Use of Image Logs in Differentiating Point Bar and Tidal Bar Deposits in the Leismer Area: Implications for SAGD Reservoir Definition in the Athabasca Oilsands

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Introduction

The interpretation of depositional environments within the McMurray Fm is fraught with uncertainty. Cross-cutting and stacking relationships make the task of correlating and delineating depositional environments particularly difficult. One of the more important factors in discerning McMurray Fm depositional environments is identifying the different types of inclined heterolithic stratification (IHS). Once the sedimentology is understood, the depositional environments can be determined. Understanding depositional environments is vital for accurately predicting the style and distribution of mud beds, which largely dictate the performance of SAGD well pairs and steam chamber development.

Unfortunately, conventional open hole well log suites are not particularly definitive in identifying McMurray environments, because lithologies vary markedly *within* depositional facies, and different depositional settings *produce* several lithologically similar facies. Core is much better suited to interpreting these facies, but *may not* be sufficient for differentiating the varieties of IHS. Image logs are similar to core in that they provide information on bedding styles, but are unique because they also yield data critical for interpreting bedding geometries. Stratigraphic correlations and delineation of depositional bodies are improved when guided by understanding their depositional geometries.

Not understanding IHS types could lead to fundamental problems in designing and producing SAGD operations. IHS associated with estuarine tidal bar deposits may have minimal effects on steam chamber production, due to the limited lateral extent of the mud layers. Conversely, lateral accretion IHS, associated with point bar deposits, display mudstone layers that are continuous for hundreds of metres, based on outcrop observations. A methodology for differentiating these IHS types is described below.

Continuous IHS Deposits: Lateral Accretion (Point Bar) IHS

Continuous IHS deposits typically correspond to lateral accretion (LA) beds, deposited on the inside bends of point bars. Mud beds in this style of IHS are deposited during periods of lower energy such as waning flow conditions, and are relatively continuous across the depositional surface of the point bar. Bioturbation is commonly present in the mud beds, with suites that contain *Cylindrichnus*, *Skolithos*, *Planolites*, *Gyrolithes*, and/or *Teichichnus* (Figure 1). Sands are deposited during periods of higher energy and commonly overlie the muds with little or no erosion. This type of IHS forms stacked heterolithic intervals of mud and sand beds that commonly dip at angles of up to 12°. These heterogeneous dipping beds are observed to extend for hundreds of metres in the McMurray Fm type

section. IHS point bars three miles wide and five miles long have been mapped in the subsurface in the Athabasca area (Brekke and Evoy 2004).

The trace fossil suite described above may not, however, be developed in lateral accretion beds deposited under higher flow settings. Higher-energy IHS emplacement is characterized by rapid accumulation and shifting substrates, which inhibits colonization by burrowing organisms. Under brackish-water conditions, the muds flocculate and become deposited as bedload intermixed with sand layers. Evidence for the bedload transport of mud lies in its interlamination with sand forming heterolithic current ripple cross-laminations (MacEachern and Dashtgard, 2009; see Figure 2).

A representative cored interval (Figure 3) and open hole well log suite (Figure 4) illustrates a succession of IHS in the lateral accretion of a point bar. The cored interval of Figure 3 is represented by the black box in the depth column of Figure 4.   This log interval shows a succession of IHS in LA beds that lack thoroughly bioturbated mud layers. Log cut-offs are commonly used to determine pay in the McMurray Fm for SAGD *in-situ* resource mapping. This interval shows excellent log pay: gamma signatures indicate clean sand with muds less than 2 m thick (yellow shading); density porosities are greater than 30% (red shading); and deep resistivity values are greater than 40 ohms.
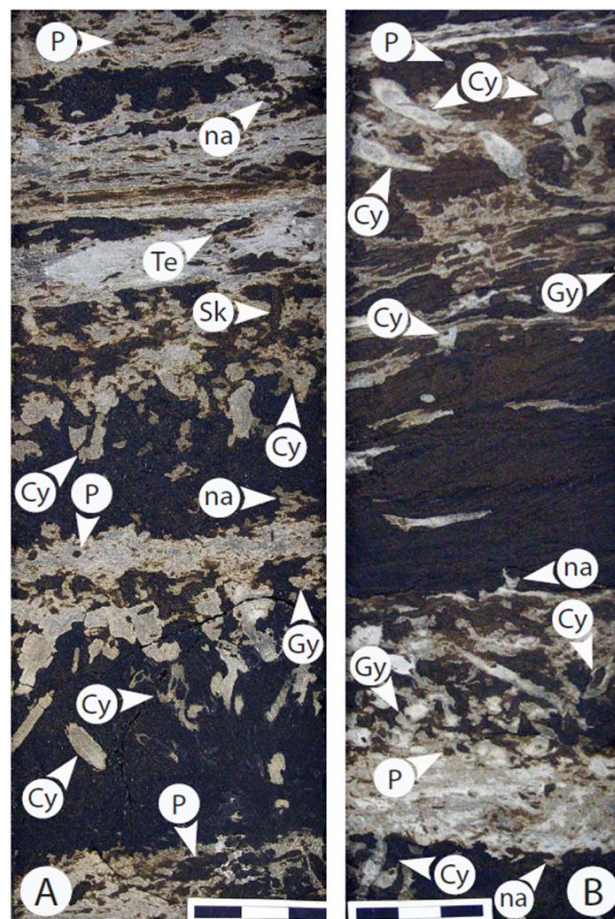

Figure 1. Bioturbated IHS beds associated with lateral accretion on a point bar in the McMurray Fm (scale is 3 cm). Bioturbation is moderate to abundant, and dominated by *Cylindrichnus*, *Skolithos*, *Gyrolithes*, *Planolites*, and *Teichichnus* with subordinate navichnia. Photo from MacEachern and Dashtgard (2009).
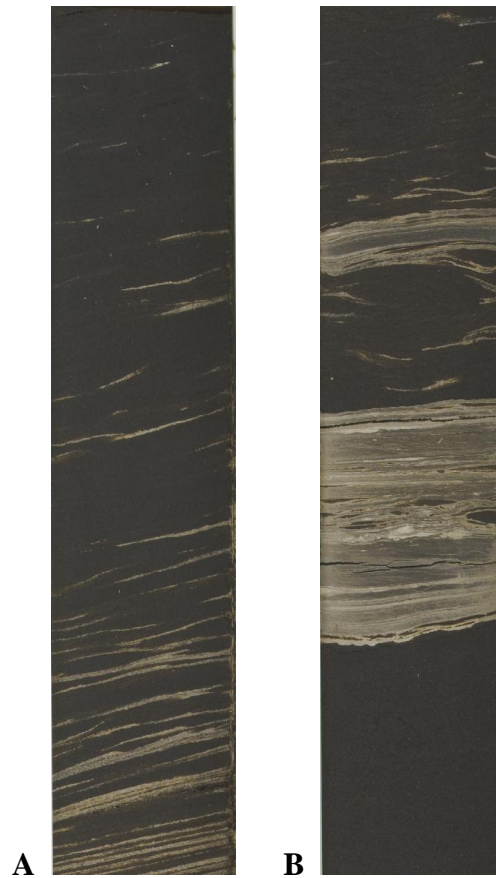
Figure 2. Continuous IHS on lateral accretion beds. These mud deposits were transported with the sand as bedload sediments and were not deposited from suspension. The lack of bioturbation in these units is consistent with a stressed environment, interpreted to be a function of elevated energy conditions. Core photos are approximately 7 cm wide. A) The mud in this unit was deposited concurrently with the sand, forming unbioturbated flaser bedding. B) Centimetre-scale laminated mud beds with silt and sand laminae.

Figure 3. Sand-dominated continuous IHS. Bioturbation is rare to absent over an eight metre section. The apparent dips on the mud beds range from 0°-16°. Mudstone rip-up clasts are present in the lower portion of the unit. These rip-ups are fragments of eroded and remobilized mud laminae from the point bar, and correspond to periods of high-energy deposition. Core tubes are approximately 7 cm wide. Top of the core is at the top right; base of the core is at the bottom left.
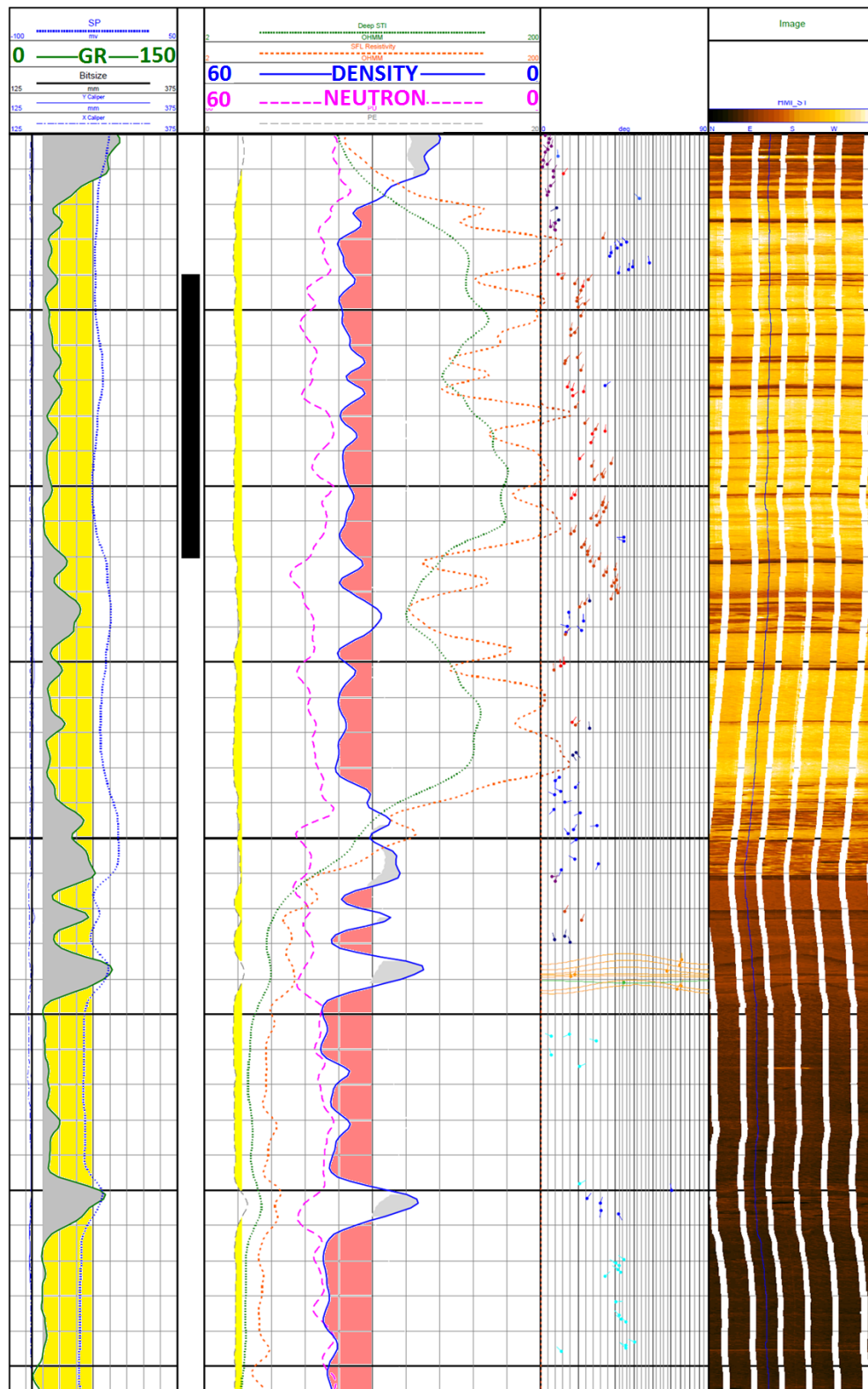
Figure 4. Sand-dominated continuous IHS from lateral accretion beds of a point bar. Depth increments on the log are one metre. Sand is shaded in yellow on the gamma ray curve at less than 75 API. Porosity is shaded in red at greater than 30% on the density curve. The thick orange dotted line is the SFLR (logarithmic scale 2-200), and shows a slightly serrated character correlated to an interbedded mud and sand interval.

Discontinuous IHS Deposits: Estuarine Tidal Bar IHS

Relatively discontinuous IHS deposits occur in cross-bedded sands interpreted as estuarine tidal bars. Estuarine tidal bar deposits consist of amalgamated trough cross-bedded sand, with varying amounts of mud as discrete beds, laminae, and flasers. Mud-clast rip-ups and breccias are also common. Dunes generated in estuarine tidal bar settings are laterally discontinuous with erosional bases, and commonly plane off underlying beds. This results in stacked cross-bedded bedsets separated by reactivation surfaces. Estuarine tidal bar mud beds are highly discontinuous compared to the lateral accretion mud beds of point bars.

Thick mud beds are uncommon in this part of the McMurray, most muds occur either as isolated layers less than 10 cm thick, or as muddy flasers within cross-beds. Muddy flasers can be observed to dip at greater than 15° and preserved cross-bed sets are typically less than one metre. With these geometries, mud beds have lateral extents of less than four metres, extents that are significantly less than those of point bars, which may extend for hundreds of metres. Figure 5a shows examples of mud deposited in a tidal bar setting. Note its similarity to the point bar muds shown in Figure 2a.

Isolated mud beds are also present as relatively low-energy deposits between and on top of dunes and ripples. Such beds are more susceptible to erosion where they are deposited on top of features, and are relatively discontinuous. Similarly, muds deposited in troughs between dunes are constrained laterally by dune spacing. Figure 5b shows current ripples capped by thin mud beds. Note that the mud beds in Figure 2b appear similar, despite accumulation in a point bar setting.

The IHS units of the estuarine tidal bar deposits are lithologically similar to those of high-energy point bar deposits. Mud beds may dip at high angles or be horizontal, thickly or thinly bedded, and show absent to sparse bioturbation due to stresses associated with high-energy migration of dunes. In like manner to the higher energy point bar deposits, rapid accumulation and substrate mobility of the estuarine tidal bars inhibits colonization by burrowing organisms. Mud floccules are deposited as bedload, and are intermixed with the sand layers (Figure 5a and 5b). Figure 6 shows a succession of IHS in LA beds that lack the characteristic thoroughly bioturbated mud beds.

The open-hole well log suite for the core in Figure 6, represented by the back box in the depth track, is shown in Figure 7, and records a thick estuarine tidal bar succession. Log characteristics for this well are similar to those of the interval noted in Figure 4. The estuarine bar deposits show excellent log pay: the gamma ray log shows clean sands, with muds less than 2 m thick, density porosities greater than 30%, and deep resistivity values greater than 40 ohms.
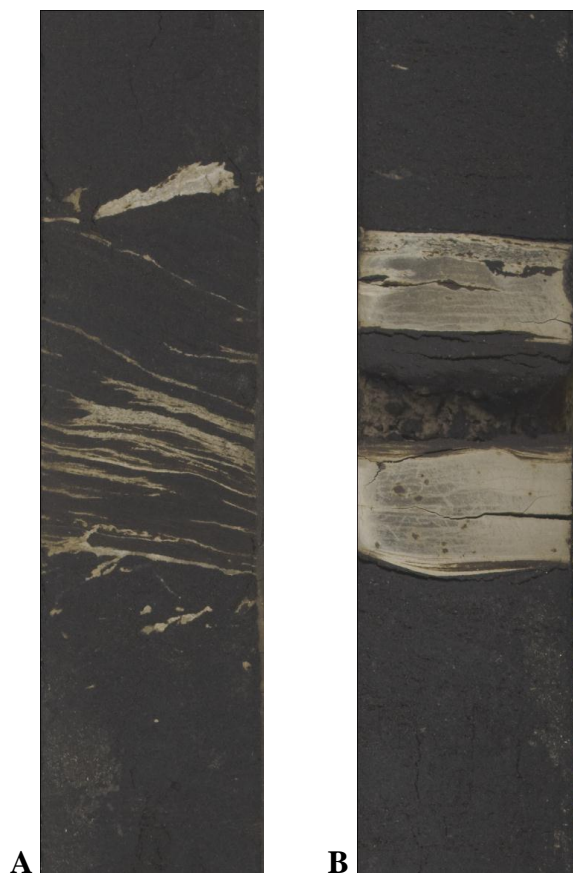
Figure 5. Discontinuous IHS from an estuarine tidal bar. A) Muddy flasers in a cross-bedded sand. These muds were transported with the sand as bedload sediments, and were not deposited from suspension. The lack of bioturbation in these units is consistent with a highly stressed environment, interpreted as high energy. Core photos are approximately 8 cm wide. B) Thicker bedded muds in a sand facies; sparse *Planolites* are limited to the upper portions of mud beds. Compare these facies with the IHS point bar deposits of Figure 2.

Figure 6. Discontinuous sand-dominated IHS. Bioturbation is rare or absent over the seven metre section. The apparent dips on the mud beds range from 0° - 25°. Compare this interval with the facies of Figure 3. Core tubes are approximately 8 cm wide. Top of the core is at the top right and base of the core at the bottom left.
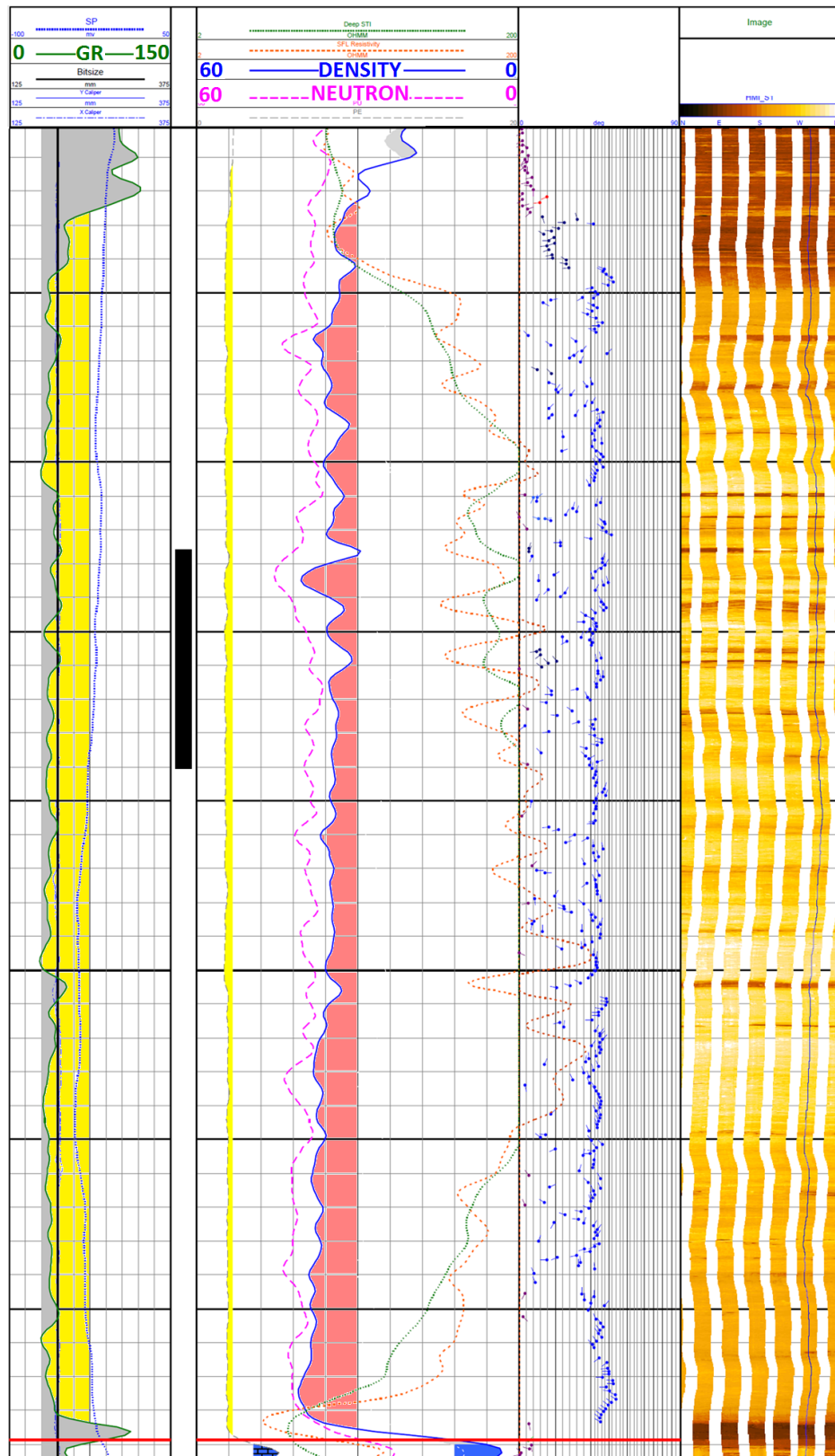
Figure 7. Sand-dominated discontinuous cross beds in an estuarine tidal bar setting. Depth increments on the log are one metre. Sand is shaded in yellow on the gamma ray curve at less than 75 API. Porosity is shaded in red at greater than 30% on the density curve. Note that the log signatures are similar to those of the lateral accretion beds in Figure 4.

Differentiating Point Bars and Estuarine Tidal Bars

As demonstrated above, standard open hole log signatures are inadequate for reliably differentiating sandy IHS deposits. Core may be useful, and where distinctively bioturbated, can be employed with substantially greater confidence to discern lateral accretion beds in point bars. Nevertheless, core is not definitive for unbioturbated IHS intervals.

Problems in reliable differentiation of point bar and tidal bar IHS can be resolved by incorporating interpretations of image logs. Point bars and tidal bars have discrete architectural features that are quite distinct from one another, which can be readily identified from image logs.

Point bars within the McMurray Fm were described by Flach and Mossop (1985) to consist of "large-scale sets of epsilon cross-strata" (IHS), with mean dips of 10° overlying trough cross-bedded sands. They also noted that the continuity of these facies types are such that the IHS merges downdip into the underlying cross-bedded sand, indicating that both facies were deposited concomitantly. Their interpretation suggested that the point bar deposits required channels on the order of 20 to 30 metres deep.

The observations by Flach and Mossop (1985) from the outcrop belt are consistent with the observations in this, as well as other subsurface studies (e.g., Brekke and Evoy, 2004). The right track in Figure 4 shows a series of tadpoles interpreted from an image log. The tadpoles are scaled 0-90° from left to right, with the dip magnitudes indicated by the position of the "head" of the tadpole. The "tail" of the tadpole indicates the dip direction of the bed. Colour is used to indicate the type of the bed that is interpreted; red tadpoles represent lateral accretion beds, whereas blue tadpoles represent cross-stratification.

The dip pattern in track three of Figure 4 shows two distinct types of bedding over the upper 20 metres of a point bar. The lower section consists of current-generated stratification (corresponding to discrete sets of dunes) and mud-clast breccia, marked by dark blue tadpoles displaying varying dip direction. This grades upward into predominantly NE-dipping lateral accretion bedsets with dips of 4-9°. Note that all of the lateral accretion beds dip in a consistent direction. This contrasts with the randomly dipping cross-stratified beds that underlie it. Some breccias and cross-stratified beds occur higher up the section, but these are secondary and are typically less than 50 cm in thickness. The upper cross-stratified beds reflect small dunes and large ripples that migrated across the surface of the point bar. Such beds are "well behaved", in that they consistently dip in the direction of current flow, 90° to the dip direction of the lateral accretion bedsets. The lateral accretion beds in this well continue upwards, with dips that steepen up to 20°, before flattening to horizontal. This shallow-to-steep-to-shallow dip pattern is characteristic of lateral accretion deposits, and has been observed in subsurface mapping at Meadow Creek (Brekke and Evoy, 2004).

Estuarine tidal bar architecture, on the other hand, contrasts markedly with the geometry of point bars. The tidal bar geometries are dominated by high-angle cross-stratification, with subordinate IHS typically confined towards the upper part of the section. Cross-beds show dips between 15° and 35°, and display a dominant downstream dip direction. Some scatter may be due to oblique current flow within the tidally dominated channels. Track three of Figure 7 displays a 36 metre-thick cross-stratified sand package recording erosionally amalgamated dunes. Cross-stratification is dominated by

dips of 20° to 32° (blue tadpoles), with varying dip directions that are dominantly oriented toward the north-northwest. Dune bedsets are apparent as clusters of similarly dipping tadpoles on the image log. Preserved thicknesses range from 20 to 100 centimetres. The dipping mud beds in this facies are millimeter to centimeter scale, and are unbioturbated (Figures 5 and 6). These characteristics are consistent with observations of tidal bar deposits as described by Dalrymple and Choi (2007).

5 – Conclusions

The consistent dip directions and the shallow-to-steep-to-shallow dip patterns of the lateral accretion beds are critical in discriminating point bar deposits. Additionally, this pattern permits assessment of preserved thicknesses of discrete point bars and allows estimations of channel scale. No other method of achieving this level of precision is currently employed. Conventional wireline logs and slabbed cores do not lead to accurate prediction of the geometry of the IHS intervals, whereas interpreted image logs can provide bedding-scale architecture and flow information. It is this architecture that is distinct, and permits the reliable differentiation of lateral accretion and tidal bar IHS.

Figure 8 is a schematic geological model illustrating a potential McMurray succession. The continuous and discontinuous IHS in this model are attributed to discrete depositional subenvironments within the estuarine channel complex. The continuous IHS reflecting lateral accretion beds are preferentially deposited in the salmon-coloured point bar on the left, whereas the discontinuous IHS are represented by the orange-coloured tidal bars in the channel in the centre of the figure. Refinements in the integration of image log interpretations and core-based facies analysis promise to lead to accurate mapping of depositional architectures and high-resolution sedimentological models for the McMurray Fm.
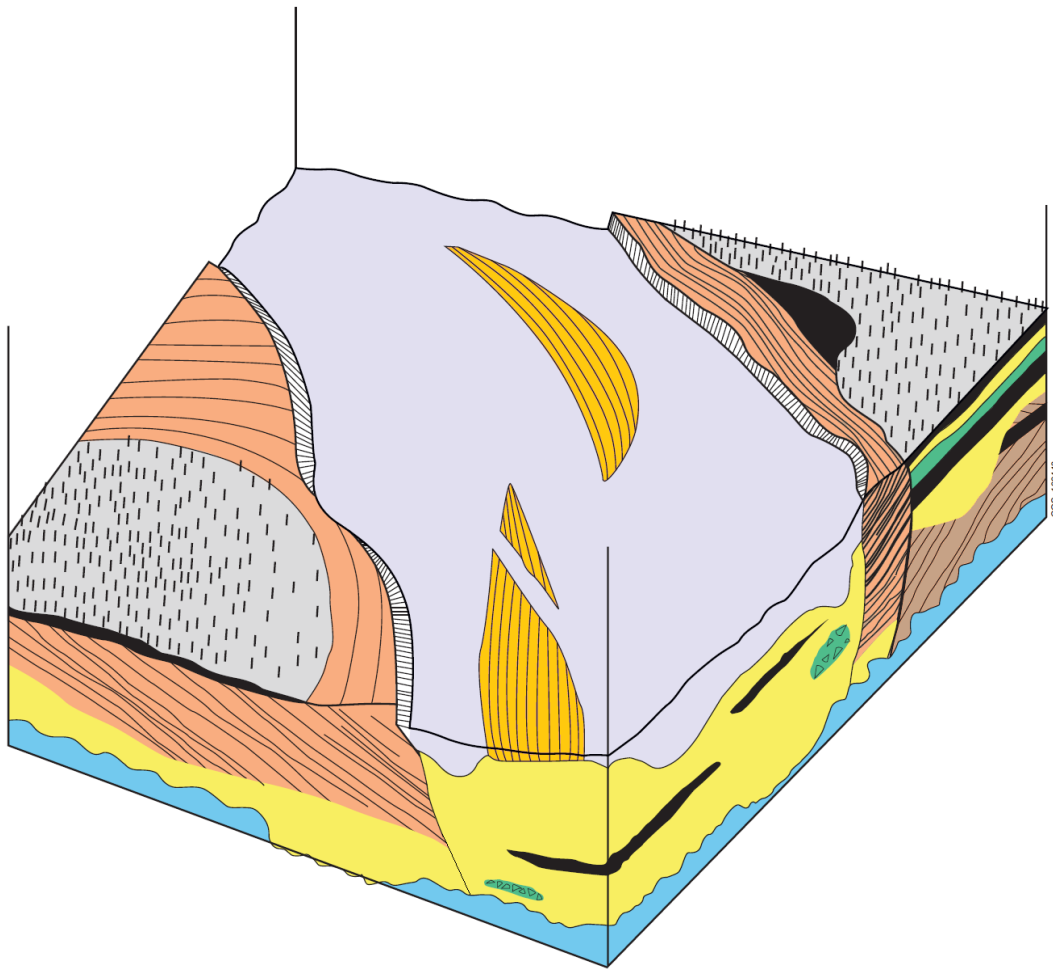
Figure 8. Geological model of McMurray Fm environments including point bar and estuarine tidal channel settings.

Dip patterns interpreted from image logs can be used to determine depositional settings, decipher stratigraphic relationships, and ultimately map depositional environments. The depositional environment provides the ultimate understanding of mud distribution, and these geological interpretations should be used to select areas for SAGD well placement to maximize well performance.

References

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