A brief overview of the geology of heavy oil, bitumen and oil sand deposits

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Introduction

There are three major oil sand areas in Canada, all in Alberta. There is also an oil sand deposit on Melville Island in the Arctic. The three major oil sand areas are from highest to lowest volume of reserves-in-place (AEUB 2003) Athabasca, Cold Lake and Peace River oil sand areas notwithstanding that bitumen reserves are also evident in subcropping carbonate rocks in Athabasca and Peace River. The oil sands reserves occur primarily in the Cretaceous upper and lower Mannville (73%) Formation, with lesser amounts in the Devonian Grosmont (19%) and Nisku (4%) Formations, the Carboniferous Debolt (3%) and Shunda (1%), and the Belloy (trace)[1]. The surface mineable area in Athabasca of Wabiskaw McMurray oil sand is defined by the AEUB (2003) as about 37 contiguous townships north of Fort McMurray where the overburden does not exceed 75 metres. Volume–in-place reserves is about 18 x 10^9 m^3, which are about one-tenth the estimated volume-in-place reserves for *in-situ* Wabiskaw McMurray recovery. Production from all other oil sand and heavy oil areas is by *in-situ* methods. Here, we will briefly review the geology of the oil sand and heavy oil areas with a slightly higher concentration of effort in the Athabasca area, as it has been the main economic focus of recent activity. Note that in all the areas, deposition and trapping in the Lower Cretaceous is substantially influenced by the topography of the Pre-Cretaceous unconformity and, depending on the area, Devonian salt solution, tectonic subsidence and fault re-activation.

Geology of the Oil Sands

Athabasca

The McMurray Formation of the Athabasca Oil Sands lies on an angular unconformity that truncates Devonian strata. In the area of Fort McMurray, Devonian strata comprise primarily limestone and calcareous shale of the Waterways Formation in the east and younger carbonate rocks of the Woodbend Group in the west. In general, the McMurray Formation accumulated in incised valleys that were formed by fluvial processes and subsequently transgressed by marginal-marine environments during an early Cretaceous sea-level rise. Thus, the McMurray displays a continuum of sedimentary environments, from fluvial in the lower parts, to estuarine in the middle, to marine shoreface near the top. This lends a tripartite aspect to the stratigraphy that forms the basis for subdivision of the McMurray Formation

Carrigy (1959) first proposed the informal threefold stratigraphy of the McMurray Formation comprising lower, middle and upper (McMurray) units. Today, this terminology is in general use, however the subdivisions have not been formalized. This is because the units are not typically mappable, and they vary in physical aspect from place to place. But, the Lower, Middle, and Upper McMurray do have some consistent lithological expressions. The Lower McMurray is generally medium- to coarse-grained, massive-appearing to crudely cross-bedded, and contains no ichnofossils. These beds are most commonly interpreted as having a fluvial nature. Middle McMurray deposits are dominated by inclined heterolithic stratification that is interpreted to represent deposition on tidally influenced point bars. Notably, the Middle McMurray contains a brackish-water trace fossil assemblage (Pemberton et al. 1982) and is thereby interpreted as representing a fossil estuary. Upper McMurray deposits are variable, but generally contain a

[1] "The crude bitumen within the Cretaceous sands was evaluated using a minimum saturation cutoff of 3 mass per cent crude bitumen and a minimum saturated zone thickness of 1.5 m for in situ areas, and 6 mass per cent and 3.0 m for surface-mineable areas. The crude bitumen within the carbonate deposits was determined using a minimum bitumen saturation of 30 per cent of pore volume and a minimum porosity value of 5 per cent" (AEUB 2002).

comparatively open marine signal. These strata are normally interpreted as shallow, low-energy shoreface deposits and small deltaic complexes (Ranger and Caplin, 2003).

The interpretation of the McMurray Formation as a complex arrangement of estuarine facies preserved within an incised valley is supported by the valley-form of the sub-Cretaceous unconformity, brackish ichnofossil assemblages, and rhythmic tidal deposits. This current understanding is a derivative of Flach and Mossop's intense scrutiny of these deposits in the 70s and 80s and Pemberton's recognition of brackish-water trace fossils preserved within the McMurray. The generalities of the 'estuary' model suit the larger picture (regional mapping scale) very well. However, most McMurray Formation workers agree that the facies inferred therein are not predictable in spite of the existence of an accepted architectural framework. There are several possible explanations for this lack of predictability: (1) the facies distribution within the McMurray Formation is too complex to be understood in cored datasets; (2) amalgamation of channelized estuary units inhibits researchers' ability to decipher closely spaced datasets; or, (3) depositional models for the McMurray Formation—particularly north of Tsp. 85—inadequately describe the facies associations observed.

Since Flach and Mossop's, and Pemberton's initiatives 20-30 years ago, outcrop work has been sporadic. The most complete review (and only modern public record) of all McMurray outcrops is represented by Dr. Fran Hein's extensive dataset, which was compiled throughout the 1990s for the Alberta Geological Survey. Although all of the previous work represents invaluable contributions, they also demonstrate that the basic 'estuary' model, as applied to the McMurray Formation, has not evolved significantly since the 1980s. This is despite the absence of a clearly predictable depositional model.

Notably, the depositional geometry of two key facies associations (FA1 and FA2, below) is inconsistent with the interpretation that McMurray strata accumulated solely in an estuary. FA1 consists of cross-stratified, rhythmically-grain-striped sand; it shows local flow reversals, and contains rare *Skolithos*, *Cylindrichnus*, and *Conichnus*. FA1 is commonly identified as fluvial due to overall low degrees of bioturbation. A more parsimonious interpretation suggests the sediments of FA1 were deposited in basinward, marginal marine locales.

Rhythmically inclined sand/mud beds representative of inclined heterolithic stratification comprise FA2. Sedimentary features include: sedimentary couplets, partial tidal bundles, local flow reversals, flaser through lenticular bedding, and locally high degrees of bioturbation. Common ichnofossils are *Gyrolithes*, *Cylindrichnus*, *Skolithos*, *Arenicolites*, and *Planolites*. FA2 is interpreted as sediment accumulation in brackish water channels. The sedimentary features of FA2 suggest deposition in more landward portions of the system, intermediate between FA1 and fluvial channels.

FA2 normally overlies FA1 above an erosional or abrupt contact. The common association of FA2 over FA1 implies the two assemblages represent a progradational succession, not genetically distinct sedimentary units. The architectural arrangement between FA1 and FA2 is demonstrated by linking them as depositional elements of an estuary in which the internal fill prograded basinward, thus possessing some of the sedimentary and stratigraphic characteristics of tide-dominated deltas. In this framework, FA1 represents an outer estuarine/deltaic tidal sand complex, and FA2 estuarine distributary channels.

Cold Lake Oil Sands

Unlike the Athabasca Oil Sands the AEUB has designated more reserves to the Grand Rapids and Clearwater Formations than the McMurray-Wabiskaw. The Clearwater Formation is presently the main target as the sands on average are 2-3 times thicker than prospective targets in the other Formations, although bitumen saturation is slightly higher in the Grand Rapids (AEUB 2003). Southward from Athabasca, the relatively deep-water Clearwater shales change facies to a near-shore deltaic and foreshore/shoreface complex. The most prospective targets include stacked distributary mouth bar sequences (Taylor 1990) and non-marine fluvial and high-energy tidal sand flats deposits (McCrimmon and Arnott 2002). Upper Grand Rapids deposition largely represents brackish water near shore deposition overlying more normal marine conditions of the lower Grand Rapids and upper Clearwater (Benyon and Pemberton 1992).

Peace River Oil Sands

The Bluesky and Gething Formations are the main targets in this area and overlie locally saturated Mississippian carbonates. The stratigraphic sequence of fluvial/non-marine (Gething) to brackish bay system (Ostracod) to a marginal marine estuarine complex (Bluesky) is similar to the McMurray Formation in the Athabasca area (i.e. accumulated during transgression; Hubbard et al. 1999). However the Peace River deposit apparently accumulated in a much smaller, wave-dominated embayment. Wilrich member shales cap the incursive sequence in the Peace River Area, thus providing a stratigraphic seal. Post-Bluesky fault re-activation along the Peace River Arch may influence reservoir distribution.

Lloydminster Area

The Lloydminster area of Alberta and Saskatchewan has been the focal point of heavy oil development for many years and geographically is the largest prospective area. Heavy oil production is from the Mannville Group sediments, with the entire suite of Mannville Formation's being prospective targets.

Conclusion

In this talk, we briefly examine regional geology and depositional environments of the primary targets in each area in order to create geological models, and to determine an association, if any, between geological models and a geophysical expression of the environments.