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McMurray Formation Type Section Outcrop: Part 1 - a world class learning lab for fluvio - tidal sedimentology, petroleum systems and reservoir characterization & Part 2 – an unparalleled portal for SAGD risk assessment, well-placement planning and production optimization studies

Milovan Fustic[1], Rudy Strobl[1], Bryce Jablonski[1], Torgrim Jacobsen[2], Eirik Vik[2], and Allard W. Martinius[1]

[1] Heavy Oil Technology Centre, Statoil Canada Ltd., Calgary, Alberta, Canada

[2] Heavy Oil Technology Centre, Statoil, Trondheim, Norway

Introduction

McMurray Formation Type Section (defined by Carrigy, 1959) is located 5km downstream from the confluence of the Athabasca and Clearwater rivers and extends 2 km along the east bank of the Athabasca River. This outstanding, up to 80 m thick exposure has been described, logged and visited by many geologists.

Since the first documentation of oil sands along the Athabasca River by Peter Pond in 1778, literature review documents early qualitative geological descriptions of this outcrop by Bell (1884), McConnell (1893), Ells, (1914), followed by descriptive logging by Carrigy (1959). Carrigy's (1959) outcrop log included (i) contact between McMurray (named by McLearn, 1917) and Clearwater Fm., (ii) McMurray subdivision into middle and upper member, and (iii) sand description based on grain size, sand mineralogy, cement type, induration, and bitumen saturation. Although regularly visited by many geologists in recent decades, the Type Section have not been documented in literature with the exception of Hein et al., (2001), who did detailed outcrop logs including description of sedimentary facies and provided depositional environment interpretation.

In the first part, this report builds on previous works (particularly on Hein et al. 2001) and aims to (i) document detailed reservoir architecture; (ii) reconstruct depositional processes characterized by the dynamic interplay of deposition and erosion on various time scale; and (iii) understand the impact of vertical and lateral compartmentalization and facies heterogeneities on reservoir oil-charge, in-reservoir biodegradation, and fluid (oil, water, and gas) migration and mixing processes which cumulatively control the geometry of high Sw geobodies in present day outcrops and subsurface.

In the second part, a detailed geological outcrop map is used as a portal to qualitatively compare the impact of the spatial distribution of various reservoir heterogeneities and lean zones on a range of SAGD well-placement configurations and production optimization strategies.

Methodology

Data was acquired through detailed two-dimensional outcrop mapping recorded on high resolution photographs and scaled photo-montages, line-drawing of various geological contacts both on outcrops and images, and detailed (cm-dm) bed-by-bed logging along selected outcrop exposures. Mapping and line drawing were further assisted by the collection of palaeoflow indicators.

To describe reservoir architecture, facies changes and the extent of high Sw zones, detailed outcrop maps of cliff exposures were combined with vertical logs (coupled with some unavoidable lateral extrapolation of geo-contacts over covered parts of the outcrop). Sedimentary facies are described and summarized. The complex architectural elements hierarchy is reported in terms of floodplain, AC-fill, sandy channel-fill, chute channel, and point bar deposits, including its subdivision into mid-, lower-, and upper point-bar and further subdivision of the upper point bar into lateral accretion sets or stories. High Sw zones are mapped as separate and distinct sub-units.

Point bar evolution is interpreted based on nature (geometry) of contacts, geometric relationship of mapped architectural elements, facies changes between architectural elements, and paleo-current indicators. The reservoir geo-history is interpreted based on sound in-reservoir fluid (oil, water and gas) migration and mixing principles in the previously interpreted reservoir architectural framework.

Hypothetical SAGD well placements are based on examples from industry and include subsurface analogue examples from various operators.

Descriptions and Interpretation

Sedimentology and Reservoir Architecture

The entire McMurray Fm. exposed at the Type Section, underlain by Devonian carbonates and overlain by Clearwater marine shales and/or glacial deposits, is comprised of two major vertically stacked units. These two units are separated by a sub-horizontal erosional contact exposed at numerous places and correlative with dozens of wells drilled behind the outcrop.

The lower unit occupies the bottom 30m of the outcrop and is mostly covered. However, in places the exposure shows a broad range of bitumen free (Sw = 100%), bitumen saturated (Sw ~ 20-30%) and/or lean (Sw 30-70%) cross-bedded and ripple laminated clean sands, and variably bitumen saturated inclined sandstone strata (ISS) and inclined heterolithic strata (IHS) packages. There is evidence of multiple horizontal and inclined (cutbank) erosional surfaces, indicative of a complex labyrinth of relatively small channel deposits (up to 10m deep). The top of the unit is marked by a brownish, commonly weathered and/or vegetation covered mud-dominated unit, interpreted as overbank floodplain deposit and muddy IHS packages of upper point bars / bars. Multiple cores from behind the outcrop show similar sedimentological features and confirm a significant lateral extent of the mud-dominated zone. Along the 2 km outcrop exposure, this mud-dominated interval is absent / eroded at two sections that are less than 100 meters long.

The upper unit is 30-40m thick and superbly exposed, but mostly is too steep for detailed close up geological investigations. The base of the unit is a laterally extensive (several square km) sub-horizontal erosional surface. Exposures show several discontinuous / patchy zones which are bitumen free (located at the base of the unit [Sw = 100%]), bitumen saturated (Sw ~ 20-30%), and/or lean (Sw 30-70%) cross-bedded and ripple laminated clean sands and variably bitumen saturated ISS and IHS packages. Several exposures show continuous, fining upward patterns characteristic of a single large-scale (up to 40 m thick) point bar. Typically, cross-bedded sands dominate the lower part of the unit with ISS and IHS overlying in the middle and upper parts respectively. However, locally ISS and IHS extend to the base of the channel. Also, some cross-beds at the base of the unit are interbedded with thick (up to 10 cm) mud deposits that extend for several meters. These mud deposits are interpreted as dune-muds (sensu Fustic et al., 2013a). A number of exposures are relatively more complex, showing a variety of features including slumps, thick (up to 2m) breccias, and sometimes dramatic lithology and enigmatic changes along inclined erosional contacts, such as tens of meters thick onlap deposits indicative of aggradation. These erosional contacts are interpreted as point-bar reactivation / re-orientation surfaces. Additionally, apparently enigmatic, narrow (up to 100m wide) linear channel bodies are locally found throughout the unit. These channel fills show a range of deposits and are interpreted as partially preserved remnants of short lived chute channels which cross-cut the point bar (sensu Fustic et al., 2013b). In general, most of the reactivation surfaces and chute channel deposits are documented along the upstream part of the outcrop, while the vertical continuity of the large-scale point bar deposit is better preserved along the downstream half of the outcrop. This variation is interpreted to be due to changes in water discharge, most likely controlled by decadal to centennial scale climate changes (sensu Labreque et al., 2011, Jablonski 2012) occurred during the evolution of this single large-scale point bar deposit.

A large scale (300m wide and up to 25m thick) channel shaped feature, comprised mostly of brownish, commonly weathered and/or vegetation covered mud-dominated deposits is interpreted as AC-fill [although this is a common feature in open pit mines and subsurface studies, this appears to be the first documentation of an AC-fill deposit in McMurray Fm. outcrops]. Considering its erosional relationship with other strata it is possible that this exposed AC-Fill is a cutbank of a younger, large-scale channel and/or of the same channel that by changing its migration course has cannibalized portion of its own previously deposited strata.

The upper most part of the McMurray formation is comprised of trough cross-bedded sand which is interpreted as late stage channel deposits; glauconitic laterally extensive sands and black marine muds of the Wabiskaw Member of the Clearwater Formation and/or; variably incised Quaternary glacial deposits. The top of the outcrop is comprised of thick (up to 4m) Holocene Muskeg.

Petroleum Systems

Spatial relationship of low-permeable architectural elements and facies versus high Sw zones clearly shows that reservoir heterogeneities had a strong control on reservoir oil-charge, in-reservoir fluid migration and mixing process. Laterally extensive floodplain deposits vertically compartmentalized the reservoir making it impossible for oil to charge the Type Section as a single unit. The upper unit shows zones of Sw = 100% only at several bottom parts of the unit (up to 4 m thick). Conversely, Sw = 100% zones are abundant throughout the lower unit. These zones have a sharp but commonly irregular contact with bitumen saturated sand. Considering that Sw = 100% zones have never received oil (sensu Fustic et al., 2013c) it is concluded that the lower unit is only partially charged, while the upper unit is almost fully charged with oil. Consequently, the 2 units had to have been charged independently. Additionally, due to extensive nature of floodplain deposits, neither migration nor mixing of oil between the 2 vertical compartments was possible except within limited areas were the floodplain was eroded.

Lean zones (Sw = 30-70%) within clean sand occur in both the lower and the upper unit. These zones (up to 2m thick and a up to a couple of hundred meters wide) are consistently found under heterogeneous (low-permeability) intervals, and are interpreted to be depleted gas caps formed from in-reservoir microbial gas generation that followed petroleum entrapment. This process was followed by water re-occupation during gas escape and bitumen immobilization (sensu Fustic et al., 2013c).

Portal for SAGD studies

Interpreted spatial relationships between low-permeability, bitumen saturated and high-water saturated reservoir flow units, is the first true 1:1 scale presentation of various reservoir heterogeneities important for SAGD. As such, the Type Section is an unparalleled portal for SAGD risk assessment, well-placement planning and production optimization studies in complex McMurray Fm. reservoirs. This outstanding, almost 2 km long exposure clearly demonstrates the range of risks of interpreting geological heterogeneities between wells drilled as close as 400 m apart and placing well-pairs at various depths. Analysis of this outcrop provides tools and concepts for improved understanding of subsurface data and their utility. Additionally, it is an analogue for scales of reservoir challenges that are commonly encountered over the life cycle of a SAGD well-pair and thus provides possibilities for conceptual consideration for optimizing wells via scab-liner, stem-split and other approaches employed when steam encounters barriers, baffles and/or lean zones.

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