Building Blocks for Process-Mimicking Modeling of the Middle McMurray Formation

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The majority of oil sand deposits of the Northern Alberta exist within estuarine channel point bar deposits of the middle McMurray Formation. This paper presents a review of estuarine tidal channels and a methodology for stochastic modeling of such an estuarine system. The ESTUSIM algorithm is a process mimicking modeling algorithm based on the parameterization of estuarine tidal channels. An example is illustrated and the idea for making dynamic channels is proposed. The algorithm is under development.

Introduction

McMurray formation of the northern Alberta, which is the oil bearing formation in Athabasca oil sands area, is known for its complex geological heterogeneity. Detailed modeling of the heterogeneity in the McMurray formation requires a better understanding of the sub-surface geology. There are different geological interpretations of the McMurray Formation that are generated based on observations of the outcrops and cores and also based on the underlying physical laws. The conceptual geological models that are built from these interpretations appear realistic and account for the geologic information, but do not offer a model for uncertainty and also rarely show the small scale heterogeneity.

Geostatistical techniques are useful tools for characterizing heterogeneity and quantifying uncertainty. The cell-based geostatistical techniques are often unable to reproduce geological realistic models. Object-based facies modeling techniques generate visually attractive and geological realistic model by mimic idealized geometries interpreted by geologists.

Several studies on the geology of the McMurray Formation in Athabasca oil sands deposits suggest that the majority of the heavy oil deposits are exist within fluvial-estuarine channel point bar deposits of the Lower Cretaceous McMurray Formation (See Paper 201 in current CCG annual report).

The scope of this research is to develop the steps for process mimicking modeling of middle McMurray Formation estuarine system. The geomorpholy and dynamics of estuarine tidal channel is reviewed and the geometrical parameters of tidal channels are parameterized. Then, a proposed methodology for stochastically generating the estuarine channelized system is presented.

Estuarine and Tidal Channels

An estuary is defined as the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial process (Dalrymple et al., 1992). If the sediment is supplied mostly from the fluvial part the site called as a delta and if the sediment is delivered to the area only by marine process the environment is known as a prograding coast. Dalrymple et al. (1992) divided the estuaries into two major groups of wave-dominated and tide-dominated estuaries based on the relative influence of waves and tides.

In the wave-dominated estuaries, tidal influence is small and the mouth of the system is dominated by relatively high wave energy which pushes sediments to move alongshore or onshore into the mouth of the estuary and develop a sub-aerial barrier.

Tide-dominated estuaries are generated if the wave action is limited and/or the tidal prism is large (Hayes, 1979). In this case the tidal current energy is dominated at the mouth of estuary and elongate sand bars are typically developed. Figure 1 shows the plan view and cross sectional view of wave and tide dominated estuaries.

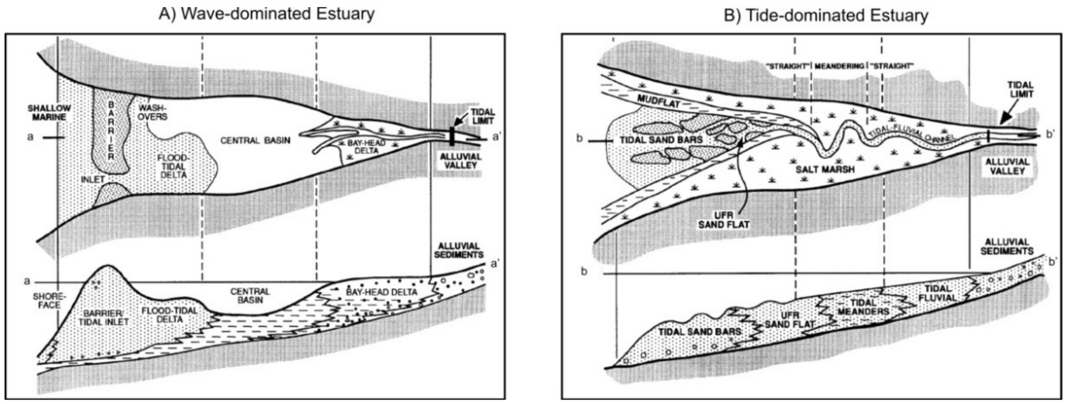

Figure 1. Distribution of morphological elements and sedimentary facies in plan-view (top) and cross sectional view (bottom) for A) Wave-dominated estuary and B) Tide-dominated estuary (modified after Dalrymple, 1992).

Tide cycles take place in a relatively short time scale of one day. Each cycle has two phases; the flood phase, when the direction of flow is from the sea to the land and the ebb phase when the flow is in the opposite direction. Flood velocities are greater than ebb velocities and the flood phase is usually shorter than the ebb-phase (Vignoli, 2005).

There are intrinsic differences between the morphology and sedimentary of tide-dominated channels and completely fluvial channels. Tidal point bars are similar in shape to that of fluvial bars. The dynamics of estuarine point bars is still poorly understood compare to the fluvial point bars (Dalrymple and Rhodes, 1995). The deposits in tidal channels are finer grained than in a fluvial channel. The stability of tidal channels subject to tidal flow dynamics is more than the fluvial channels and occurrence of channel abandonment by chute cut-off and avulsion is lower in tidal channels because of higher water elevation and lower velocity. Channels in fluvial setting are much deeper than the tidal channels. Development of levee and crevasse in the tidal channels are rare or absent (Barwis, 1978).

The dynamics of tidal channel is a complex phenomenon that reveals the presence of several spatial and temporal scales. Tidal range is important parameters for characterization of facies in the tide dominated estuaries. It may vary from micro scale to mega scale.

Estuarine Modeling

Parameterization of estuarine tidal channel is required for stochastic modeling of estuarine system. Channel convergence factor, width to depth ratio, channel branching, channel curvature, channel profile are some of the most important parameters of tidal channels.

Channel Convergence

Tide-dominated estuaries are usually funnel-shaped which means that the main channel typically narrows as moving from the sea to the land (Dalrymple et al., 1992). This change in the channel width relative to the intrinsic length of the channel is called the channel convergence. Channel convergence may appreciably affect the distribution of point bars within the tidal channel. Several authors have discussed about the challenges that the channel convergence may introduced into the tidal estuarine system (Jay, 1991; Lanzoni and Seminara, 1998; Marani et al., 2002). Marani et al. (2002) investigated several tidal channels and noticed that there is an exponential relationship between the channel half width and the intrinsic length of tidal channels (see Figure 2).

Width to Depth Ratio

Width to depth ratio (or aspect ratio) of tidal channel is an important parameter that has strong effect on the erosional and migration mechanism of meandering development. Studies on the tidal channels reveals clear differences in the value of width to depth ratio. In salt marshes, the ratio is mostly in the range of 5 to 7 (Marani et al, 2002). This range is quite different from the value observed in the meandering rivers by Millar, 2000 (8 to 48). The width to depth ratio for the river like pattern tidal flats is pretty much the same as the fluvial rivers (8 to 50).

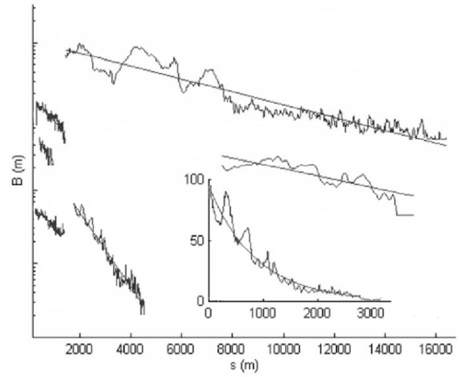

Figure 2. Logarithm of the half width of channels versus the intrinsic coordinate (Marani, et al., 2002).

Channel Branching

Investigation of tidal environment such as the estuarine and deltaic system, reveal that during the evolution of main channel several channels may be branched from it. The branching may take place for the branched channel itself. Considering the main channel as the first level channel, all the channels branching from the first level is called the second level channels and all the channels branched from the second level is called third level channel, and so on. Depends on the scale of the investigation, up to four channel levels may be expected. Figure 3 shows aerial photo of a portion of a tidal channel networks in the lagoon of Venice. As it is clearly shown in the digitized photo, most of the channel branching appears at the high channel curvature. This fact may be supported by the physical laws where at the higher curvature the flow velocity is higher and there is higher chance of channel branching.

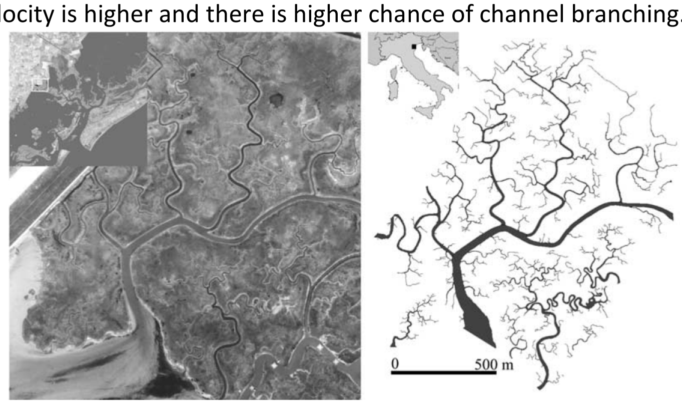

Figure 3. The aerial photo of a portion of lagoon of venice (left) and the digitized image (right) which shows all the channels in the tidal network (Marani, et al., 2002).

Channel Curvature

Channel curvature is an important geometrical parameter of tidal channel to identifying the branching locations. Curvature is generally defined as a parameter that shows the amount of deviation from the strait line. There are different mathematical definitions for curvature. The curvature at each location on the curve can be defined as the inverse of radius of the unique circle that touches the curve at that location:

$$C(s) = \frac{1}{r_s}$$

where r_s is the radius of tangent circle. The curvature can also been defined as the gradient of tangent angle between two points on the curve:

$$C(s) = \frac{d\theta}{ds}$$

where θ is the tangent angle and s is intrinsic distance on the curve.

In the both above definitions the curvature is not dimensionless and may not numerically make sense. Here, for the application of tidal channels, we define another definition for curvature that is dimensionless. Considering a channel streamline and the associated discretization points on the channel curve with discretization distance of t . The curvature for each discretization point is defined as the ratio of the distance between the point and centre of the line passing the two adjacent points to the discretization distance (see Figure 4). The clockwise curvature is defined as positive and the counter-clockwise curve as a negative value.

$$C_i = \frac{d_i}{t} = \frac{\sqrt{\left(x_i - \left(\frac{x_{i-1}+x_{i+1}}{2}\right)\right)^2 + \left(y_i - \left(\frac{y_{i-1}+y_{i+1}}{2}\right)\right)^2}}{t}$$

where d_i is the distance between the discretization point and the centre of line connecting two adjacent points, x_i and y_i are the Cartesian coordinates of the discretization point. Figure 5 shows and example of channel streamline and the calculated curvature for all discretization points on the channel.

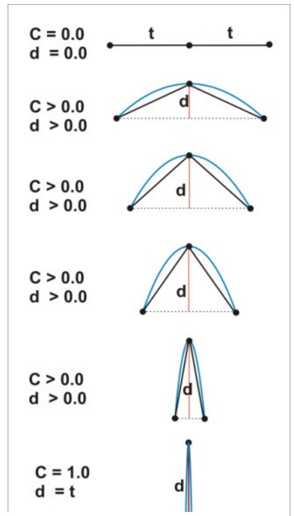

Figure 4. Dimensionless curvature definition for three discretization points on the channel streamline.

Channel Streamline

Channel streamline represents the central axes of the channel. The disturbed periodic model that has been introduced by Frguson (1976) provides a realistic streamline model. This model has been used for stochastic modeling of fluvial channel meandering (Pyrcz, 2004).

$$\theta + \frac{2h}{k}\frac{d\theta}{ds} + \frac{1}{k^2}\frac{d^2\theta}{ds^2} = \varepsilon(s)$$

where θ is the tangent angle, k is related to the primary wavelength, h is the dampening factor and $\varepsilon(s)$ is the disturbance value. The discrete approximation of the periodic model can be achieved by a second order autoregressive model of the following form:

$$\theta_i - b_1\theta_{i-1} - b_2\theta_{i-2} = \varepsilon_i$$

Where the coefficients are defined as:

$$b_1 = 2\exp(-kh)\cos(k\cos\phi)$$
$$b_2 = -\exp(-2kh)$$

This approximation can be applied to stochastically model the channel streamline.

Channel Profile

The vertical channel profile can be defined based on the available fluvial object based modeling tools (FLUVSIM; Deutsch and Tran, 2002 and ALLUVSIM; Pyrcz, 2004). The channel is parameterized by a streamline, relative thalweg, width to depth ratio and depth.

ESTUSIM Algorithm

An algorithm for stochastic modeling of estuarine environment is developed. The objective of this modeling is to stochastically generate a channel network such as the one in Figure 3. The simulation is started by generating a channel streamline for the main estuary channel (level 1). A random point is selected from the user specified coastal line. The channel width is calculated for all discretization points on the main channel based on the random picked initial channel width value. Then the channel is cut from the discretization point that has the width less than the minimum channel width. The next step is to find the candidate locations for channel branching. This requires calculation of the channel curvature at all discretization points and finding the local maximum and minimum channel curvature locations. Once the candidate branching locations are defined, the simulation proceeds by generating a new channel at

second level that starts from the branching candidate locations. This algorithm continues for all channel levels until the pre-specified channel to non-channel ratio is reached.
Figure 6 shows an example of the estuarine model generated with the ESTUSIM. There are three different channel levels. The initial channel width for each channel in the model is set to a fraction of the branching location's width in the mother channel. The maximum number of channels is specified at each level.

Making Dynamic Channel Model

The methodology presented above is appropriate to generate a snapshot of tidal channel network for a specific time step. The static model such as the one presented in the example may be suitable to be used as training image for the cases that the channel and non-channel facies is important. The fact is that the channels in tidal channel environment may migrate laterally during a long time period. The lateral migration of tidal channels leads to development of inclined heterolithic stratification (IHS) bedsets over the channel accretionary bank (Thomas et al., 1987). IHS sets are one of the important facies associations of the middle McMurray Formation in the Athabasca oil sand deposits. A detailed understanding of IHS deposits of the middle McMurray Formation has been of particular interest of many researchers because these heterogeneous elements play an important role in development of in-situ processes.

Pyrcz and Deutsch (2004), proposed a methodology to stochastically model the IHS accretionary surfaces. The accretionary surfaces are generated by migration the channel based on the bank retreat model of Howard (1992). Applying the bank retreat model for the tidal channels of estuary may not be a good option since the evolution and migration of tidal channels are completely different from the fluvial channels. The bi-directional flow in the tidal channel, suggests the migration of channel in the direction of tide. One possible process for making the tidal channels dynamic is channel rotation and stretch/compression. This process is more likely the same as the process that taken place in migration of tidal channels in the estuarine system. Figure shows the dynamic channel streamlines with rotation and stretch/compression process and generation of IHS sets.

Conclusion

The geometrical parameters of estuarine tidal channels are parameterized and a methodology for process mimicking modeling of estuarine system is presented. An unconditional example of estuarine modeling is illustrated. This model may be used as a training image for inferring statistical information for multiple-point geostatistical modeling. Making dynamic channels for generation of IHS sets would be the future work of this research. Conditioning the model to the areal and vertical trend of IHS thickness, and providing a GSLIB program for estuarine modeling are other possible researches.

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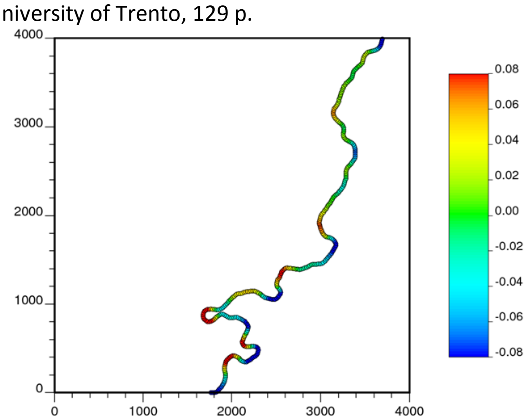

Figure 5. An example of channel streamline and the calculated dimensionless curvature.

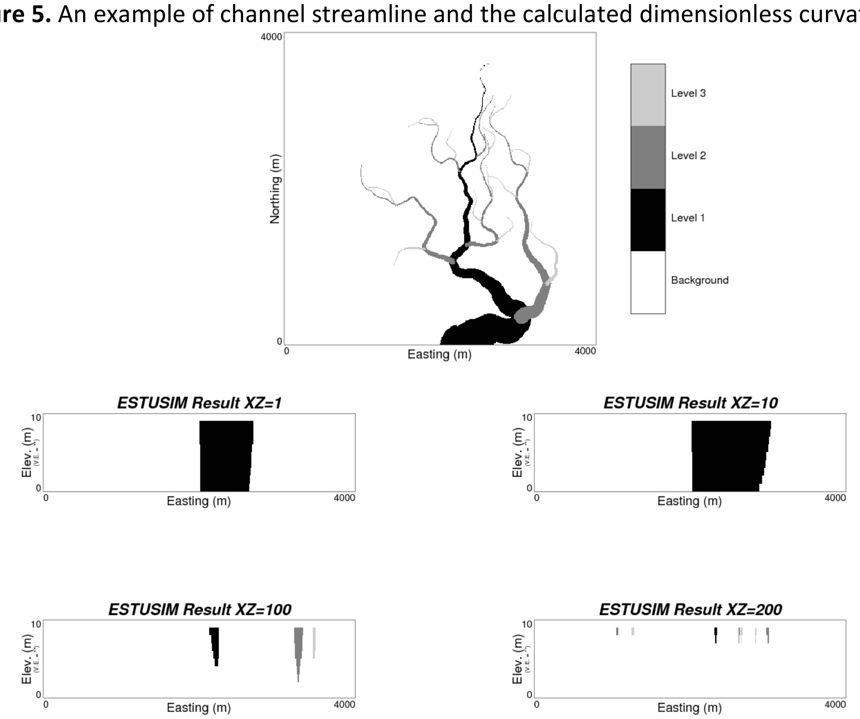

Figure 6. Plan view of estuarine model (top), and the vertical cross sections.

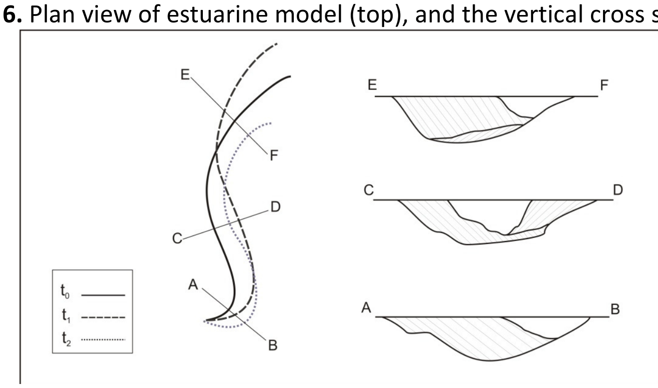

Figure 7. Possible dynamic channel process and generation of IHS sets.