

Facies Modeling of the McMurray Formation: A Comparative Case Study

Mehran M. Hassanpour

Characterizing the geological setting of the McMurray Formation is challenging due to its complexity. Conventional facies modeling approaches such as widely used sequential indicator simulation (SIS) are generally unable to capture the geometry of geological features. The grid-free facies modeling technique is developed to capture complex geometry of the most important facies association in the McMurray Formation (the Inclined Heterolithic Stratification (IHS) facie). This work provides an illustration of the Grid-free facies modeling technique applied to the real McMurray Formation data. A data set from the McMurray Formation is assembled and a full geostatistical modeling is performed. Both the grid-free and a conventional facies modeling technique (SIS) are applied and the final results are compared.

1. Introduction

The purpose of this study is: 1) to provide a comprehensive McMurray Formation reservoir modeling workflow using real data set, 2) to show an extended example of grid-free IHS facies modeling and, 3) to evaluate and compare the effect of different facies models when processed through a transfer function such as SAGD thermal simulation. This study set up is as follows:

- 1) Data assembly
- 2) Geological analysis
- 3) Structural modeling
- 4) Data transformation and upscaling
- 5) Statistical analysis
- 6) Facies Modeling
- 7) Petrophysical property modeling
- 8) Flow simulation
- 9) Comparison of results

For the facies modeling part, two different methods are applied. Two conditional realizations of grid-free facies modeling and sequential indicator simulation are generated for the whole area. Then a suitable place for the horizontal well pad is selected based on the large scale models. Facies models are generated for the pad area and petrophysical models are populated within each facies. Then a 2D slice is picked from the pad models and thermal flow simulation is run on both grid-free based and SIS-based models. Results are compared based on some of the flow simulation output parameters.

2. Data Assembly

The Data set used for this study was picked from a SAGD operation area in Athabasca Oilsand area. An area with the extension of approximately 2 sections by two sections is selected (section is a square area of about 1.6 km by 1.6 km). The total modeling area is a square of about 3.5 km by 3.5 km. There are ten vertical wells within the study area. For confidentiality, the coordinates of wells are transformed to range of 0 to 3500 m. Figure 1 shows the location map of wells within the study area.

The Only available information for this area is the digital well log. All wells contain well logs for the whole McMurray Formation interval (from the top of the McMurray up to the top of Devonian Formation). Well logs include effective porosity, water saturation, and volume of shale at 0.125 m intervals. Structural tops for the top and base of McMurray Formation are also available for all wells.

There is no facies data in the data set. Three pseudo-facies of clean sand (cross stratified), IHS, and mud are considered. Cutoffs are applied to the effective porosity and volume of shale to define these three facies. Table 1 shows the cutoffs for each facies. These cutoffs are calculated based on some expert knowledge and geological description of the McMurray Formation. In order to make the facies data and the petrophysical properties consistent, cutoffs are applied to the upscaled porosity and Vsh values. This step is performed after data upscaling scale (Figure 2).

Table 1: Cutoffs used to generate facies data.

Facies	Cutoffs
Cross Stratified Sand (CSS)	$\phi > 0.28$ $V_{sh} < 0.1$
Inclined Heterolithic Stratification (IHS)	$0.12 \leq \phi$ $0.05 \leq V_{sh} \leq 0.6$
Mud	$\phi < 0.12$ $V_{sh} > 0.6$

3. Geological Analysis

McMurray Formation comprises of three stratigraphic units; lower, middle and upper. Here, since the well markers for these units are not available in the data set, the whole McMurray Formation is considered to be a single unit. Since there is no core description in the area so the only available information to extract the geological information is well logs.

In order to get a better sense of the geology of the area, 2D trend maps of properties are generated. Well logs including porosity, water saturation, and volume of shale are averaged up for each well. Facies codes (which were calculated based on the cutoffs in Table 1 at the log scale) are also averaged up for each well and facies proportions are calculated.

Global Kriging was used to generate 2D maps of upscaled properties in the modeling area. A spherical variogram with the range of 3500m and nugget effect of 0.3 is used for all properties. Figure 3 shows 2D trends for the facies proportions and three properties.

Looking at the porosity and V_{sh} trends suggests a SE-NW estuarine channel deposit which has high porosity and low volume of shale. As suggested by Mud trend, there is package of mud west side of the large estuarine channel. Within the estuarine channel, sand proportion trend shows higher proportion of sand at the North of the study area. This suggests that the North part was probably more close to the estuarine mouth and therefore has more tidal sand bars and less muddy IHS. As we go from the NW to the SE the proportion of IHS facies increases. This is consistent with the idea of North side proximity to the estuarine mouth. Although this interpretation may not be exact since it is derived based on limited information, but at least it helps to infer the anisotropy direction in the modeling area and also helps to infer some of the IHS parameters needed for grid-free facies modeling which will be discussed in the following.

4. Structural Modeling

There are only two structural markers; top and base of the McMurray Formation. All ten wells have structural tops for both structural controls. Isochore thicknesses are also calculated for all ten wells. Global kriging was used to generate structural surfaces. Since there are limited wells in the area, calculating reasonable horizontal variograms for tops are very challenging. So a Gaussian Variogram with the range of 3500m was considered for both tops and isochore thickness. Figure 4 shows the top McMurray, Base McMurray and, the thickness maps.

The SE-NW trend of the estuarine deposit is also visible on the McMurray top surface. Thickness map shows that the McMurray Formation thickness increases as we go from North to South of the study area varying from 50m to 83m.

5. Data Transformation and Upscaling

The vertical coordinate which was basically in measured depth (MD) were transformed to stratigraphic coordinate system relative to top McMurray pick at each well. The new vertical coordinate was defined as the difference between the McMurray depth and log measured depth. In other word, the McMurray top surface was set to zero elevation and all the log reading below that got a negative elevation value:

$$\text{New vertical elevation} = \text{McMurray pick (MD)} - \text{log reading (MD)}$$

For the purpose of geostatistical modeling the well log data were upscaled to 0.5m scale and all the statistical analysis was performed on the upscaled data. The effect of upscaling was checked for all variables to make sure that there is no significant change in statistical parameters between 0.125m scale to 0.5m scale.

As mentioned earlier, facies data is generated after the upscaling step. Cutoffs are applied on the upscaled porosity and volume of shale and the corresponding facies code is assigned at 0.5 *m* scale.

All upscaled data are then transformed to the normal unit. The normal score transformed data are used for the experimental variogram calculation.

6. Statistical Data Analysis

Histogram of all upscaled variables are generated both globally and by-facies. Figure 5 and Figure 6 show the global and the by-facies histograms. Summary of statistics are provided in Table 2.

Table 2 Summary statistics of the data set in the McMurray Formation

	Variable	Number of Data	Mean	Standard Deviation	Minimum	Maximum
Global	Porosity	1120	0.23	0.11	0.0003	0.35
	Sw	1166	0.51	0.29	0.075	1.0
	Vsh	1096	0.29	0.23	0.0	1.0
CSS	Porosity	249	0.34	0.01	0.28	0.35
	Sw	249	0.36	0.29	0.075	1.0
	Vsh	249	0.06	0.025	0.0	0.0993
IHS	Porosity	685	0.24	0.06	0.12	0.35
	Sw	685	0.44	0.21	0.075	1.0
	Vsh	685	0.26	0.12	0.016	0.55
Mud	Porosity	195	0.046	0.041	0.0003	0.12
	Sw	195	0.90	0.16	0.27	1.0
	Vsh	195	0.66	0.19	0.065	1.0

The Variography was performed for porosity and Sw globally and by-facies. Variables were first transformed from original unit to the normal score unit. The normal score variograms were then calculated at three directions (two horizontal and vertical). The horizontal variograms were calculated along the direction of main channel (azimuth of -45.0) and perpendicular to main channel (azimuth of 45.0).

The indicator variograms were also calculated for CSS, IHS, and Mud along and across channel and vertical direction. The variogram sill for each indicator variogram was set based on the global facies proportions.

All continues and indicator variograms were modeled. Figure 7 to Figure 9 show the experimental variogram points and the fitted models.

7. Facies Modeling

Facies modeling was performed in two steps. First, large scale facies models were generated for the whole area. Then a representative area for the thermal flow simulation was picked and facies models were built in the pad scale. The reason to perform two-steps facies modeling was to capture the large scale geological features such as point bars especially for the grid-free modeling purpose.

Large-Scale Facies Modeling

For the purpose of large-scale modeling, grid with size of 50m by 50m by 0.5m was considered. This results in 70 by 70 by 144 cells with total of 705600 cells.

The SISIM program of GSLIB was used to generate a large-scale conditional indicator simulation realization. Upscaled facies data and modeled indicator variograms were used. Figure 10 shows 3D view of the SIS realization. The realization was clean up with the GSLIB program of MAPS.

The program IHSSIM was used to generate large-scale conditional grid-free realization. Parameters for the IHSSIM program were selected based on the geological analysis and some assumptions. The parameter file used for the IHSSIM program is shown in Table 3. High standard deviation was considered for most of the parameters to make it easier for the program to select object for the conditioning.

For grid-free conditioning, facies data has been converted to the intervals. Only IHS and Mud facies were considered as conditioning data and CSS was assumed as background facies. IHS was considered as PBS element and mud was considered as CHF element (See paper 203 in Report 12). Only intervals with more than 4 *m* Mud

thickness were considered as conditioning data. IHS intervals greater than 30 m thickness were also divided into sub intervals. After all, the data set for grid-free conditioning contains 51 facies intervals including 42 IHS intervals and 9 mud intervals.

Conditioning grid-free model to the centimeter scale shale drapes was not in the focus of this work. Shale drapes were randomly populated within the IHS facies based on the IHSSIM input parameters. Frequency of shale drapes were selected so that more shally IHS were populated at the top and bottom of the model. Five aggradational levels were considered. Elevation of these five levels selected based on the conditioning facies data. Some other hard coded parameters such as mismatch tolerance was relaxed to a large number to make the conditioning easier. Among the 51 facies interval, only one interval was not matched. The computation time for conditional grid-free simulation for this data set was less than a minute on a 2.33GHz machine.

The grid-free model was rasterized to the grid specification mentioned earlier. The IHSSIM program was used for rasterization. Due to the computational time, shale drapes were not rasterized for this step of the modeling. Figure 11 shows 3D view of rasterized grid-free model.

A rectangular area of 700 m by 900 m was selected as a drainage area for the SAGD thermal simulation. Figure 12 shows place of the pad imposed on top of two facies realization generated in previous steps. Several factors were considered to select the best possible pad area for comparison study. Good reservoir portion, combination of all facies, geological features, and proximity to the vertical well area are among the factors.

Table 3 The IHSSIM parameter file used for grid-free facies modeling.

Parameters for IHSSIM	

START OF PARAMETERS:	
Facies_intervals.prn	-file for well data
1 2 3 4 5 6	- column for well ID,x,y,ztop,zbot,facies code
ihssim.gfm	-file for output grid-free model
0.0 3500.0	-xmn, xmx
0.0 3500.0	-ymn, ymx
-72.0 0.0	-zmn, zmx
3500 500 10 200	-CH source: mx, stdevx, my, stdevy
-45 25	-CH azimuth angle: m, stdev
0	-CH sinuosity: 1=highest, -1=lowest
1200 100	-IHS Length: m, stdev
1300 200	-IHS width: m,stdev
15 5.5	-IHS thickness: m, stdev
15 1	-IHS dip: m, stdev
700	-max. number of accretionary surfaces
5 -62 -52 -24 -15 0	-number of levels, level elevations
3 1 1 1 1	-number of channel in each level
0.9 0.5 0.5 0.8 0.9	-shale drape frequency in each level
2	-shale drape option: 1=realistic, 2=,parallel
0.1 0.05	-top shale thickness(% of IHS thickness): m, stdev
0.1 0.05	-breccia thickness(% of IHS thickness): m, stdev
0.9 0.05 0.05	-profile probability for:sigmoidal,convex-up,concave-up
65709	-random number seed
1	-number of realization to generate

Pad-scale Modeling

The pad is placed at the north part of the project area. Well 5,7, and 8 are placed within the pad area. For the purpose of pad scale modeling, grid with size of 2m by 50m by 0.5m was considered. This results in 350 by 18 by 144 cells with total of 907200 cells.

Indicator simulation realization for the pad area was generated in the same way as the large-scale modeling step. All the well data are used for the pad-scale modeling. The grid-free model is re-rasterized at the

pad scale. This time shale drapes are rasterized within the IHS facies. The computational time for rasterization of the pad was around 30 min. To compare two facies realization, a well section through well 5, 7, and 8 was generated. Figure 13 shows this well section.

8. Property Modeling

Reservoir property models such as porosity, permeability are required for the flow simulation. Sequential Gaussian simulation was used to generate porosity and water saturation models at the pad scale. The program SGSIM from the GSLIB was used for this simulations. Porosity realization is generated by-facies. Well data and by-facies variogram models were used for the simulation. By-facies porosity models were combined to each other using the SIS facies and grid-free models. So two realizations of porosity each related to one facies models were generated.

Since there was no permeability data for this area, synthetic permeability models were generated using the porosity realizations. The following relationship was used for the horizontal permeability modeling:

$$k_h = 7222222 * \phi^7$$

For the vertical permeability modeling, kv/kh ratio models were generated using the following relationship:

$$\frac{k_v}{k_h} = 1.9 * \phi^{0.7}$$

Vertical permeability were modeled using the kv/kh ratio and the kh model. Figure 14 and Figure 15 show 2D slices of the pad model showing facies and the corresponding horizontal permeability model.

9. Flow Simulation

SAGD thermal simulations were run on the SIS and grid-free based models using CMG STARS simulator. 2D slices models were used as property models in thermal simulations. Four horizontal well pairs were placed at the bottom of the reservoir layer. Well pairs are 140 m apart from each other. The injector (top) and producer (bottom) wells are placed 5 m apart from each other.

Initial oil saturation was set to the constant value of 0.9 for both SIS and GFM based models. Only two phase of oil and water was considered in the system. All the fluid properties and initial and boundary conditions were set the same for both cases.

Thermal flow simulation were run for 5040 days (about 14 years). Heaters were placed at the well locations for the first 90 days of the simulation to heat up the reservoir before the steam injection.

10. Comparison of Results

Oil saturation maps are shown in time lapses of 120, 720, 2160, 3600, and 5040 days in Figure 16 and Figure 17. Comparing two cases visually shows that steam chamber has grown more evenly in the SIS based model after 5040 days. This means that the SIS based model does not perfectly captured the heterogeneity of the reservoir as opposed to the GFM based model. Comparing two maps also reveals that the distribution of shale drapes has significant effect on the SAGD performance. As we can see in the oil saturation map of the GFM based case after 5040 days, shale drapes placed at the top of well pair 1 and 2 significantly reduced the steam chamber growth.

Comparing the flow simulation output parameters such as water cut, steam oil ratio and the cumulative oil production also indicates the difference between the two cases. Figure 18 shows these parameters for both cases.

11. Conclusions

A comparative case study was performed on a real data set in the McMurray Formation. SIS and grid-free facies models are generated and processed through a thermal flow simulation transfer function. Although this illustration may not be generalized for all cases but some points can be concluded. SIS facies modeling cannot capture complex geological heterogeneity of the McMurray Formation and as a result they might not perform well in the flow simulations. Grid-free facies modeling technique performs better in this sense however conditioning to the trend model and well data is not as good as SIS models.

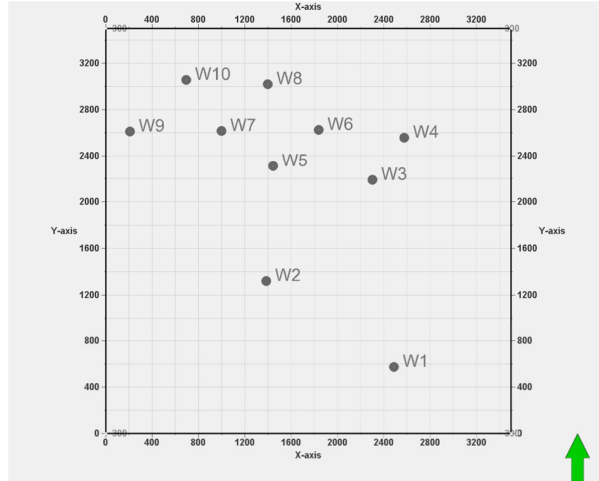


Figure 1 Location map of well data in the modeling area.

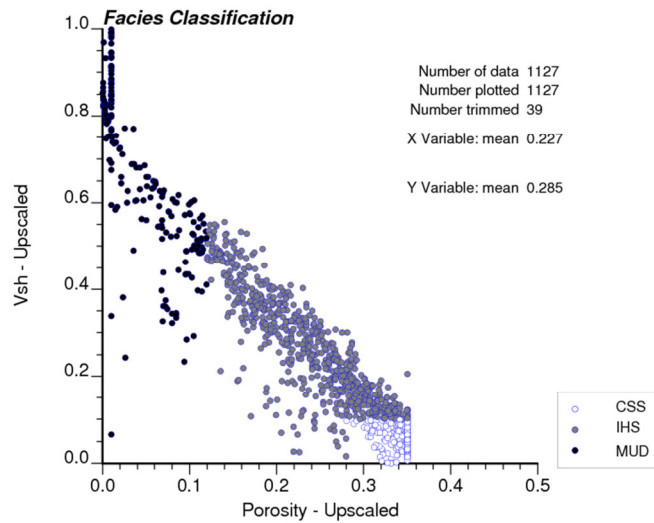


Figure 2 Facies data generation using porosity and Vsh cutoffs.

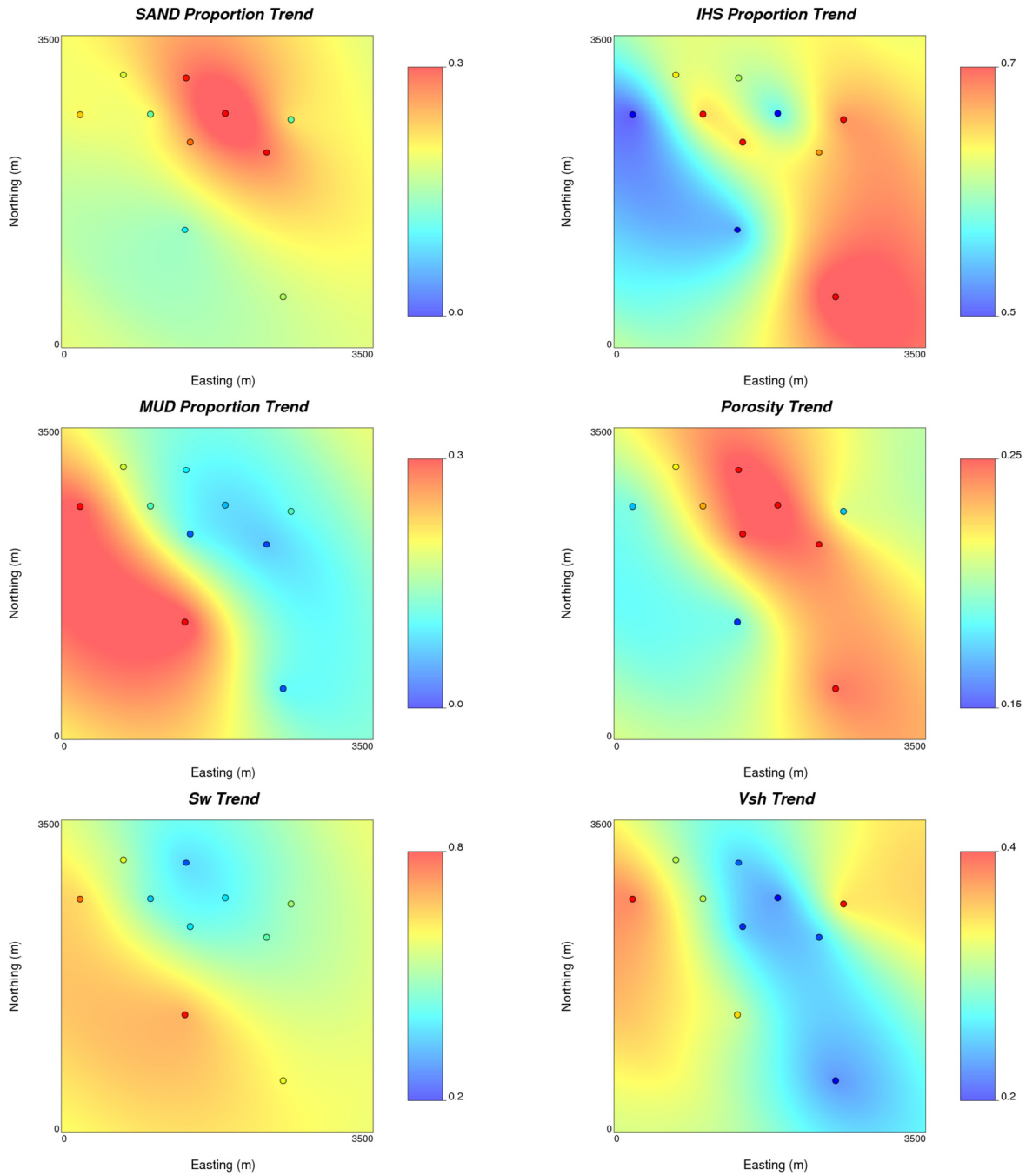


Figure 3 2D trend maps of facies proportions and reservoir properties in the modeling are.

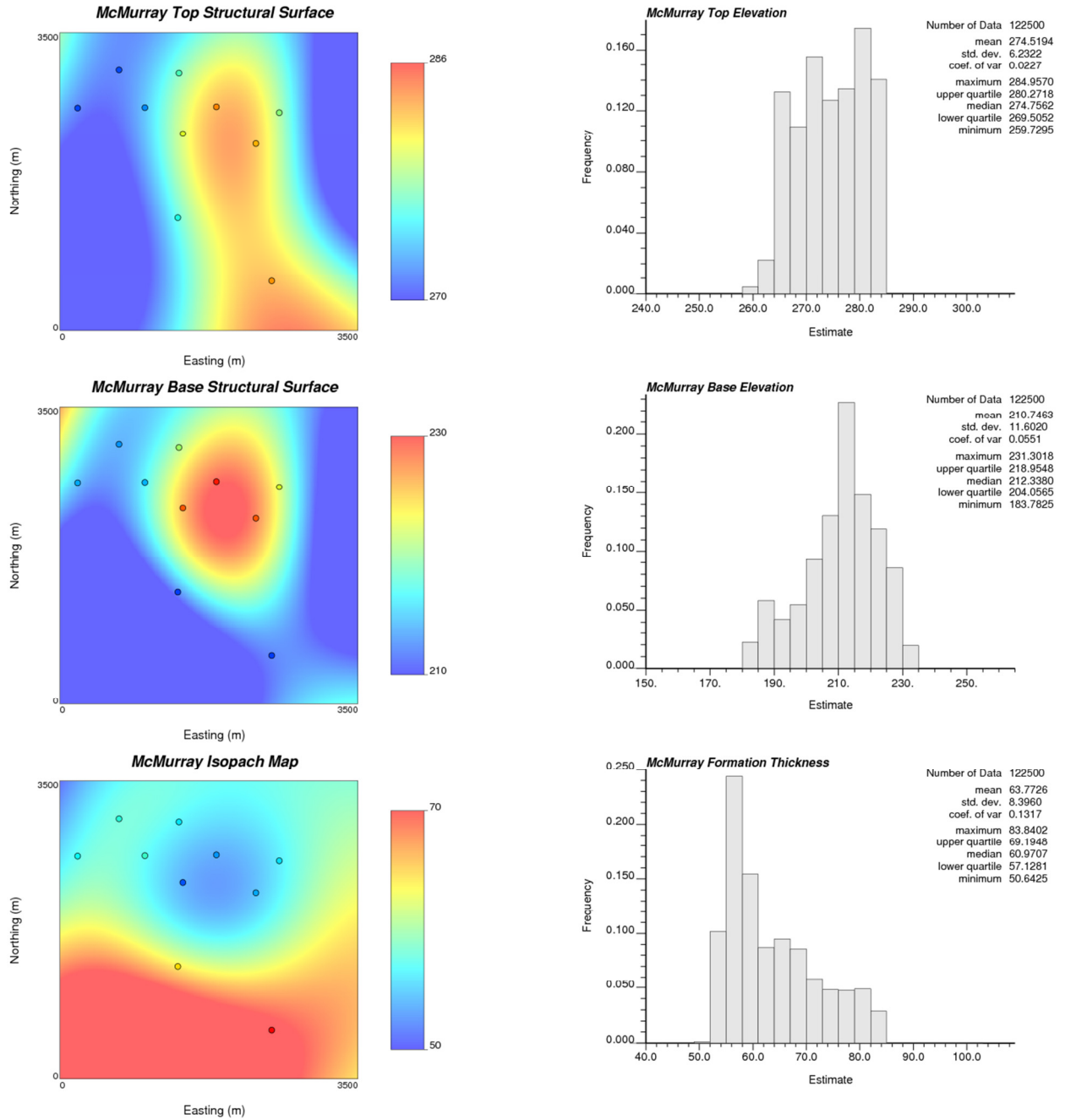


Figure 4 Structural surfaces of the McMurray Formation in the modeling area.

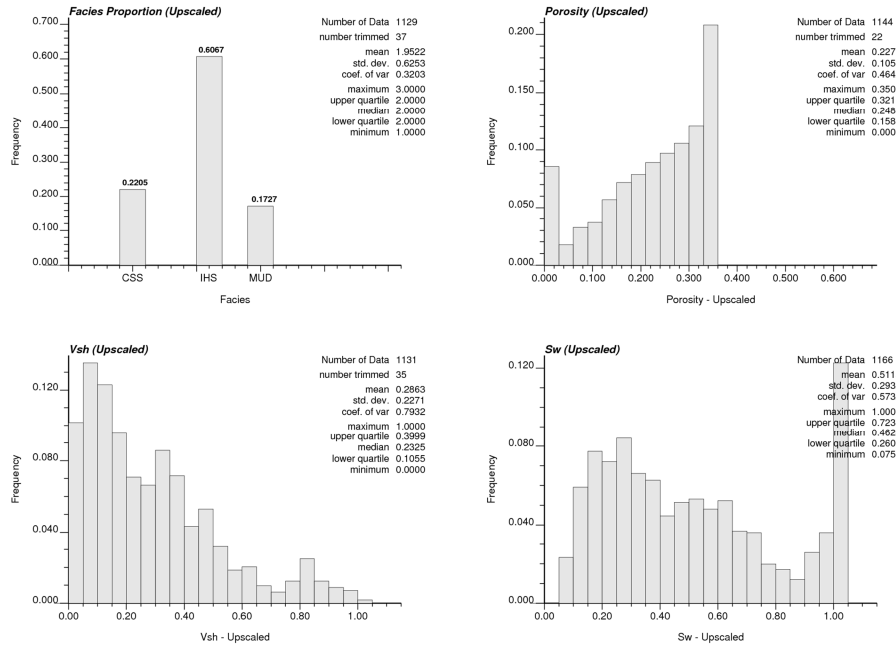


Figure 5 Global histograms of facies, porosity, Vsh, and Sw.

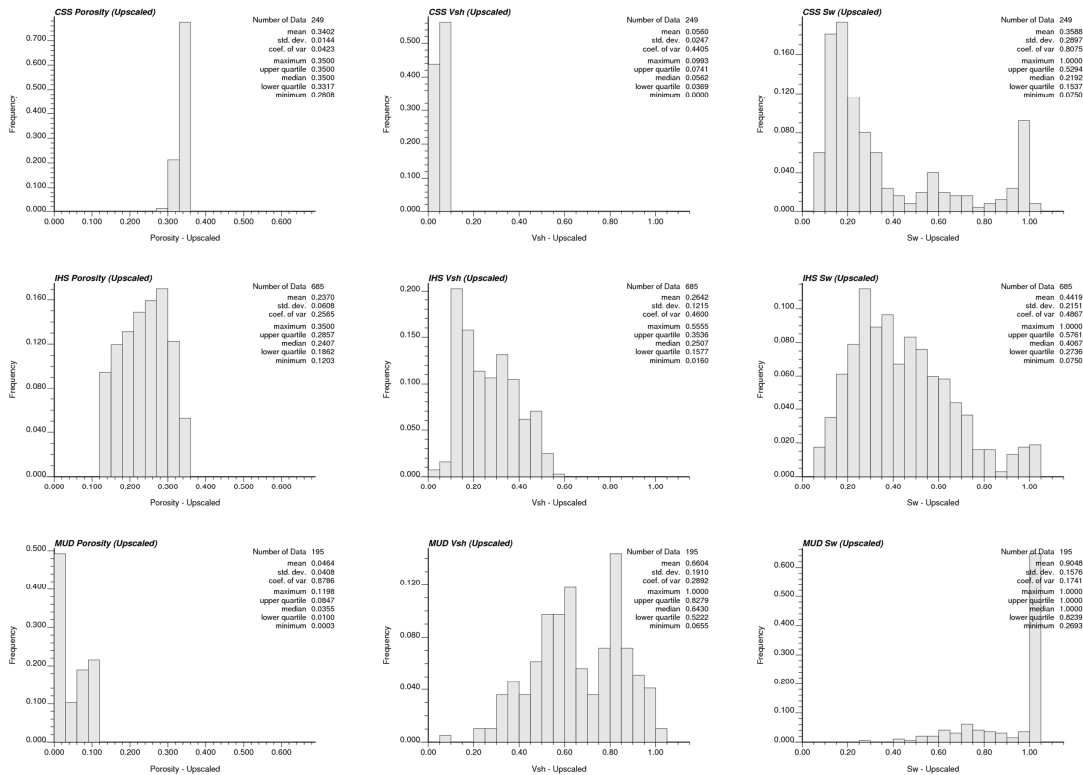


Figure 6: By-facies histograms of porosity, Sw, and Vsh in CSS(top), IHS(middle), and mud (bottom).

Indicator Variogram Models

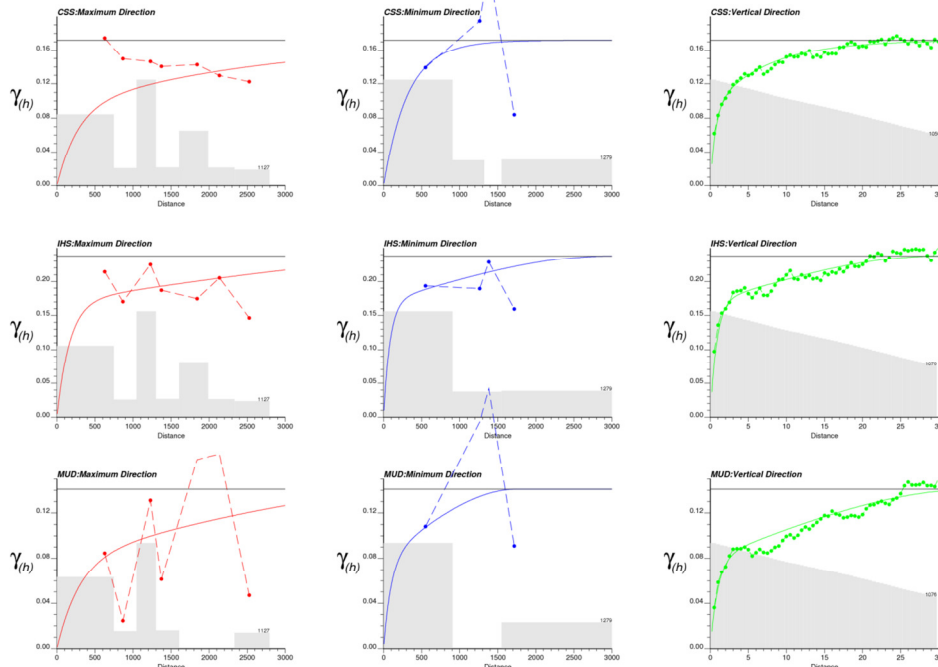


Figure 7: 3D Indicator variogram models for CSS (top), IHS (middle), and mud (bottom).

By-Facies Porosity Variogram Models

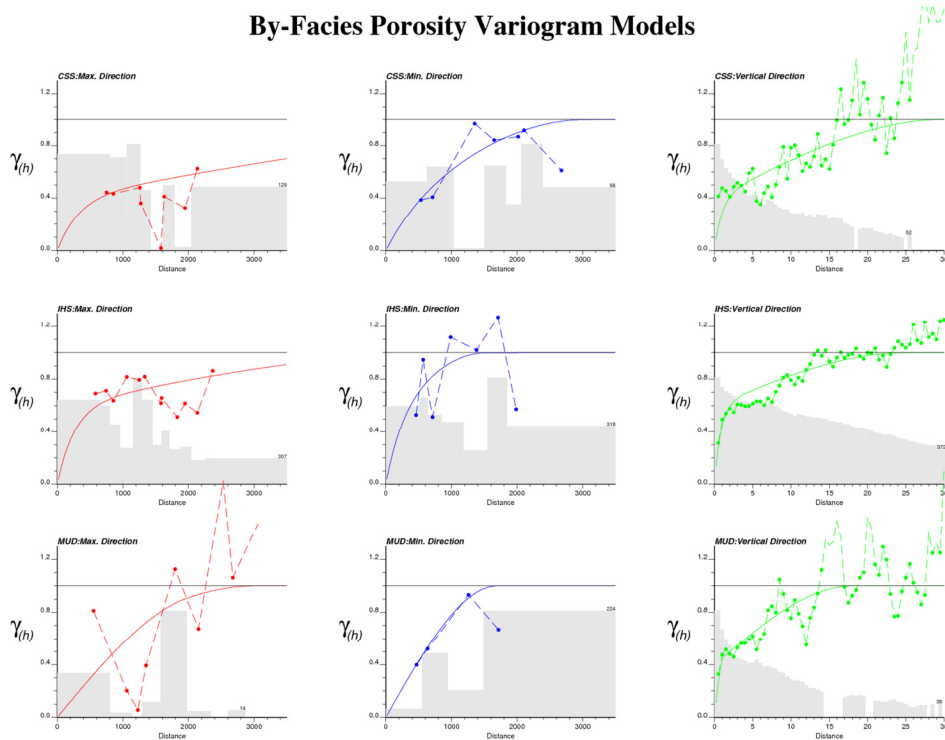


Figure 8: 3D porosity variogram models in CSS (top), IHS (middle), and mud (bottom).

By-Facies Sw Variogram Models

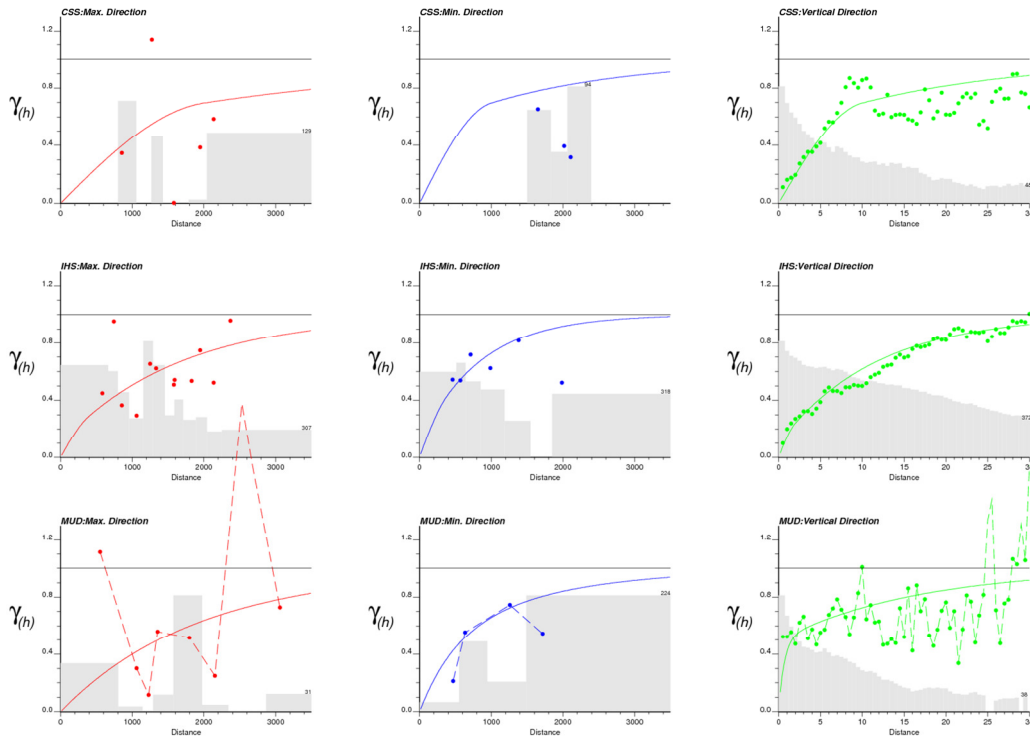


Figure 9: 3D Sw variogram models in CSS (top), IHS (middle), and mud (bottom).

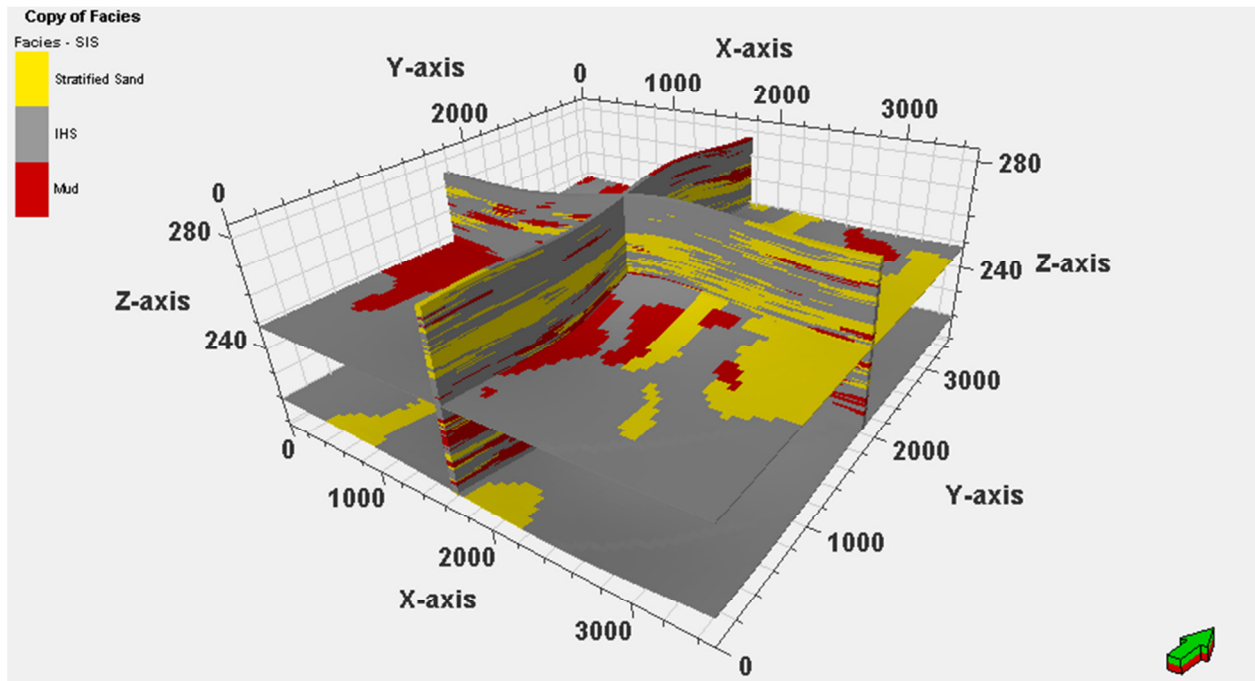


Figure 10: 3D view of conditional facies models generated with SIS technique.

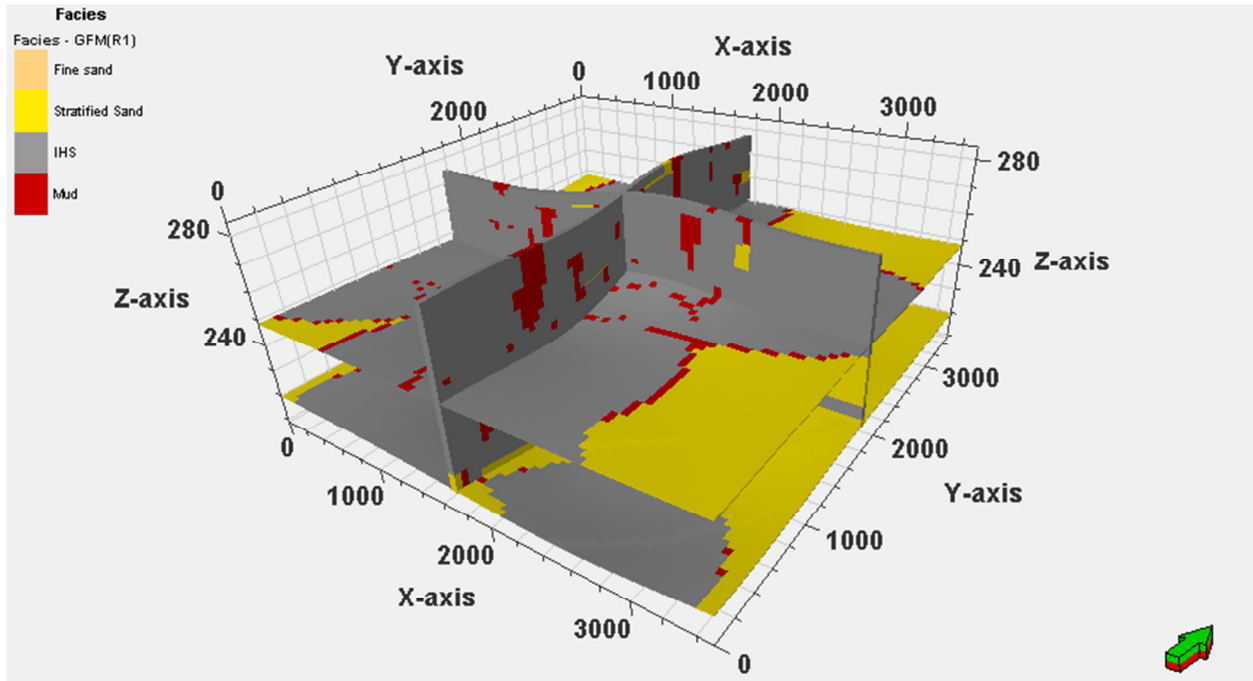


Figure 11: 3D view of conditional facies models generated with grid-free technique.

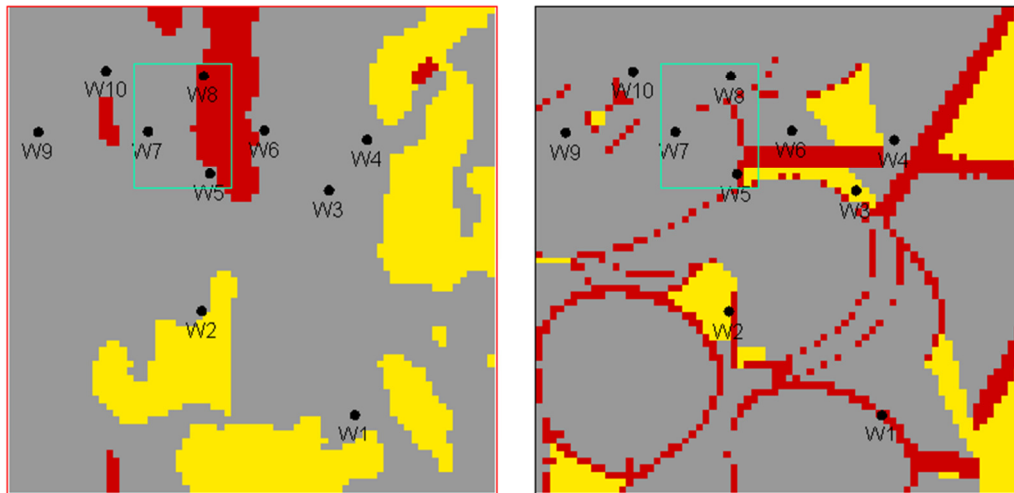


Figure 12 Location of SAGD pad imposed on top of SIS (left) and GFM (right) based models.

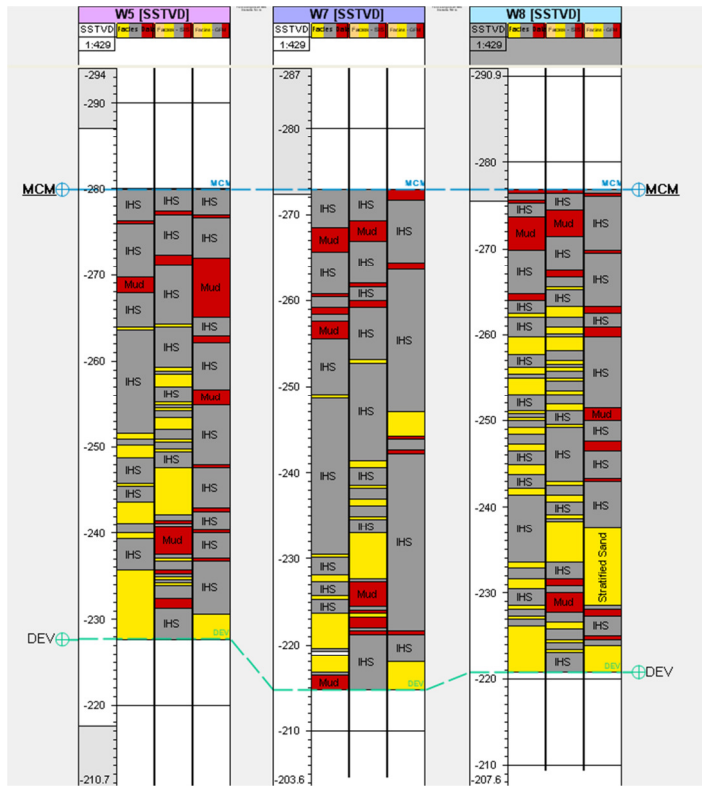


Figure 13: Well cross section of well 5, 7, and 8 showing facies data reproduction. For each well the left track is the facies data, the middle is the SIS and the right is the GFM model.

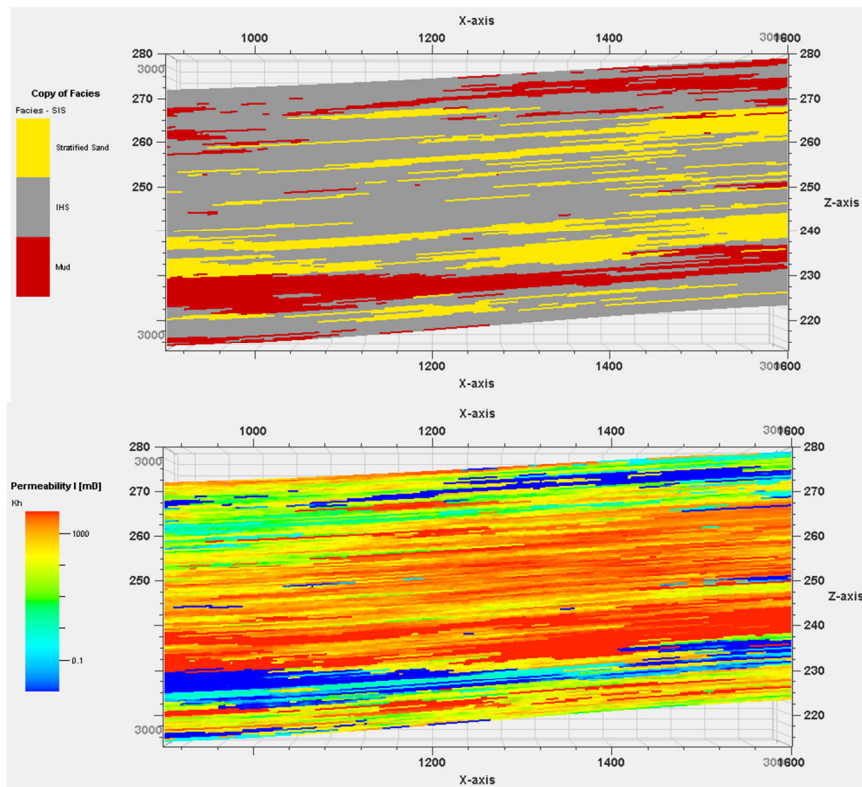


Figure 14: 2D slice of SIS facies (top) and the corresponding horizontal permeability model (bottom).

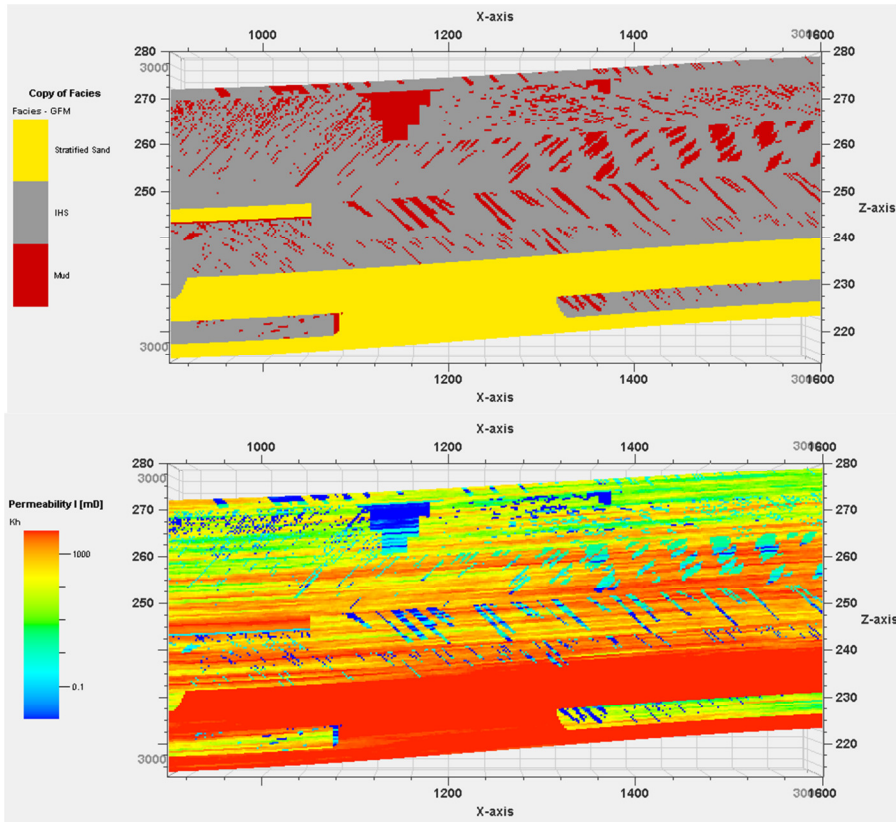


Figure 15: 2D slice of GFM facies (top) and the corresponding horizontal permeability model (bottom).

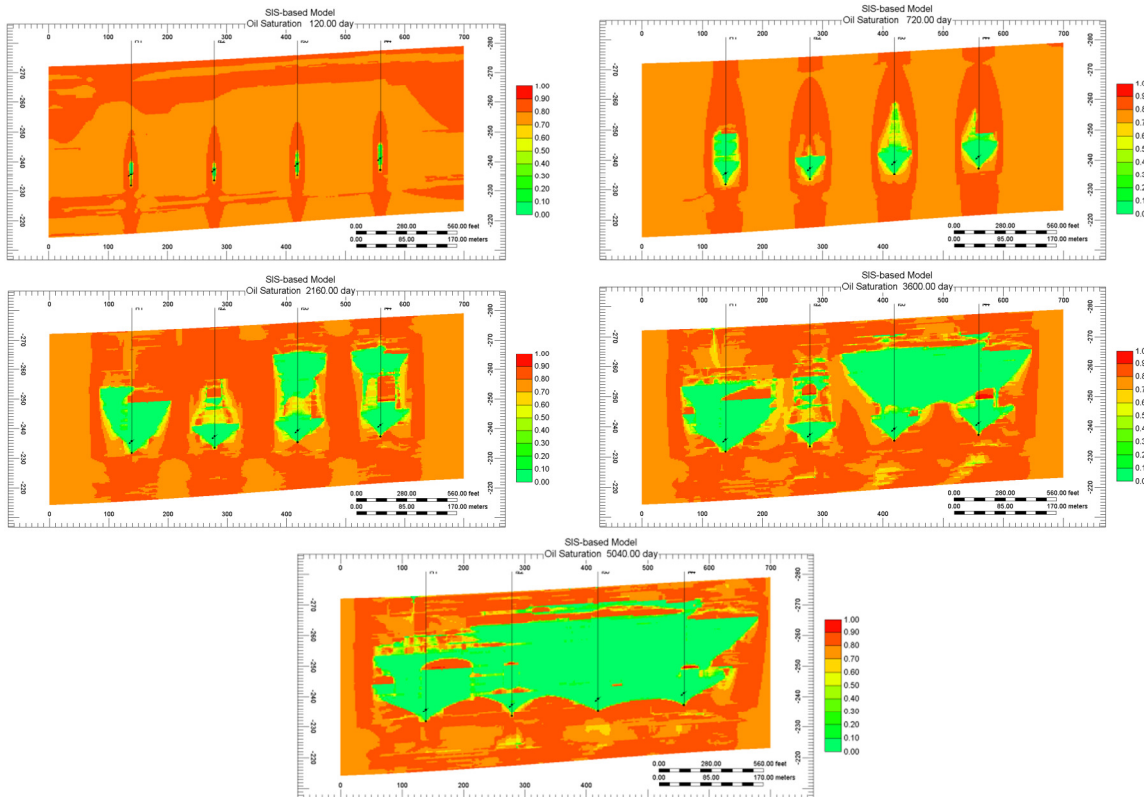


Figure 16: Oil saturation map for SIS-based model at different time steps.

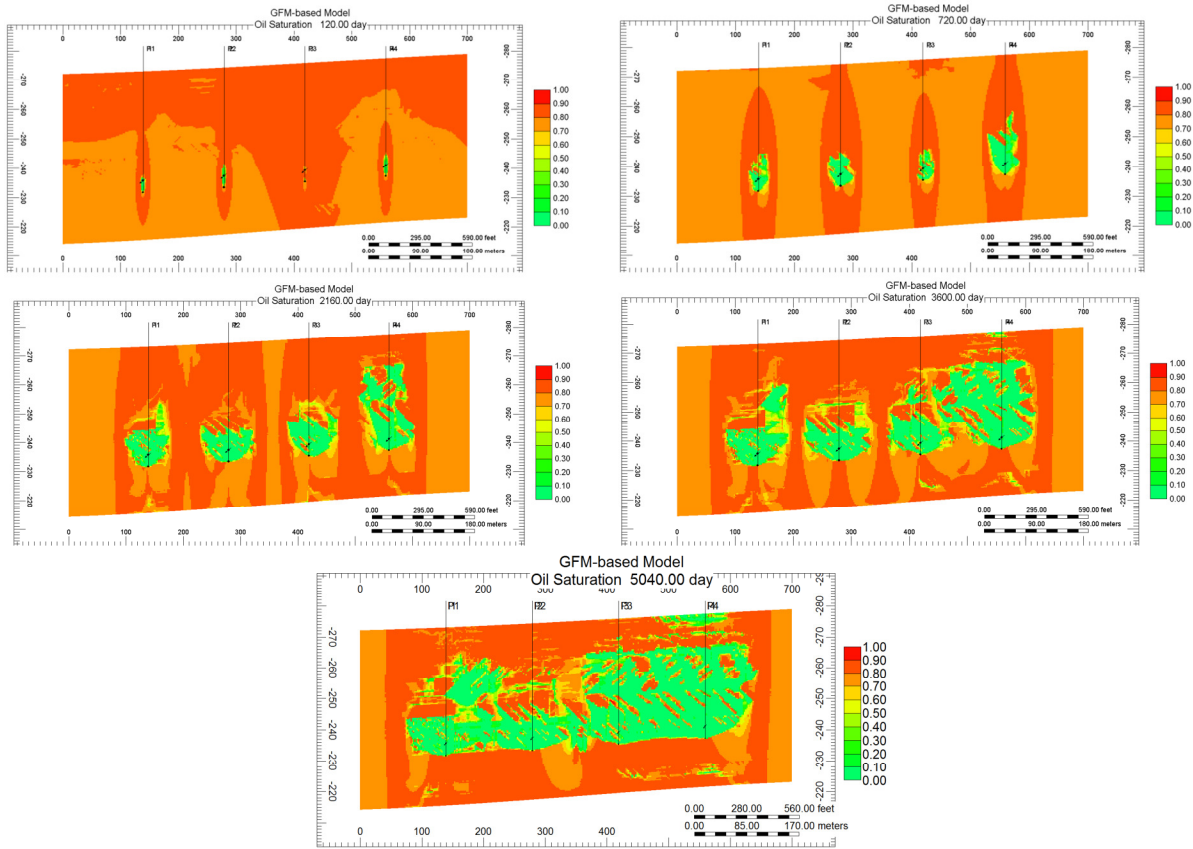


Figure 17: Oil saturation map for GFM-based model at different time steps.

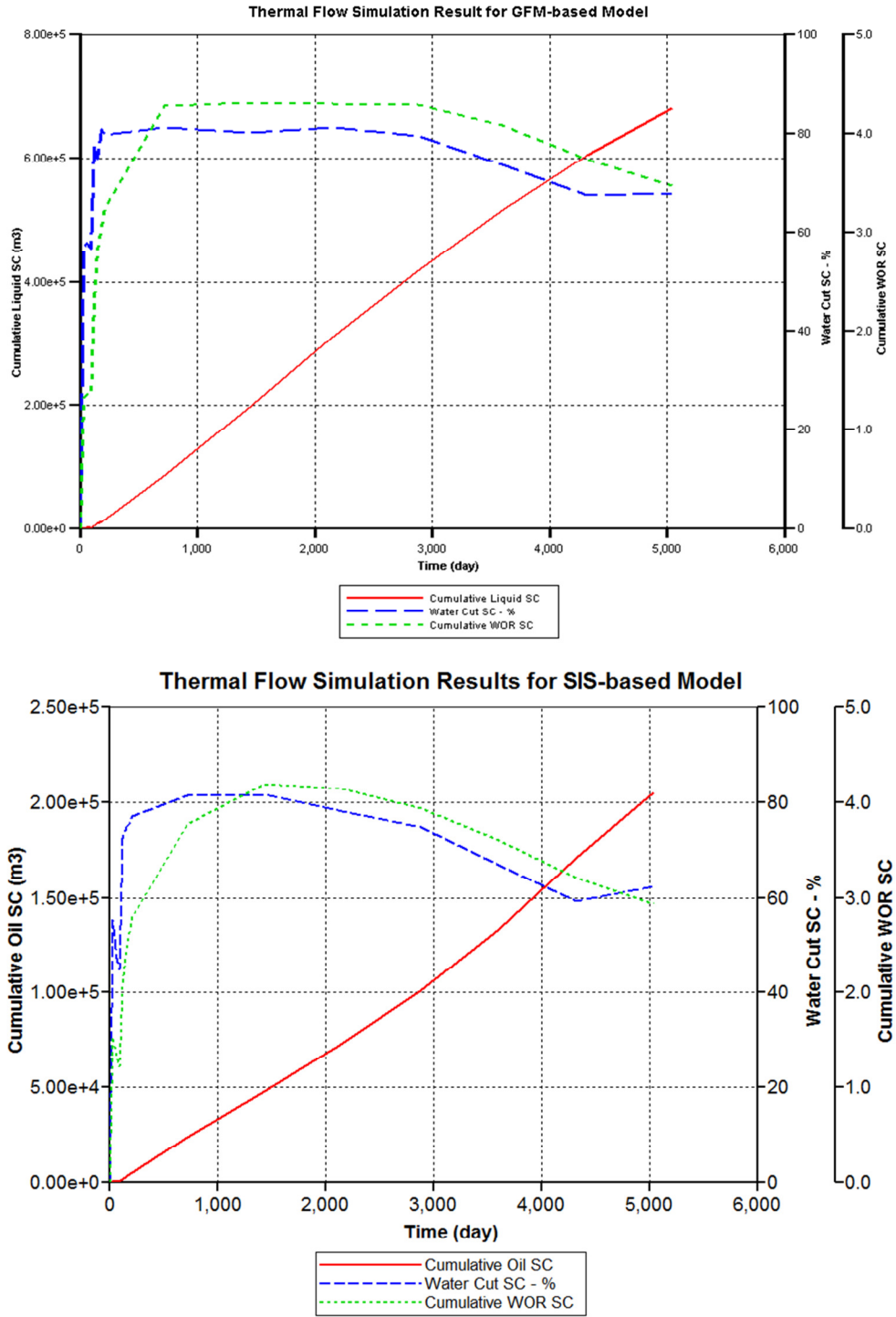


Figure 18: Comparison of thermal flow simulation performance for the GFM (top) and the SIS (bottom) models.