

Grid-Free Object-based Modeling of IHS Facies in the McMurray Formation

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The McMurray Formation contains multi-scale complex geological features that were partially formed in an estuarine depositional environment. The inclined heterolithic stratifications deposited as part of tidal channels contain centimeter scale features that are important for flow characterization of SAGD processes. These tidal channels are common and interrelated over many square kilometers. Modeling the detailed facies in such estuarine systems requires a methodology that reflects heterogeneity over many scales. The grid-free approach presented in the paper 107 in this report is applied to the estuarine facies of the McMurray Formation.

1. Introduction

The Alberta oil sands deposits are the largest oil sands deposits in the world with estimated initial oil in place of 1.7 trillion barrels of oil (Government of Alberta, 2007). The Majority of oil sands in the Athabasca oil sand exist within the channel point bar of the McMurray Formation.

The McMurray Formation was deposited within the fluvial-estuarine environment (Carrigy, 1959; Flach, 1984; Smith, 1987). Carrigy (1959) subdivided the McMurray Formation into three stratigraphic units. The Lower McMurray unit mainly contains massive or high angle fine to coarse pebbly sands and considered to be deposited within the fluvial environment. The Upper Unit of the McMurray Formation is known by horizontal strata which are often in sharp contrast to Inclined Heterolithic Strata (IHS) beds of the middle McMurray. The middle unit of the McMurray Formation is thickest and contains the best reservoir sands that were deposited within a tidally influenced middle to outer estuarine system (Ranger and ginger, 2003).

Beside the abandoned channel-fill facies which are predominated by mud and considered as permeability barriers, there are two distinct reservoir facies associations available in the middle McMurray unit (Ranger and ginger, 2003); the large scale cross-stratified sand and the inclined heterolithic stratification.

The cross-stratified sand is characterized by excellent porosity and permeability and high bitumen saturation. Ranger and Gingras (2003) suggested considering this facies in the lower (outer) estuary proximal to the estuary mouth. The clean sand of this facies association is the most desirable reservoir facies.

The IHS is the main reservoir facies in the McMurray Formation. IHS packages consist of inclined repetitive sets of decimeter to meter thick couplets of sand and mud. IHS varies in contents from those dominated by clean sand to those composed almost of mud. It has been proven that the majority of IHS deposits are generated as a result of point bar lateral accretion within meandering channel of freshwater rivers, tidally influenced rivers and creeks draining intertidal mudflats (Thomas et al., 1987). IHS facies association has very complex geology and is the cause of most of the heterogeneities in the McMurray Formation. The IHS deposited as part of tidal channels contain centimeter scale features. These tidal channels are common and interrelated over many square kilometers. The geological complexity of IHS exists at many scales. Figure 1 shows geology of IHS deposits at three scales of interest.

Modeling the detailed facies in estuarine systems that contain multi-scales geological features requires a methodology that captures heterogeneity over multiple scales. Pyrcz and Deutsch (2004) presented a stochastic event-based methodology that generates IHS models based on the lateral migration of meandering channels. Mud drapes are modeled separately and incorporated into the IHS model. The resulting model looks realistic but lacks important details of IHS architectures such as shale drape geometry. Wen (2004) presented an surface-based modeling approach to generate 3D IHS beds. Patruyo et al. (2009) modeled IHS set by analyzing the high quality seismic reflection time slices.

In this paper, a new methodology is presented in the grid free mode (see paper 107) for IHS modeling of the McMurray Formation. This methodology enables us to model kilometer scale IHS sets with small scale features. Parameterization of IHS set is explained in detail, followed by a simulation algorithm and examples.

2. Architectural Elements and Parameterization

Figure 2 shows the architectural elements of a single IHS set. Five architectural elements (lithofacies) are considered; (1) CSS, (2) PBS, (3) SH, (4) BR, and (5) CHF.

The cross-stratified sands facies (CSS), as discussed earlier, is the best reservoir sand and considered as a background facies. This facies has as strong tidal indicators and suggested to be part of outer estuarine system (Pemberton et al., 1982; Rnagers and Gingras, 2003). Lateral migration of tidal channels that are incised into CSS eroded this facies and generated the IHS packages.

The basic lithological building blocks of the IHS set are inclined units that comprises of alternating sand and mud. The point bar sands (PBS) is the sand member of this unit that has been seen in the majority of outcrops to be homolithic (Thomas et al., 1987). So, this facies is considered to be the background facies inside the IHS set volume.

The mud member of the inclined unit is called mud or shale drapes (SH). Individual shale drapes are known from outcrops to be laterally continuous from the top of a facies unit to near the base with decreasing thickness. There is a general fining-upward trend inside this facies that make it heterolithic; however, for simplicity it will be assumed that the shale drapes are considered to be homolithic. The IHS set are usually capped by a sheet layer of shale that has the same facies characteristic (top). Here top shale is modeled as a separate element that contains the same facies type as the shale drapes.

The mud clast breccias (BR) can be found at the bottom of a channel succession as a result of erosion of previously deposited muddy point bars and overbank collapse. This element is assumed to be a thin layer positioned in the bottom of the IHS volume.

The channel fill element (CHF) is the channel geometry that bounds the IHS set and can be filled with mud and sand but usually acts as a permeability barrier. If channel abandonment occurred, the channel is filled mostly by mud in a fining-upward trend.

Parameterization of a single IHS set involves 3D representation of volume, top shale, bottom breccias, and shale drapes. Details of parameterization are presented in the following sections.

IHS Volume

The IHS volume is the framework that all the facies associations are placed inside of or attached to (Figure 3). A simple IHS set volume geometry can be characterized by two lobe-shape planes on the top and bottom that are connected together with two inclined sigmoidal surfaces in the front and back. In plan view (bottom left corner of Figure 3) it is clear that the bottom lobe-shape plane has the same geometry as the top, but with a larger surface area. This difference in the surface area of the top and bottom planes is closely related to the dipping of strata from top to the bottom. A larger dip angles results in less difference between top and bottom plane size.

Any x - y cross section of the IHS volume is a lobe-shape geometry that has greater surface area than the top plane and lesser than the bottom plane. This geometric feature simplifies the parameterization of IHS volumes. Assuming a uniform vertical profile for the front and back surfaces would further simplify the parameterization and reduce the problem to parameterization of a single plane and the vertical profile.

As shown in Figure 3, the top plane can be parameterized with five parameters. W_{\min} is the opening width of the IHS set which can be related to the meandering wavelength of initial channel meanders. W_{\max} is the maximum width of the IHS set and can get arbitrary value. L is the length of IHS set which is related to the channel migration distance. The bi coefficient identifies the relative location of maximum IHS width as fraction of length (L), and ci relates to the curvature of initial channel. Using these five parameters, the coordinates of six key points can be calculated relative to the point P_0 in the figure that is called the anchor points of IHS set. In the grid free simulation mode (see paper 107 in this report), the IHS volume is represented with these key points. The anchor point is not only important in positioning of the IHS set but it will be used in the parameterization of shale drapes and the rasterization of IHS sets.

A smooth interpolator, such as a cubic spline, can be used to connect the key points and generate the boundaries of the top plane. Figure 3 shows some examples of IHS sets with different parameters in plan view.

$$\begin{aligned}
 P_1 : \begin{cases} x_1 = x_0 + 0.5 * W_{\min} \\ y_1 = y_0 \end{cases} , & P_2 : \begin{cases} x_2 = x_0 + 0.5 * W_{\max} \\ y_2 = y_0 + bi * L \end{cases} \\
 P_3 : \begin{cases} x_3 = x_0 \\ y_3 = y_0 + L \end{cases} , & P_4 : \begin{cases} x_4 = x_0 - 0.5 * W_{\max} \\ y_4 = y_0 + bi * L \end{cases} \\
 P_5 : \begin{cases} x_5 = x_0 - 0.5 * W_{\min} \\ y_5 = y_0 \end{cases} , & P_6 : \begin{cases} x_6 = x_0 \\ y_6 = y_0 + ci * L \end{cases}
 \end{aligned} \tag{1}$$

According to Thomas et al. (1987), the vertical profile of inclined strata can be characterized as straight, sigmoidal, concave-upward, or convex-upward. A cubic polynomial shown in Equation (2) is utilized to generate different IHS vertical profiles.

$$Z(s) = a_1 \cdot s^3 + a_2 \cdot s^2 + a_3 \cdot s + a_4 \tag{2}$$

where a_i 's are the coefficients and s is the distance in any channel migration direction. The coefficients of the cubic equation can be calculated by considering the IHS set's thickness (h), dip angle (α), profile slope on top (m_t), and profile slope in bottom (m_b). Different vertical profile can be generated by changing the top and bottom slopes. Figure 4 shows different possible profiles that can be generated with Equation (2). Note that the vertical profile is assumed to be constant in all directions.

The IHS volume is fully characterized by the top six points and the vertical profile parameters.

Top Shale and Breccia

Top shale and the breccia facies in the bottom of IHS set are considered as sheet layers and can be parameterized as a fraction of the total thickness of the IHS set. These two elements of IHS set are optional and can be excluded by setting the thickness to zero.

Shale Drape

Shale drapes are the most important elements of the IHS set that impose heterogeneity in the IHS sets and effect SAGD performance. Figure 5 shows the detailed parameterization of shale drapes. To place the shale drapes in the IHS volume, the location of the accretionary surfaces must be determined first. Then the shale drapes are placed on top of the accretionary surfaces. For simplicity, the accretionary surfaces are assumed to be parallel to each other with a constant offset following the same curvature as the initial channel curvature. The only parameter required to determine the location of accretionary surfaces is the number of accretionary surfaces (n_{acs}). The accretionary distance ($(1-bi)*L$) is then divided into $n_{acs} + 1$ sections and the coordinates of accretionary surfaces are calculated relative to the anchor point. Note that the accretionary surfaces are not generated as objects in the modeling but they are only used to indicate the relative location of shale drapes.

As shown in Figure 5, shale drapes are lense-shape objects with different thicknesses that are either completely or partially extended over the accretionary surfaces. In the vertical direction, they follow the same profile as the IHS volume with decreasing thickness from top to bottom. Top horizontal thickness (t_{drape}) and vertical extension of shale drapes (h_{drape}) are the parameters that are used for shale drape modeling. In grid free simulation, shale drapes are characterized with four key points on the top plane and the vertical profile. Coordinates of the key points are calculated with the relative location of the accretionary surface and t_{drape} . The vertical thickness variation is assumed to be linear. Figure 7 shows example of a single IHS set with the associate architectural elements.

Channel

Figure 6 shows the bounding channel parameterization. Since the inner bank of the channel has already been generated by the IHS volume, the vertical geometry of the channel can be easily generated with the vertical channel width function. A quadratic function is used to model the channel width in the vertical direction.

$$W(z) = a_1 z^2 + a_2 z + a_3 \tag{3}$$

where a_i 's are the coefficients and z is distance in the vertical direction. The channel maximum depth (h), channel thalweg (t), and the top channel width ($W(h)$) are used to calculate the coefficients of Equation (3). As shown in Figure 6, the maximum channel depth is equal to the IHS thickness and the top channel thickness is related to the IHS dip and the channel thalweg.

3. Grid-Free Modeling Algorithm

A grid-free modeling algorithm is proposed for unconditional simulation of IHS sets. As discussed in paper 107 in this report the simulation engine and the rasterization should be developed. Since, only one geo-object (IHS set) is used in this modeling, there is not any significant advantage to creating a separate geological database. The geological object database is integrated into two other components.

Simulation Engine

The simulation engine is a stochastic object/event based technique. Objects are generated based on some geological rules and stored in a grid free format. Vertical and lateral channel stacking are the two main geological rules implemented. Only the location and the key parameters of objects are stored in the output file. Objects are recorded based on their geological time (older to younger). A FORTRAN program called IHSSIM is developed to implement the grid-free simulation (see paper 403 in this report).

Vertical stacking starts from the base of the model. The number of aggradation levels is provided to the simulator to control the vertical stacking. This information may be provided by the well logs, outcrops or analogue data. More aggradation level leads to generation of complex cosets that are superimposed and overlap.

Within each vertical stacking level, several lateral stacking occur. The lateral stacking of IHS sets are controlled with the number of meandering channels in each aggradation level. More channels leads to generation of more amalgamated IHS sets.

The meandering channels are not generated, instead, a channel line which represents the general orientation of the meandering channel is considered. The channel line is represented by a source location and an azimuth angle and IHS sets are attached to the line in such a way as to generate a realistic meandering channel pattern. Figure 8 shows how several IHS packages are attached to the channel line.

Channel meandering wavelength, amplitude to wavelength ratio, and IHS width to the wavelength ratio are required for IHS generation. These variables are used to calculate the top key points of the IHS body discussed previously and the location of IHS's anchor point. Other required parameters for the IHS set are picked from the associated Gaussian distribution. Once the IHS volume is generated, other associated architectural elements are placed.

The number of shale drapes in each aggradation level is controlled with the shale frequency parameter. Higher shale frequency results in muddier IHS packages. Generation of IHS sets along the channel line halts when the new IHS set anchor point falls outside the modeling area.

Rasterization Engine

A program called IHSTAST is developed to rasterize the grid-free model generated by the simulation engine. Details of IHS rasterization is presented in paper 413 in this report.

Geo-objects are rasterized in the order of their geological time (older objects first). IHS volume is rasterized first, slice by slice in the z direction. For each slice in the z direction, the transformation distance is calculated using the cubic equation of vertical profile, the top six points of IHS body are then transformed by that distance. A cubic spline interpolator is used to make smooth the boundary of the IHS at the current z slice. All grid cells in x - y plane that fall inside the IHS boundary are coded as point bar sands (PBS). Top shale (SH), breccia (BR), channel fill (CHF) and the shale drapes (SH) are rasterized with the same procedure. The linear thickness variation (thicker at the top) should also be considered in the rasterization of shale drapes. Figure 9 shows a single channel line with four attached IHS sets in different cross sections generated with IHSSIM and IHSTAST.

4. Example

To demonstrate the methodology, an unconditional facies model for the middle McMurray Formation is presented. A modeling area of 5 km by 5 km by 50 m is considered. A general South-North direction is assumed for the channel lines. Four aggradation levels are considered with 5, 7, 5, and 10 channels in each level respectively. Shale drape frequencies are selected in a way to reproduce a vertical trend in the shale contents of the model; the

IHS sets in the upper levels are muddier. To visualize the model it has been rasterized with 10m by 10m by 0.5m grid cells for the whole area, a total of 5 million cells. Figure 10 shows multiple cross sections of the generated facies model. Small scale features are well reproduced because of the small grid size in the vertical direction. In the plan view some features may have been missed with the 10m by 10m grid. Rasterization with a smaller grid size of 2m by 2m by 0.5m (Figure 11) shows all the desired features.

5. Conclusions

A methodology for grid-free modeling of IHS sets in the McMurray Formation is presented. The simulation is computationally efficient as grid cells are never estimated individually. Moreover, unconditional facies models of any resolution can be generated. The unconditional facies models can be used as training images in multiple point simulation. Conditioning the simulation algorithm to the available geological data is considered future work. More estuarine geological objects such as tidal channels and tidal flat are required to generate a complete geological object data base.

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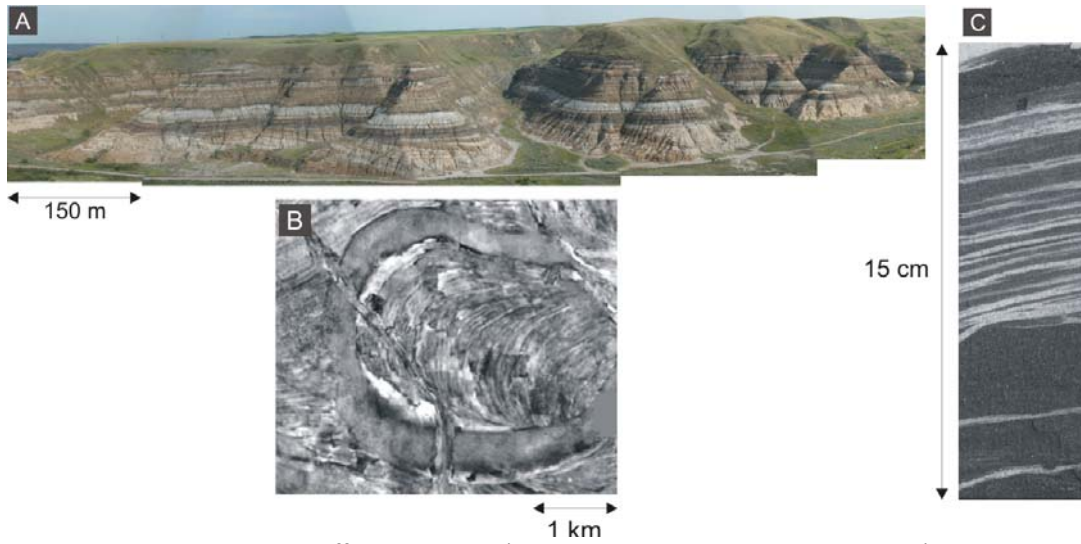


Figure 1: IHS geology Complexity in different scales. A) IHS outcrop in Drumheller, Alberta. B) seismic time slice of a single IHS set extended over 4 km (Fustic et al., 2008), C) a core photo from IHS in McMurray Formation.

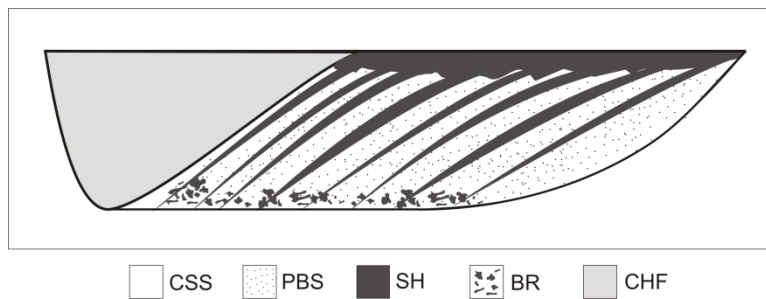


Figure 2: Architectural Elements of Inclined Heterolithic Stratification (IHS).

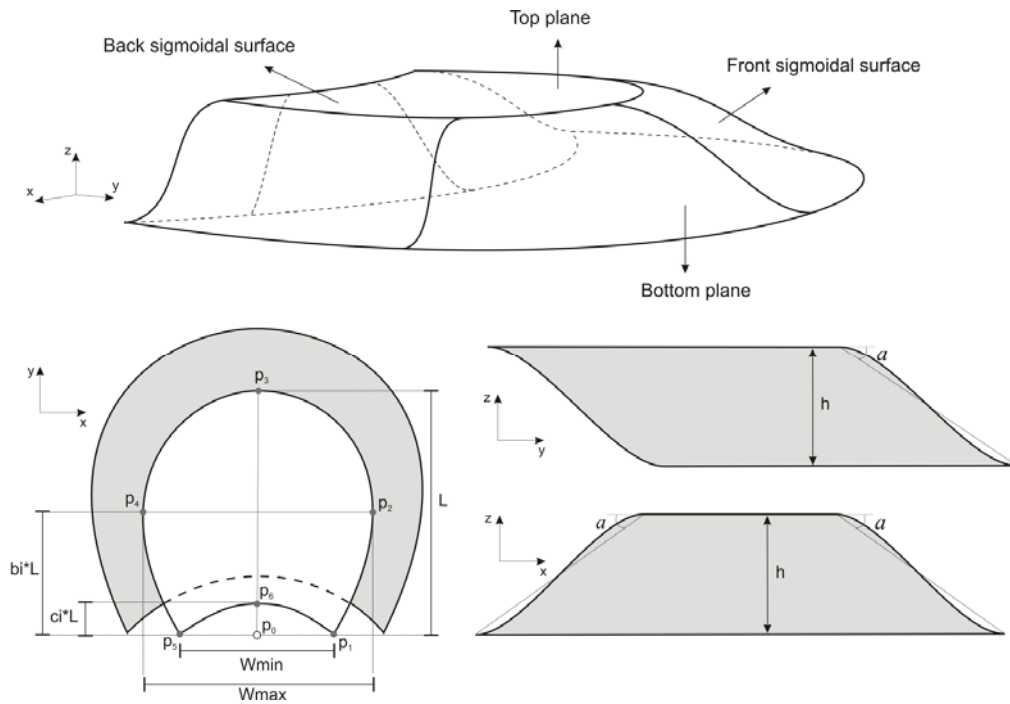


Figure 3: IHS Volume Parameterization.

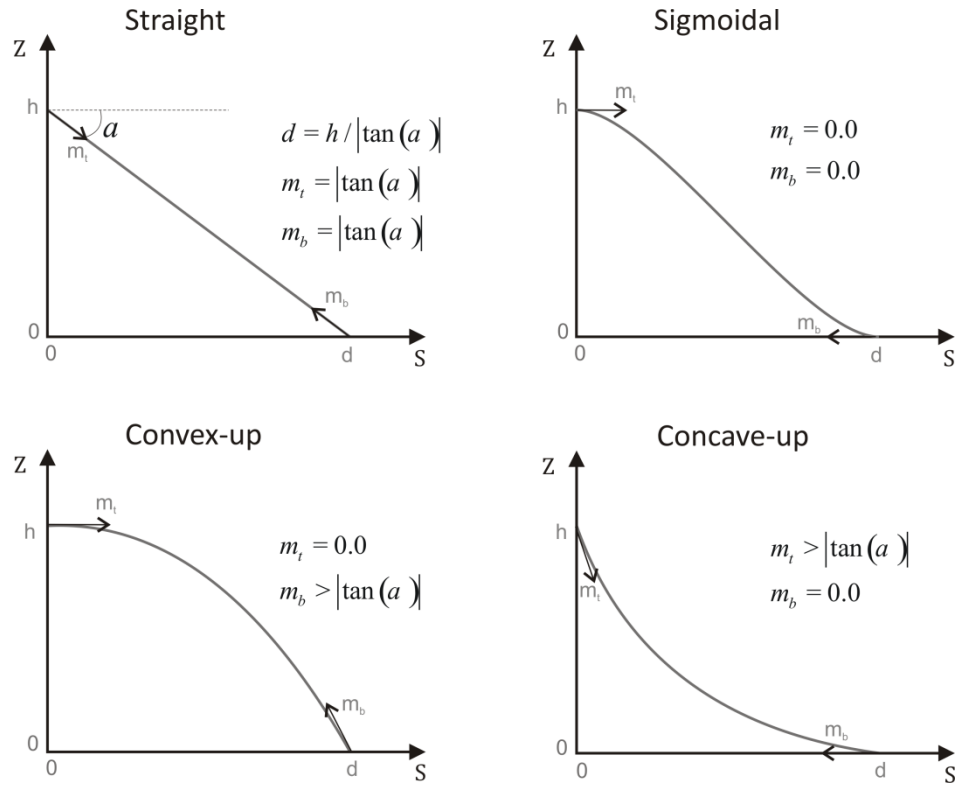


Figure 4: Vertical Profile Parameterization.

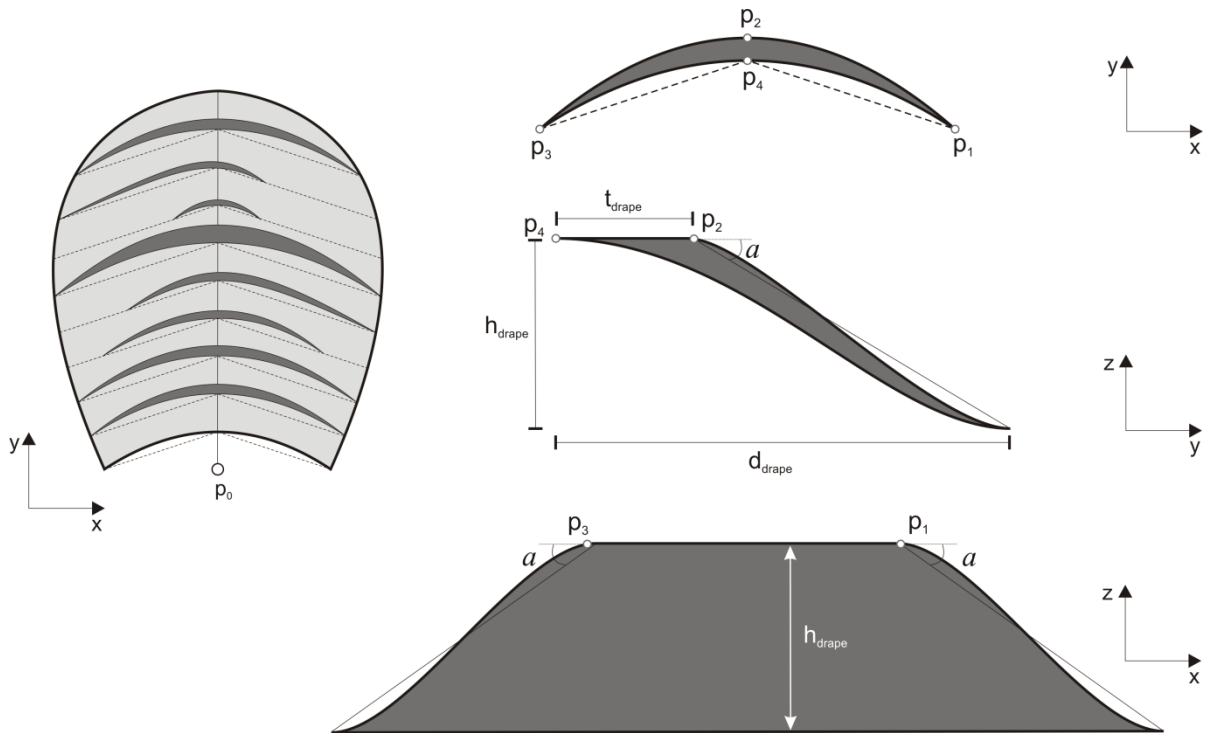


Figure 5: Shale drape parameterization.

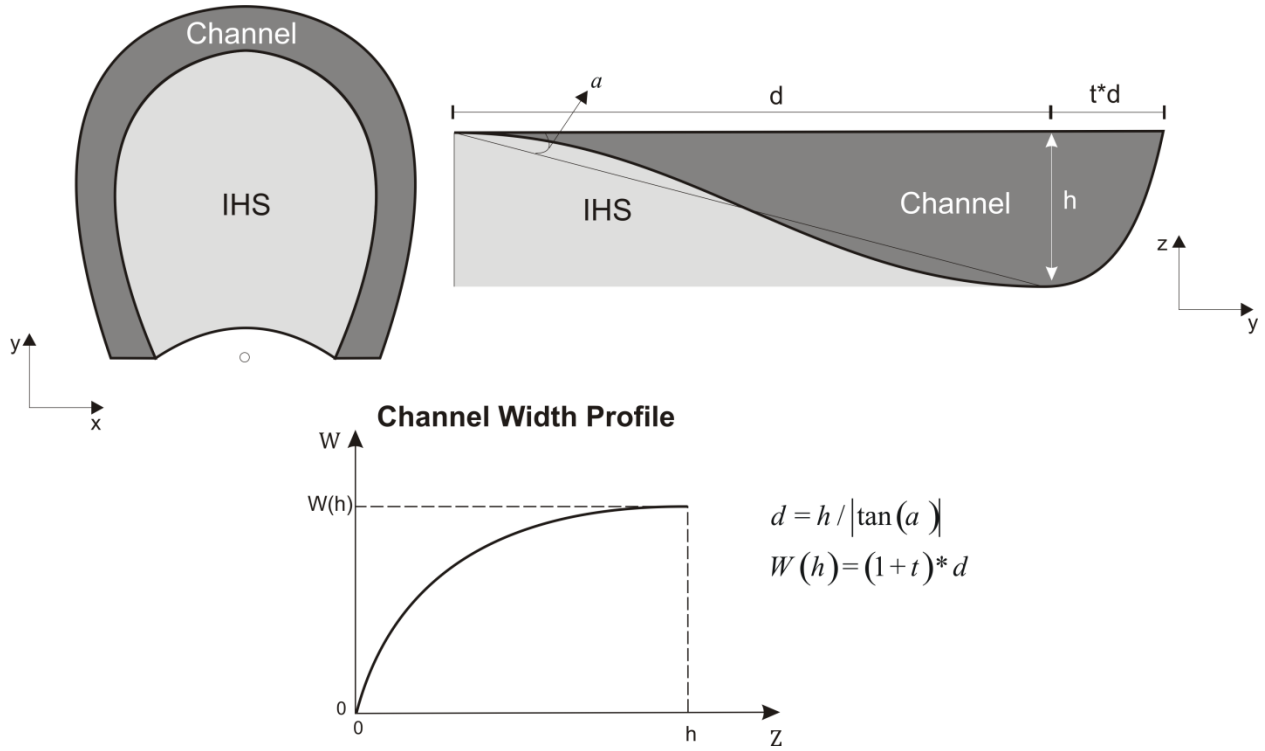


Figure 6: Channel Profile parameterization.

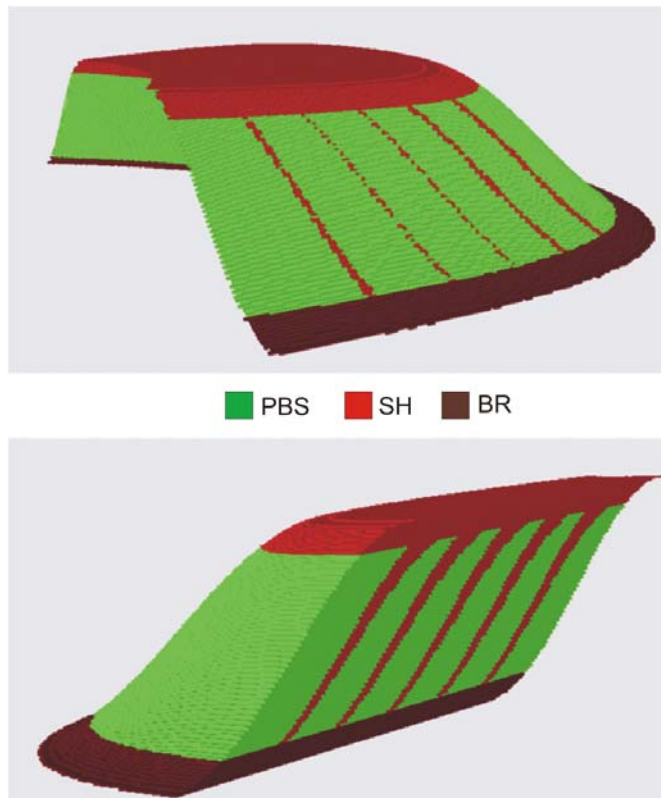


Figure 7: Example of IHS Set and the associated architectural elements, 3D view (top) and the cross section (bottom).

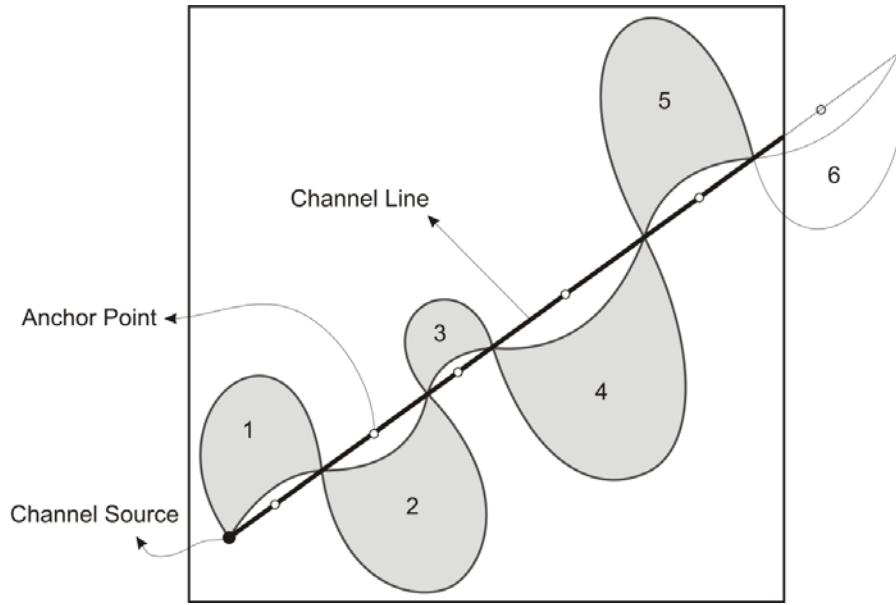


Figure 8: Process of attaching IHS sets to the channel line. The order of attachment is shown with numbers. IHS set number 6 is not included because its anchor point falls outside the modeling area.

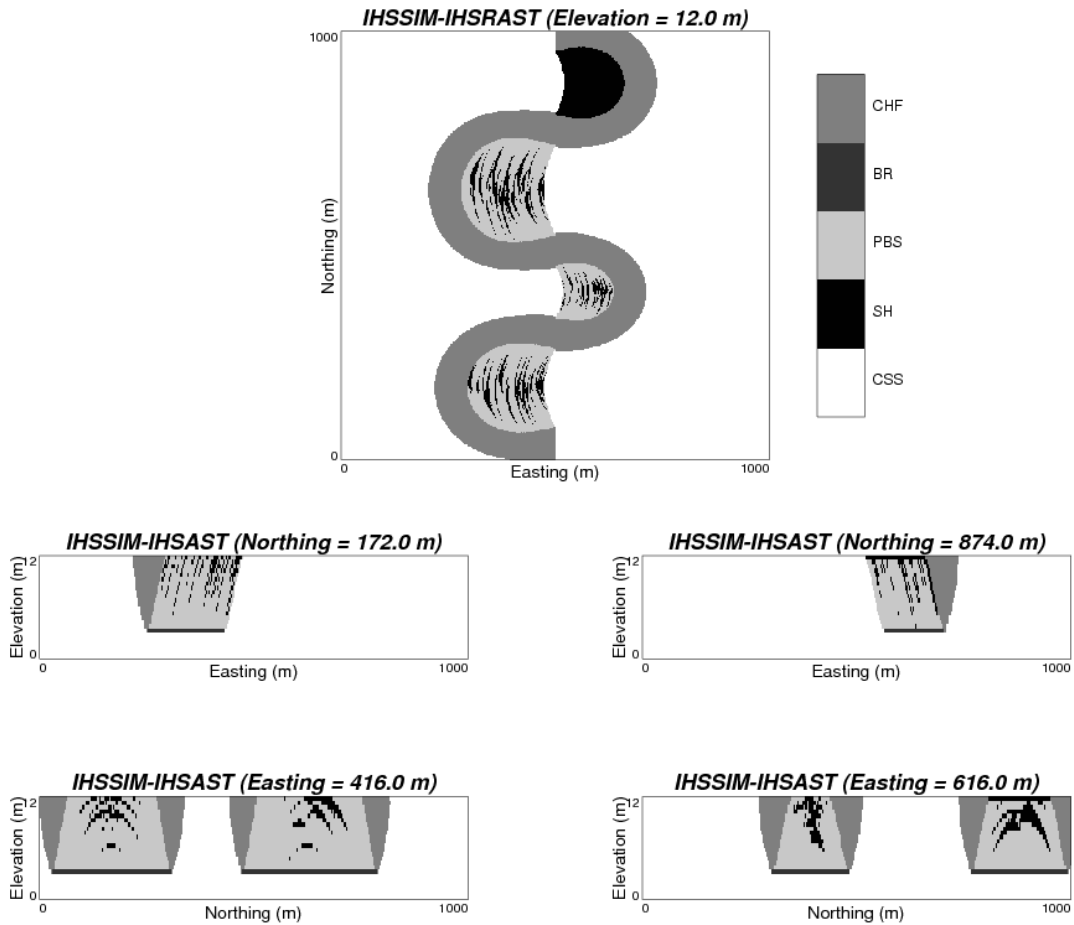


Figure 9: Single Channel line with attached IHS sets generated with IHSSIM and IHSRAST programs. The vertical sections are exaggerated 20 times.

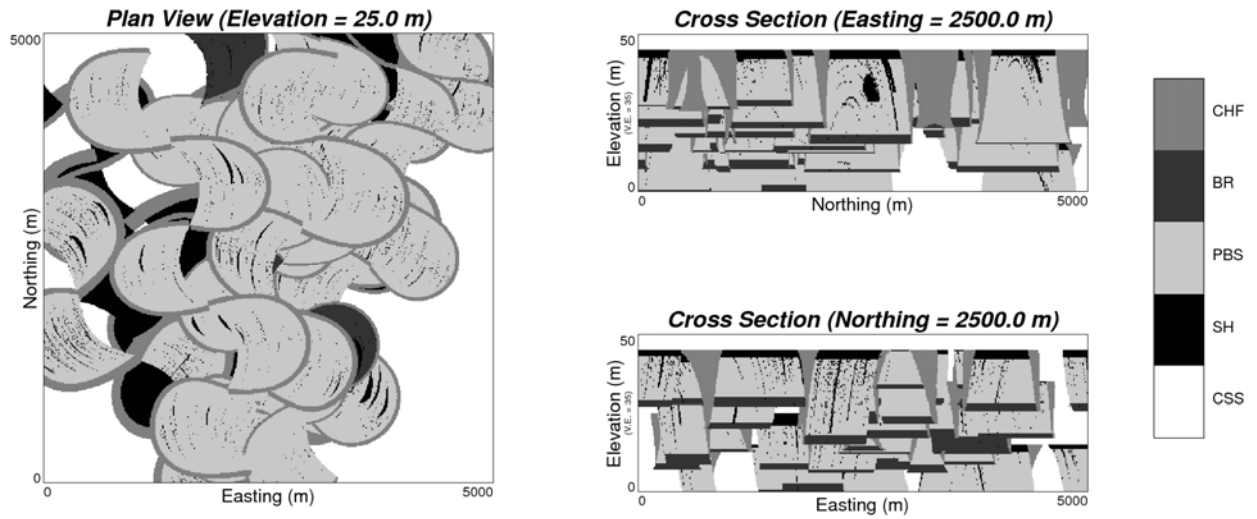


Figure 10: Example of IHS Facies Model for the McMurray Formation. The vertical sections are exaggerated 35 times.

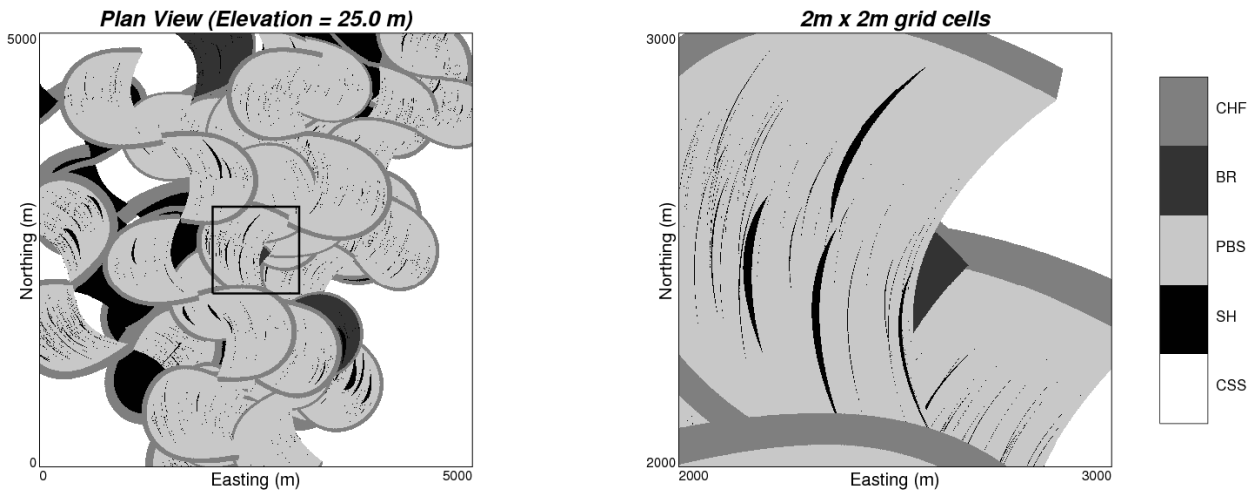


Figure 11: Rasterization of selected area (left) with smaller grids (right).