, Alberta Geological Survey, Open File Report 2014-07, 32 p.
1571
- 1572 Smith, D., Hubbard, S., Leckie, D., and Fustic, M. 2009. Counter point bar deposits: Lithofacies and
1573 reservoir significance in the meandering modern Peace River and ancient McMurray Formation, Alberta,
1574 Canada. *Sedimentology*. **56**: 1655-1669.
1575
- 1576 Stoakes, F., Verhoef, M., and Mahood, R. 2014a. Multiphase solution removal of the Prairie Evaporite
1577 Formation in northeast Alberta (implications for the oil sands mining community) (abstract). Canadian
1578 Society of Petroleum Geologists, 2014 GeoConvention, Calgary.
1579

- 1580 Stoakes, F., Verhoef, M., and Mahood, R. 2014b. Evolution of a regional interconnected diagenetic
1581 aquifer in the lower Prairie Evaporite of northeast Alberta (abstract). Canadian Society of Petroleum
1582 Geologists, 2014 GeoConvention, Calgary.
1583
- 1584 Strobl, R., Fustic, M., and Jablonski, B. 2013. Elongate tidal bar, amalgamated sub-tidal channel and
1585 estuarine point-bar successions of a sand-dominated open estuarine system; integration of outcrop and
1586 subsurface data, McMurray Formation, Ft. McKay, Alberta (abstract). Canadian Society of Petroleum
1587 geologists, 2013 GeoConvention, Calgary.
1588
- 1589 Visser, M. J. 1980. Neap–spring cycles reflected in Holocene subtidal large-scale bedform deposits: a
1590 preliminary note. *Geology*, **8**: 543–546.
1591
- 1592 Wightman, D., and Pemberton, S. 1993. The McMurray Formation: An overview of the surface mineable
1593 area. Oil Sands Our Petroleum Future Conference, Edmonton, Alberta Oil Sands Technology and
1594 Research Authority, pp. 3-32.
1595
- 1596 Wightman, D., Attalla, M., Wynne, D., Strobl, R., Berhane, H., Cotterill, D., and Bereznuik, T. 1995.
1597 Resource characterization of the McMurray/Wabiskaw deposit in the Athabasca oil sands area: A
1598 synthesis. Alberta Department of Energy, Alberta Oil Sands Technology and Research Authority,
1599 Technical Publication, Series 10, 220 p.
1600
- 1601 Wightman, D., and Pemberton, S. 1997. The Lower Cretaceous (Aptian) McMurray Formation: An
1602 overview of the Fort McMurray area, northeastern Alberta. *In* *Petroleum Geology of the Cretaceous*
1603 *Mannville Group, Western Canada. Edited by S. Pemberton and D. James. Canadian Society of Petroleum*
1604 *Geologists, Memoir 18, pp. 312-344.*
1605
- 1606 Williams, G. 1984. Some musings on the Devonian Elk Point basin, Western Canada. *Bulletin of*
1607 *Canadian Petroleum Geology*, **32**: 216-232.
1608
- 1609 Wozniwicz, J., Stoakes, F., Davies, M., Verhoef, M., and Mahood, R. 2014. Update on Devonian
1610 hydrostratigraphy in the Athabasca mineable oil sands area, NE Alberta (abstract). Canadian Society of
1611 Petroleum Geologists, 2014 GeoConvention, Calgary.
1612
1613

Figures

Fig. 1. Location of oil sand deposits in northern Alberta and the study area across the northern Athabasca Deposit.

Fig. 2. Geologic overview of the Athabasca Oil Sands Deposit: (A) stratigraphic thickness of the McMurray Formation (Aptian) and overlying Wabiskaw Member of the Clearwater Formation (Albian) with 10 m contour intervals. Green overlay illustrates bitumen distribution (>10 m). The salt scarp (pink) separates undisturbed salt beds in the underlying Prairie Evaporite (Middle Devonian) to the west from salt removal areas to the east. The main paleovalley on the sub-Cretaceous structure parallels the underlying salt scarp, which demarcates the westernmost migration limit for the salt dissolution front; (B) the 50 km long V-shaped Bitumount Trough across the southern study area is the largest salt dissolution-collapse feature on sub-Cretaceous structure. Northwestern advances by the dissolution front and realignment of the salt scarp across the study area resulted in a down structure estuary funnel, permitting southward encroachment by the Boreal Sea. The resulting tidal processes impacted the distribution, geometric configuration and intra-bar architecture of the middle McMurray fluvio-tidal point bars across the study area and beyond. Trace of cross-section A-A' is illustrated (Fig. 5B). Modified from Broughton (2013a, 2015).

Two southeast oriented bitumen mining districts aligned along McMurray fills of multi-km long troughs on the sub-Cretaceous structure. The Steepbank River mining district, 5-10 km south of the study area, includes: Suncor Millennium (1), Steepbank (2), Base (3) and North (4) Mines. The mines within the study area are aligned along the fills of the Bitumount Trough. These mines are: Imperial Oil Kearl Lake (5), Shell Canada Jackpine (6) and Muskeg River (7), Syncrude Aurora North (8) and Canadian Natural Resources Horizon (9).

Fig. 3. Representative channel architecture for the upper estuary is illustrated by seismic imaging of the area near the Nexen SAGD project at Long Lake (Twp. 84, Rge. 6-7): (A) seismic time slice across a 12 km wide channel complex consisting of mud plugged abandoned 5-7 km wide channels and 3-5 km point bar-I.H.S. complexes with lateral accretion scrolling proximal to the meander bends (Hubbard et al. 2011). The horizontal amplitude slice on 3D pre-stack time migrated seismic volume is a time slice approximately 12 m below the datum at the top of the middle McMurray point bar complex. The tightly looped meander channels with northward paleo-flow are 400-500 m wide, but now mud-plugged and abandoned; (B) representative log profiles for wells located at 1AA/13-20-84-07W4M and 1AA/09-28-

84-07W4M illustrating the point bar and the abandoned channel lithofacies for the approximate log-depth of the seismic time slice.

Fig. 4. Sub-Cretaceous structure across the study area: (A) structure of the 50 km long V-shaped Bitumount Trough, central collapse area and a segment of the main paleovalley trend. The 10 m contours are elevations above sea-level; (B) interpretation of the large collapse features on the sub-Cretaceous structure; location of the Muskeg River, Aurora North Mines and the Jackpine Mine; cross-section traces and well control.

Fig. 5. Regional tectono-stratigraphy across the northern Athabasca Oil Sands Deposit: (A) diagrammatic SW-NE profile (modified from Ranger and Gingras, 2006, 2010); (B) cross-section with thinned Devonian strata that resulted from pre-Cretaceous erosion on the paleo-topography during the prolonged pre-Aptian hiatus and Middle Jurassic-Cretaceous sub-surface salt removal. Trace of cross-section A-A' located on Figure 2B.

Fig. 6. Structural cross-section B-B' across the western Bitumount Trough illustrating the stair step down structures by en-echelon block faulting northward towards and into the Deep Trough. Accommodation space from differential subsidence of the Bitumount Trough floor was concurrently filled with lower McMurray sands. The salt dissolution underlying the northern Trough margin resulted in collapse of a 25 km long chain of Upper Devonian blocks, the Deep Trough, which filled with lower McMurray sands. Subsidence continued into the overlying middle interval deposition as the dissolution front below the Deep Trough migrated northward and embayed the salt scarp, resulting in the 200 km² central collapse depression. Trace of the cross-section on Figure 4B.

Fig. 7. Structural cross-section C-C' illustrating the collapse of the sub-Cretaceous structure along the northern margin of the Bitumount Trough northward into the central collapse, resulting in overly thickened lower and middle McMurray strata. Trace of cross-section on Figure 4B.

Fig. 8. Muskeg River and Jackpine Mines developed across the southern study area along the east bank of the Athabasca River: (A) satellite image of the open pit excavations; (B) map of the sub-Cretaceous structure across the Bitumount Trough floor and northward into the central collapse. The Muskeg River (a) and Jackpine (b) Mines are structurally high areas where the bitumen saturated McMurray beds draped over buried Keg River mound. The structural low on the sub-Cretaceous structure along the eastern

margin of the Muskeg River Mine (a) coincides with the margin of the underlying salt scarp. The dense well control is illustrated.

Fig. 9. Distribution of multi-km long middle McMurray bitumen saturated sand complexes (BWB>10%) across the northern Athabasca Deposit: (A) tidal sand bars, up to 3 km long, parallel and collinearly aligned NW-SE at the proposed site of the Fort Hills Mine, westward of the main paleovalley trend; (B) large longitudinal tidal sand bars up to 7 km long collinearly aligned NW-SE along sub-parallel tidal channels, which are 10-30 km long. Large tidal sand dune complexes oriented NE-SW perpendicular to the tidal channel axes were partially anchored along structural terraces along the southern rim of the central collapse depression on the sub-Cretaceous structure. The benches along the southern rim of the central collapse consist of aligned fault blocks of Upper Devonian and lower McMurray strata that stair step down northward.

Fig. 10. The robustness of many burrow traces in middle McMurray beds accumulated from the Bitumount Trough to north of the central collapse area suggests significantly increased impacts by stronger tidal processes dominating over fluvial processes responding to voluminous shifting sands and tidal reworking: (A-C) examples of exceptionally large *Teichichnus* burrows, often 10-15 cm and as much as 40-50 cm, in contrast with widespread 2-4 cm long burrows in beds south of the study area; (D) Robust *Rosella* burrows with sizes as large as 10-20 cm, in contrast with 2-4 cm long burrows in middle McMurray deposits south of the Bitumount Trough; (E) the northernmost study area (Twp. 99-101), northward of the central collapse, accumulated middle McMurray point bars along lower delta distributary channels in areas closer to southward encroachments by the Boreal Sea. These fluvio-tidal point bars were overlain by near marine mud beds with very large *Asterosoma*.

Fig. 11. Examples of dune beds in the basal middle McMurray interval of the study area: (A) overlapping dunes in an outcrop along the northern reaches of the Athabasca River Valley, where it transects central collapse area across the lower estuary funnel in Section 25, Township 97, Range 11, West 4th Meridian. The ripple laminated stratification separates the truncated planar-laminar foreset-bottomset of a dune from planar foreset-toeset of the overlying dune (courtesy of M. Ranger); (B) amalgamated dunes, possibly compound, located along the Ells River a km to the west of its confluence with the Athabasca River, northern Twp. 95, Rge. 11 W4M, and to the west of the northern Muskeg River Mine lease. The tops of the dune beds are usually truncated (courtesy of M. Gingras). Locations of these dunes are on Figure 9.

Fig. 12. Examples of double mud couplets, indicative of tidal impact during deposition of the upper point bar of the Jackpine Mine deposit.

Fig. 13. Aurora North Mine cut benches, oriented east-west cut, excavate the middle of a large middle McMurray point bar sand complex accumulated above a step down on the sub-Cretaceous structure: (A) the several McMurray Formation intervals accumulated as a 65 thick deposits with the middle interval consist of two overlying point bars. The lower and upper point bars are separated by an erosion surface that extends across the width of the deposit. Channels with coeval flows northward cut into the point bar accretion beds that dip 10-15° northward; (B) and (C): cut faces of the middle interval located further to the west illustrating internal architecture of two overlying point bars and eroded remnants of a third bar. The channel fill deposits and lateral accretion beds of each point bar were truncated by an overlying erosion surface, onto which aggradation resumed.

Fig. 14 Muskeg River cut benches, oriented east-west at the southern, up structure, end of the McMurray deposit excavated by the adjacent Aurora North Mine (Fig. 13): (A) fluvial lower interval braided river deposit consisting of a point bar covered by muddy I.H.S.; (B) Sub-horizontal lateral accretion deposits of the middle interval point bar with low bed dips (5-10°) northward; (C) steeply dipping (45°) I.H.S. beds of the middle interval point bar dominate the southern margins of the point bar complex.

Fig. 15. Example of a middle McMurray stacked point bar sand complex at the Jackpine Mine. Aggradation extended along the SW-NE oriented structural terrace that stair stepped down towards the central collapse area and banked against the high wall of the back-step: (A) thickness map of very clean sand beds (BWB>14%) illustrating the NE-SW orientation of the sand complex elongated to the structural grain in the substrate; (B) overlay of the point bar complex on the sub-Cretaceous structure, which illustrates the SW-NE oriented sand aggradation trend. The structure and dimensions of the underlying structural bench stabilized aggradation and constrained forward migration further northward towards the central collapse area; (C) overlay of the sand bar complex on lower McMurray structure, which overprints the step-down structure northward of the underlying sub-Cretaceous structure; (D) thickness of the middle McMurray sand complex (BWB>14%) with traces of cross-sections D-D', E-E' and F-F' (Figs. 16-18). Well control illustrated.

Fig. 16. Structural cross-section D-D' illustrating lithofacies in cored intervals of the T-shaped middle McMurray point bar complex at the Jackpine Mine site. The sand complex, banked against and draped over a sub-Cretaceous structural high, extends northwestward over a structural terrace formed by

1748 collapsed and rotated Upper Devonian fault blocks. The collapse and rotation of the Upper Devonian fault
1749 blocks in the substrate was concurrent with deposition of overly thickened lower McMurray strata. The
1750 stacked point bar, Facies A and B, were overlain by a larger and more extensive sand aggradation, with
1751 steeply sandy I.H.S. bed dips, Facies C.

1752
1753 **Fig. 17.** Structural cross-section E-E' oriented E-W across the width of the T-shaped geometric
1754 configuration of the stacked point bar complex at the Jackpine Mine site cored intervals illustrating the
1755 litho-facies. Aggradation of the several overlying point bars centered above a northward facing structural
1756 terrace of Upper Devonian fault blocks that stair step down into central collapse.

1757
1758 **Fig. 18.** Structural cross-section F-F' oriented N-S along the length of the T-shaped point bar complex at
1759 the Jackpine Mine site. The sand I.H.S. beds, Facies C, were at least temporarily anchored over a breccia
1760 pipe-sinkhole complex that probably compacted and provided a shallow depocenter for aggradation along
1761 the structural high backside of the step down terrace.

1762
1763 **Fig. 19.** Schematic illustration of two 25 km long parallel McMurray sand trends accumulated across the
1764 northern Athabasca Deposit: (A) location of the lower and middle-upper interval sand trends across the
1765 western Bitumount Trough, adjacent central collapse area, and the middle interval sand complex at the
1766 Jackpine Mine site. The largest tidal mega-channel pathway (red arrow) transported sand to the Jackpine
1767 Mine site and further northward into the central collapse; (B) illustration of the lower McMurray sand
1768 trend morphogenesis. The linear accommodation space developed as the Deep Trough chain of collapsed
1769 fault blocks along the northern margin of the western Bitumount Trough; (C) illustration of the
1770 dissolution trend underlying the Deep Trough expansion northward into the central collapse area during
1771 deposition of the middle-upper McMurray interval. This northward migration of the salt dissolution front
1772 resulted in a second 25 km long syndepositional sand trend that paralleled the lower McMurray trend.

1773
1774 **Fig. 20.** Collinear alignment of giant middle-upper bitumen point bar sand complexes along the Firebag
1775 fairway, the largest of the mega-channels developed across the northern Athabasca Oil Sands Deposit.
1776 This fluvio-tidal channel trended northwestward diagonally across the northward structural tilt of the
1777 eastern Bitumount Trough to the Jackpine Mine site at the V-join of the Bitumount Trough and turns into
1778 the central collapse area. The aggradation sites for stacked point bars developed over stair step down
1779 structural terraces developed along the southern rim of the central collapse depression (see Fig. 9B). The
1780 trace of cross-section G-G' (Fig. 21) is located.

1781

1782 **Fig. 21.** Cross-section G-G' transects a mega-channel pathway (Fig. 20), illustrating the transition from
1783 off-channel stratigraphic differentiation between middle and upper McMurray intervals to
1784 undifferentiated aggradation along the step down channel fairway. The sand complexes were established
1785 at sites along the mega-channel pathway link to upper Devonian fault block sag sites in the substrate.

Draft

A

B

Syncrude Aurora
1AC/10-12-96-10-W4M

509 E'
Southeast