Stochastic Simulation of Inclined Heterolithic Stratification with Streamline-based Stochastic Models

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Abstract

Inclined heterolithic stratification (IHS) sets are commonly encountered in the host rock of the Alberta oil sands. Important features in petrophysical properties have been identified with respect to these sets. Remnant shales constrained by the IHS geometries are of primary interest in marine influenced depositional settings. Trends in the shale fraction and grain size are also present. These geologic features may have a significant impact on the response to exploitation through steam assisted gravity drainage (SAGD).

The streamline-base stochastic fluvial model, alluvsim, incorperates realistic architectural element geometries, highly sinuous channel morphologies and meander, avulsion and aggradation operations. This model results in the realistic reproduction of complicated lateral accretion architectural element geometries and interrelationships; therefore, provides a good model of IHS sets derrived from later accretion elements.

Multiple realizations of IHS geometries are calculate with the alluvsim algorithm. Stochastic mud drape models and hierarchical trend models are incorperated into the IHS geometries for the construction of IHS porosity trend models. These trends models are applied as locally variable mean models for sequential Gaussian simulation of porosity. The resulting models may be applied as training images for multiple-point simulation and to assess the impact of IHS geometries and heterogeneities on reservoir response.

Keywords: Reservoir Characterization; Geostatistics; Facies Modeling; Inclined Heterolithic Stratification Sets

1 Introduction

Inclined heterolithic stratification (IHS) sets are of special interest in channel belt (CB type) reservoirs since they (**1**) are often a dominant component of these reservoirs, (**2**) often include a large component of good reservoir quality, (**3**) have inherent patterns of heterogeneity that may have a significant impact on reservoir response and (**4**) they have complicated geometries that are often difficult to model.

Two examples of reservoir settings that have significant components of IHS sets are the McMurray Formation (Mossop and Flach, 1983, Thomas et al., 1987) and Daqing Oil Field, China (Jin et al., 1985, Thomas et al., 1987). In both of these examples the IHS sets developed from a meandering fluvial depositional setting. IHS sets have also been identified in deltaic channels, estuarine channels, low sinuosity streams and deepwater channels (Thomas et. al., 1987).

IHS sets are characterized as siliciclastic sequences that are parallel to subparallel with original dips (Thomas et. al., 1987). These strata generally result from the lateral growth of large-scale

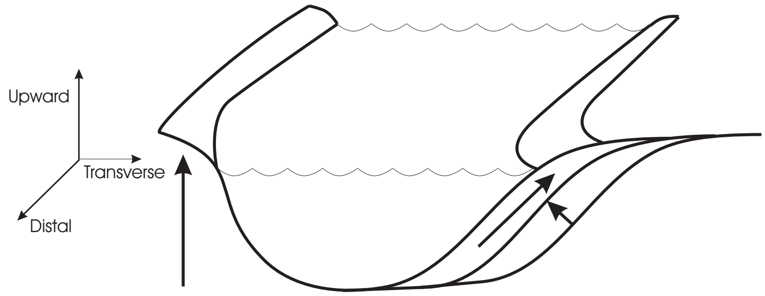

Figure 1: An illustration of three fining trends identified by Thomas et al. (1987).

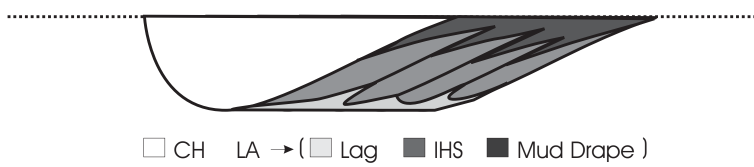

Figure 2: A schematic dip section of the morphology of IHS sets associated with meandering fluvial systems. Adapted from Thomas et al. (1987)

bedforms such as point bars (lateral accretion elements). The internal geometry is characterized by growth units with fining outward trends. These units are separated by accretionary surfaces (Thomas et. al., 1987). The external geometry is described by Miall (1996) as point bar lenses flanked by shale filled abandoned channels.

Accretionary surfaces may provide valuable control for the construction of IHS property trend models and in the assessment of recovery factors. In addition, IHS sets demonstrate a variety of characteristic trends within growth units. For example, Thomas et. al. (1987) identified seven possible grain size fining trends associated with IHS deposits. These grain size trends include fining upwards, fining lateral and fining perpendicular to the IHS sets (see Figure 1). These trends may have a significant control of the porosity and permeability distribution of IHS set dominant sand bodies.

A schematic of a typical IHS morphology for a mixed to suspended load meandering river is shown in Figure 2. This model is adapted from Thomas et al. (1987) and is similar to the *simple point-bar model* from Galloway and Hobday (1996).

The mud drapes along accretionary surfaces and associated property trends often have significant impact on reservoir response. This is confirmed in an analog study based on high resolution ground penetrating radar and outcrop to model a single IHS set (Li and White, 2003). The impact of IHS morphologies on water flooding in the Daqing field is discussed by Jin et al. (1985) and on stream assisted gravity drainage (SAGD) in the McMurray Formation by Smith (1985).

Yet, the internal and external geometry of IHS sets is complicated. The internal geometry is the result of channel geometry and the meander evolution of low to high sinuous channels and the aggradation and avulsion of the fluvial system. External geometry is controlled by the vertical and lateral imbrication of sets within composite sets. Lateral imbrication is caused by the reocupation an abandoned floodplain and vertical imbrication is caused by system aggradation resulting in subsequent IHS sets with truncated contacts with the older IHS sets. These complicated geometries have been discussed by authors such as Diaz-Molina (1993), Thomas et al. (1987) and Willis (1993).

The streamline-based algorithm, `alluvsim`, is applied to generate realistic models of IHS set geometries. These geometric models are applied to calculate stochastic property models. This procedure is demonstrated with parameters derived from studies of the McMurray formation (Mossop and Flach, 1983, Thomas et al., 1987).

2 Stochastic Inclined Heterolithic Stratification with alluvsim

The `alluvsim` algorithm was modified for the construction of IHS geometry models. (**1**) The CH profile was modified to reproduce sigmoidal accretionary surface geometries. (**2**) The base of each CH element is stored, eroded and written to a file. (**3**) Only channel fill elements are considered.

2.1 Sigmoidal Geometries

A variety of sigmoidal geometries are often observed in IHS sets (see mixed and suspended load IHS profiles in Thomas et al., 1987). A multiplicative component was added to the CH element profile equation. This multiplier is based on a parabola constrained to unity at the thalweg and the point bar edge of the channel and to a maximum sigmoidal multiplier ($0 > i > 1$) at the mid point.

$$F = 1 + i \cdot \left\{ \left[\frac{\mathbf{w} - \frac{W(\mathbf{s})}{2} \cdot (1 + a(\mathbf{s}))}{\frac{W(\mathbf{s})}{2} \cdot (1 - a(\mathbf{s}))} \right]^2 - 1 \right\} \tag{1}$$

where $W(\mathbf{s})$ is the channel width and $a(\mathbf{s})$ is the thalweg location at location $\mathbf{s}$ along the streamline and $\mathbf{w}$ is the location normal to the streamline.

The application of the sigmoidal multiplier is illustrated in Figure 3 and example channel profiles are shown in Figure 4. The result is a simple parameterized CH element profile that may reproduce a variety of accretionary surface geometries.

2.2 Erosion Rules

For the construction of IHS set models `alluvsim` algorithm is modified to store the bases of all CH elements. These surfaces are post-processed to reproduce erosion rules based on the sequence of streamline evolution. Accretionary surfaces are eroded by younger accretionary surfaces.

2.3 Architectural Elements

The levees and crevasse splay elements are not considered in this implimentation of the `alluvsim` model. These elements are often eroded by subsequent channels in settings dominated by amalgamated lateral accretion deposits and the exclusion improves computational efficiency.

2.4 Aggradation, Avulsion and Meander Migration

The rates of aggradation, avulsion and meander migration are constrained in the `alluvsim` algorithm. Frequent alvusion and rapid aggradation result in poorly developed IHS sets. The impact of aggradation and avulsion on the development of IHS sets is illustrated in Figure 5.

The spacing accretionary surfaces is based on a Gaussian distribution with mean and standard deviation supplied by the user. A variety of scenarios are shown in Figure 6.

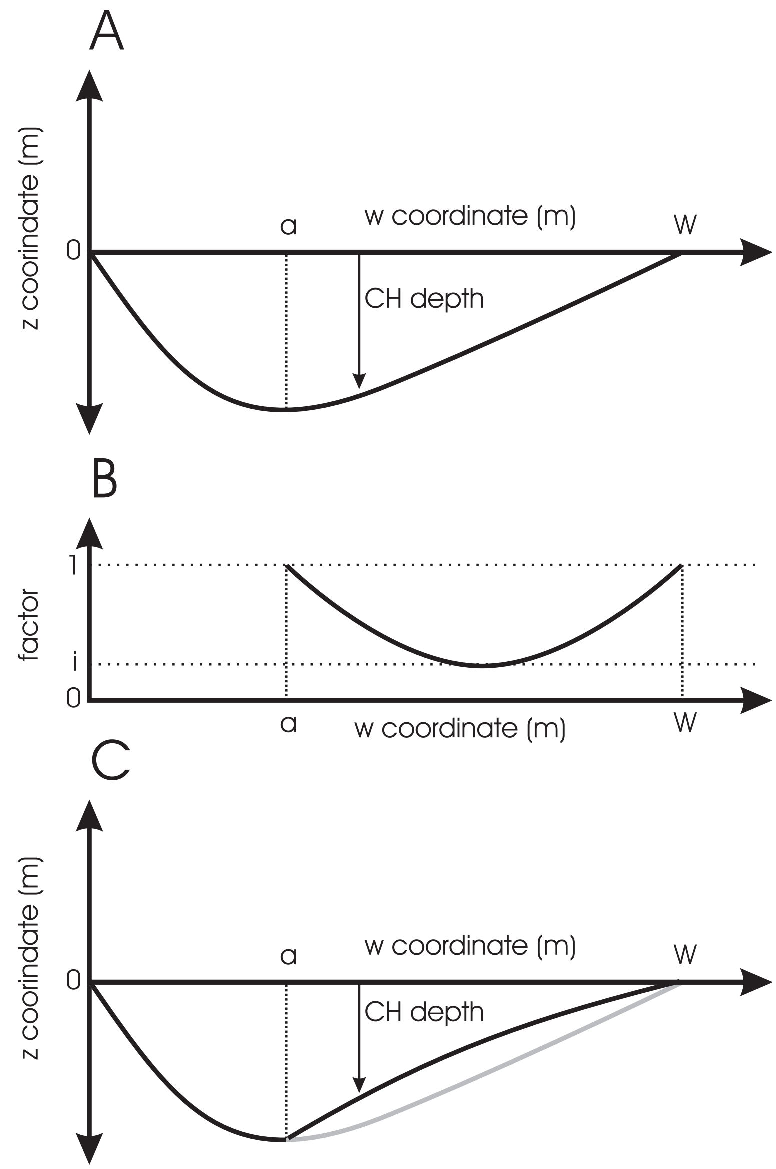

Figure 3: A schematic of the sigmoidal channel profile calculation. A - channel profile based on . B - sigmoidal multiplier applied to CH depth. C - modified channel profile. Note a is the thalweg location and W is the channel width.

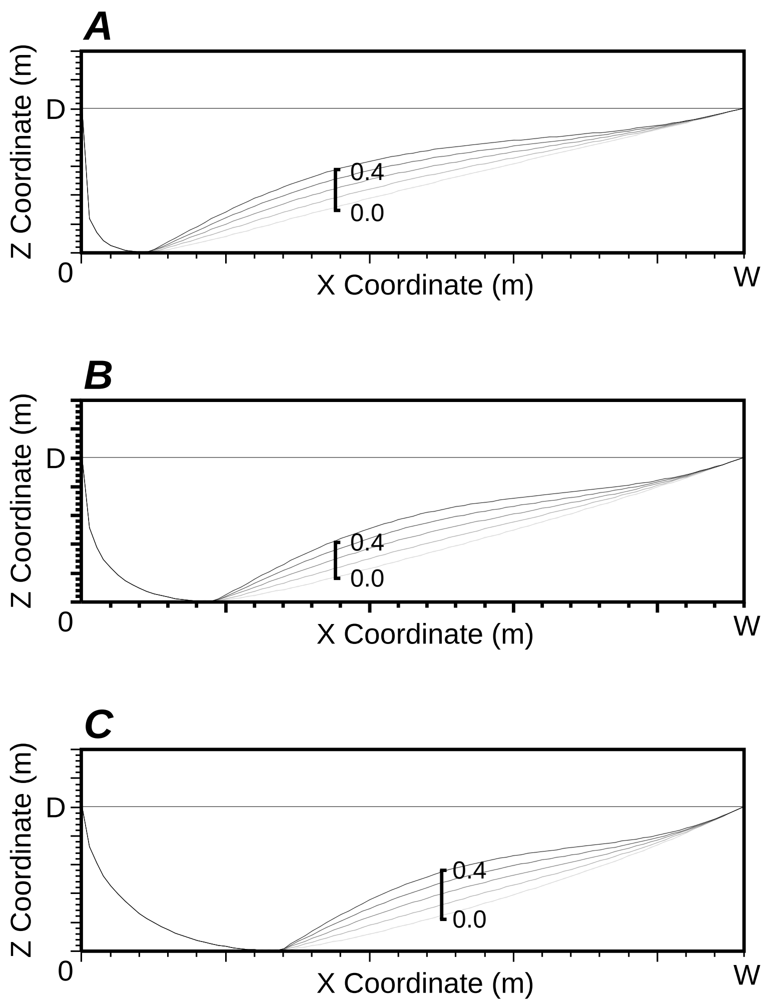

Figure 4: Examples of the modified sigmoidal channel profile. A - thalweg location $a = 0.1$ and intensities $i = 0.0, 0.1, \ldots, 0.4$. B - thalweg location $a = 0.2$ and intensities $i = 0.0, 0.1, \ldots, 0.4$. C - thalweg location $a = 0.4$ and intensities $i = 0.0, 0.1, \ldots, 0.4$. Note W is the channel width and D is the channel depth.

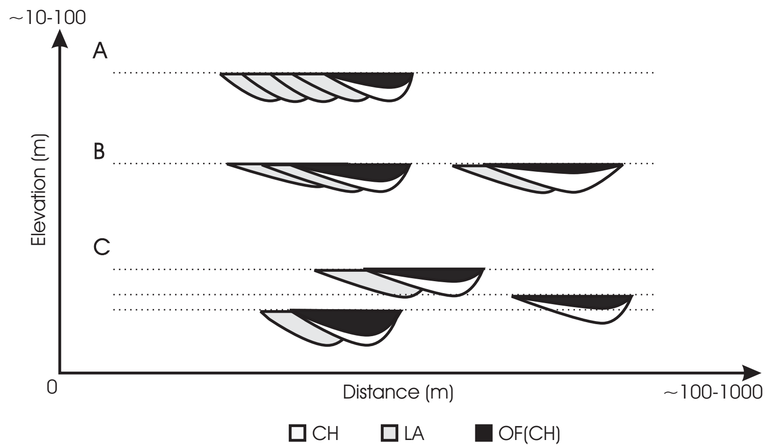

Figure 5: A example of various aggradation and avulsion rates. A - Low rate of aggradation and avulsion results in well developed IHS sets. B - High rate of avulsion breaks up IHS sets. C - High rates of aggradation and avulsion results in isolated, poorly developed IHS sets.

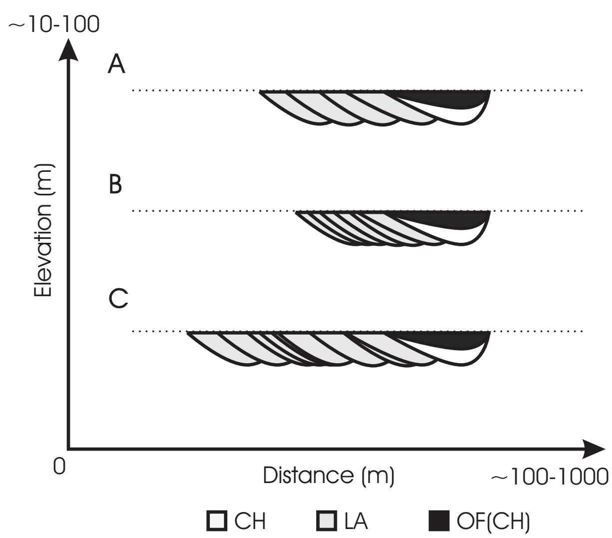

Figure 6: A variety of meander step distributions. A - Large meander steps results in thick lateral accretion units. B - Small meander steps results in thinnly bedded IHS and C - a wide distribution of steps sizes results in variable bedding.

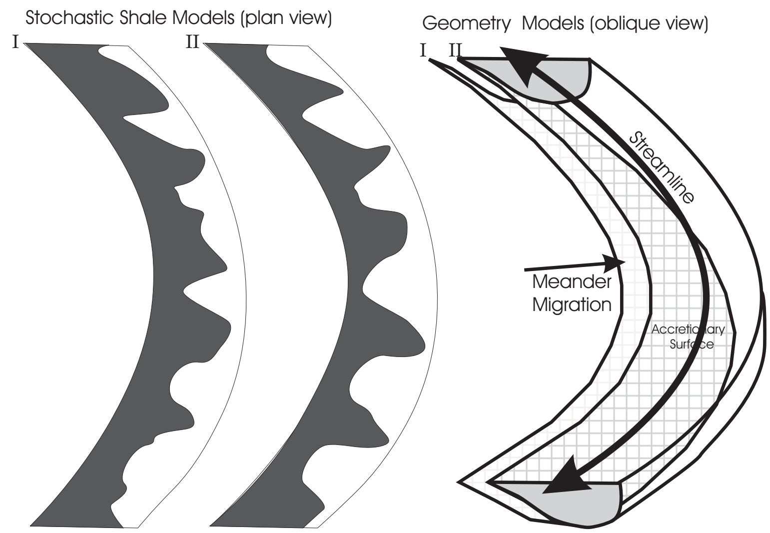

Figure 7: A graphical illustration of the placement of stochastic mud drape models within a geometric model of accretionary surfaces.

2.5 Stochastic Mud Drape Models

Stochastic mud drapes may be positioned along the accretionary surfaces. This is illustrated in Figure 7. The mud drape models should integrate information with regard to the ocntinuity of mud drapes observed in the reservoir. For example, sequential indicator simulation may be applied to model categories representing the presence of mud drapes (Li and White, 2003). Example models of mud drapes along a single accretionary surface are shown in Figure 8. Additional information such as trends in mud drape preservation along dip may be integrated into these mud drape models.

3 Well Data Conditioning

This paper does not discuss the issues realated to conditioning to well data. In the CCG paper on the `alluvsim` in this report by Pyrcz and Deutsch (2004b) and the Geostatistics Congress Paper by Pyrcz and Deutsch (2004c) issues related to well conditioning are discussed.

This conditioning technique entails the translation of large-scale elements to honor small scale data; therefore, it is only suitable for settings with sparse conditioning data. Settings with dense data will be intractable and may result in artifacts.

The current implementation considers only CH′ elements. It may be useful to extend this algorithm to honor a variety of architectural elements identified in well data. Also, is is assumed that the wells are vertical. In this CCG paper examples without well conditioning are shown. Future examples will be conditional.

4 Example Stochastic Inclined Heterolithic Strata Geometry Models

An example stochastic IHS model is constructed based on the study of the McMurray Formation by Mossop and Flach (1983). This study identifies geometric parameters that may be reproduced with the `alluvsim` model such as accretionary surface dips and IHS set thickness and also includes

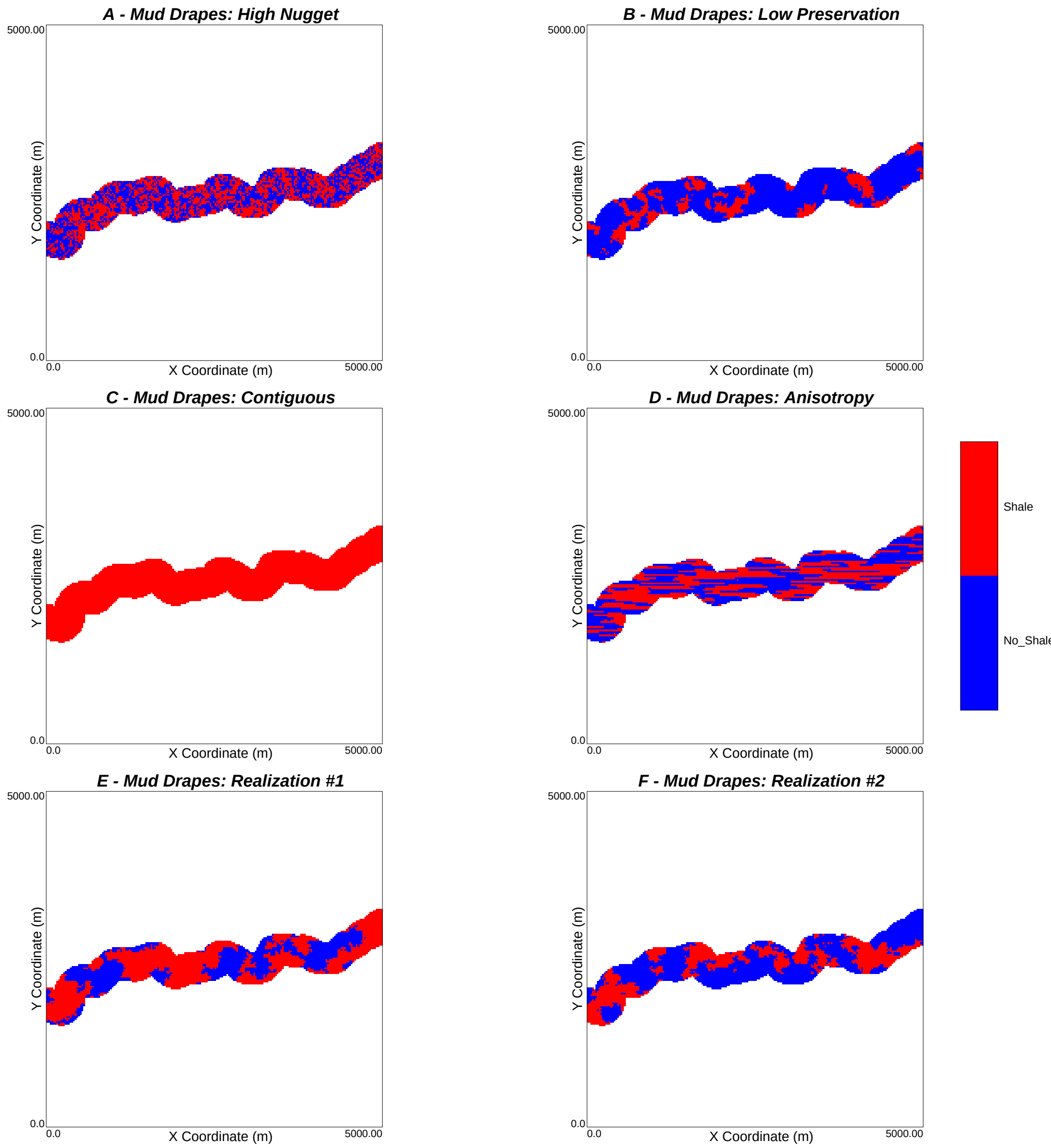

Figure 8: Stochastic mud drape models with a variety of continuity styles. A - discontinuous mud drapes calculated with a large nugget effect semivariogram model, B - poorly preserved mud drapes calculated with a low global proportion of shale category, C - contiguous shale model, anisotropy in mud drape continuity calculated with an anisotropic semivariogram model, E and F - two mud drape realizations calculated with the same semivariogram model.

Parameter	**Value**
Channel Depth	$25 - 40\ m$
Channel Width:Depth	16
Sinuosity	1.6
Sinuosity Wavelength	$2500\ m$
Accretionary Surface Dip	4^0
Maximum Isopach IHS Bed Thickness	$2.0\ m$
Maximum Channel Migration	$30\ m$

Table 1: Morphological characteristics of McMurray formation paleochannels from Mossop and Flach (1983).

paleo-flow information such as channel width to depth ratio, channel depth and channel sinuosity. These parameters are shown in Table 1. The maximum IHS bed thickness (isopach) is combined with the accretionary surface dip to calculate the maximum channel migration for each migration step.

$$\Delta_{max} = \frac{T_{max}}{sin\phi} \tag{2}$$

where Δ_{max} is the maximum channel migration step, T_{max} is the maximum IHS bed thickness and ϕ is the dip of the accretionary surfaces.

Two realizations were calculated with these parameters. A plan view of the migrating channel streamlines and three cross sections are shown in Figures 9 and 10.

5 Example Stochastic Inclined Heterolithic Strata Property Models

Geometric models of IHS sets are applied to calculate hierarchical trend models (Pyrcz, 2004) with mud drape models. These IHS trend models are applied to constrain porosity realizations. The geometric IHS models provide the complicate geometries of vertically and horizontally imbricated IHS sets. The mud drape models integrate information with regard to the preservation and continuity of mud drapes along accreationary surfaces. The hierarchical trend models integrate information with regard to porosity trends due to grain size fining in a variety of directions (see Figure 11).

IHS porosity trend models may be applied to calculate multiple realizations of porosity for the application of flow simulation. An example IHS porosity trend model and associated porosity realizations are shown in Figure 12.

6 Conclusions

The streamline-based approach is a flexible and efficient tool for the construction of stochastic geometric models of IHS sets. These geometric models may be combined with mud drape models and hierarchical trends to construct advanced porosity trend models for IHS sets. Simulated porosity realizations with these trend models are realistic in appearance and should result in better flow simulation results.

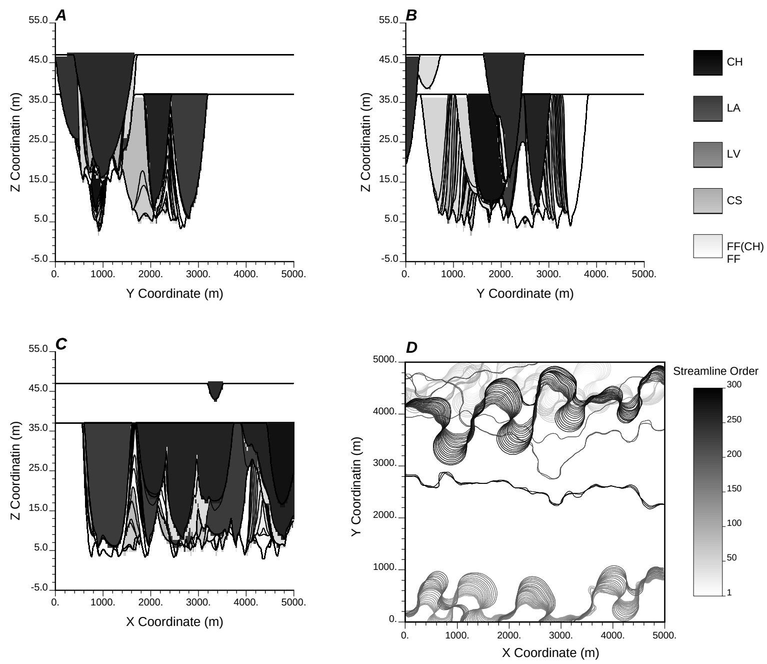

Figure 9: First realization of IHS sets generated with the `alluvsim` algorithm and parameters based on the Mossop and Flach (1983) study of the McMurray Formation. A - cross section at $X = 1500$ meters, B - cross section at $X = 4000$ meters, C - long section at $Y = 2500$ meters and D - all of the streamlines applied to construct this model. Few streamlines were generated for visualization. In the McMurray Formation IHS sets are more extensive and FF is poorly preserved. Note W is the channel width and D is the channel depth.

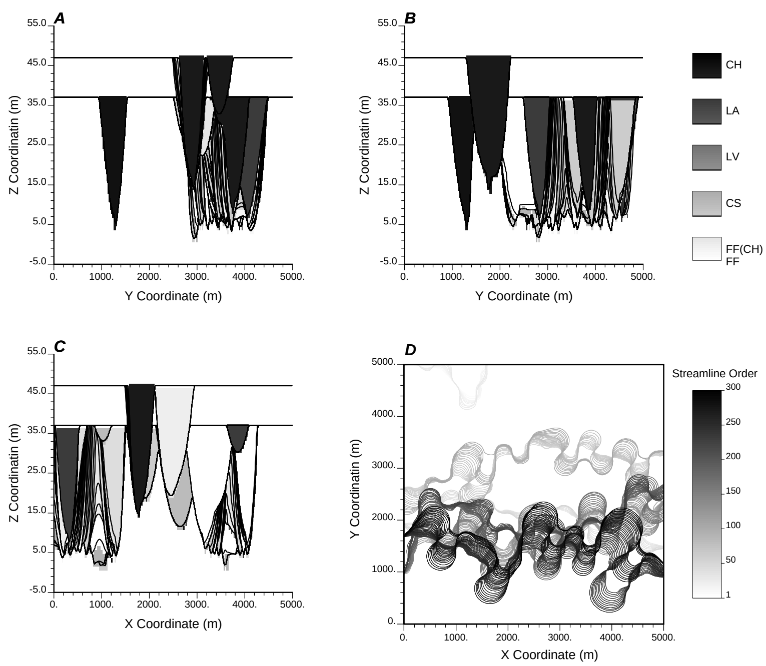

Figure 10: Second realization of IHS sets generated with the `alluvsim` algorithm and parameters based on the Mossop and Flach (1983) study of the McMurray Formation. A - cross section at $X = 1500$ meters, B - cross section at $X = 4000$ meters, C - long section at $Y = 2500$ meters and D - all of the streamlines applied to construct this model. Few streamlines were generated for visualization. In the McMurray Formation IHS sets are more extensive and FF is poorly preserved.

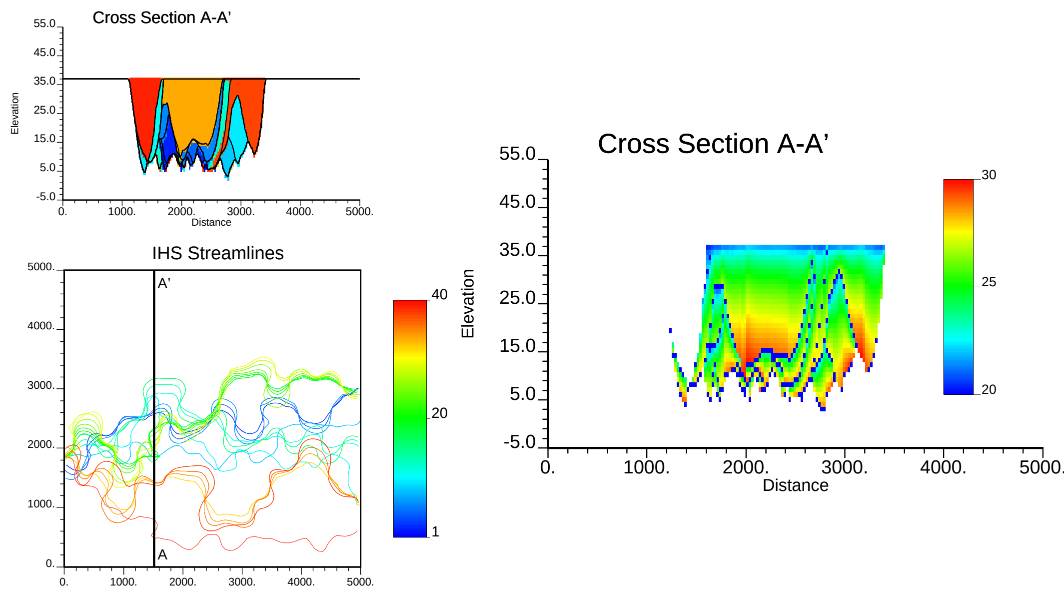

Figure 11: An example of a mud drape model and heirarchical trend models integrated into a geometric IHS model. A and B - the geometric model of accretionary surfaces and abandoned channel fills. C - a porosity trend model with discontinuous mud drapes along accretionary surfaces, fining upwards and outwards within lateral accretion elements and no porosity in fine grained abandoned channel fills.

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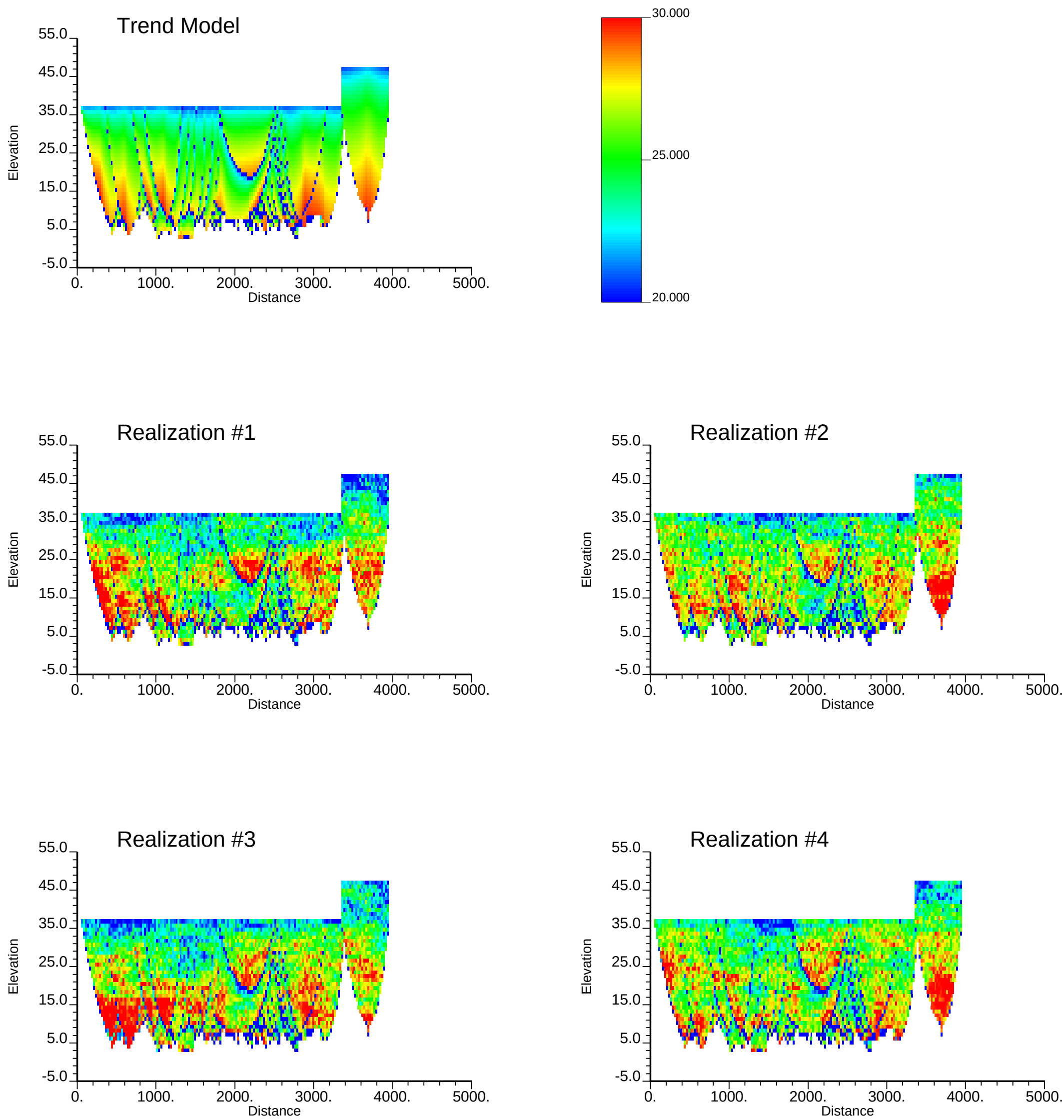

Figure 12: A cross section of an IHS trend model and associated stochastic realizations of porosity. The units are in percent porosity.

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