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Fluvial Seasonality: A predictive tool for deciphering the sedimentological complexity of inclined heterolithic stratification deposited on large-scale tidal-fluvial point bars?

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Abstract

The lower Cretaceous (Aptian-Albian) McMurray Formation is known for its world class examples of Inclined Heterolithic Stratification (IHS; Thomas et al., 1987). This alternation of sand and mud is volumetrically significant within the McMurray Formation, particularly when dealing with large tidal-fluvial point bars that typify parts of the McMurray. Understanding the distribution and character of IHS is, therefore, fundamental to *in-situ* extraction techniques (i.e., Steam Assisted Gravity Drainage-SAGD; Cyclic Steam Stimulation- CSS) of the McMurray oil sands, due to the negative impact of reservoir heterogeneity and importance of vertical permeability (K_v) (Strobl, 2012) on these recovery methods. Outcrops along the lower Steepbank River in northeastern Alberta, Canada, provide excellent 2-dimensional (and pseudo 3-dimentionsal) exposures of IHS formed on a tidal-fluvial point bar. Further investigation of these outcrops allows us to understand the depositional complexity associated with IHS sedimentation better.

The individual sand beds (5-30 cm thick) within the IHS exposed in Steepbank River Outcrops 3 and 4 are comprised of fine-grained sand that contains unidirectional current-generated structures (dominantly current-ripple lamination, but dune-scale cross bedding is also evident). There is an absence of clear tidal indicators within these sand beds, however, thin silt drapes are rarely found draping ripple sets suggesting a very weak and temporally inconsistent tidal signal. Bioturbation is also rare to absent in the sands (Bioturbation Index-BI = 0-2) but some beds contain isolated vertical burrows (*Cylindrichnus* predominates). The intervening mud beds (comprised mostly of silt-sized quartz grains) are relatively thin (0-10 cm) compared to the sand beds. Tidal-rhythmite lamination is observed in some occurrences; however, these mud beds are usually structureless due to intense vertical and horizontal burrowing (BI = 5-6). *Cylindrichnus* again dominates but there are also significant numbers of *Planolites* and *Gyrolithes* traces.

Together, these sand-mud couplets are believed to represent annual deposition on a "seasonally controlled" point bar. During a fluvial-flood interval (flood stage), sand beds are deposited rapidly by unidirectional river floods in water that is either fully fresh or only slightly brackish. At flood stage within the fluvial to marine transition zone (Fig. 1), the strong fluvial currents push the salinity node and tidal node seaward, causing much of the transition zone to be temporarily fluvially dominated. Throughout the subsequent period of waning fluvial discharge and low-flow stage, the decrease of fluvial energy allows landward migration of the salinity and tidal nodes, so that a large proportion of the transition zone is tidally influenced. It is during this low-flow stage that the mud beds are formed from suspension fall out, draping the point bar surface. Mud deposition is modulated by tidal currents creating the tidal rhythmites, which are subsequently burrowed in a brackish-water environment.

Previous workers have interpreted these outcrops as having accumulated in an “estuarine” environment. Although this is strictly correct, it is an imprecise interpretation. We believe that they were formed in the fluvially dominated, tidally influenced portion of the fluvial-to-marine transition zone (Fig. 1; i.e., in the innermost part of the transition). This is based on the fact that river-flood deposits are volumetrically predominant in the succession, and that river-flood deposition occurred under conditions of essentially unidirectional flow and nearly fresh water. Such river-flood currents are also known to be the “channel-forming” discharge (Bridge, 2003) and likely controlled the larger scale channel and point-bar morphology. Tidal action and brackish-water conditions only penetrated this far up the river during times of low river discharge when the fluvial system was largely inactive. We suggest that the presence of a clear river-generated seasonality in a deposit is an indication that deposition occurred in a fluvially dominated setting. Similar seasonally controlled IHS has been found in the modern Fraser River (Sisulak and Dashtgard, 2012).

The mud-sand couplets of the Steepbank River outcrops also displays a larger, metre-scale cyclicity which are termed “metre-scale cycles” (MSCs). Each MSC package is defined by an upward decrease in sand-bed thickness, an upward increase in mud-bed frequency, and an upward increase in bioturbation intensity. MSCs range in thickness from 0.5-3 metres. Laterally, individual MSCs have been correlated distances of at least 400 metres in outcrop. The number of recognizable sand-mud couplets within these cycles ranges from 3 to 20; thus, these cycles are “decadal” in duration and presumably reflect interannual variations in river discharge (Fig. 2). We suggest that MSCs may be an important architectural element of these point bars which are likely present in other McMurray deposits (*sensu* Labreque et al., 2011).

The existence of MSCs may be important for *in-situ* oil extraction. Even though each individual mud bed within an MSC may be thin (typically 2 cm, but maximum 10 cm), the increased frequency of mud beds near the top of an MSC may serve as a vertical permeability barrier, especially given that the composite muddy interval is more laterally continuous than the individual mud beds within it. Therefore, the sandy basal portion of each MSC potentially represents a bitumen reservoir flow unit capped by a flow barrier (mixed to mud-dominated IHS near the top of an MSC) (Fig. 3). With lateral extents of 400 metres or more, these barriers may have a significant impact on production and recovery factors from subsurface oil-sands deposits. The identification and correlation of MSCs over their relatively large horizontal extents may improve predictably between well pairs for point-bar reservoirs and lead to optimization of well-pair placement and spacing.

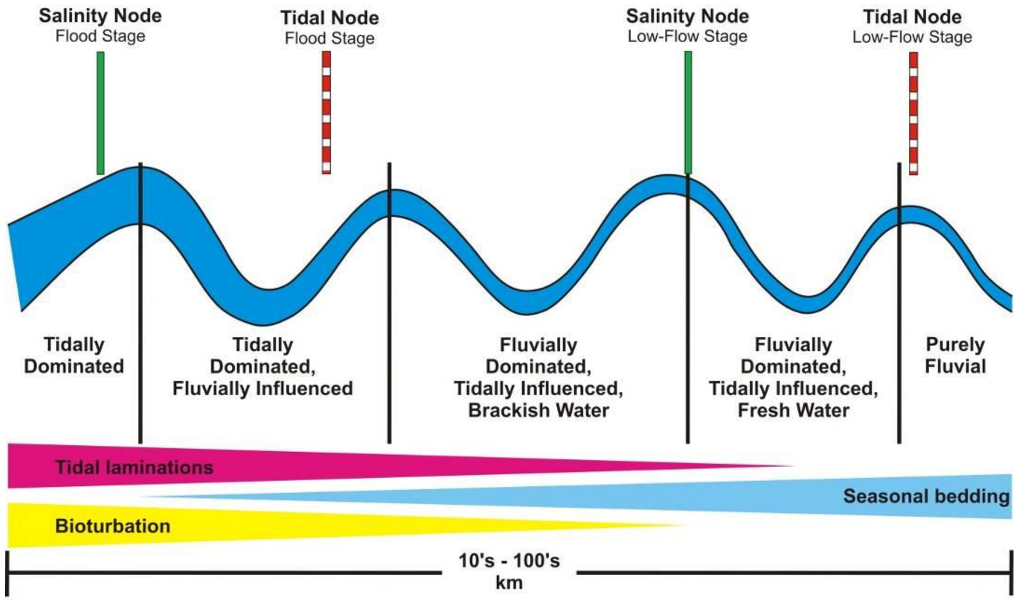

Figure 1: Schematic map of the fluvial-tidal transition displaying the variation in depositional conditions and structures as a function of the relative importance of fluvial and tidal energy. Through the transition, there is a change in the relative abundance of tidal sedimentary structures (e.g., tidal bundles, tidal rhythmites), the amount of bioturbation, and the prominence of bedding related to seasonal variations in river discharge. The migration of the salinity and tidal nodes (i.e., the limit of salinity and tidal intrusion up the river) in response to seasonal variations in river discharge is also shown.

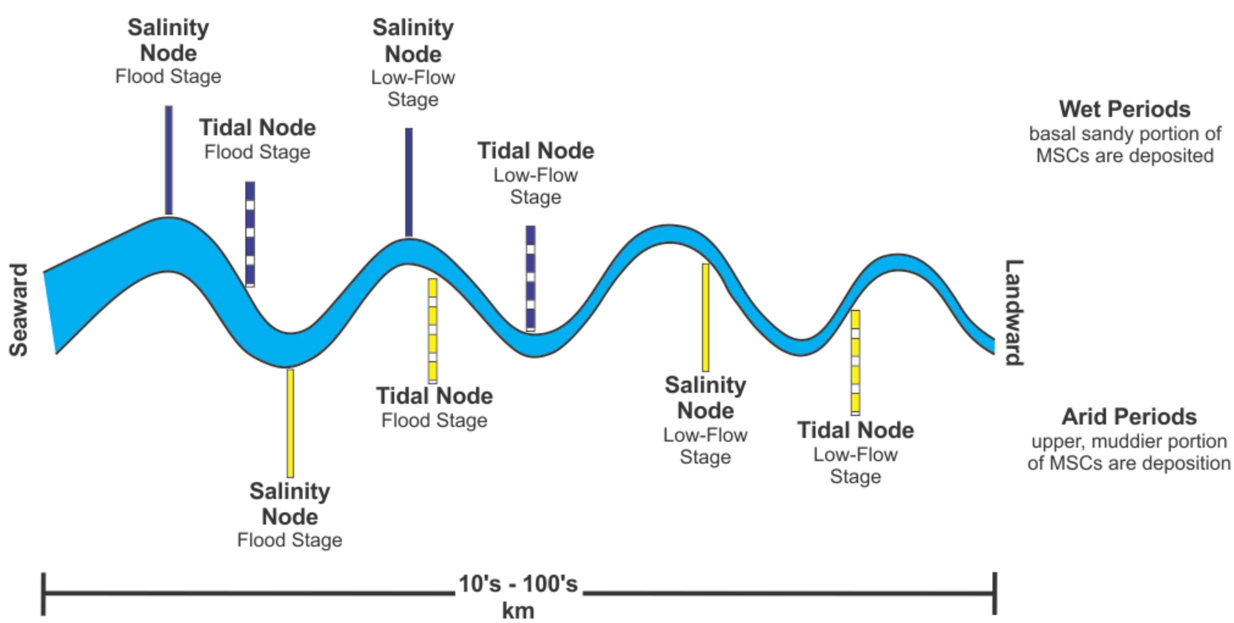

Figure 2: Theoretical displacement of the salinity and tidal nodes as a function of the variations in river discharge both seasonally and over decadal climate cycles. During wet periods (upper part of diagram), nodes (both low-flow and flood-stage) are pushed farther seaward and the basal sandy part of an MSC forms, while during dry periods (lower part of diagram) there is a landward incursion of the nodes during which time the muddier upper portion of an MSC is deposited. The displacement in location of the seasonal nodes is thought to be more pronounced during dry periods, when river discharge is lower. Depending on the size of the river, the displacement of the nodes could be 10’s to 100’s of kilometres (Kravtsova et al., 2009; Purnachandra Roa et al., 2011). The positions of the nodes are relative and represent the most extreme conditions. Hypothetically, there is a continuum of nodal locations that continually change.

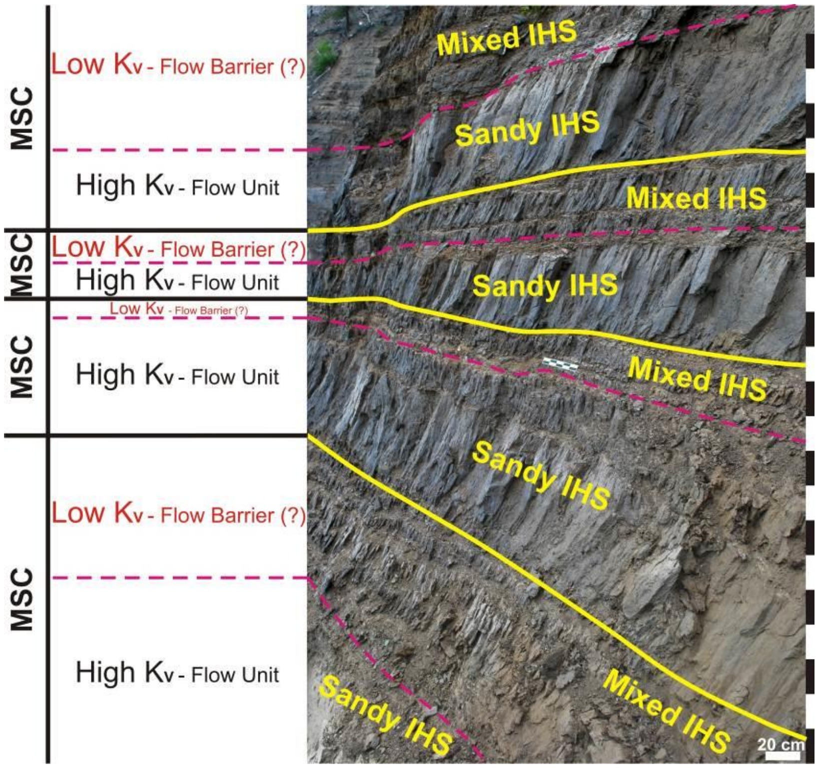

Figure 3: Stacked MSCs (denoted by yellow lines) in outcrop. Though individual mud beds within the muddier IHS (mixed IHS) are relatively thin (< 10 cm thickness) their concentration within a small vertical interval likely creates vertical permeability barriers. The basal sandier portions of an MSC (sandy IHS) will have higher relative permeability and may form potential bitumen reservoirs/flow units.

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