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3D Geological Modeling and Uncertainty Analysis of Pilot Pad in the Long Lake Field with Lean Zone and Shale Layer

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Summary

Three-dimensional geological modeling plays an important role in field development. This modeling provides the best technique for linking all existing data. To assess economic risks properly, an uncertainty analysis has to be thoroughly applied in a geological model. The studied reservoir is a pilot pad in the Long Lake field, which locates in southeastern Fort McMurray, Alberta, Canada. Intersected lean zones and shale layers have been reported in this area. These baffles have a detrimental effect on the steam-assisted gravity drainage (SAGD), which can increase the steam–oil ratio and decrease oil recovery. Thus, a detailed characterization of the lean zone and shale layer is important for the Long Lake field development.

This paper presents a reservoir modeling workflow and an uncertainty analysis for stock-tank original oil in place. The distribution of lean zones and shale layers is also discussed.

Introduction

The majority of oil sand resources in Athabsaca contain lower Cretaceous McMurray Formation. Steam-assisted gravity drainage (SAGD) is widely used in developing oil sands to achieve optimum economic benefits. However, SAGD is sensitive to heterogeneities, such as a lean zone and a shale layer. Owing to the complex succession of sands and mud deposited in fluvial to marginal marine environments, the lean zone and shale layer are widely distributed in the upper and middle parts of the McMurray Formation in the Long Lake field. Thus, applying SAGD in this lease is a challenge.

To understand the spatial distribution of lithofacies and associated reservoir parameters better, a geological model comprising well log, core data, structure, and lithological facies should be developed. This model is used to analyze the distribution of the lean zone and shale layer. An uncertainty analysis on stock-tank original oil in place (STOOIP) is also performed to evaluate economic risks.

Theory and/or Method

This study is conducted in two steps. First, a geological model is constructed under the control of geological structures and lithological facies. Second, an uncertainty analysis on STOOIP is performed to obtain results with a less error.

In the first step, drilled cores, well logs, lithological interpretation, well tops, and geological structural data are integrated to construct a static model. The structural map for the top of the McMurray and Beaverhill Lake formation is constructed by using geological structural data. After correlating well logs and core data, a geostatistical analysis is conducted for lithological facies, porosity, water saturation, and permeability. A lithological model is then constructed using the sequential Gaussian simulation (SGS) method. Under the control of geological structure and the lithological model, a petrophysical model of water saturation, porosity, and permeability is obtained.

In the second step, the water saturation multiplier (SwMulti), porosity multiplier (PorMulti), and formation volume factor (Bo) are employed to conduct the uncertainty analysis on STOOIP. The sampling methods of Monte Carlo are used in this step. After the analysis, P10, P50, and P90 STOOIP values are obtained.

Examples

Pad 1 is a pilot pad in the Long Lake field. The area of Pad 1 is 44,3261 m^2. Twelve observation wells (OB1A, OB2A, OB3A, OB1B, OB2B, OB3B, OB1C, OB2C, OB3C, OFFSET 09, OFFSET 11, and OFFSET 12) and six SAGD wells (01S01, 01P01, 01S02, 01P02, 01S03, and 01P03) exist in the studied area. The production started in April 2003. Based on the data (well logs, well tops, core analysis, and well path) of these wells, we conduct the study with the following workflow (All of the data used are public data obtained from the Long Lake Annual Report, studies presented by the Society of Petroleum Engineers, AccuMap, and Divestco.):

- Well Logs and Core Analyses
- Geostatistical Analysis
- Structural and Lithological Models
- Petrophysical Model
- Lean Zone and Shale Layer Analyses
- Uncertainty Analysis

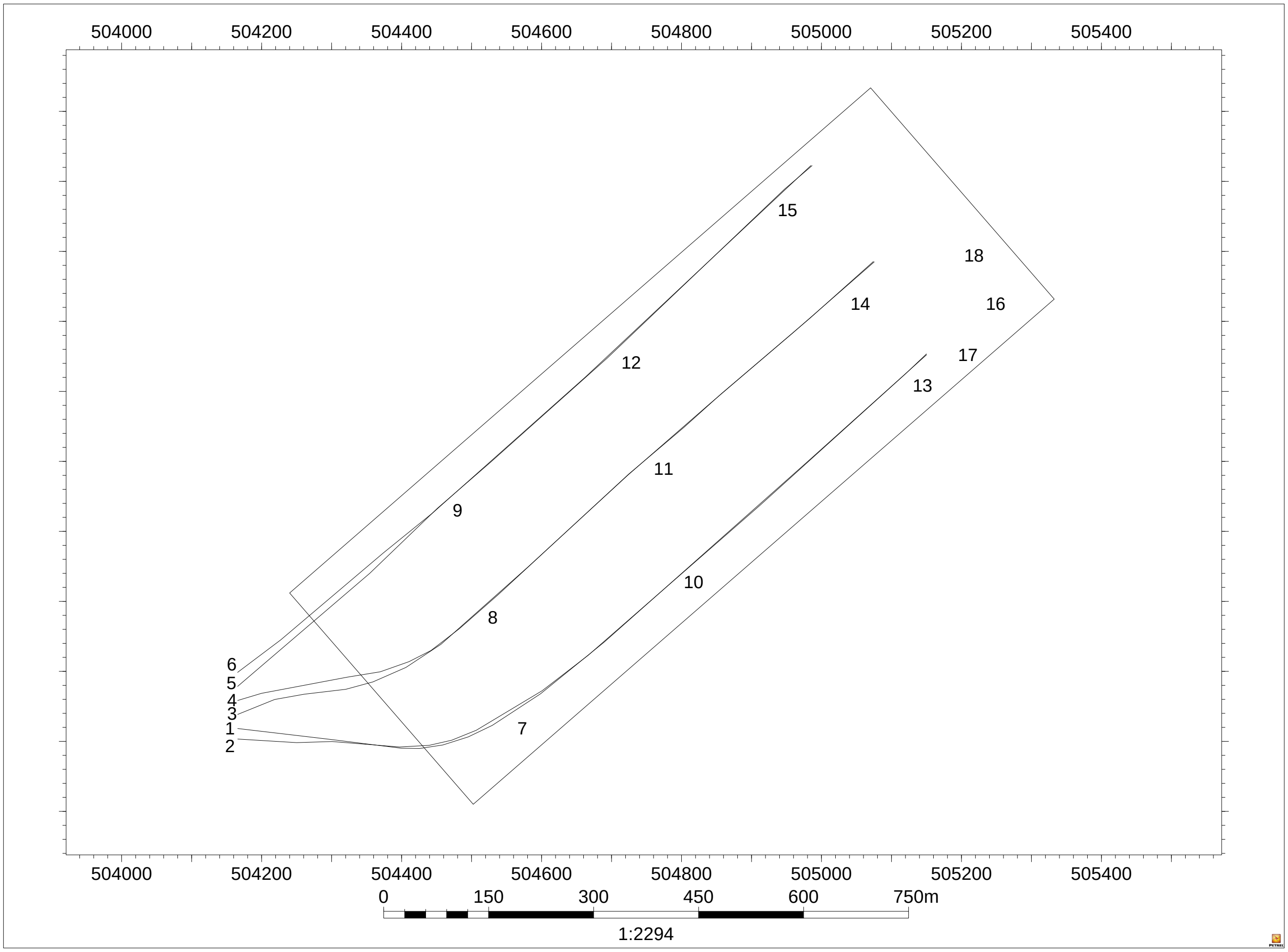


Figure 1: Study Area Map (①: 01P01; ②: 01S01; ③: 01P02; ④: 01S02; ⑤: 01P03; ⑥: 01S03; ⑦: OB3A; ⑧: OB2A; ⑨: OB1A; ⑩: OB3C; ⑪: OB2B; ⑫: OB1B; ⑬: OB3C; ⑭: OB2C; ⑮: OB1C; ⑯: OFFSET 12; ⑰: OFFSET 09; ⑱: OFFSET 11)

Well Logs and Core Analyses

Well logs and core analyses are the first step to develop the model. The lithology in the Long Lake field is classified as sandstone, sandy inclined heterolithic strata (IHS), muddy IHS, mudplug, breccia, and limestone. Nine observation wells with lithological interpretation are upscaled, as shown in Fig. 2. Sandstone mainly locates in the middle and lower parts of McMurray. Mudplug and breccia intersect in the sandstone. A transition zone of sandy IHS and muddy IHS exists between the mudplug and sandstone.

The correlation between well logs and core data is also evaluated. For example, we analyze the correlation between the porosity from core and the density porosity from well logs (DPSS) and obtain a good fit, as shown in Fig. 3.

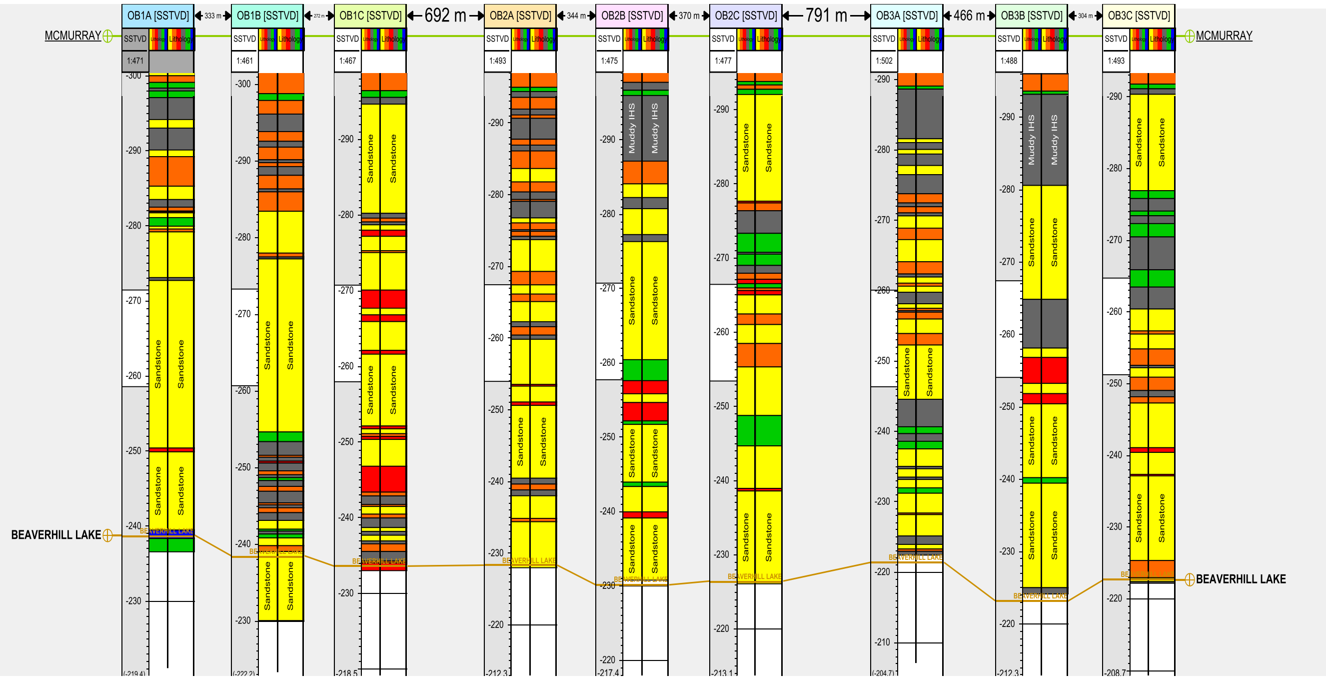


Figure 2: Lithological Interpretation of Observation Wells

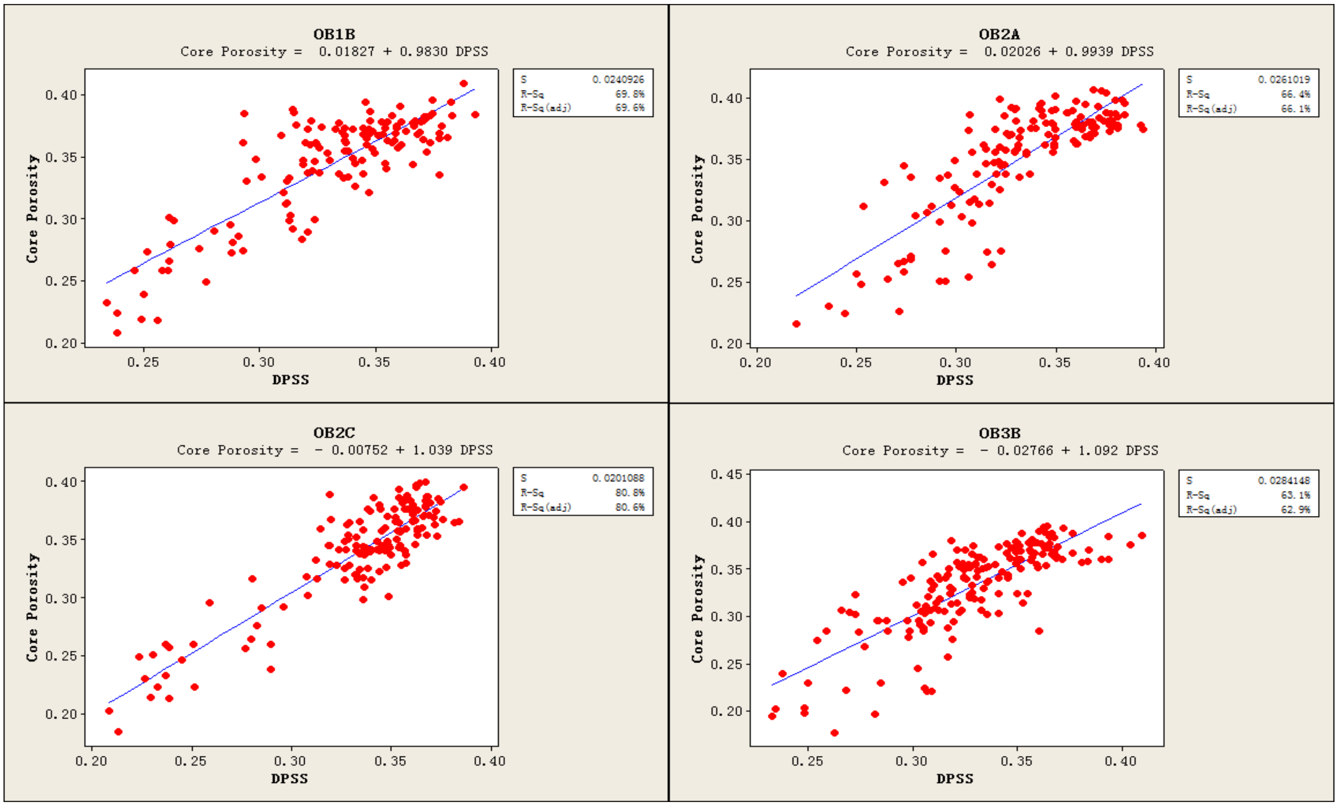


Figure 3: Correlation of Porosity between Core Data and Well Log Data

Geostatistical Analysis

Before constructing the lithological and petrophysical models, a geostatistical analysis on variograms for upscaled reservoir parameters should be conducted. A variogram is a tool for measuring the spatial relationship of any attribute of a group of 3D points. Variograms have three kinds; one is for the vertical direction, and the other two are for the horizontal direction. A geostatistical analysis aims to make a good match between the experimental and theoretical variograms.

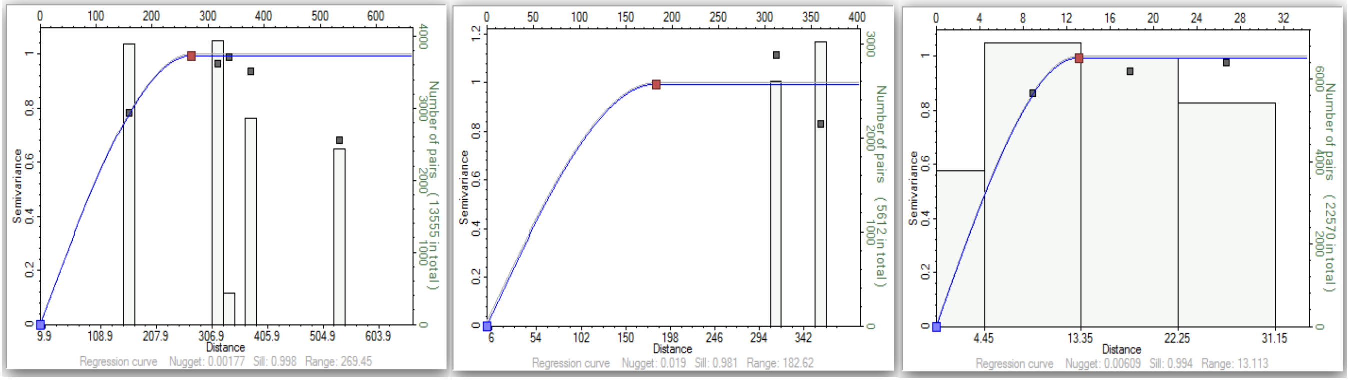


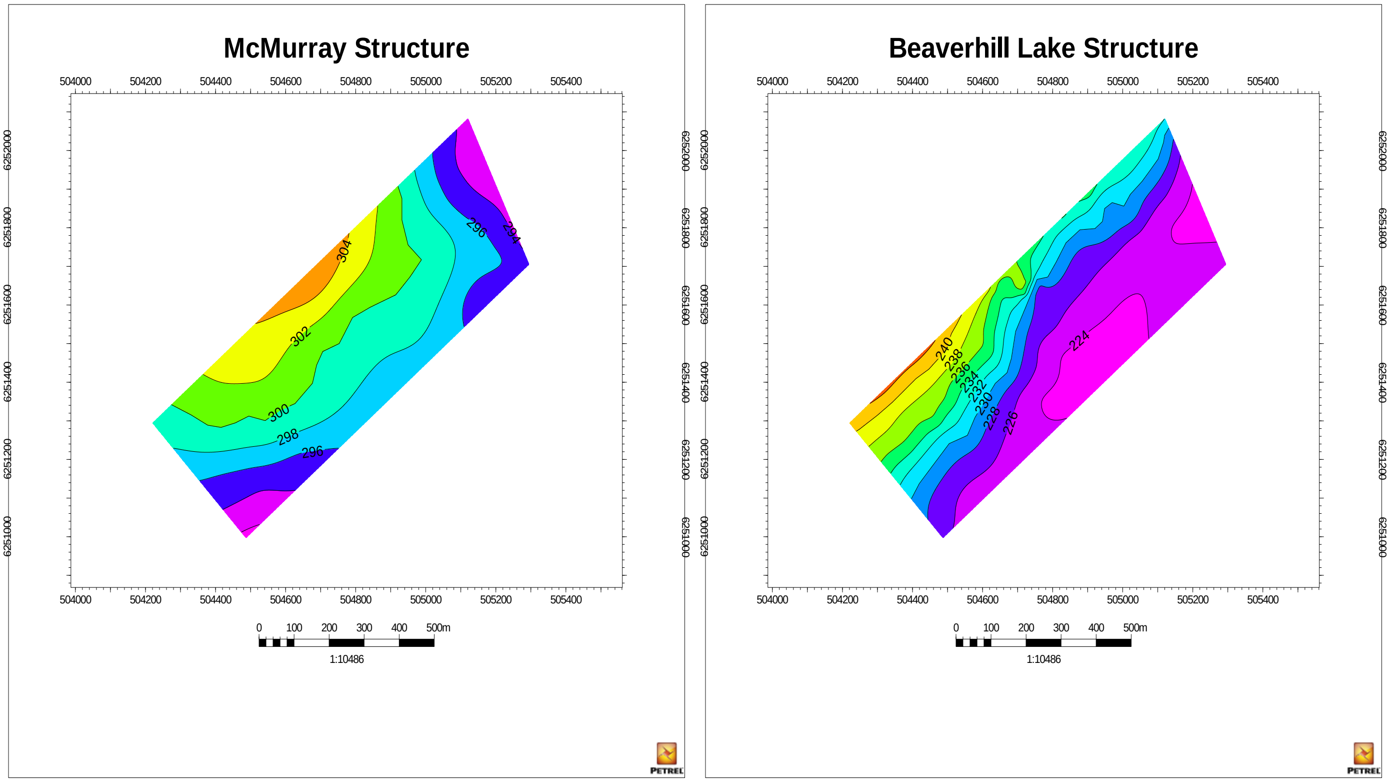
Figure 4: Variograms of Three Directions (Major, Minor, and Vertical) for Lithological Facies (The blue line is for the theoretical variogram, and the black line is for the experimental variogram.)

We first perform the geological analysis for lithological facies. The major direction of anisotropy is set as northwest (the direction of migration). After the match, we obtain a major range of 269.45 m, a minor range of 182.62 m, and a vertical range of 13.11 m. Under the controlling of lithological facies, we then perform the geostatistical analysis for each reservoir parameter (porosity, water saturation, permeability in the horizontal direction, and permeability in the vertical direction).

Structural and Lithological Models

A petrophysical model needs to be confined by the geological structural and lithological models. We construct the structural model using the interpolation method, as shown in Fig. 5. No significant change is found on the elevation for the surface of the top of McMurray and Beaverhill Lake. The average thickness of the McMurray formation in the studied area is 70.30 m.

We set the grid size of the model as 1 m × 1 m × 1 m. The total grid number is 39,400,560. Under the confinement of variograms, we construct the the lithological model using the SGS method. Fig. 6 shows that shale layers exist in the top of the McMurray formation. Most sandstones locate in the middle and low parts of the McMurray formation. The horizontal wells go through the sandstones, and most pay zones stand above the producer.



McMurray Structure

Beaverhill Lake Structure

Figure 5: Structural Model of the McMurray and Beaverhill Lake Formation.

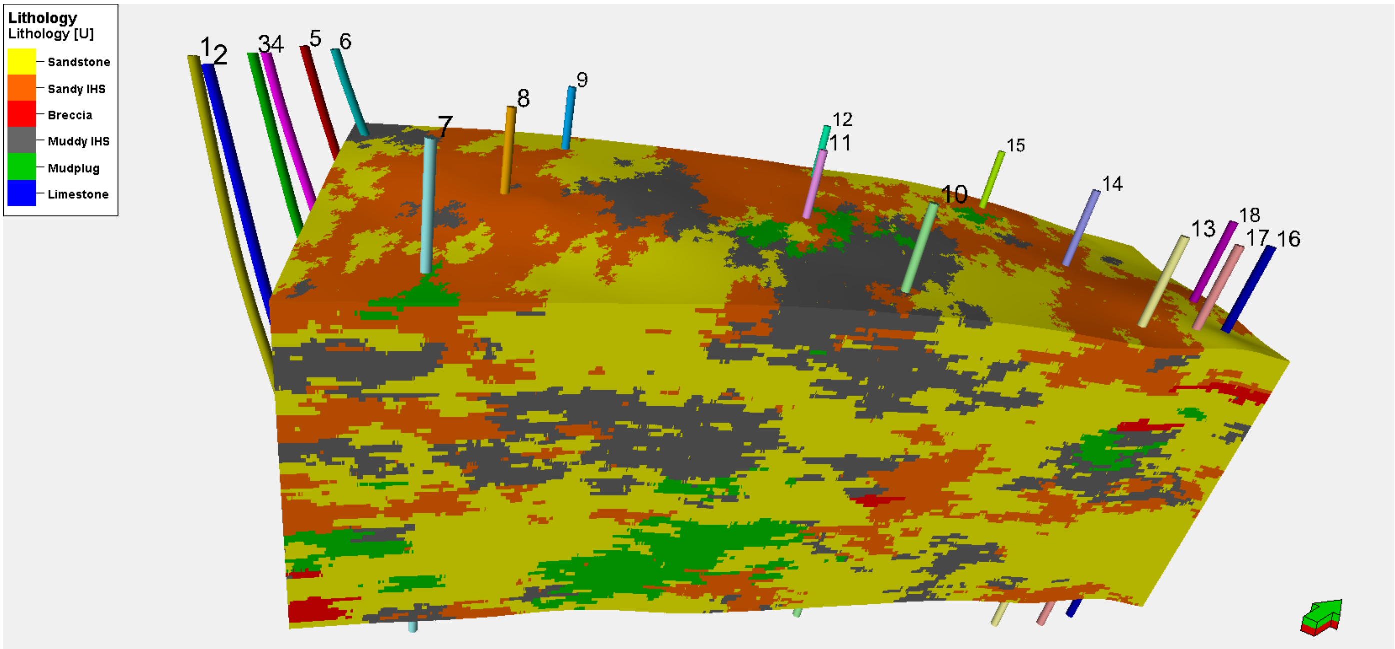


Figure 6: Lithological Model (①: 01P01; ②: 01S01; ③: 01P02; ④: 01S02; ⑤: 01P03; ⑥: 01S03; ⑦: OB3A; ⑧: OB2A; ⑨: OB1A; ⑩: OB3C; ⑪: OB2B; ⑫: OB1B; ⑬: OB3C; ⑭: OB2C; ⑮: OB1C; ⑯: OFFSET 12; ⑰: OFFSET 09; ⑱: OFFSET 11)

Petrophysical Model

Under the controlling by the structural and lithological models, we develop the petrophysical model for the reservoir parameters, including porosity, permeability, water saturation, and net–gross ratio (NTG). We use the SGS method to construct the petrophysical model. Fig. 7 shows that the porosity and permeability in the lithological facies of sandstone, sandy IHS, and muddy IHS are higher than those in the lithological facies of limestone, breccia, and mud plug. The average porosity is 0.3338; the average water saturation is 0.3561; the average permeability in the horizontal direction (Permeability IJ) is 5373.8303 md; the average permeability in the vertical direction (Permeability K) is 4440.9578 md. The reservoir condition is suitable for SAGD operation. However, the intersected lean zone and shale layer are a considerable challenge in Long Lake.

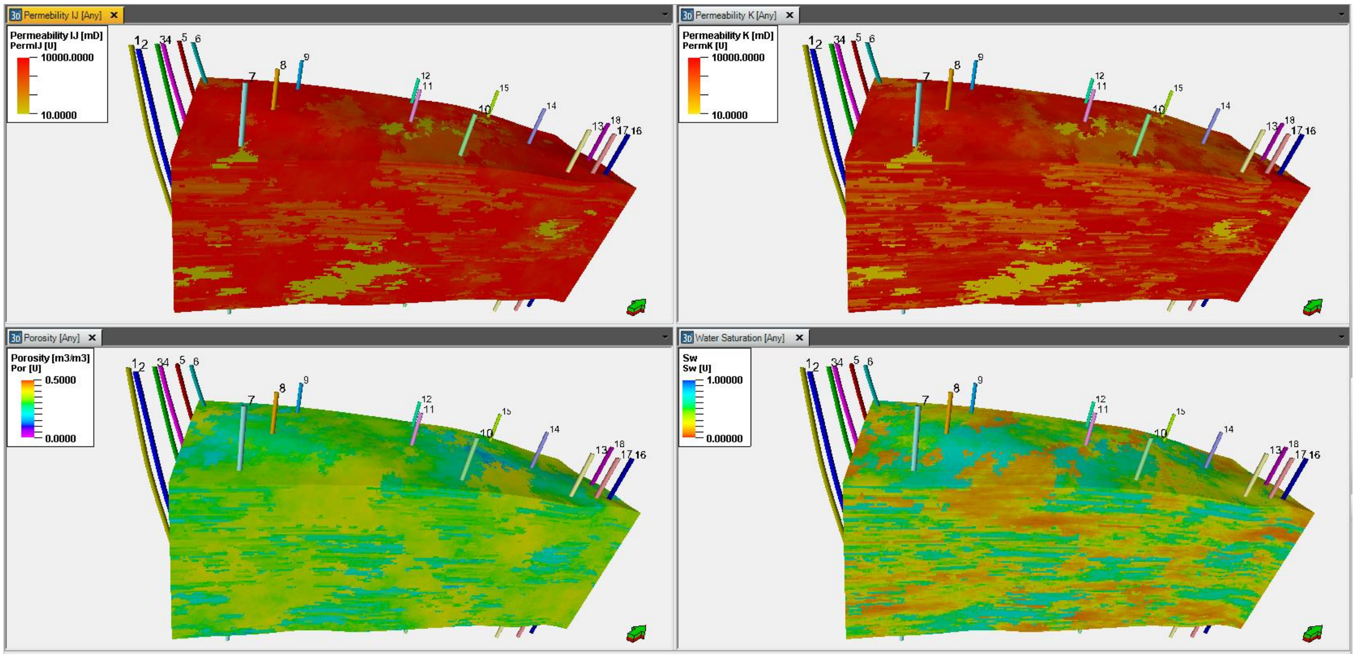


Figure 7: Petrophysical Models of Permeability IJ, and Permeability K, Poristy and Water Saturation (①: 01P01; ②: 01S01; ③: 01P02; ④: 01S02; ⑤: 01P03; ⑥: 01S03; ⑦: OB3A; ⑧: OB2A; ⑨: OB1A; ⑩: OB3C; ⑪: OB2B; ⑫: OB1B; ⑬: OB3C; ⑭: OB2C; ⑮: OB1C; ⑯: OFFSET 12; ⑰: OFFSET 09; ⑱: OFFSET 11)

We also develop an net gross ratio (NTG) model, as shown in Fig. 8. We set the NTGs of sandstone, sandy IHS, and muddy IHS as 1, while those of the other parts, including mud plug, breccia, and limestone, are set as 0. Based on the petrophysical model, we obtain the base value of STOOIP for this model as 6.5983×10^6 m^3.

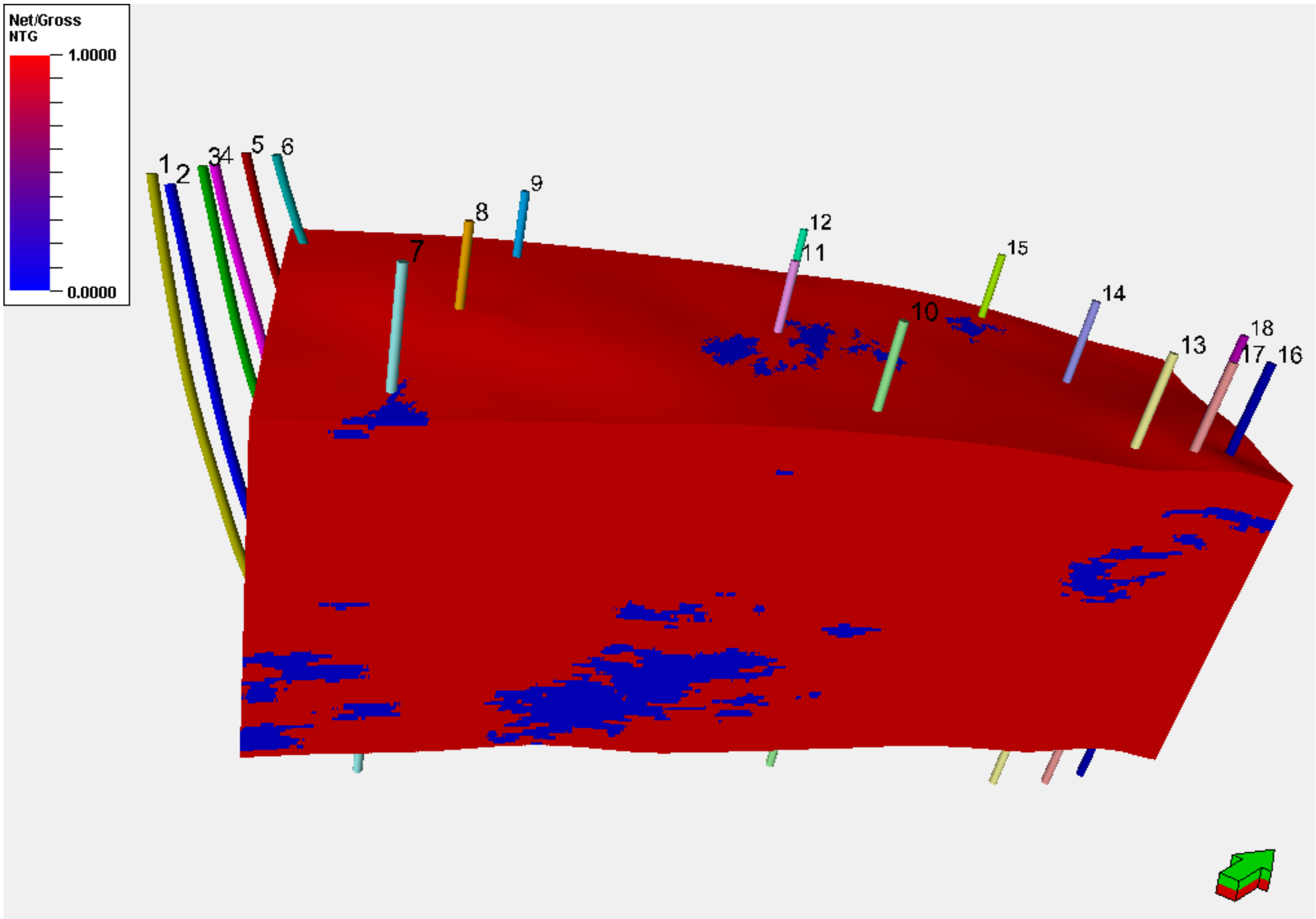


Figure 8: NTG Model (①: 01P01; ②: 01S01; ③: 01P02; ④: 01S02; ⑤: 01P03; ⑥: 01S03; ⑦: OB3A; ⑧: OB2A; ⑨: OB1A; ⑩: OB3C; ⑪: OB2B; ⑫: OB1B; ⑬: OB3C; ⑭: OB2C; ⑮: OB1C; ⑯: OFFSET 12; ⑰: OFFSET 09; ⑱: OFFSET 11)

Lean Zone and Shale Layer

The lean zone (Sw>0.5) and shale layer affect the SAGD operation by decreasing oil recovery and increasing the steam–oil ratio. An in-depth understanding of the distribution of the lean zone and shale layer is essential. In the intersection of three well pairs, as shown in Figs. 9 to 11, the shale layer mainly locates in the upper part of the McMurray formation, while the lean zone mainly locates in the up and low parts of McMurray. The well path for the SAGD well pairs is successful because they mainly path the sandstone and is far away from the lean zone. However, the lean zone and shale layer still have a significant effect when the steam chamber arrives in them.

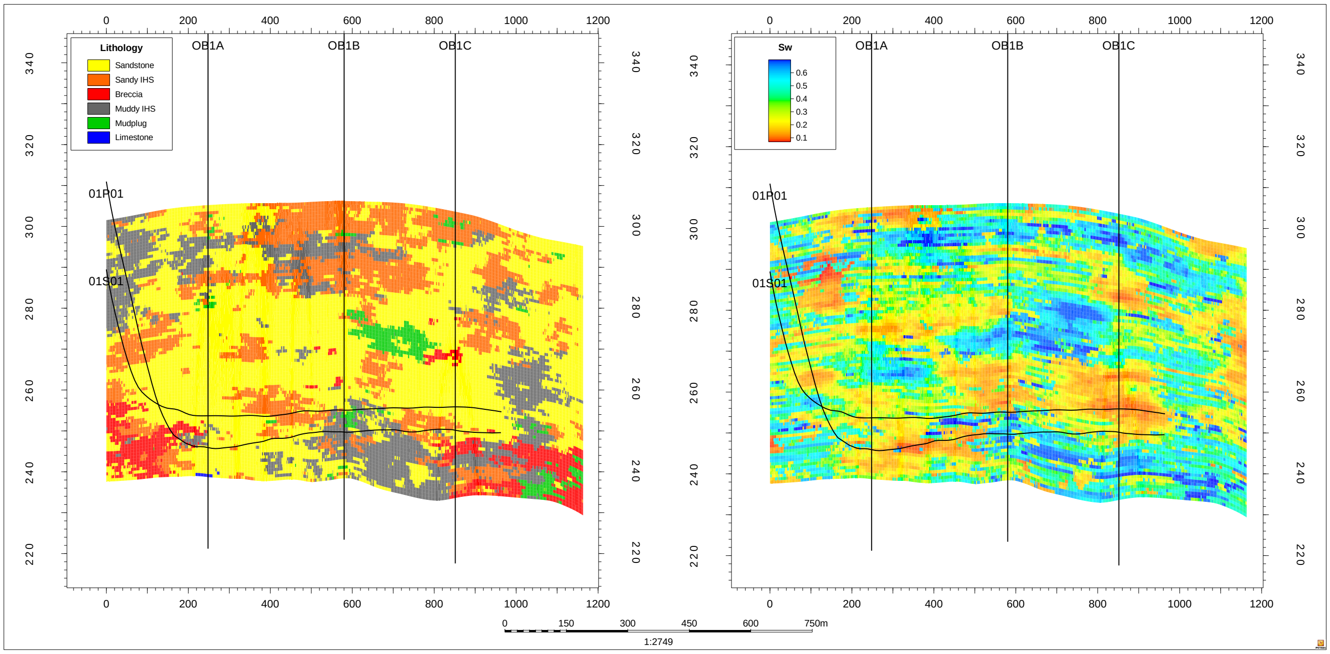


Figure 9: Intersection of Lithological Facies and Water Saturation for Well Pair 1

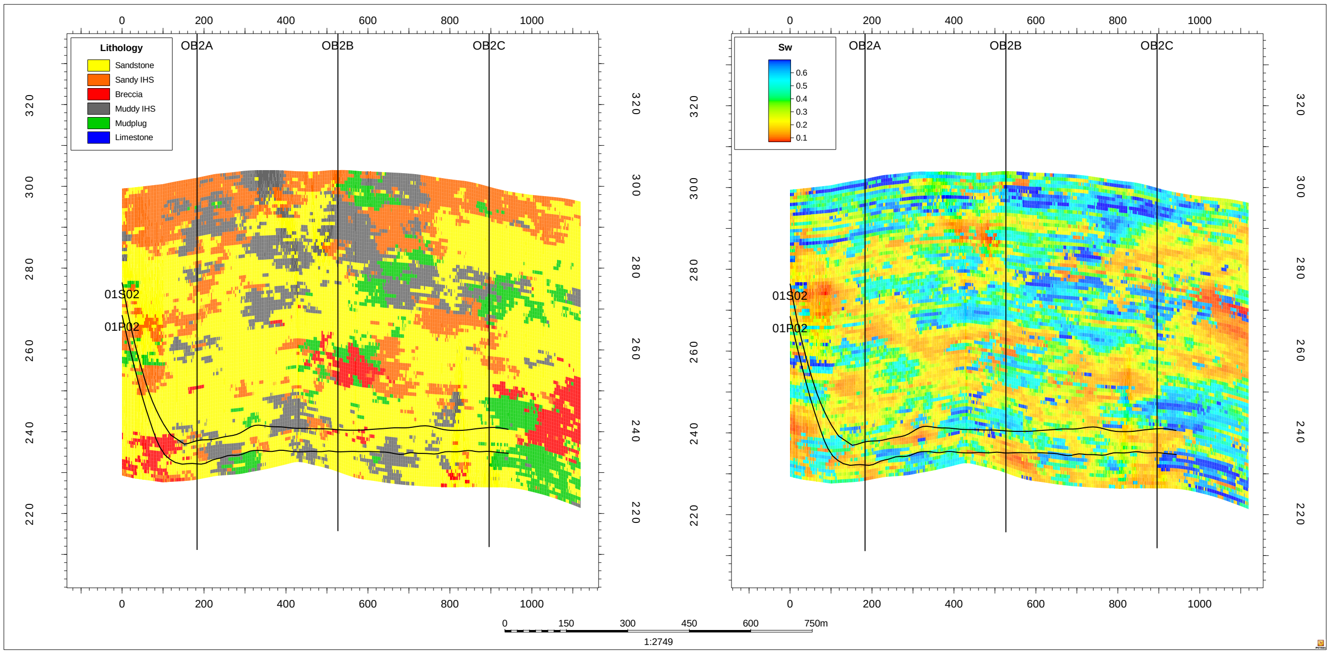


Figure 10: Intersection of Lithological Facies and Water Saturation for Well Pair 2

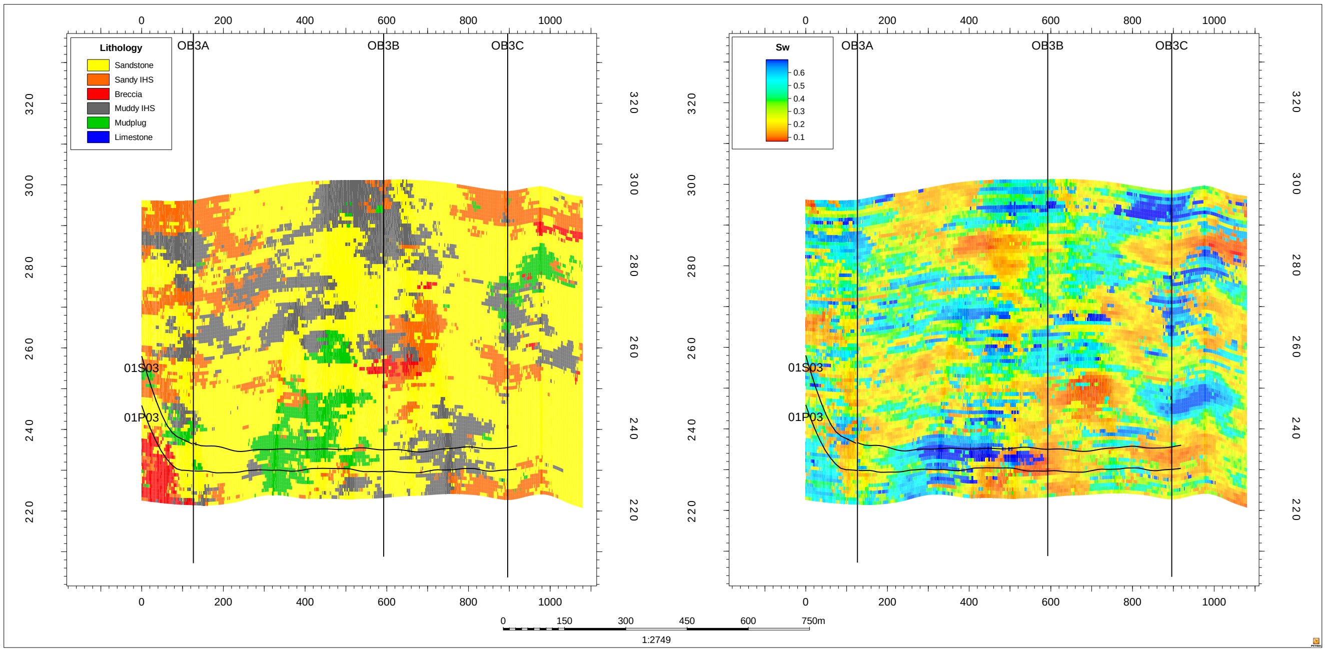


Figure 11: Intersection of Lithological Facies and Water Saturation for Well Pair 3

Uncertainty Analysis

The oil and gas reserve calculation is realized using the following formula (gas saturation equals to zero in our model):

$$\mathrm{STOIIP} = \frac{\mathrm{V_b} \times \mathrm{NTG} \times \varphi \times \mathrm{S_o}}{\mathrm{B_o}} \quad (1)$$

Where STOIIP is stock-tank original oil in place, $\mathrm{sm^3}$; $\mathrm{V_b}$ is the bulk volume, $\mathrm{rm^3}$; NTG is the net gross ratio; φ is the porosity; $\mathrm{S_o}$ is the oil saturation and $\mathrm{B_o}$ is the oil formation volume factor, $\mathrm{rm^3/\ sm^3}$.

However, this calculation is a probability problem that contains numerous uncertainties. On one hand, uncertainties exist because geological parameters cannot be measured directly. People only use data according to a core analysis, well logging, and other indirect measurement methods in the estimation. However, the core analysis represents only a small fraction of underground situations. Regarding interpretation, the well logging result differs significantly because of human factors. On the other hand, the volumetric method is employed frequently for its simplicity. This method, however, increases uncertainty because it uses the average value of parameters to calculate. The average value is only a determined value of numerous potential values. Thus, the heterogeneity of reservoirs cannot be reflected accurately. Aiming at these problems, other methods need to be developed.

We use two sampling methods in this study—an equal spacing sampling method and the Monte Carlo sampling method.

(1)Equal Spacing Sampling Method

An equal spacing sampling method is a deterministic sampling method. Each parameter requires maximum and minimum values to determine its interval. The sampler divides the interval to several equal small portions. The dividing points of portions are the sampling points. This method employs several values instead of only the average value, thereby increasing the reliability of calculation results.

(2)Monte Carlo Sampling Method

The Monte Carlo sampling method is a stochastic sampling method involving repetitive random sampling according to given probability distribution functions. The sampler uses thousands of sampling values to calculate. Each calculation produces a potential result. Eventually, all results are combined to draw a probability distribution curve. Different probability distribution functions are used in different situations.

(a) Uniform

This function is used when only two values of the variable are available or the occurrence probability of values in the interval is equally likely.

(b) Normal

The normal distributed pattern is efficient when the variable obeys normal distribution; i.e., the mean values in the middle are more likely to occur. The mean value and the standard deviation should be input.

(c) Triangular

The maximum, minimum, and most likely values are assigned in this function. Higher chance exists for the values around the most likely value to occur.

Nevertheless, the Monte Carlo sampling method might grasp points within certain portions, while ignoring the values in other portions. In the PetrelTM Software, the Monte Carlo sampler can be integrated with the Latin hypercube sampling method, which enables to carry less iteration but cover the whole interval better. The Latin hypercube sampling method divides the whole interval into several parts, which have the same probability rather than the same area. The sampler then obtains a value from each part. In this way, the Latin hypercube sampling method avoids gathering values by chance.

The section below uses both the equal spacing and Monte Carlo sampling methods coupled with the Latin hypercube sampling method to obtain values for the following geological parameters and calculate STOOIP.

Table 1 Parameters and Levels

Parameters	Base Value	Minimum Value	Maximum Value
SwMulti	1	0.7	1.3
B_o	1	1	1.1
PorMulti	1	0.7	1.3

After determining the parameters and their levels, the following several steps are performed:

(1) The parameters that influence the STOOIP are identified, and their levels are determined according to the practical situations of the reservoir.

(2) The equal spacing and Monte Carlo sampling methods with the Latin hypercube sampling method are used to conduct stochastic sampling for the selected parameters.

(3) Step 2 is repeated until the sampling number reaches the given number.

(4) Multiple sampling values are used to calculate potential STOOIP repeatedly.

(5) A sensitivity analysis is conducted through a tornado graph to identify the most influential parameters.

(6) A STOOIP distribution curve is constructed, and the values of P10, P50, and P90 are obtained.

We conduct 1050 realizations for each of the two methods. When the above-mentioned operation steps are finished, the following results can be drawn as in Figs. 12 to 15.

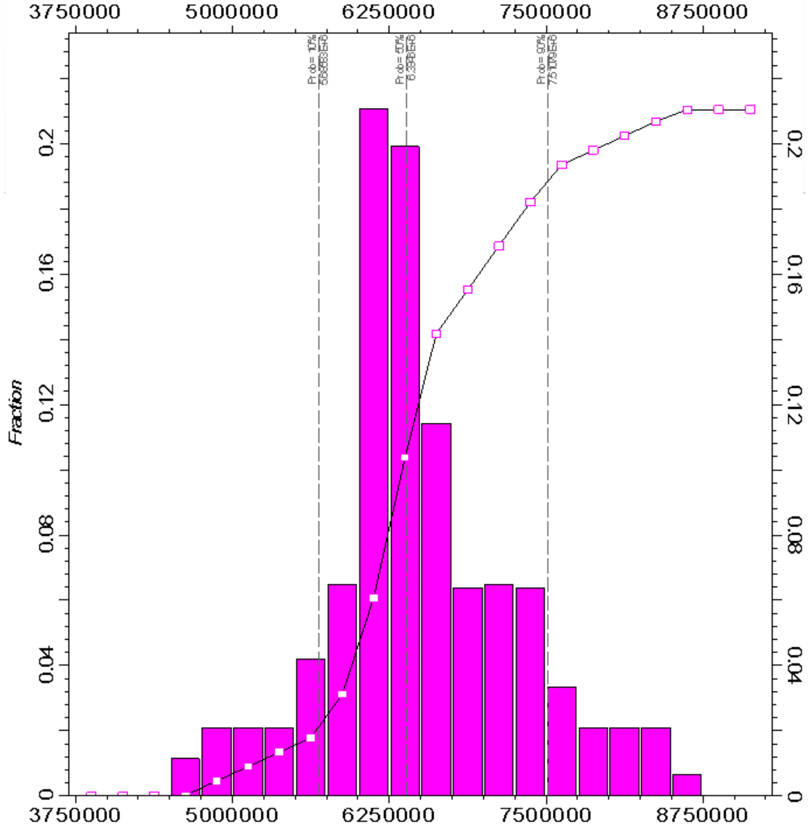


Figure 12: Histogram of the Equal Spacing Sampling Method

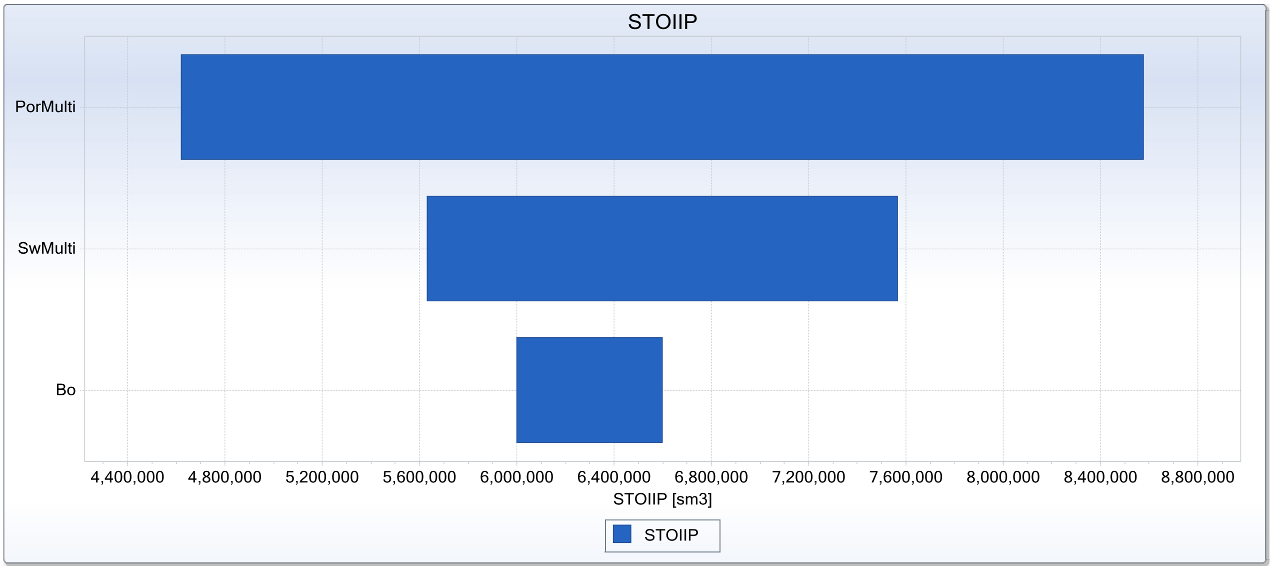


Figure 13: Tornado Plot of the Equal Spacing Sampling Method

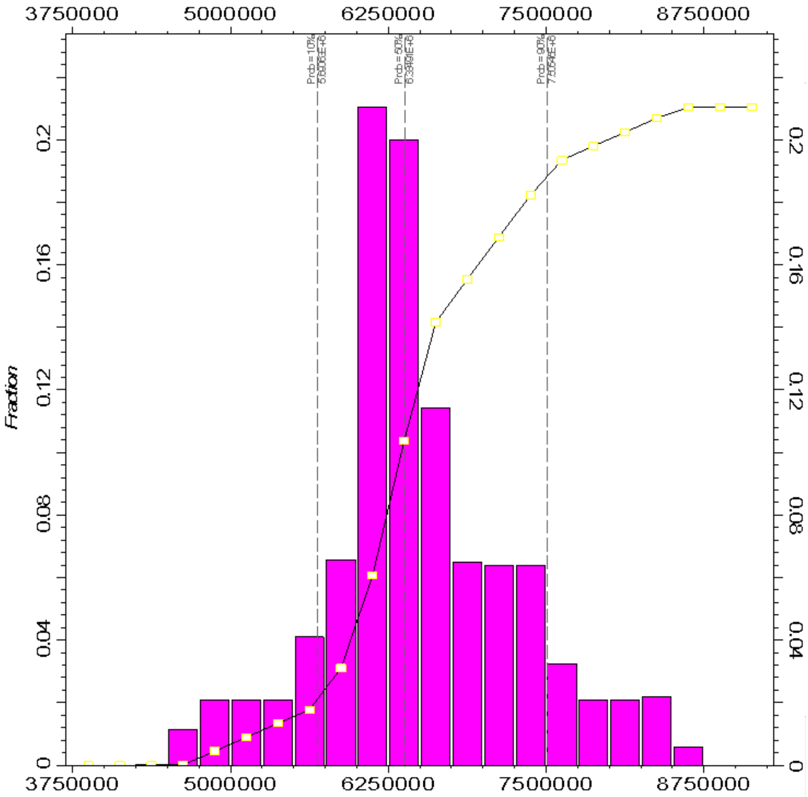


Figure 14: Histogram of the Monte Carlo Sampling Method

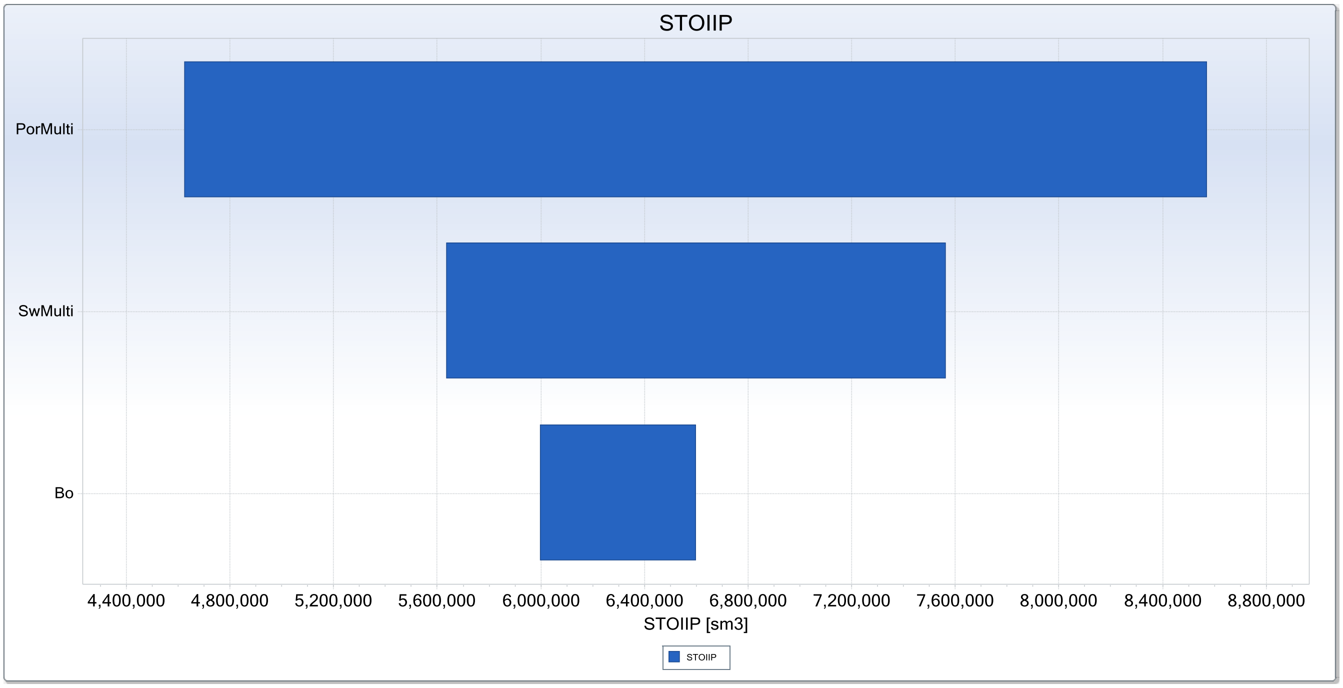


Figure 15: Tornado Plot of the Monte Carlo Sampling Method

The above figures show that the two methods obtain similar results. P10, P50, and P90 calculated by two different methods are close. The P50 calculated using the equal spacing sampling method (6.3346×10^6 m^3) and the P50 calculated using the Monte Carlo sampling method (6.3849×10^6 m^3) have the same base value (6.5983×10^6 m^3), with errors of 3.9664% and 3.2341%, respectively. Thus, the Monte Carlo sampling method is more accurate in this case. However, both predictions have high accuracy, which means that the model is reliable. In terms of the three influence parameters, the patterns are the same, but the porosity multiplier has the largest effect on STOOIP, followed by the water saturation multiplier and the formation volume factor.

Conclusions

1. Under the controlling of structural and lithological models, a 3D petrophysical model is constructed. This model integrates all available data and provides a better understanding of the reservoir parameters. According to the reservoir simulation result, the constructed model is instrumental.

2. An uncertainty analysis is a necessity in the evaluation of STOOIP given many uncertainties in the process. The equal spacing and Monte Carlo sampling methods are the two main methods used to conduct estimation. These two methods can help to identify the most influential parameters and estimate the potential STOOIP (P10, P50, and P90).

Acknowledgements

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