High Resolution Geomodeling, Ranking and Flow Simulation at SAGD Pad Scale

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Increasing computer power and improved reservoir simulation software facilitates building better and better geocellular models. This paper describes the methodology used for characterizing Steam Assisted Gravity Drainage (SAGD) pads with high resolution geological modeling, ranking and flow simulation at StatoilHydro Canada. There are 3 steps involved in the process: (1) generate high resolution geocellular models accounting for geological uncertainty, (2) rank the realizations with a static measure calibrated to a flow response, and (3) flow simulate select realizations for uncertainty assessment. The high resolution modeling permits detailed assessment of reservoir performance and sensitivities. Ranking different realizations and flow simulating select realizations allows an accurate uncertainty assessment with minimal effort. This paper was presented at the World Heavy Oil Congress earlier this year.

Introduction

There is always uncertainty when planning a SAGD pad. The uncertainty is a result of limited geological data and uncertainty in the predictions of reservoir properties. We propose a methodology that can be used to quantify the resulting uncertainty in the SAGD pad performance. The methodology is composed of three components: (1) building high resolution geocellular models that account for the geological uncertainty, (2) ranking the models with a static measure calibrated to previous flow simulation results and (3) flow simulating a few selected realizations based on the ranking results.

The first step in the workflow is to build the pad scale models. These models should use all available information and also account for uncertainty in the predictions. The ranking is used to select a few realizations from the multiple realizations built as part of step 1. It is common to build anywhere from 20-100 realizations of the geology. However, it is not feasible to flow simulate that many models. The ranking is used to predict the relative performance of each pad. Then, select realizations can be flow simulated. The results of the flow simulation provide the range of uncertainty for the planned SAGD pad.

SAGD depletion simulations were performed using Exotherm (T.T. & Associates) and STARS (Computer Modeling Group) numerical modeling tools. Similar results were obtained by both models.

SAGD Pad Modeling

Pad models were generated based on a 6 well pair design which covers an area approximately 1100m long by 700m wide. The pad models were built with a 100m buffer on all sides of the pad to minimize boundary effects inherent with reservoir simulation.

Several structural controls were used for building the pad models. The models were hung from the McMurray Top surface and brought down to the Devonian surface. Within this interval, top and base of SAGD surfaces were used to construct a porosity trend model. The trend model was made with 2 vertical trend curves; one vertical trend inside the SAGD interval, and a second vertical trend for the regional parasequences.

Sequential Gaussian simulation (SGS) was used to populate the pad models with porosity and water saturation values. In addition, an oil-water contact surface that was constructed from well data was used to model the bottom water contact. Top water was not estimated directly, the saturations were generated in the Gaussian simulation based on well data. Top gas on the other hand was estimated directly using well data in conjunction with 3D seismic. The seismic was used to generate the areal gas extent while well data was used to define gas channel thickness.

Horizontal permeability was calculated as a function of the modeled effective porosity which is consistent with standard Shaley Sand analysis techniques. As a first trial, vertical permeability was taken as a fraction of the horizontal permeability.

Grid Definition

A global grid definition was not used for the pad models; instead small local grids aligned with basic pad outlines were used. This simplified placing the wells in the model in Exotherm / STARS and removed the need to rescale a global model to the local grid.

Cell size is critical in thermal reservoir simulation and a number of sensitivities were run to determine an appropriate size. The selected cell size measures 1m vertically, 2m laterally and 100m longitudinally. The vertical cell size was kept fixed, it was not proportional.

The pad models were built starting from the McMurray surface down to the Devonian. Since a fixed vertical cell size was used and the gross thickness was not constant, some model cells below the Devonian were clipped. Figure 1 shows a pad model with grid lines. The bottom of the model is clipped due to the Devonian.

Cells that fell below the Devonian had to be present for the flow simulation and could not be nulled out. If the cells were nulled there was no avenue for heat transfer through the base of the model in the flow simulation, and the underburden would go effectively unmodeled. Accordingly, cells residing below the Devonian surface were assigned properties that allowed for thermal conduction.

All pads were not the same 6 well pair base size. Some pads were smaller due to McMurray channel dimensions and the presence of other pads which clipped the odd pad corner. The number of grid cells was specified so that the models matched the each pad dimension with the surrounding 100m buffer. The rotation angle of the pad was also needed to build the pad models. The grid was rotated to match the pad orientation.

Structural Controls

Some structural controls were used for building the pad models. The pad models were constrained at the top by the McMurray Top surface and at the bottom by the Devonian surface. Between these 2 surfaces, the top and base of SAGD were used to help constrain the channel and the oil-water contact was used to set some of the saturations.

Structurally controlling surfaces were generated from well data, 3D seismic or a combination of the two. Some surfaces such as the Wabiskaw C (McMurray Top) and the Devonian can be reasonably defined from seismic alone due to the larger seismic contrast. Other surfaces, such as the top of SAGD and the oil-water contact, are generally built from well data alone and then tuned where appropriate using seismic interpretation.

Data Analysis and Upscaling

The first step of the data analysis was to assess the sensitivity of the well data to upscaling. Some changes will occur in the log data when going to a larger scale and significant changes are undesirable. The following methodology was used to assess the scale sensitivity of the data:

1. Calculate the histograms of Effective Porosity (porosity), Water Saturation (Sw) and Volume of Shale (Vsh) at the log scale.
2. Upscale the well data to a larger size, called X.
3. Calculate the histograms of porosity, Sw, and Vsh from the upscaled data. Compared the upscaled results to the original histograms from step 1. The histograms should have the same mean and variance. An additional comparison with a Q-Q plot can reveal subtle differences.
4. Return to step 2 and repeat the process with another larger cell size X.
5. Stop when finished with all possible cell sizes.

The results of the upscaling analysis for porosity are shown in Figure 2. Porosity was the most sensitive variable to the upscaling. Sw was the second most sensitive and Vsh had only minor changes during the upscaling. The log data does not exhibit any significant changes until the scale becomes greater than 1 meter. Some changes do occur at a scale of 1m, but they were considered minor. The well data was upscaled to 1m since there were no significant changes to the distribution and it coincided to a good dimension for thermal reservoir simulation.

Two main data analysis steps were undertaken: (1) variogram analysis and (2) the porosity to permeability transformation. The variograms were calculated along the direction of the channel, perpendicular to the channel and vertically. For the estimation, the variogram was rotated to align with the pad orientation. Aligning the variogram with the pad forced the continuity to follow the local channel orientations (most pads are laid out parallel to the McMurray channel direction). Effective porosity and water saturation had almost identical experimental variograms. Since they were so close, the same variogram model was used for both variables. The variogram model is shown in Figure 3 and Equation (1).

$$\gamma(\mathbf{h}) = 0.60 \cdot Exp_{\substack{along=800 \\ across=600 \\ vertical=10}} + 0.40 \cdot Sph_{\substack{along=7500 \\ across=2500 \\ vertical=30}} \tag{1}$$

Permeability was calculated as a function of the modelled porosity. The well logs contained a calculated permeability that has been calibrated to the cores and other logged variables. The effective porosity was cross plotted with the calculated permeability. A regression was fit to the cross plot. The porosity-permeability crossplots are shown in Figure 4. The points above and below the red line are due to a few wells that had a slightly different transformations.

Property Modeling

The trend model was constructed using the top and base SAGD surfaces and a vertical trend calculated from the data. The goal was to produce a trend model with low porosity values outside of the channel environment and high porosity values inside the channel. The trend was considered soft information. It is only used when estimating far distances from a well location. Near the wells, the well log information is predominantly used.

The first step of the trend modeling was to calculate the vertical trend for 2 populations. The first population is inside the channel. The second is outside the channel. The trends were calculated by averaging all the samples from one population for a given stratigraphic layer. Recall that the model grids were built from the McMurray down in 1m layers. A stratigraphic layer refers to a layer that is a specific distance down from the McMurray.

The vertical trend models and the Top and Base of SAGD surfaces were used to build a 3D trend model for all of the pad models. The 3D models were built by calculating the relative elevation of the grid cell, determining if the grid cell was inside the channel or not, and then assigning the correct trend value to the block. Figure 1 shows one 3D trend model. It is easy to see the predicted channel location in the trend model.

Sequential Gaussian simulation was used to populate the models. Two variables were simulated; porosity and water saturation. The porosity was simulated using the trend model as a collocated secondary variable. The correlation between the trend model and the logged porosity was calculated and used for the modeling. The correlation was 0.6. This produced a more realistic model than using the trend model as a locally varying mean secondary attribute.

Water Saturation was simulated using the previously simulated porosity models. The correlation between porosity and water saturation was -0.7. Some variance inflation occurred with the water saturation simulations. The variance reduction factor was used to correct for the variance inflation. The correction applied varied by pad.

A bottom oil-water contact surface was used to constrain the bottom water in the model. The surface was estimated using the OWC picks at the well locations. Any cell that fell below the OWC was set to a water saturation of 1.0.

Ranking Realizations

Fifty realizations were generated for each pad. It is unrealistic to flow simulate all 50 pad realizations in a thermal simulator as the number of blocks is on the order of 400,000 cells and it would be too CPU intensive. The realizations need to first be ranked and only a few of them flow simulated to assess the uncertainty in cumulative oil production (COP), steam-oil ratios (CSOR) and recovery factors (RF).

The first possible ranking is based on original bitumen in place (OBIP). However, this ranking does not work well. It does not account for the “connectedness” of the model. Large continuous flow barriers will reduce recoveries and increase the steam-oil ratio.

A more realistic ranking is one that calculates a connected net volume within the 3D model. This better accounts for flow barriers and is more accurate than a simple OBIP based ranking. The ranking methodology is as follows:

1. Consider the model in 2D and go to the first X-Y cell in the model,
2. Go to the bottom of the model,
3. Scan from the bottom to the top of the model calculating the proportion of cells that are net (>25% porosity) within a 10m window of the cell. Keep track of these proportions.
4. Go to the cell with the highest proportion from step 3. If there is more than 1 block with the highest proportion, go to the block with the lowest elevation.
5. Scan down from this center cell and start calculating a connected flag. A cell is considered connected if all of the cells between the center cell, from step 4, and the cell of interest are all net. Stop scanning when a continuous set of non-net cells is encountered. This is a required input from the user. It defines the minimum size of a shale bed that would block flow. For example, 100m along the length of the pad and 50m across the pad could constitute a large enough flow barrier.
6. Scan up from the centre cell and calculate the connected cells upwards. Stop when a continuous set of non-net cells is encountered.
7. Move to the next X-Y location in the model and go back to Step 2.
8. Repeat Steps 2-7 until all X-Y locations have been visited.
9. Calculate the connected OBIP for the realization. This is the number that will be used for the ranking.

The connected OBIP, or connected volume, is then ranked and specific realizations can be extracted for flow simulation. The following realizations are usually extracted for flow simulation, but others can be extracted as well including P10, P50 and P90 cases.

A slice of the porosity model for one pad is shown in Figure 5. There is a centre channel with very good porosity. As you move up through the channel, we start to see some lower porosity layers that may prevent the steam chamber from reaching some of the good porosity near the top of the channel. Figure 6 shows the connected cells that were calculated during the ranking. Note that the high porosity zone near the top of the model is not considered connected. That means that there was a low permeability barrier that was at least 100m by 50m, the parameters used for the run, which is assumed to prevent the steam from recovering that bitumen. Figure 7 shows a 3D view of one of the pad models. It also shows 6 planned SAGD well pairs for the pad.

Figure 8 shows a cross plot of connected volume versus net volume from the ranking. It is interesting to note that the OBIP ranking can be very different from the connected volume ranking. For example, the worst realization according to the connected volume does not necessarily have the lowest OBIP. There is something going on in that realization that impacts the recoverable bitumen in place.

The connected volume ranking was compared to the flow simulation results. It is important to note that the ranking is not meant to replace flow simulation. The ranking should be used to select several representative realizations for flow simulation. For example, an optimistic case, a pessimistic case and a median case could be selected for flow simulation.

The results of the comparison are shown in Figures 8 through 10. Figure 9 shows the standardized cumulative oil production versus the connected volume ranking. The cumulative steam injection versus the ranking is shown in Figure 10 and Figure 11 shows the cumulative steam oil ratio (CSOR) versus the connected ranking.

When the pad has been operating for 3 months, the ranking does not correlate as well with the flow response compared to later years. Consider the CSOR plot shown in Figure 11. When the pad has been operating for 3 months, the correlation between the ranking and the flow result is only -0.38. However, when the pad has been operating for 5 years, the correlation between the CSOR and the ranking has increased to -0.81.

There was also a large spread in the flow simulation response. For example, the highest COP was 6 times larger than the lowest. This was due to selectively simulating multiple realizations for the same pad.

Conclusion

There can be significant uncertainty in the performance of planned SAGD pads. It is important to assess this uncertainty during the planning stages, especially for facilities development and resource evaluations.

The proposed workflow can be used to assess the uncertainty in a planned SAGD pad and subsequent field development planning. The workflow is comprised of 3 main steps: (1) building geocellular models, (2) ranking those models and (3) flow simulating a few selected realizations, usually an optimistic case, an expected case and a pessimistic case.

Acknowledgement

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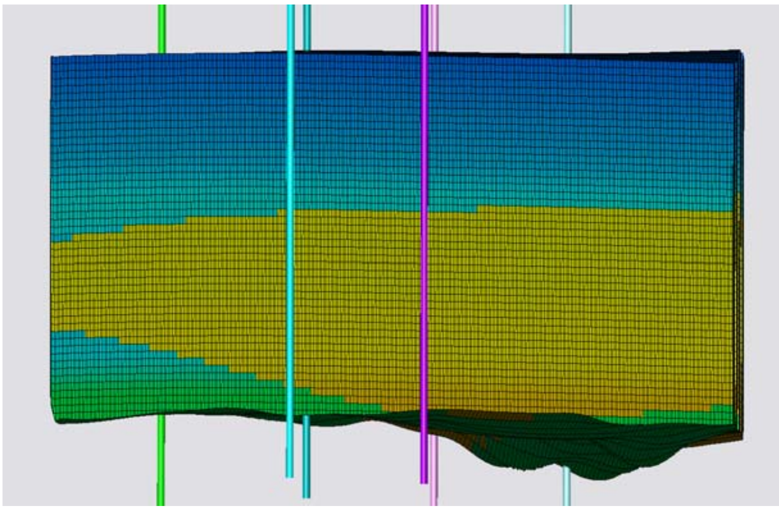

Figure 1: Basal unconformity for a local grid.

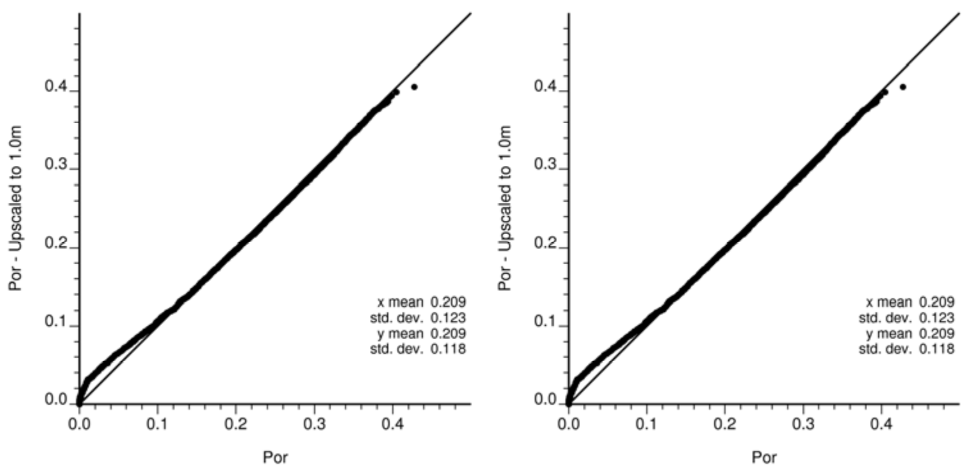

Figure 2: Q-Q plots of the upscaled porosity.

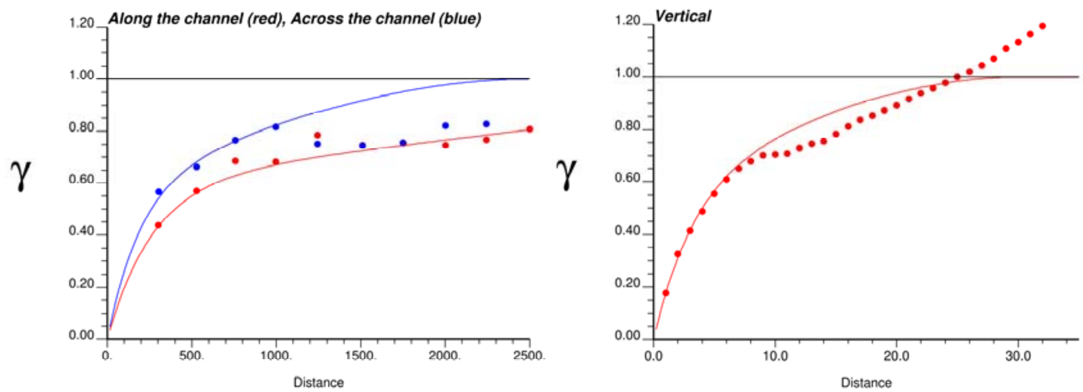

Figure 3: Modeled variogram.

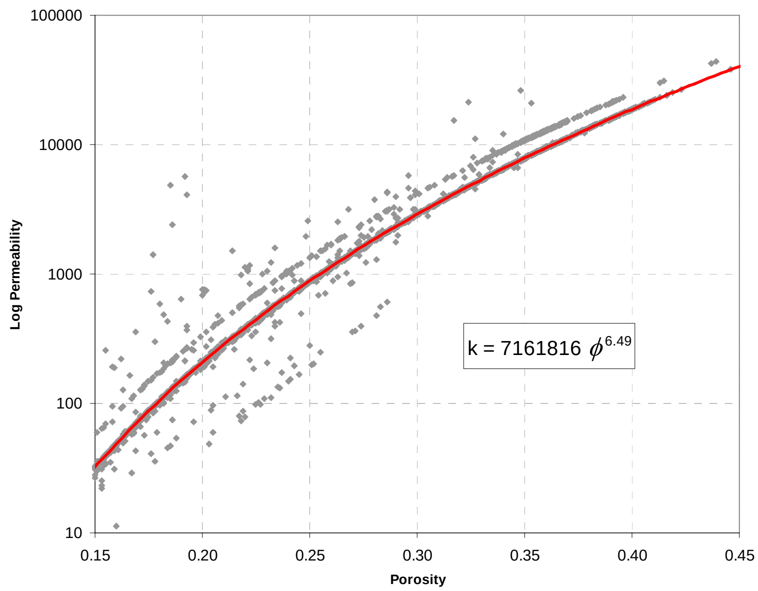

Figure 4: Porosity and permeability relationship.

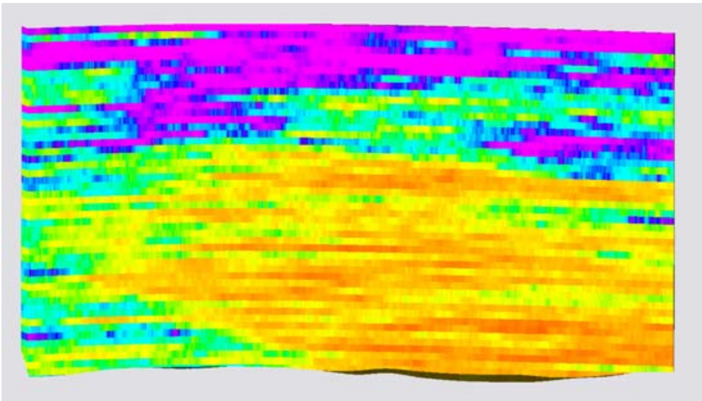

Figure 5: Porosity cross-section.

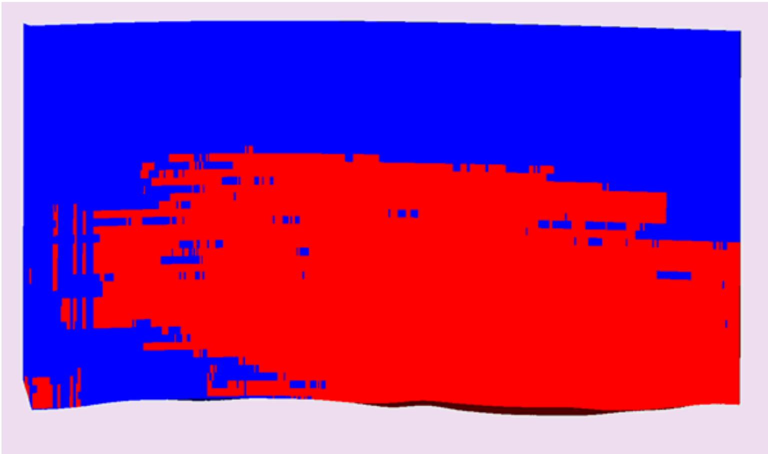

Figure 6: Connected flag cross-section.

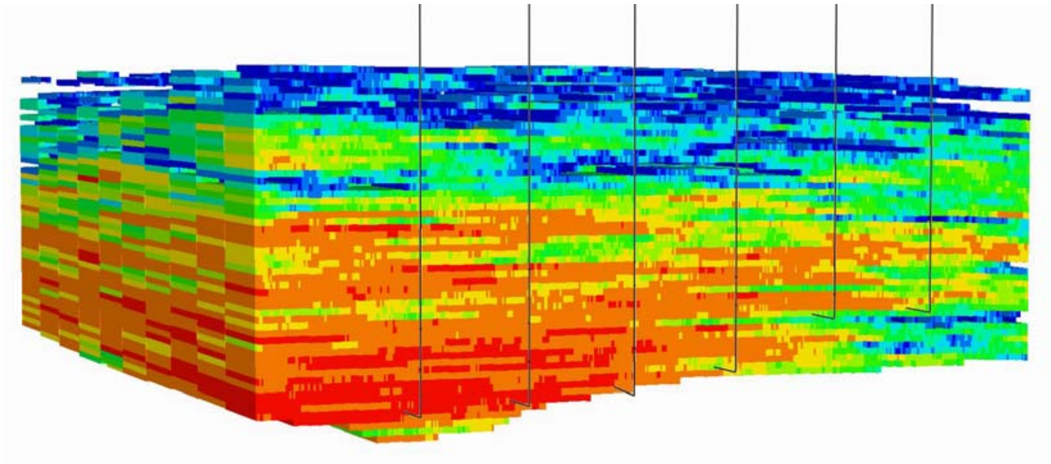

Figure 7: 3D view of a pad model with six well pairs.

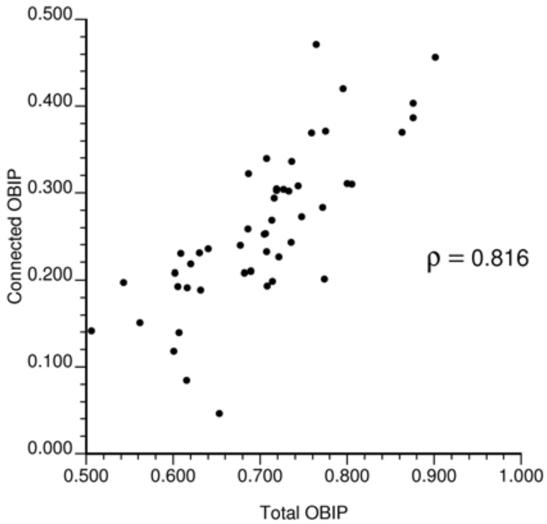

Figure 8: Connected ranking versus total OBIP ranking.

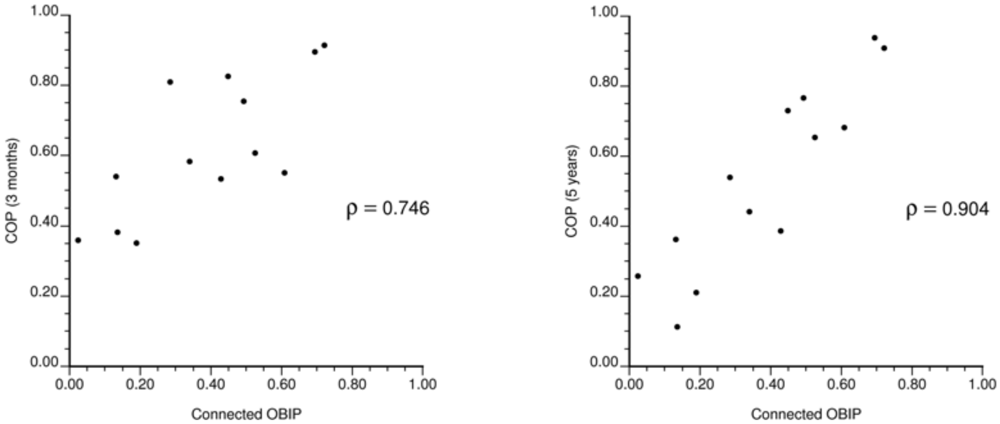

Figure 9: Cumulative oil production versus the connected OBIP at 2 stages during flow simulation.

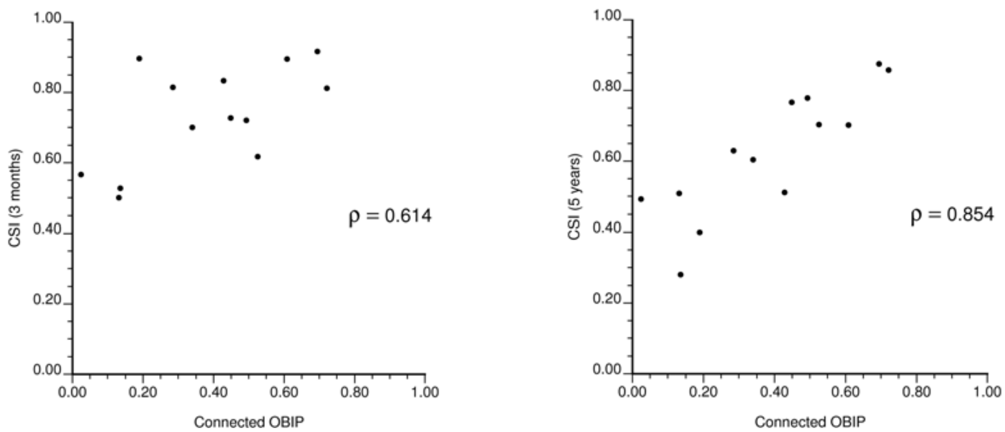

Figure 10: Cumulative steam injection versus the connected OBIP ranking at 2 stages during the flow simulation.

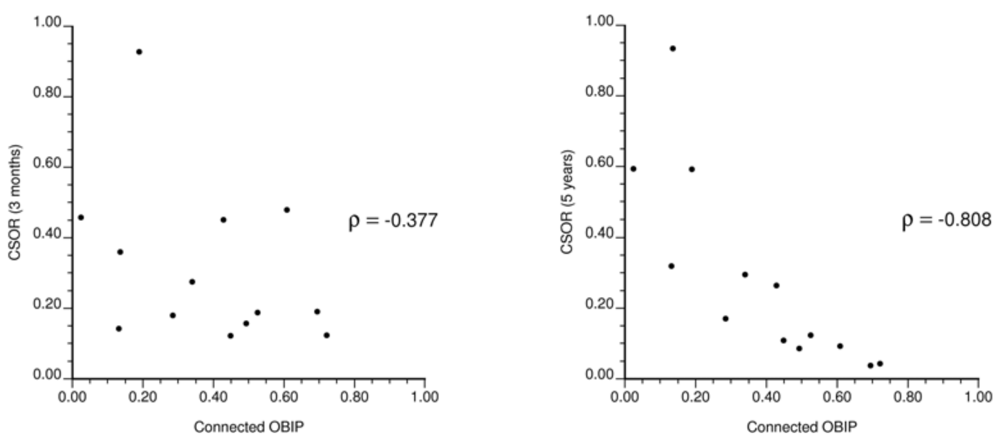

Figure 11: Cumulative steam-oil ratio versus the connected OBIP ranking at 2 stages during the flow simulation.