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Lithofacies distribution and depositional environment in the Lower Cretaceous McMurray Formation, BlackGold Lease, northern Alberta: implications for geometry and distribution of oil sand reservoirs

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ABSTRACT: Within BlackGold Lease located in northern Alberta, the Lower Cretaceous McMurray Formation contains the most prolific bitumen reservoirs deposited in fluvial to tidally-influenced estuarine environments. Based on core descriptions and wire-line log evaluation, this study reveals six lithofacies: cross-stratified sandstone and mudstone-clast breccia (Lf1), sandstone-dominated IHS (Lf2), mudstone-dominated IHS (Lf3), thinly interbedded sandstone and mudstone (Lf4), laminated mudstone (Lf5), and clean sandstone with interbedded mudstone (Lf6). To understand the evolution of depositional environments vertical and lateral associations of lithofacies are examined using well cross-sections and lithofacies slice maps. During overall rise in relative sea level, the McMurray Formation evolved through three stages of deposition: early stage represents fluvial channels with minor tidal influence, middle stage represents tidally-influenced estuary with well-developed meandering channels, and late stage represents a drowning of tidally-influenced estuary. The potential bitumen reservoirs are fluvial channel sandstones in the early stage and lower point-bar deposits in the middle stage. The fluvial channel sandstones are well stacked and correlatable between wells, forming sheet-like sandstone bodies that align in a SW–NE direction parallel to the inferred orientation of major channel systems. The lower point-bar deposits consist mainly of base-of-channel and sandstone-dominated IHS deposits. The direction of point-bar migration, which is crucial in horizontal well design for bitumen production, is inferred from lithofacies slice maps. The lateral changes in lithofacies from base-of-channel to abandoned channel-fills through IHS deposits, shown in lithofacies slice maps, probably indicate that the point bar once migrated toward abandoned channel-fills. Based on this lateral lithofacies trend, the dip direction of some point-bar deposits are approximately estimated to be southwestward or northwestward, which is oblique or perpendicular to the major channel orientation.

Key words: McMurray Formation, oil sand reservoir, point-bar deposit, lithofacies slice map

1. INTRODUCTION

The McMurray Formation shows a great potential for producing crude bitumen in Athabasca Oil Sands area which hosts over 235 billion cubic meters of initial in-place bitumen (Energy Resources Conservation Board, 2011). Bitumen reservoirs of the formation have been recognized in either fluvial deposits or tide-dominated successions deposited in tidally-influenced, meandering river systems (Wightman and Pemberton, 1997). The tide-dominated successions consist primarily of point-bar deposits that are stacked both laterally and vertically. The point-bar deposits typically comprise alternating interbeds of sandstone and mudstone deposited on a large-scale inclined surface, classified as Inclined Heterolithic Stratification (IHS). The IHS deposit is considered to be a major portion of the bitumen reservoirs in the McMurray Formation.

In order to extract viscous bitumen from the reservoirs, the commercially successful process is Steam-Assisted Gravity Drainage (SAGD), which uses two horizontal wells (a few meters apart vertically) intersecting bitumen pay. Steam from the upper injector well reduces the viscosity of the bitumen, causing the heated bitumen to drain by gravity into the lower producing well. An important consideration with regard to steam rise and SAGD production is the lateral and vertical continuity of the permeability barrier (Strobl, 2011). Delineating the geometry and extent of the IHS deposit is crucial in predicting reservoir behavior in flow simulation and optimizing well pair placement and production (Strobl et al., 1997; Strobl, 2011). The point-bar architecture has long been known from ancient outcrop studies (Flach and Mossop, 1985; Thomas et al., 1987; Miall, 1996; Pranter et al., 2007; Musial et al., 2012), recently dipmeter and/or image log analysis (Brekke and Evoy, 2004; Fustic, 2007; Brekke and Couch, 2011), and 3-D seismic interpretation (Miall, 2002; Carter, 2003; Sarzalejo and Hart, 2006; Smith et al., 2009; Hubbard et al., 2011).

The main objectives of this study are 1) to describe and interpret lithofacies based on cores and wire-line logs in BlackGold Lease area, 2) to illustrate the distribution of lithofacies in order to understand the depositional environments of the McMurray Formation, and 3) to delineate the geometry and distribution of bitumen-saturated reservoirs. The principal

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reservoirs in the McMurray Formation are considered as braided-channel sandstone sheet and tidally-influenced fluvial channel-fills made up of cross-stratified sandstone and sandstone-dominated IHS (Mossop and Flach, 1983; Hubbard et al., 2011; Musial et al., 2012). Without dipmeter logs and 3-D seismic images, it is difficult to predict the dip direction and internal architecture of IHS deposits (e.g., Sarzalejo and Hart, 2006; Fustic, 2007). Lithofacies slice maps at a certain stratigraphic interval are useful for capturing mosaic images of the distribution of IHS deposits, which provides a possible direction of individual point-bar migration at a certain time increment. This study provides important implications for predicting the distribution and geometry of the principal bitumen reservoirs, which largely dictate the performance of SAGD well pairs and steam chamber developments.

2. GEOLOGICAL SETTING AND STUDY AREA

The Western Canada Sedimentary Basin commenced in the Early to Middle Jurassic as part of foreland basin (Leckie and Smith, 1992; Stockmal et al., 1992). The basin evolution was mainly controlled by crustal flexure related to the progressive deformation of the orogenic belt (Leckie and Smith, 1992). The present configuration of the basin represents a southwest-dipping and asymmetric trough, which formed by combined effects of thrust-plated loading in the orogenic belt and subsidiary sediment loading in the basin itself (Leckie and Smith, 1992). The asymmetric subsidence resulted in westward-thickening clastic wedges of the Mesozoic strata and affected drainage patterns that were largely parallel to the basin axis (Fig. 1) (Leckie and Smith, 1992). Concurrent with the tectonic deformation of the basin, eustatic sea-level fluctuation imposed additional controls on the evolution of the Mesozoic succession (Jervey, 1992; Cant, 1996). The Lower Cretaceous Mannville Group is a third-order depositional sequence that recorded multiple depositional cycles of transgression and regression in its internal stratigraphy (Stockmal et al., 1992; Cant and Abrahamson, 1996). The McMurray Formation, the lowest succession within the Mannville Group in the study area (Fig. 2), covers the pre-Mannville topography of pre-existing valley and terraces during eustatic sea-level rise. The transgressive deposition

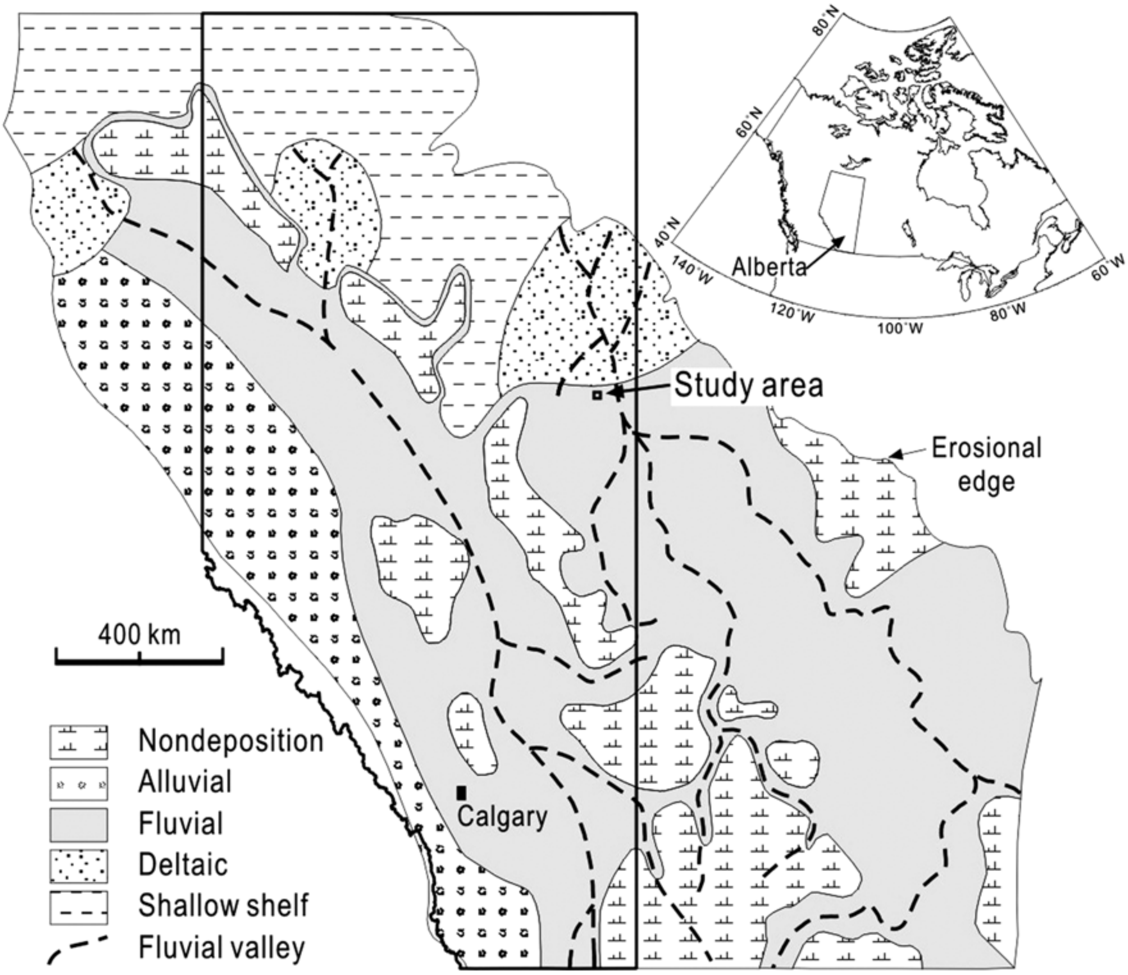

Fig. 1. Paleogeographic framework for the Lower Cretaceous McMurray Formation (modified from Smith, 1994) and the location of the study area.

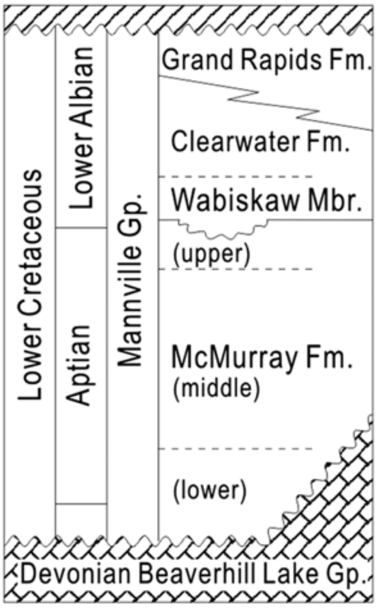

Fig. 2. Stratigraphic column for the McMurray Formation (modified from Hayes et al., 1994).

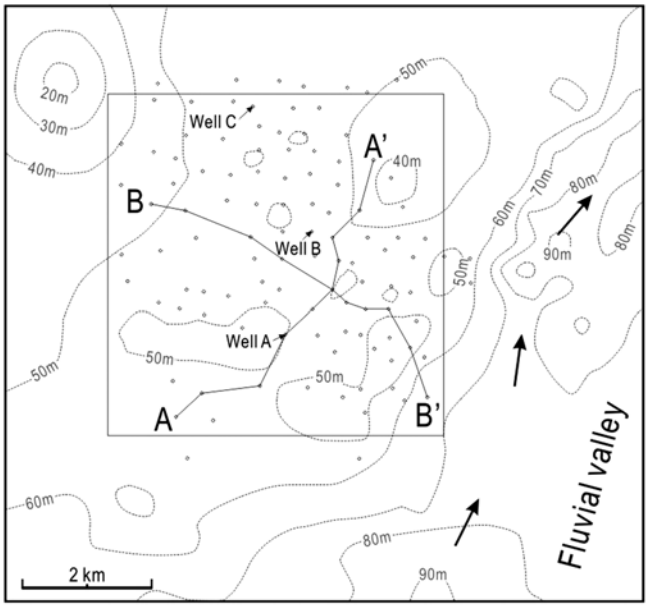

Fig. 3. Location of measured cores (inside box) and isopach map of the McMurray Formation. Thick lines denote the locations of well cross-sections. Contours in meters.

of the McMurray Formation was terminated by marine sedimentation of the Clearwater Formation. A maximum flooding surface is placed at the base of the Clearwater Formation overlying the McMurray Formation (Crerar and Arnott, 2007).

Based on lithological variation, the McMurray Formation has been divided into three intervals; 'Lower McMurray' consists of valley-filled fluvial deposits, 'Middle McMurray' represents tidally-influenced channel and estuarine complex, and 'Upper McMurray' comprises mud-dominated bay-fills or marginal marine deposits (Carrigy, 1959; Flach and Mossop, 1985; Ranger and Pemberton, 1997; Wightman and Pemberton, 1997). The Lower McMurray succession represents lowstand, braided-fluvial deposits that infilled the pre-existing paleotopographic lows (Hein et al., 2000; Crerar and Arnott, 2007). The lowstand fluvial deposits were regionally floored by coals or overbank mudstones formed during widespread flooding prior to emplacement of the overlying Middle McMurray transgressive deposits (Hein et al., 2000). The Middle McMurray Formation was extensively deposited in tidally-influenced fluvial to coastal environments as the incised valley was progressively drowned. During the Middle McMurray time, the paleovalleys developed with a linear trend of SE–NW (Fig. 1). Sediments were transported northwestward by fluvial drainage systems and ultimately deposited in deltaic to shallow shelf environments. The Upper McMurray Formation consists primarily of fine-grained deposits dominated by bay-fills and marginal marine lithofacies (Flach and Mossop, 1985). Hein et al. (2000), however, argued that the distinction of the Middle and Upper McMurray formations is difficult using petrography and fossil content, and then proposed a lower fluvial member and an upper estuarine–coastal-plain member in the McMurray Formation.

The study area covers BlackGold Lease area acquired by Korean National Oil Corporation, which is located 140 km southeast of Fort McMurray within the Athabasca Oil Sands region of northern Alberta (Fig. 1). The McMurray Formation in BlackGold Lease area was most likely deposited in the outside of the major paleovalley during the McMurray time. The thickness of the McMurray Formation is 40–70 m in the study area and more than 70 m along the northeastward-flowing, major fluvial valley (Fig. 3). The McMurray Formation was locally incised in the late stage by Wabiskaw D sandstone unit.

3. LITHOFACIES ANALYSIS

The lithofacies, originally described from cores by Korea National Oil Corporation, provide a basis for constructing lithofacies distribution maps and delineating reservoir types. The original lithofacies were revised in detail, using high resolution photograph images.

3.1. Lithofacies 1 (Cross-stratified Sandstone and Mudstone-clast Breccia)

Lithofacies 1 (Lf1) primarily comprises cross-stratified sandstone and mudstone-clast breccia (Figs. 4 and 5). Cross-stratified sandstones are commonly saturated with bitumen, showing dark gray or black in color. It is well-sorted and fine- to medium-grained, with a sharp and erosional base. The angle and direction of cross-beds are fairly consistent. Individual

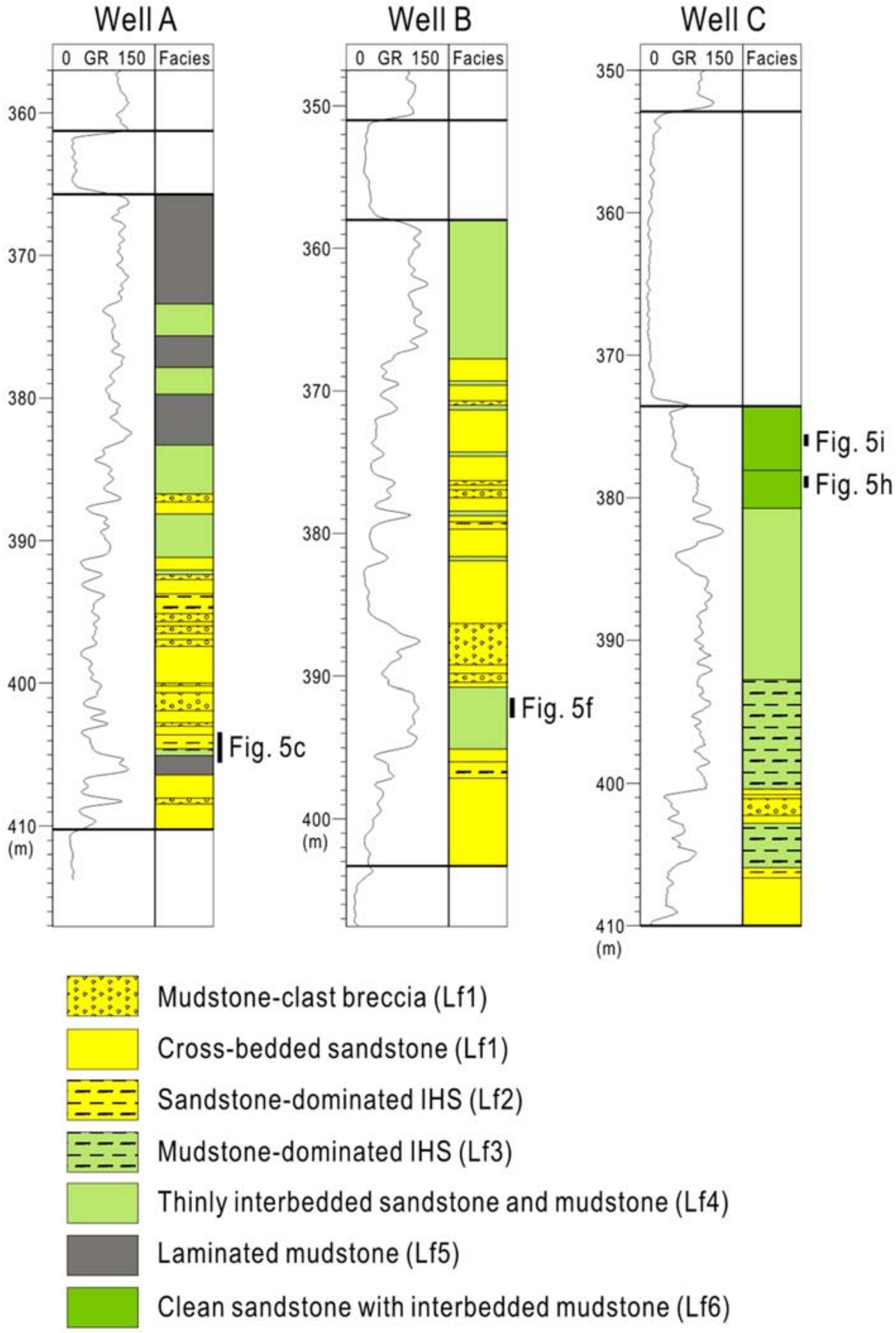

Fig. 4. Gamma ray logs and lithofacies descriptions showing overall fining-upward successions including base-of-channel, point bar, and interchannel deposits.

cross-bed ranges in thickness from a few centimeters, up to tens of centimeters. Sandstone beds are commonly amalgamated and interbedded with mudstone-clast breccias, forming a stacked unit that averages about 3 m thick. Mudstone clasts are variable in size and degrees of roundness and sorting, generally subangular to subrounded. Scattered mudstone clasts are aligned in places, with their long axis parallel to the cross beds. Matrix of the breccia is composed of sandstone and partly of muddy sandstone. Mudstone-clast breccia beds are either clast-supported or matrix-supported, ranging in thickness from a few centimeters to a few meters. Bioturbation is absent in sandstone beds, whereas some biogenic sedimentary structures occur within large mudstone clasts. Mudstone-clast breccia, which is supported by sandstone matrix, has low, blocky gamma ray readings similar to those of cross-stratified sandstone, whereas if supported by mudstone clasts, it shows high gamma ray peaks due to the high mud contents of breccia (Well A and B in Fig. 4). Lf1 is a dominant component of the lower part of the McMurray Formation and exhibits upward decrease in its proportion (Fig. 6). This facies is most commonly interbedded with inclined heterolithic stratified deposits (Lf2, Lf3) in the middle

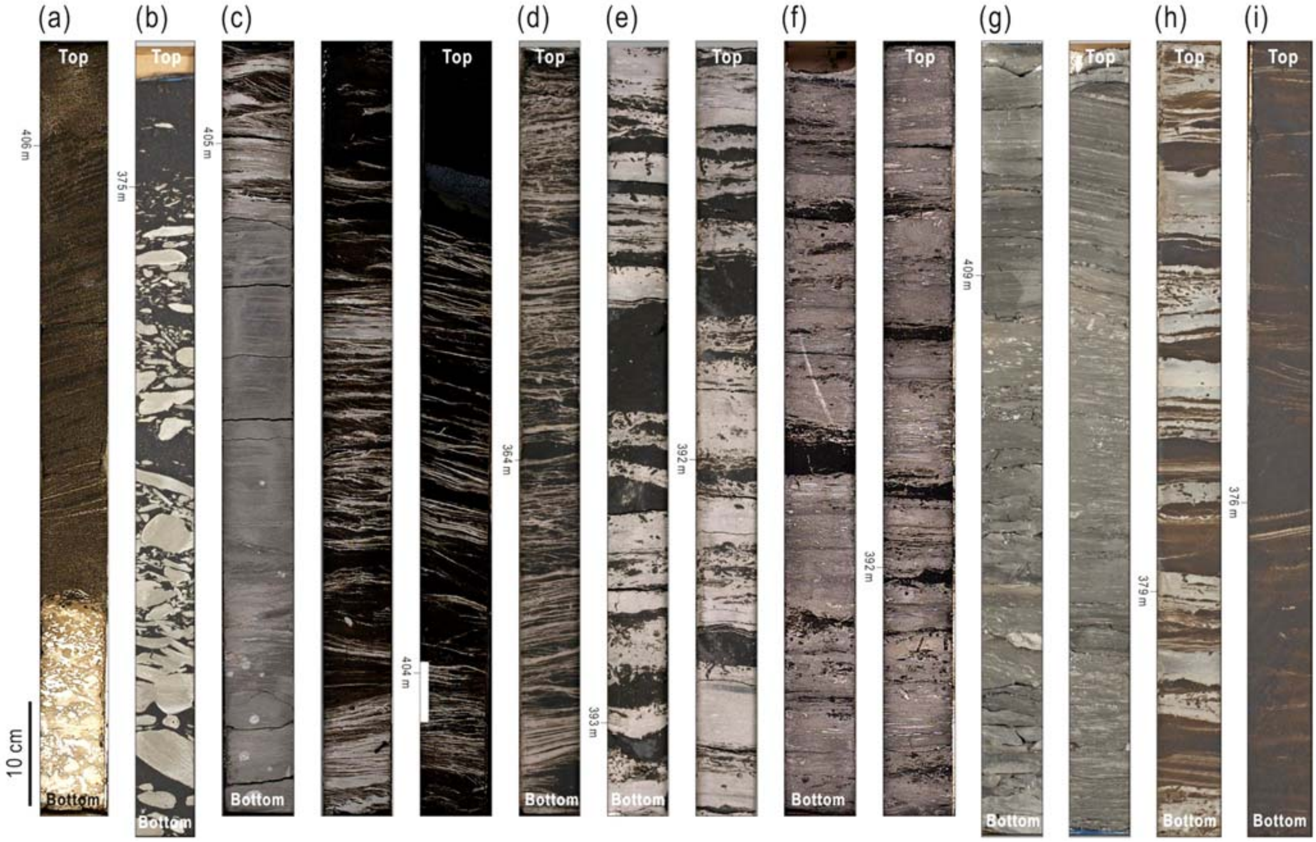

Fig. 5. Photographs of representative lithofacies in the McMurray Formation. (a) Cross-stratified sandstone (Lf1) unconformably overlying Devonian carbonate rocks. (b) mudstone-clast breccia (Lf1). (c) Sandstone-dominated IHS (Lf2) overlying a laminated mudstone bed. (d) Mudstone-dominated IHS (Lf3). (e) and (f) Interbedded sandstone and mudstone with varying sand-to-mud ratio (Lf4). (g) Laminated mudstone (Lf5). (h) Interbedded mudstone with sandstone-filled burrows (lower division of Lf6). (i) Low angle cross-stratified, clean sandstone (upper division of Lf6).

part of the formation.

Well-sorted, cross-stratified, medium sandstone is a typical bitumen-rich reservoir in the McMurray Formation. Unidirectional cross-stratification is attributed to tractive currents that flow along the thalweg of fluvial channels. The cross-stratified sandstone is interpreted as a result of subaqueous dune migration on the base of fluvial channels (Harms et al., 1982). Subaqueous dune migration is also common on the lower (deeper) part of point-bar surfaces within meandering channels (Thomas et al., 1987; Labrecque et al., 2011). Mudstone-clast breccia most likely represents slumping and/or redeposition of mud beds from semi-consolidated cut bank or upper (shallower) point-bar surface (Choi, 2011).

3.2. Lithofacies 2 (Sandstone-dominated IHS)

Lithofacies 2 (Lf2) consists primarily of sandstone-dominated, inclined interbedded sandstone and mudstone (Figs. 4 and 5). Its thickness is about 1.8 m in average and reaches up to 5 m (Fig. 4). Inclined sandstone interbeds (a few centimeters thick) are thicker and more frequent than mudstone interbeds, constituting more than 60% of Lf2 in thickness. Interbedded sandstones are either wavy-laminated, planar- to ripple cross-laminated or cross-stratified, commonly draped by siltstone and mudstone. Double mud drapes and rhythmic alternation of sandstone and mudstone laminae are occasionally observed. Horizontal lamination is partly present in relatively thick mudstone interbeds. The apparent dips of mudstone interbeds are about 0–15°. Lf2 is well associated with cross-stratified sandstone and mudstone-clast breccia, and mudstone-dominated IHS (Fig. 6). This lithofacies association is dominant in the middle part of the McMurray Formation in the study area, characterized by fining-upward response on gamma ray logs (Figs. 4 and 6).

Interstratified, inclined sandstone and mudstone are interpreted as lateral accretion deposits formed by point-bar migration (Mossop and Flach, 1983; Flach and Mossop, 1985), known as Inclined Heterolithic Stratification (IHS). Inclined sand-mud layers in the point-bar deposits were probably produced by seasonal river floods, with sand deposition during the bankfull stage and mud deposition during the falling flood stage (Thomas et al., 1987; Smith, 1988). The rhythmic alternation of sandstone and mudstone commonly occurs in tidally-influenced depositional environments, reflecting the

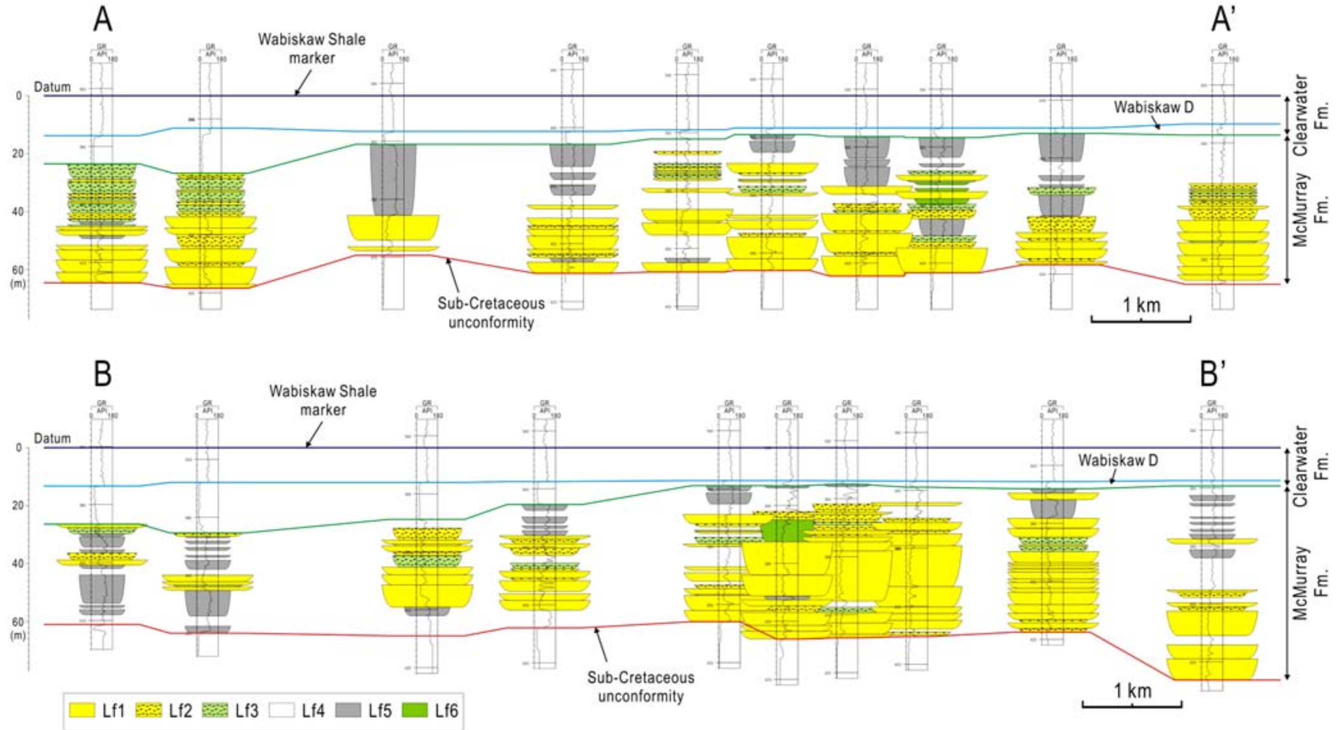

Fig. 6. Well cross-sections showing vertical and lateral lithofacies relationships. For the location of the section, see Figure 3.

periodic fluctuations of current velocity and water levels associated with tidal cycles. Millimeter-thick mud drapes on ripple cross-laminated beds were formed by suspension fallout during periods of slack water (Visser, 1980; Dalrymple et al., 1991). The associated cross-stratified sandstone and mudstone-clast breccia predominantly occur in the lower (deeper) point bars of meandering channels because fluvial processes are more sustainable than tidal processes. The close association of IHS deposits with cross-stratified sandstone, and tidal sedimentary structures suggest that lithofacies 2 represents point-bar deposits within tidally-influenced, meandering rivers. Tidal influence on IHS deposits of meandering river has been documented in the McMurray Formation in Alberta (e.g., Thomas et al., 1987; Smith, 1988; Labrecque et al., 2011) and in modern analogues (e.g., Choi et al., 2004).

3.3. Lithofacies 3 (Mudstone-dominated IHS)

Lithofacies 3 (Lf3) is composed of mudstone-dominated, inclined interbedded sandstone and mudstone (Figs. 4 and 5). Mudstone interbeds are either faintly laminated or apparently homogeneous, constituting more than 60% of Lf3 in thickness. Weak to moderate bioturbations such as vertical and subvertical burrows are common. Lenticular bedding and cyclic alternation of sandstone and mudstone layers are occasionally preserved. Mudstone interbeds range in thickness from a few to tens of centimeters. Sandstone interbeds are characterized by planar- to ripple cross-lamination with sharp lower contacts. Cross-stratified fine sandstones are interlayered in places. The maximum thickness of Lf3 is about 5 m, but most of Lf3 is less than 2 m. Lf3 is gradational with sandstone-dominated IHS (Lf2) and muddier lithofacies (Lf4 and Lf5) (Fig. 6).

Compared with Lf1 and Lf2, lithofacies 3 has low bitumen grade because sandstone interbeds are relatively thin and less common. The alternated sandstone and mudstone are interpreted as IHS deposits formed by lateral migration of point bar. Mudstone-dominated IHS deposits were probably formed in the upper (shallower) part of point bar. Relatively thick mudstone interbeds and their thickness variation within the mudstone-dominated IHS suggest that suspended load deposition was prevalent and controlled by seasonal variation in fluvial discharge and temporal migration of turbidity maximum (Allen et al., 1980; Allen, 1991; Ainsworth and Walker, 1994; Lettley and Pemberton, 2004).

3.4. Lithofacies 4 (Thinly Interbedded Sandstone and Mudstone)

Lithofacies 4 (Lf4) consists mainly of thinly interbedded sandstone (or siltstone) and mudstone with varying sand-to-mud ratio (Figs. 4 and 5). Mudstone is commonly moderately to intensely bioturbated, with abundant sandstone-filled burrows. Mudstone beds commonly contain sandstone lenses and streaks. Interbeded fine sandstone (and siltstone) has erosional base and diffuse top, ranging in thickness from a few cm to 15 cm. Sandstone has planar to ripple cross-lamination draped by mudstone laminae. Rhythmically laminated to very thinly interbedded rippled sandstone and mudstone are present in place. Coaly fragments are partly dispersed. Lf4 is present at multiple stratigraphic levels, mainly constituting the upper part of the McMurray Formation in the study area (Fig. 6).

The interbedded sandstone and mudstone reflect alternating episodes of bedload and suspension sedimentation. Mud-draped cross-lamination and partly preserved rhythmite indicate fluctuating flow condition with suspension settling of mud during the period of slack water (Reineck and Singh, 1980; Nio and Yang, 1991). Occasional intercalation of cross-stratified sandstone is indicative of the local presence of small dunes in tidal flats. Lithofacies 4 is interpreted to be deposited from bedload and suspension fallout from fluctuating tidal currents in tidal flats (Hein et al., 2000). The variable degrees of bioturbation and sand-to-mud ratio suggest that Lf4 represents the varying magnitudes of tidal currents and wave energy (e.g., Choi et al., 2004).

3.5. Lithofacies 5 (Lf5) (Laminated Mudstone)

Lithofacies 5 (Lf5) consists mainly of light to medium gray, laminated mudstone (or siltstone) (Figs. 4 and 5). Mudstone is slightly bioturbated and laminated with siltstone lenses or streaks. Horizontal burrows (*Planolites)* are commonly observed. Mudstone beds have sharp contacts and averages about 3.5 m thick. Well-sorted sandstones with cross-lamination are thinly intercalated occasionally, which accounts for less than 20% of Lf5 in thickness. Lf5 generally exhibits high, blocky gamma radiation (Well A in Fig. 4), but it is poorly identified on gamma ray logs from other mudstone-dominated lithofacies (Lf3, Lf4). This facies is gradational with other lithofacies.

The thick, laminated mudstone beds with minor sandstone beds were deposited from suspension fallout in a quiescent setting. The rare intercalation of sandy deposits indicates low-energy depositional environments such as abandoned channels or oxbow lakes in interchannels protected from wave and tidal processes (Mossop and Flach, 1983). Lithofacies 5 is interpreted as interchannel and/or abandoned channel deposits, representing the vertical aggradation during abandonment phases of estuarine complexes (Hein et al., 2000; Crerar and Arnott, 2007).

3.6. Lithofacies 6 (Clean Sandstone with Interbedded Mudstone)

Lithofacies 6 (Lf6) is represented by upward sandier succession mainly comprising lower mudstone-dominated and upper sandstone-dominated divisions (Figs. 4 and 5). Sandstone is fine-grained, well-sorted, and commonly low angle cross-stratified with a few mudstone laminae. Small mudstone clasts are observed in places. Mudstone (or silty mudstone) is moderately to highly bioturbated with sandstone-filled burrows. Mudstone-dominated lower division is a few meter in thickness and gradually transitional into sandstone-dominated upper division with increasing thickness of sandstone bed. This upward sandier succession is well recognized in gamma ray logs (Well C in Fig. 4). Lf6 is a minor component of the McMurray Formation and occasionally occurs in the middle to upper part of the formation (Fig. 6).

Well-sorted, clean sandstone with low angle cross-bedding is interpreted as deposition in upper shoreface. Mudstone with sandstone-filled burrows in the lower part of upward sandier succession most likely represents lower shoreface (Hein et al., 2000).

4. LITHOFACIES DISTRIBUTION AND DEPOSITIONAL ENVIRONMENT

The examined lithofacies in the core were used to construct lithofacies slice maps of the McMurray Formation (Fig. 7). With a reference to the Wabiskaw (WBK) Shale marker, lithofacies slice maps were built at every 2-meter increment. Assuming that the WBK Shale marker is a flooding surface, a lithofacies slice map at a certain depth interval probably reflects a depositional surface at a certain time interval (a stratigraphic interval). Kriging method was applied to populate lithofacies between wells.

On the basis of discernable changes in lithofacies distribution, three stages of depositional evolution are recognized: early stage (64–42 m below WBK Shale marker) represents fluvial channels with minor tidal influence, middle stage (42–24 m below WBK Shale marker) represents tidally-influenced estuary with meandering channels, and late stage (<24 m below WBK Shale marker) represents a drowning of tide-influenced estuary (Fig. 7). The boundary between each stage is either gradational or obscure in cores and well log responses.

In the early stage of the McMurray deposition, the pre-existing Devonian carbonates were mainly covered by cross-stratified sandstones associated with mudstone-clast breccias (64–42 m in Fig. 7). The amalgamated sandstones extensively occurred and coexisted with patchy, isolated tidal flat and interchannel deposits (or abandoned channel-fills). IHS deposits were poorly developed during this stage.

The incipient valley-fills in the McMurray Formation have been known as braided-fluvial deposits comprising pebbly sandstones and cross-stratified sandstone confined locally to paleo-topographic lows (Flach and Mossop, 1985; Crerar and Arnott, 2007; Jo and Ha, 2013). The lower part of the McMurray Formation in the study area is likely comparable to the incipient braided-fluvial deposits. However, cross-stratified sandstones are multiply staked with mudstone-clast breccias and are poorly confined by topographic relief along the sub-Cretaceous unconformity. The abundance of mudstone-clast breccia suggests that interchannel banks were well developed in study area and that the lower McMurray

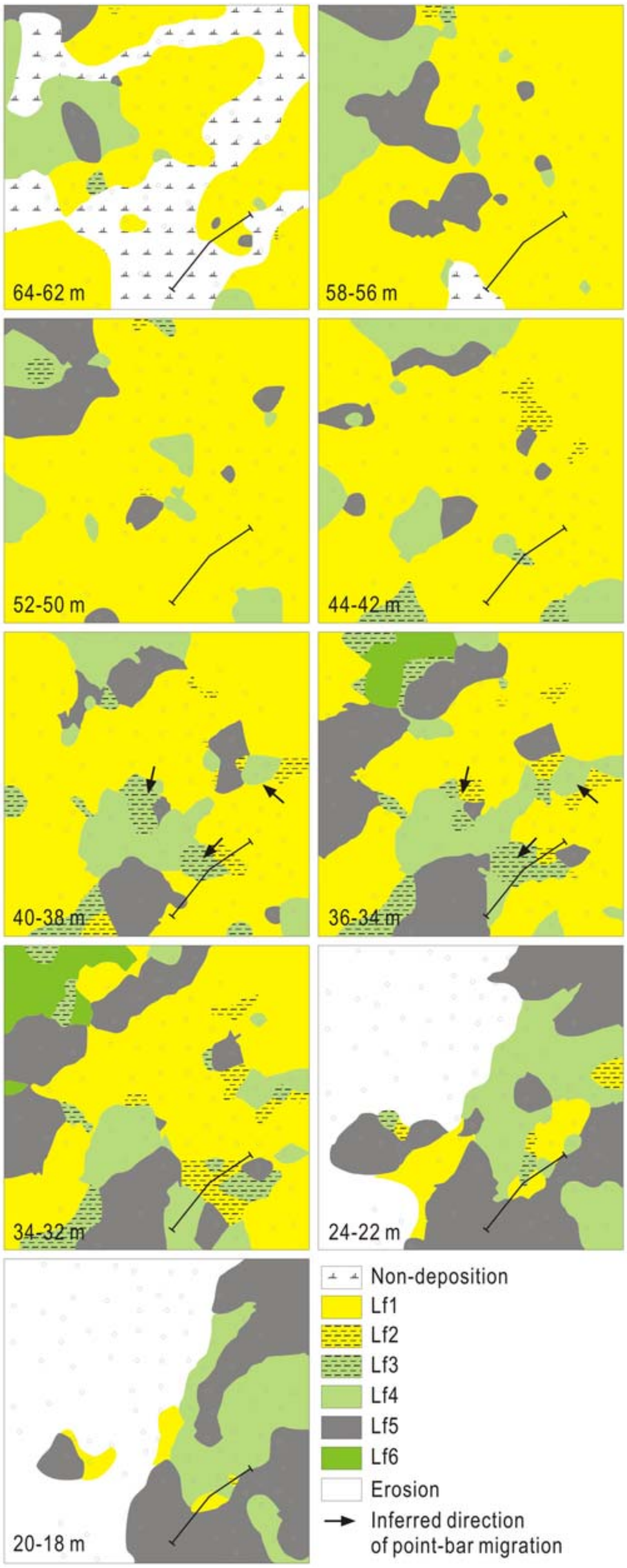

Fig. 7. Lithofacies slice maps constructed at every 2-m increments with a reference to a flooding surface (WBK Shale marker horizon). For the location of the map, see Figure 3.

channels may represent deposition in a low-accommodation fluvial-dominated system (e.g., Arnott et al., 2002; Crerar and Arnott, 2007). Low accommodation could have caused the early McMurray channels to migrate laterally and to cannibalize interchannel deposits, resulting in multiply stacked, sheet-like channel-fills with rarely-preserved interchannel deposits (Crerar and Arnott, 2007). The early McMurray channels in the study area were locally developed outside of the nearby main paleovalley in the southeast. They most likely formed a fluvial tributary system at upstream areas where tidal processes became less effective.

Sedimentary successions in the middle stage of the McMurray Formation were much muddier than those of the early stage, as shown by an increase in the preserved extent of IHS deposits and abandoned channel-fills (42–24 m in Fig. 7). Tidal flat deposits were dominant in the central-south of the study area and closely associated with IHS deposits. Abandoned channel-fills show NE-trending linear distribution and gradual increase in extent during the middle stage. Shoreface deposits locally occurred in the northwestern part of the study area.

The high content of mudstone and decrease in grain size of sandstone generally indicate that the depositional system received high amounts of mixed bedload and suspended load. Cross-stratified sandstone and mudstone-clast breccia are multiply stacked and closely associated with IHS deposits during this stage. This association is interpreted to represent deposition within tidally-influenced meandering channel systems. The channel-fills are dominated by point-bar successions (IHS deposits) and base-of-channel sandstones (Lf1), contrasting to those in the early stage. The finer grained channel-fills with more common tidal sedimentary structures suggest a landward shift from fluvial-dominated system in the early stage to tidally-influenced estuarine system in the middle stage. In addition, abandoned channel-fills were locally preserved through this time, which suggests that vertical aggradation occurred progressively along the marginal part of the channel systems. These vertical aggradation deposits were rarely preserved along the major axis of the channel systems because they might have been intensively reworked and removed by younger channels. The distribution of channel-fills confined by lateral migration of the channel system appears to represent a meander belt roughly trending SW–NE and NW–SE (Fig. 7).

The upper part of the McMurray Formation is significantly eroded by the disconformable surface under the Wabiskaw D sandstone (24–18 m in Fig. 7). The upper McMurray Formation is only present in the east of the study area and dominated by tidal flat and pod-like abandoned channel-fills. The point-bar successions account for the minor proportion of the McMurray Formation during this stage. Vertical accretion of tidal-flat deposits and abandoned channel-fills might have been caused by either relocation of major estuarine system or drowning of estuarine system during the continued transgression.

5. IMPLICATION FOR RESERVOIR GEOMETRY AND DISTRIBUTION

Bitumen-saturated reservoirs have been known to be imbedded in fluvial to tidally-influenced channel deposits with varying bitumen grades. Two reservoir types are recognized from the channel-fills on the basis of lithofacies characteristics, inferred bed thickness and continuity.

5.1. Reservoir Type I

Reservoir type I represents fluvial channel-fills comprising medium- to coarse-grained, cross-stratified sandstone and intercalated mudstone-clast breccia (Lf1). This reservoir type was well developed during the early stage of the McMurray deposition. Although thin mud layers are intercalated in reservoir type I, they are not considered to be major permeability barriers because they are too thin and discontinuous in the core. Reservoir type I is expected to have good vertical and lateral communication. It is, however, noteworthy that the reservoir quality can be degraded due to interbedded mudstone-clast breccias. The clast-supported breccias with a low content of sandstone matrix are particularly inferred to act as significant permeability barriers where multiple breccia beds are stacked both laterally and vertically. Mudstone clasts scattered within the bitumen-saturated sandstone are expected to be less impact on flow communication because sandstone matrix is permeable sufficiently to maintain bitumen flow during the SAGD production.

Vertical amalgamation of cross-stratified sandstones is characteristic of reservoir type I, most likely forming sheet-like geometry. The amalgamated units have an average thick-

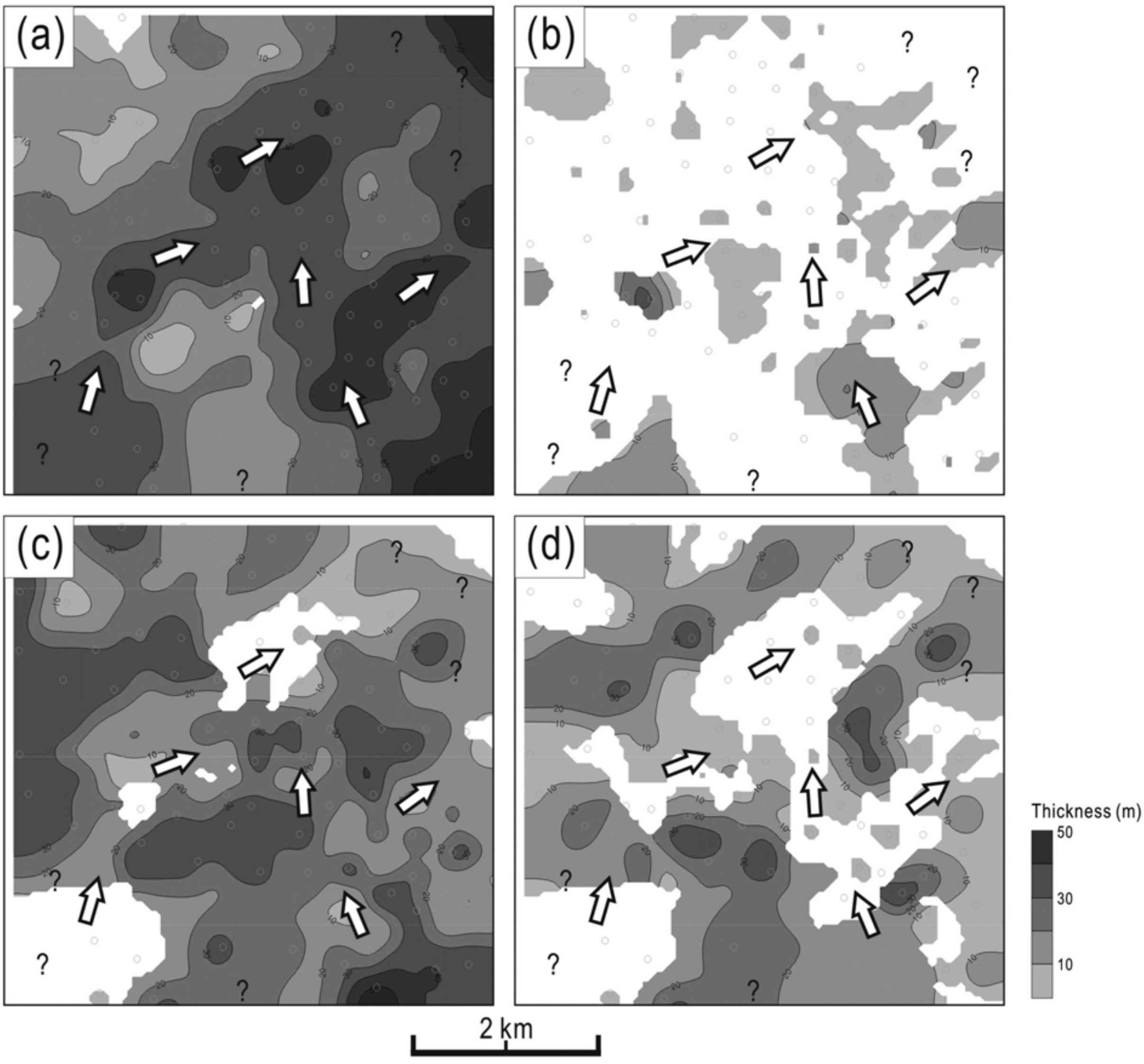

Fig. 8. Gross thickness maps for major lithofacies. (a) Channel-base fills (Lf1). (b) IHS deposits (Lf2 and Lf3). (c) Tidal flat complex (Lf4). (d) Abandoned channel-fills (Lf5). Arrows denote possible directions of major channel systems.

ness of 3 m in the core. Gross thickness of the reservoir is less than about 50 m in the McMurray Formation (Fig. 8). The lateral extent of the reservoir thicker than 30 m in gross thickness shows a depositional trend of SW–NE or S–N, indicating the possible orientation of fluvial systems. The NE-trending axis is considered as potential fairways that represent fluvial channel system filled with stacked and variably connected sheet sandstone bodies. The sandstone bodies are most likely separated upward either by interchannel deposits or by interfigering IHS deposits.

5.2. Reservoir Type II

Reservoir type II represents lower point-bar deposits comprising cross-stratified sandstones (Lf1) and sandstone-dominated IHS deposits (Lf2). It was dominant in the middle stage of the McMurray deposition, formed by lateral migration of tidally-influenced meandering channels. Compared to fluvial channel-fills of reservoir type I, cross-stratified sandstones of reservoir type II are generally finer grained and thinner, more commonly associated with IHS and interchannel deposits. Cross-stratified sandstones represent deposition in the base of channel and/or in the lower point bar. Sandstone-dominated IHS deposits merge downdip into the base-of-channel sandstones and contain sandstone interbeds more than roughly 60% in thickness. Therefore, the reservoir quality of the lower point-bar deposits is better than the upper point-bar deposits which consist mostly of mudstone-dominated IHS deposits. The connectivity of sandstone beds of the lower point-bar deposits may be affected by continuity and thickness of interstratified mudstones. The interstratified mudstones are most likely discontinuous due to bioturbation and erosion by intermittent tractive currents, suggesting that they are likely permeable to varying degrees during SAGD operations (Hu, 2004). The fact that the upper point bar is commonly interfingered or juxtaposed with tidal flat or abandoned channel-fills suggests the significant development of internal discontinuities and mud breaks.

5.3. Inferred Direction of Point-Bar Migration

A complete, tidally-influenced point bar commonly shows an upward-fining succession from channel-base lag to inclined interstratified sandstone and mudstone, forming laterally accreted depositional elements (Fig. 9). Lateral migrations occur as a consequence of relatively continuous erosion on the outer bank and deposition on the inner bank. The resulting point-bar succession is usually laterally continuous, except when channel cutoffs and avulsion occur. The complete point-bar succession fines updip along a point-bar surface, comprising lower sandstone-dominated IHS and upper mudstone-dominated IHS deposits. In a cross-sectional view, there is a gradual transition between the upper and the lower

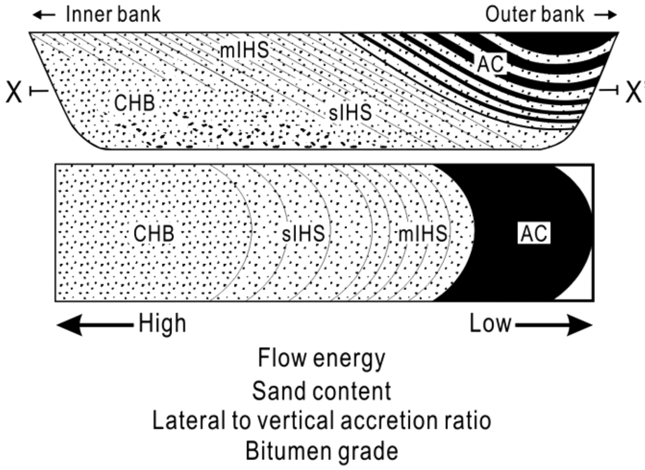

Fig. 9. Schematic diagram illustrating simplified architecture of single point bar succession (modified from Wightman and Pemberton, 1997). CHB = channel-base fills, mIHS = muddy IHS, sIHS = sandy IHS, AC = abandoned channel-fills.

point-bar deposits. This gradual boundary slightly dips toward the outer bank (cut bank), with dip angle lower than point bar surfaces (Fig. 9). In a plan-sectional view along a reference slice, lithofacies distribution exhibits a lateral shift from channel-base sandstone to abandoned channel-fills through sandstone-dominated IHS and/or mudstone-dominated IHS. Such a lithofacies belt most likely reflects the direction of the lateral migration of a complete point bar. For instance, a lateral change from the lower point bar to abandoned channel-fills indicates that the point bar once migrated toward the abandoned channel-fills. Based on this scenario, IHS deposits are assumed to dip toward the abandoned channel-fills. Grain size decreases toward the outer bank and bitumen grade also decreases laterally toward the migration direction of the point bar.

The conceptual model was used to interpret a representative seismic section crossing point-bar deposits in the southern part of the study area (Fig. 10). The representative seismic section and its interpretation calibrated by gamma-ray logs and core descriptions show that inclined reflectors, which dip toward the southwest, are correlated with dipping strata of IHS deposits (Fig. 10). The inclined reflection packages are interpreted as point-bar deposits produced by the southwestward migration of meandering channels. The lower point-bar deposits are composed of channel-base sandstones (Lf 1) and sandstone-dominated IHS (Lf 2), grading updip into mudstone-dominated IHS (Lf 3), i.e., the upper point-bar deposits. The lithofacies slice maps partly record such lateral lithofacies association, also indicating the southwestward migration (Fig. 7). The inclined reflectors merge with underlying high-amplitude and continuous reflectors corresponding to relatively thick, sheet-like sandstone bodies formed in early fluvial-dominated environments.

The lateral lithofacies association in the study area sug-

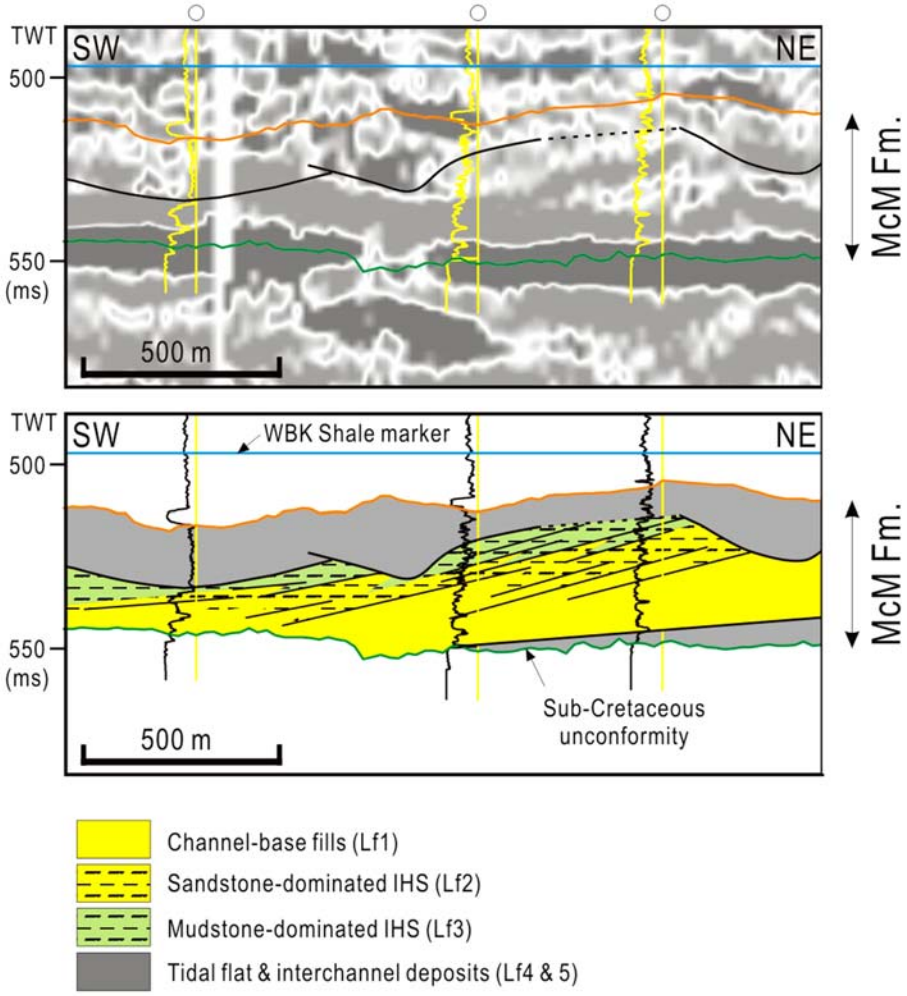

Fig. 10. A representative seismic section and its interpretation, crossing point-bar deposits. For the location of the section, see Figure 7.

gests that the direction of migration at a given increment is approximately oblique or perpendicular to the direction of the main channel axis (Fig. 7). However, the inferred migration direction is not always indicative of the individual point-bar migration because the point-bar deposits in natural system are multiply stacked with varying cut-and-fill geometries. In addition, the point-bar architecture and channel geometry are scarcely discernable under the present resolution of the seismic data. It is important to note that this indirect approach is based on the simplified point-bar architecture, and the inferred migration trend needs to be proved by outcrop studies and high-resolution analysis using dipmeter logs and 3-D seismic images.

The thickness of point-bar successions is variable in the McMurray Formation in the study area. The IHS deposits (Lf2 and Lf3) are generally less than 10 m in gross thickness and disseminated with limited lateral extent (Fig. 8). The lateral extent of IHS deposits is roughly estimated to be less than 1,000 m in the gross thickness map. Because the preserved IHS deposits are isolated remnants separated by a complex pattern of channel avulsion and cutoff, lateral extent and thickness approximated in this study may be underestimated. Previous studies described the thickness of the point-bar succession to be more than 28 m at Long Lake (Hubbard et al., 2011), 30–60 m at the Muskeg River Mine (Fustic, 2007), and 20–30 m in northern Athabasca (Flach and Mossop, 1985).

6. CONCLUSIONS

The Lower Cretaceous McMurray Formation is a prolific producer of crude bitumen in Athabasca Oil Sands of northern Alberta. A lithofacies analysis using conventional cores from about 90 wells established six lithofacies: cross-stratified sandstone and mudstone-clast breccia (Lf1), sandstone-dominated IHS (Lf2), mudstone-dominated IHS (Lf3), thinly interbedded sandstone and mudstone (Lf4), laminated mudstone (Lf5), and clean sandstone with interbedded mudstone (Lf6). The lithofacies characteristics and their lateral and vertical relationships reveal that the McMurray Formation was deposited in fluvial to tidally-influenced estuarine environments during overall rise in relative sea level. Based on lithofacies distribution, three depositional stages for the McMurray Formation are proposed: early stage represents fluvial channels with minor tidal influence, middle stage represents tidally-influenced estuary with meandering channels, and late stage represents a drowning of tidally-influenced estuary.

The most promising reservoir type in the study area is amalgamated sandstones deposited in the early fluvial channel systems. This sandstone reservoir forms as sheet-like sandstone body that is predicted to align in a SW–NE direction parallel to the inferred orientation of major channels. The second reservoir type is the lower point-bar deposits mainly preserved in the middle stage, which is mainly composed of cross-stratified sandstone and sandstone-dominated IHS. The direction of channel migration is estimated on the basis of lateral lithofacies association. A complete point-bar deposit tends to record a lithofacies shift from channel base to abandoned channel-fills though IHS deposits as the channel laterally migrates toward cut bank. Based on lithofacies slice maps, the dip direction of some point-bar deposits are approximately estimated to be southwestward or northwestward, which is oblique or perpendicular to the major channel orientation. However, the inferred migration direction from lithofacies slice maps should be confirmed by dipmeter log analysis and 3-D seismic images, because most point-bar deposits within the study area are incomplete and multiply stacked.

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