PS An Updated Semivariogram "Atlas" for Carbonate Reservoirs Impact on Geological Models and Dynamic Model Production Forecasts*

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Abstract

Many stochastic (geostatistical) reservoir property-modeling algorithms use the semivariogram as a primary measure of spatial continuity. Generally, the semivariogram is derived from the available reservoir data, usually well logs and/or core data, though occasionally seismic data is also used. In the absence of sufficient available field data (e.g. limited number of wells), the semivariogram used for reservoir modeling may be derived from analog reservoirs or may be treated as an uncertainty during probabilistic modeling. Based on a survey of published semivariograms derived from reservoirs with abundant well control, an effort has been made to correlate the semivariogram range parameters with depositional environment. For example, the horizontal (XY) range parameter is typically 1500 ± 500 meters with little directional anisotropy for ramp, shelf, and platform carbonates. The vertical semivariogram (Z) range is typically 5-10 meters in these carbonate reservoirs. For carbonate buildups, the semivariogram XY range is about 500 ± 250 meters and the Z range about 5-10 meters. The smaller XY range for the carbonate buildup reservoirs almost certainly reflects the generally closer well spacing in these reservoirs compared to the other types of carbonate reservoirs. Other trends based on the published studies include: (1) Limestone reservoirs have an average XY range of about 1700 meters compared to average XY range of about 1300 meters for dolomite reservoirs; (2) there is a slight negative correlation between the age of the carbonate reservoir and the XY range with reservoirs less than 100 Ma have an XY range of about 2000 meters compared to an XY range of about 1100 meters for those with an age of 250-500 Ma; (3) the average XY range anisotropy is low, about 1.4, suggesting that directional trends are minimal in carbonate reservoirs; and (4) the XY range for individual stratigraphic units within some carbonate reservoirs has significant variability. Most carbonate reservoirs included in this survey are located primarily in the Middle East, Permian Basin (USA), western Canada, and central Asia.

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An Updated Semivariogram "Atlas" for Carbonate Reservoirs
Impact on Geological Models and Dynamic Model Production Forecasts

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Abstract

Many stochastic (geostatistical) reservoir property-modeling algorithms use the semivariogram as a primary measure of spatial continuity. Generally, the semivariogram is derived from the available reservoir data, usually well logs and/or core data, though occasionally seismic data is also used. In the absence of sufficient available field data (e.g. limited number of wells), the semivariogram used for reservoir modeling may be derived from analog reservoirs or may be treated as an uncertainty during probabilistic modeling.

Based on a survey of published semivariograms derived from reservoirs with abundant well control, an effort has been made to correlate the semivariogram range parameters with depositional environment. For example, the horizontal (XY) range parameter is typically 1500 ± 500 meters with little directional anisotropy for ramp, shelf, and platform carbonates. The vertical semivariogram (Z) range is typically 5-10 meters in these carbonate reservoirs. For carbonate buildups, the semivariogram XY range is about 500 ± 250 meters and the Z range about 5-10 meters. The smaller XY range for the carbonate buildup reservoirs almost certainly reflect the generally closer well spacing in these reservoirs compared to the other types of carbonate reservoirs.

Other trends based on the published studies include: (1) Limestone-dominant reservoirs have an average XY range of about 1700 meters compared to average XY range of about 1300 meters for dolomite-dominant reservoirs; (2) there is a slight negative correlation between the age of the carbonate reservoir and the XY range with reservoirs less than 100 Ma have an XY range of about 2000 meters compared to an XY range of about 1100 meters for those with an age of 250-500 Ma; (3) the average XY range anisotropy is low, about 1.4, suggesting that directional trends are minimal in carbonate reservoirs; and (4) the XY range for individual stratigraphic units within some carbonate reservoirs has significant variability.

The majority of carbonate reservoirs included in this survey are located primarily in the Middle East, Permian Basin (USA), western Canada, and central Asia.

Note: This poster is an update of a presentation given at the 2010 EAGE Annual Meeting (with co-authors W. Terry Osterloh and Hong Tang).

Introduction

The stochastic algorithms that are used to populate reservoir models typically use the semivariogram as a measure of spatial continuity. For reservoirs with abundant, good quality well log data the semivariogram parameters can be defined and their uncertainty established. For fields with few wells the semivariogram parameters are usually taken from an analog or inferred from the likely geometry of depositional elements. In data limited cases, it is difficult to assess appropriateness of the analog derived parameters or assign appropriate ranges to the parameters as part of an uncertainty assessment.

Data and Analysis. A survey of published porosity semivariogram model parameters from carbonate reservoirs with abundant, high quality, porosity well logs was used to investigate the variability of the range parameter and to determine if the observed variation could be attributed to reservoir age, depositional setting, or carbonate type. Surveyed carbonate reservoirs include several in the Permian Basin of the United States, several in western Canada, many from the Middle East, and a few in Asia (***Figure 1***). The typical well spacing of the reservoirs included is 200 m or larger; many of the reservoirs included in the survey have a well spacing on the order of 400-500 m.

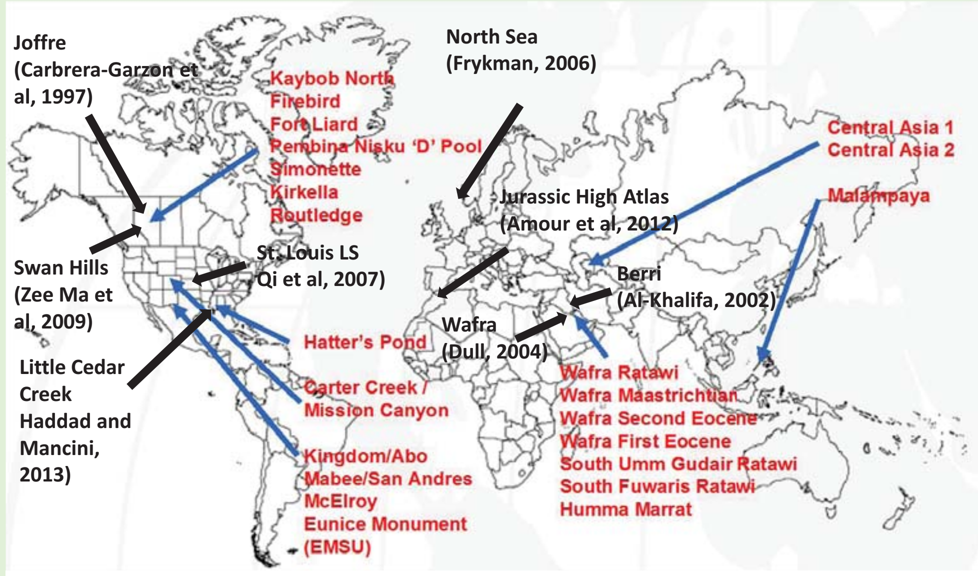


Figure 1. Location of the carbonate reservoirs included in this survey of semivariogram model parameters. The author's studies are shown in red; literature-based studies shown in black.

Figure 2 summarizes the results of the survey by depositional setting. Note that the range parameter for reservoirs developed in carbonate build-ups is substantially lower than other settings. This difference likely reflects the generally smaller well spacing, typically less than 400 m, for the carbonate build-up reservoirs as compared to typically greater than 400 m well spacing for many of the reservoirs developed in ramp, shelf, or platform settings.

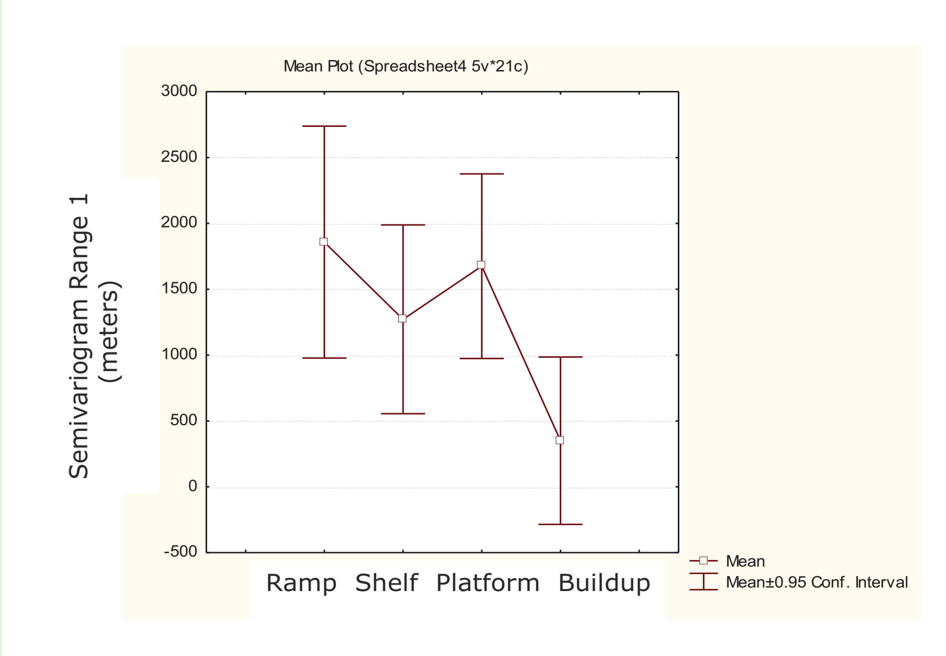


Figure 2. Plot showing the variation of the semivariogram range parameter for various depositional settings. Note that only the small carbonate build ups (e.g. pinnacle "reefs") have a significantly smaller semivariogram range.

Figure 3 shows that dolomite-dominated reservoirs have slightly lower semivariogram range values than do limestone-dominated reservoirs. ***Figure 4*** shows a plot of the semivariogram range parameter vs. the age of the reservoir rock. Note that there is a slight trend towards lower values for the range parameter in older reservoirs. Note that many of the younger age reservoirs occur in ramp settings. Insufficient data exists to compare variation by both age and depositional environment.

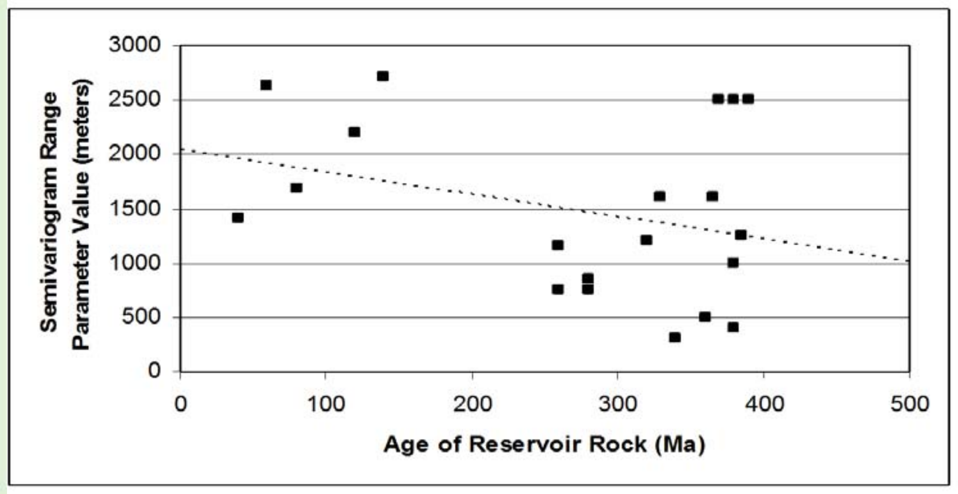


Figure 4. Plot showing the variation of the semivariogram range parameter for dolomite-dominated vs. limestone-dominated reservoirs included in the survey.

Figure 5 provides a bar graph summarizing the semivariogram range values collected during the survey. Note that the variation by individual stratigraphic layer exceeds the variation between reservoirs. Summary statistics for the data shown in Figure 5 are given in ***Table 1***. Note that some of the reservoirs included in the study were defined by a single stratigraphic layer and others had up to 20 sequence stratigraphic layers.

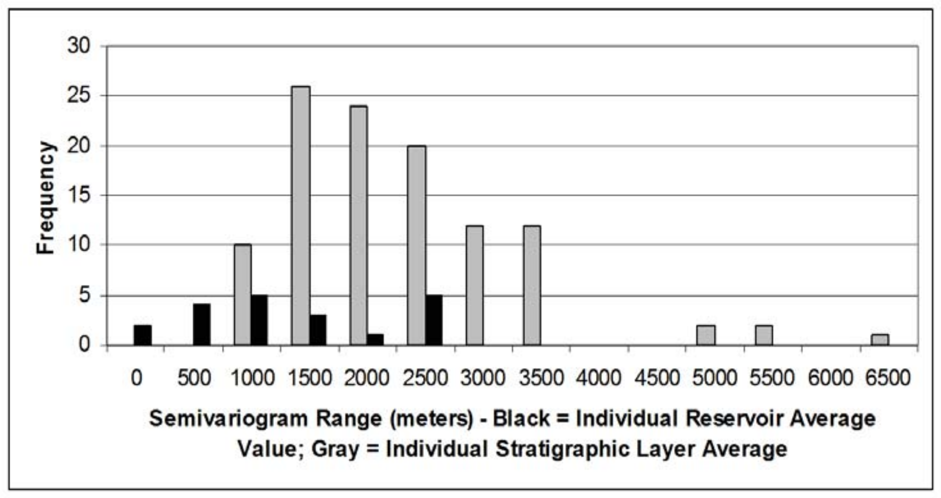


Figure 5. Histogram showing spread of average semivariogram range values by individual stratigraphic layers (gray) and by whole reservoirs (black).

Table 1. Summary statistics for semivariogram range parameters by individual stratigraphic layers and by whole reservoir.

	Stratigraphic Layers	Whole Field
Minimum (meters)	300	300
Maximum (meters)	6460	2715
Average (meters)	2055	1475
Std. Dev. (meters)	1035	795
Number of Samples	110	20

Figure 6 shows an example of the semivariograms obtained from the Eunice Monument South Unit (EMSU) full field study. ***Table 2*** summarizes the semivariogram model parameters for the EMSU reservoir. ***Figure 7*** shows the variation of the range and anisotropy (directional trend) for the EMSU reservoir. The EMSU reservoir is a good example of a typical Permian Basin (USA) carbonate reservoir.

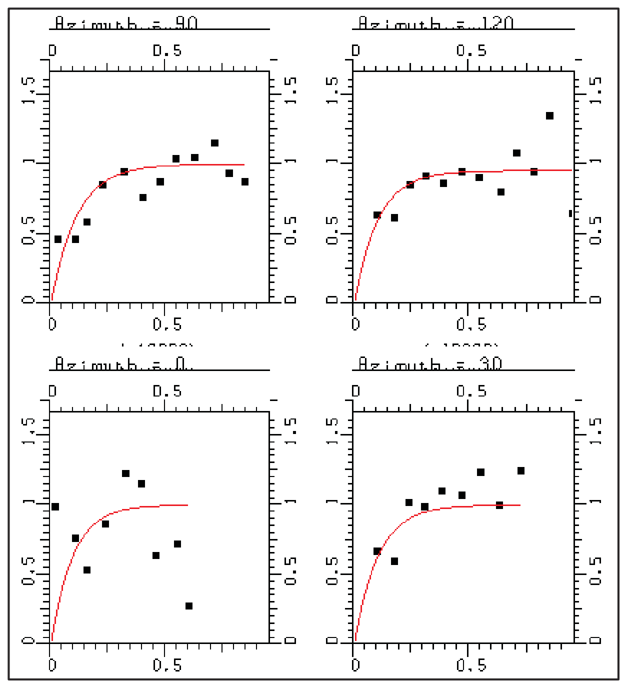
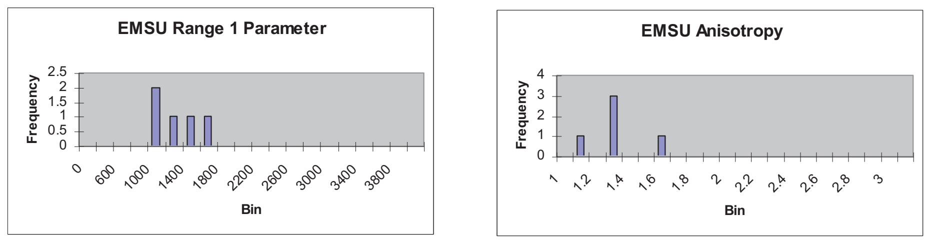


Figure 6. Semivariogram models for porosity for four stratigraphic layers within the Eunice Monument South Unit (EMSU) reservoir, Permian Basin, USA

The average anisotropy (defined by the ratio of semivariogram range 1 to semivariogram range 2) for the individual stratigraphic layers in the reservoirs included in the study is 1.46 suggesting that most carbonate reservoirs show little, if any, directional trend as far as the distribution of porosity is concerned (***Figure 8***).

Table 2. Summary statistics for semivariogram range parameters by individual stratigraphic layers for the EMSU reservoir.

Interval	Range 1 (meters)	Range 2 (meters)	Azimuth	Ratio of Range 1 to Range 2	Range 3	Range 3 (feet)	Sill	Nugget	Form	Interval Thickness	Mean Porosity
GB - Z2	990	770	50	1.29	0.33	16.2	1	0	EXP	49	0.065
Z2-Z2A	1440	925	110	1.56	0.32	16.0	1	0	EXP	50	0.087
Z2A-Z3	1070	880	75	1.22	0.38	17.9	1	0	EXP	47	0.087
Z3-Z4	995	910	5	1.09	0.34	14.6	1	0	EXP	43	0.081
Z4-Z5	1295	1050	20	1.23	0.17	9.0	1	0	EXP	53	0.088



Mean = 1160 m Range = 445 m

Mean = 1.28 Range = 0.45

Figure 7 (above). Histogram showing spread of average semivariogram range and anisotropy (directional trend) values by individual stratigraphic layers (left) for the EMSU reservoir.

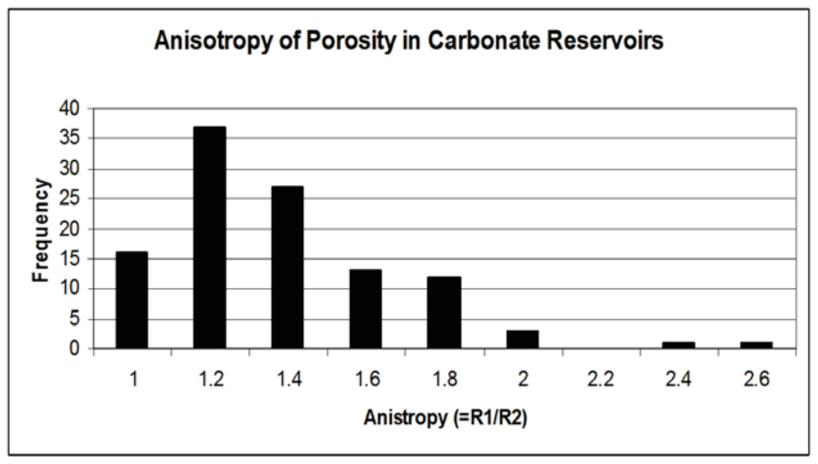


Figure 8. Histogram showing spread of average anisotropy (directional trend) values for the carbonate reservoirs included in the study. Depositional environment and/or mineralogy has no systematic input on anisotropy.

Effect of Data Spacing (Data Density) on the Semivariogram Range. It should be noted that as the data density increases (data spacing decreases), the semivariogram range parameter decreases. There is, unfortunately, a paucity of published studies on large fields incorporating data from closely spaced wells due to either pilot projects or closely spaced infill drilling programs. In a recent study of the First Eocene reservoir, property models were generated in 2007-2008 for a 40-acre steamflood pilot with a total of 60 wells (including five cored wells), 56 of which were drilled in 2007-2008. The average well spacing is less than 40 m (well pair separation ranges from 12 m to 100 m.

Geostatistical analysis of the pilot project and surrounding wells yields semivariogram models with an average XY range of 290 m (range 135-480 m). Wells at full field development spacing (about 500 m) in the same part of the field give semivariogram model range values of about 1600 m, a factor of 4-5 times larger than obtained from the pilot project wells. This is shown in **Figure 9**.

Carbonate Reservoir Survey Conclusions. The results summarized in the tables and figures above show the following: (1) the semivariogram areal (XY) range parameter is typically 1000-2000 m with little anisotropy; (2) the overall variation of semivariogram parameters between reservoirs is similar to the

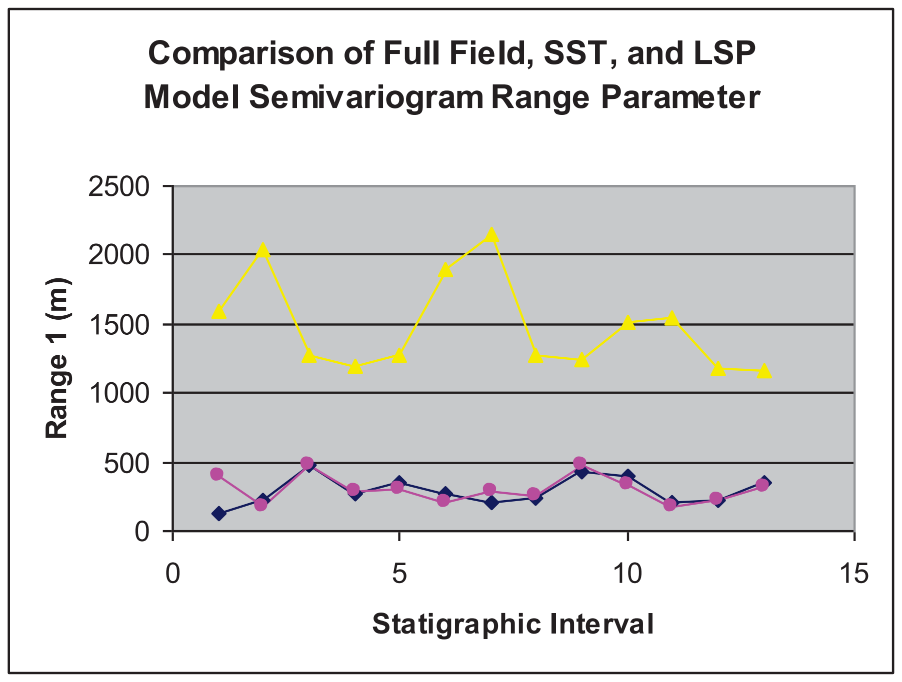


Figure 9. Plots showing a comparison of the range 1 semivariogram parameter obtained from the First Eocene reservoir Full Field study with average well spacing = 500 m and the steamflood pilots with average well spacing of less than 50 m.

stratigraphic layer variation within reservoirs; (3) there is no significant correlation of the range parameter with depositional age and only a slight correlation with depositional setting; and (4) limestone-dominant or dolomite-dominant reservoirs have similar values for the range parameter. Based on the survey results the following guidance is suggested for semivariogram model parameters for full field, data-limited projects: low-case recommended value for the semivariogram range is 500-1000 m; mid-case recommended value for the semivariogram range is 1000-1500 m; and, high-case recommended value for the semivariogram range is 1500-3000 m. The suggested guidance includes the recommendation to use isotropic semivariogram models unless there is clear evidence to the contrary.

Practical Considerations – (1) The Impact of Semivariogram Parameters on Fluid Recovery Forecasts Derived from Reservoir Models

While variability in the semivariogram parameters does exist among carbonate reservoirs, the variation observed is of minor importance in terms of fluid recovery. As shown in ***Figure 10***, the recovery obtained from dynamic models generated using small semivariogram ranges from the steamflood pilot (25m spacing) and the larger range values from the full field wells (500 m spacing) is on the order of 5% for waterflooding and less than 0.5% for steamflooding.

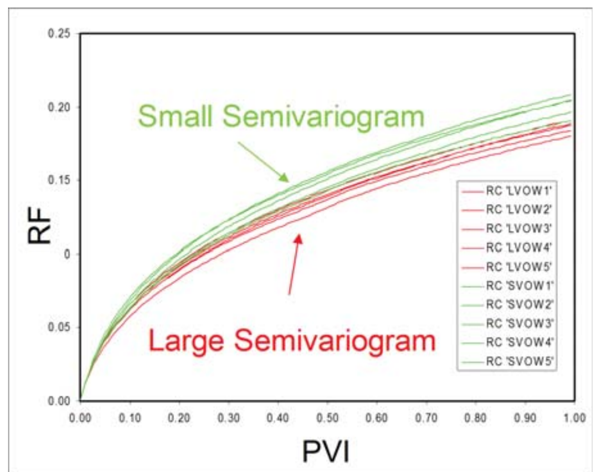


Figure 10. Impact of semivariogram range on recovery via waterflood is very small; on the order of about 1-2% of forecast recovery. Results from multiple realizations are shown, RF = Recovery Factor, PVI = Pore Volume Injected.

Figure 11 shows areal and vertical sections generated using the large and small semivariogram range models. *Figure 12* shows that forecast steamflood production rate and producer breakthrough time is not significantly impacted by the semivariogram range parameter,

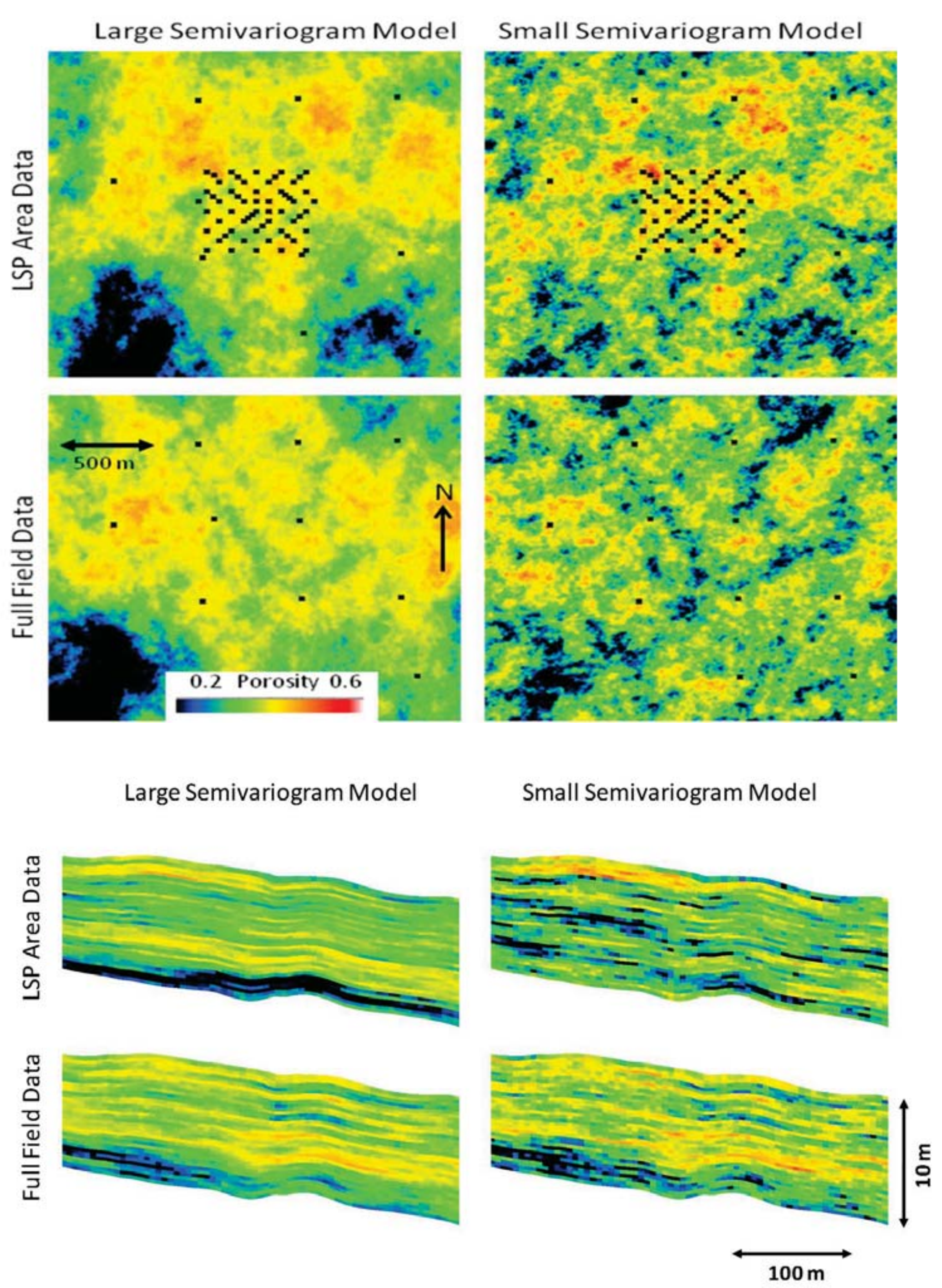


Figure 11. Map and vertical sections generated using the large and small semivariogram models for the steamflood pilot area.

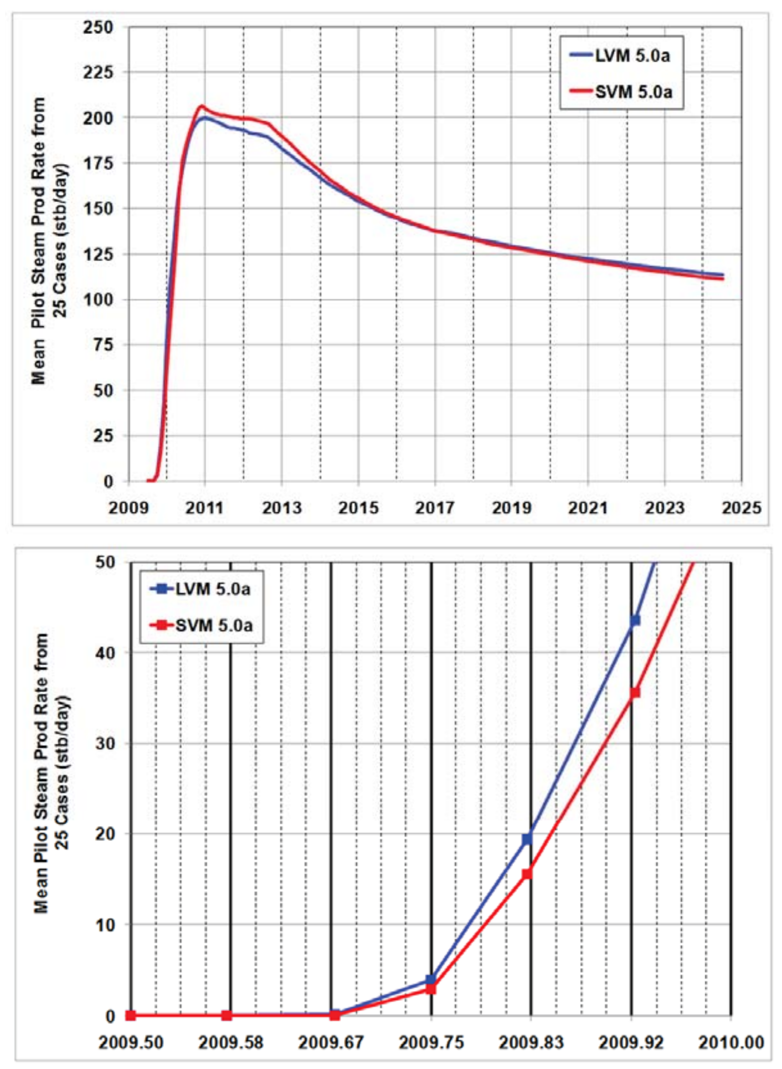


Figure 12. Impact of semivariogram range on recovery via steamflood. Note that forecast recovery (top chart) and steam breakthrough (lower chart) is essentially the same for the small (SVM) and large variogram (LVM) based models.

What Does Significantly Impact Forecast Recovery and Breakthrough Times? Why are Forecasts Generally Optimistic?

Given that the prior discussion has focused on the minimal impact of the semivariogram model parameters on forecast recovery, the principle question becomes - what does impact recovery forecasts? As part of an ongoing investigation focused on understanding why reservoir forecasts are typically optimistic the significant technical issues relate primarily to the use of dynamic reservoir models with cells that are too large, sparse data, and human biases, and well location optimization (Meddaugh, 2006), Meddaugh et al 2011, 2015, and Meddaugh, 2018). This section discusses the relative impact of the following on production forecasts:

1. Model Grid Size
2. Model Heterogeneity (Semivariogram Range)
3. Model Stratigraphic Detail
4. Sparse Data

Model Grid Size

Generally, the greater the number of model cells (or grid blocks) and their smaller size, the more realistic the forecast recovery in terms of fluid volume as well as breakthrough times. *Figure 13* shows a comparison between a true giga-cell dynamic model and a "coarse" model published by Obi et al. (2014). *Figure 14* shows results obtained keeping all model parameters the same except for the input grid size (Meddaugh et al., 2010). Note that as the number of model cells decreases (and the cell size increases), forecast recovery increases significantly.

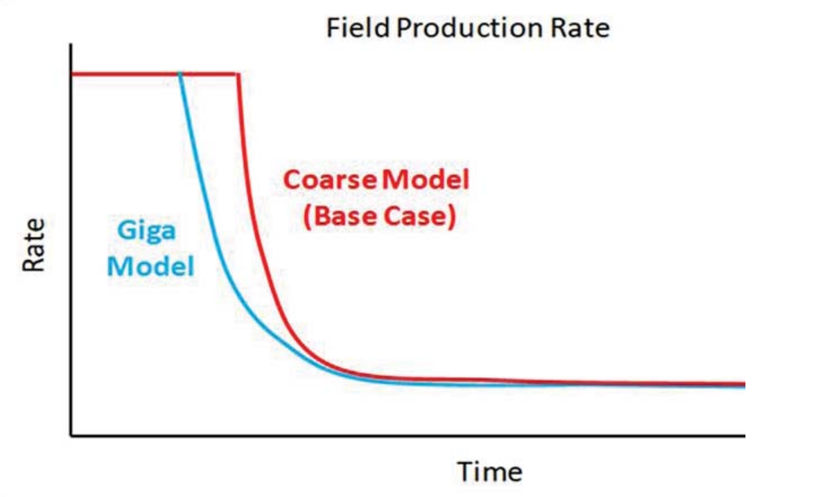


Figure 13. Coarse Model forecast 10-15% more oil than a Giga-Cell Reservoir Model (After Obi et al., 2014)

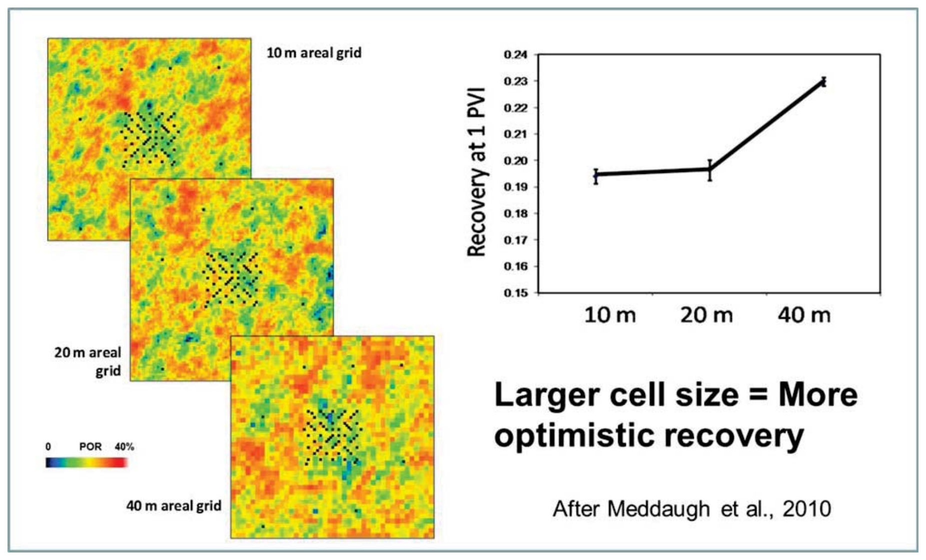


Figure 14. Larger cell size yields more optimistic recovery (Meddaugh et al., 2010).

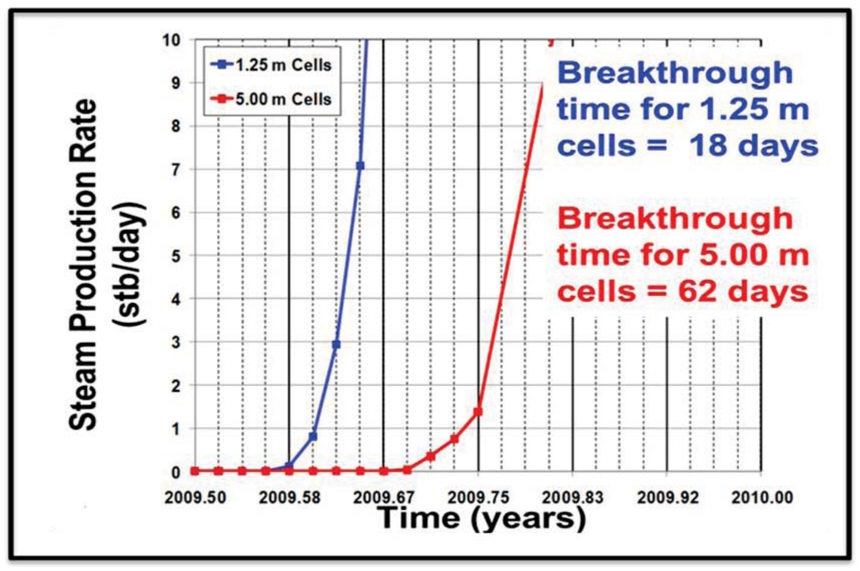


Figure 15. Larger grid size (5 m) gives longer breakthrough time compared to smaller grid (1.25 m). Actual field data showed hot water movement from injector to producer took even less time than forecast by the 1.25 meter cell size model. (Meddaugh et al, 2010).

Figure 15 shows that models with smaller grid cells give faster breakthrough times. Field data for the steamflood pilot project showed that hot water moved from injector to producer wells within a couple of days; significantly faster than even the 1.25 m cell model "predicted". It is worth noting that early breakthrough times (actual vs. forecast) is also a significant issue in forecast accuracy (Nandurdikar and Wallace, 2011).

Model Heterogeneity (Semivariogram Range)

As shown in Figure 10, the semivariogram range has a best a minor impact on fluid recovery for both waterflood and steamflood projects.

Model Stratigraphic Detail

Meddaugh (2006) reviewed results obtained from dynamic models generated using varying levels of stratigraphic detail. The cases investigated included clastic and carbonate reservoirs. For the Northwest Stevens Reservoir, the following stratigraphic control cases were investigated:

- Top/Bottom Marker Only
- Top, Bottom, One Intermediate Marker
- Nine Marker-defined Detailed Stratigraphy

Figure 16 summarizes the geostatistical analysis for each case. *Figure 17* shows a porosity model cross section for the three cases investigated and *Table 2* shows the similarity of forecast recovery for all cases.

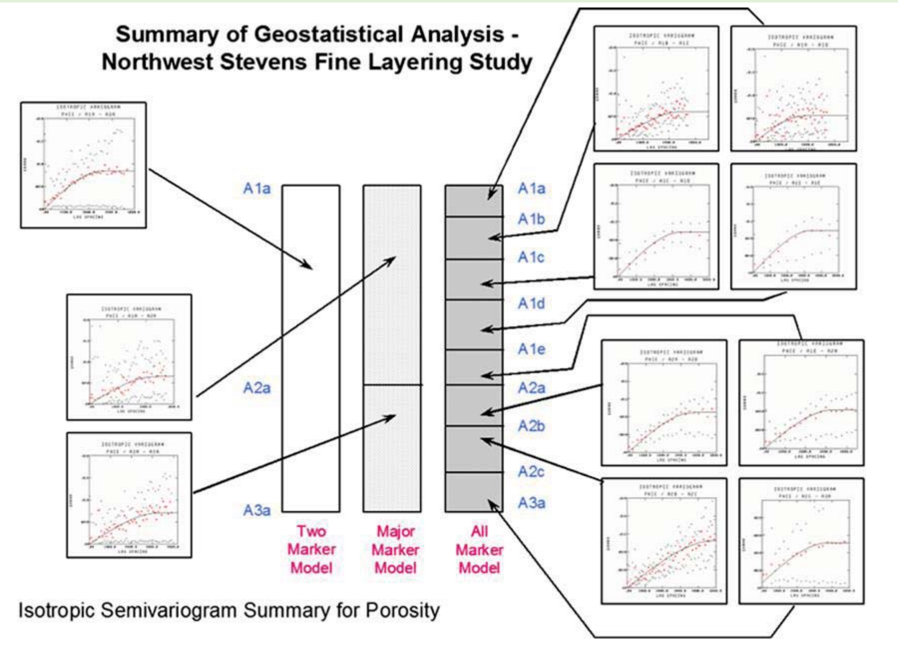


Figure 16. Northwest Stevens (NWS) reservoir summary for three cases of "stratigraphic" detail.

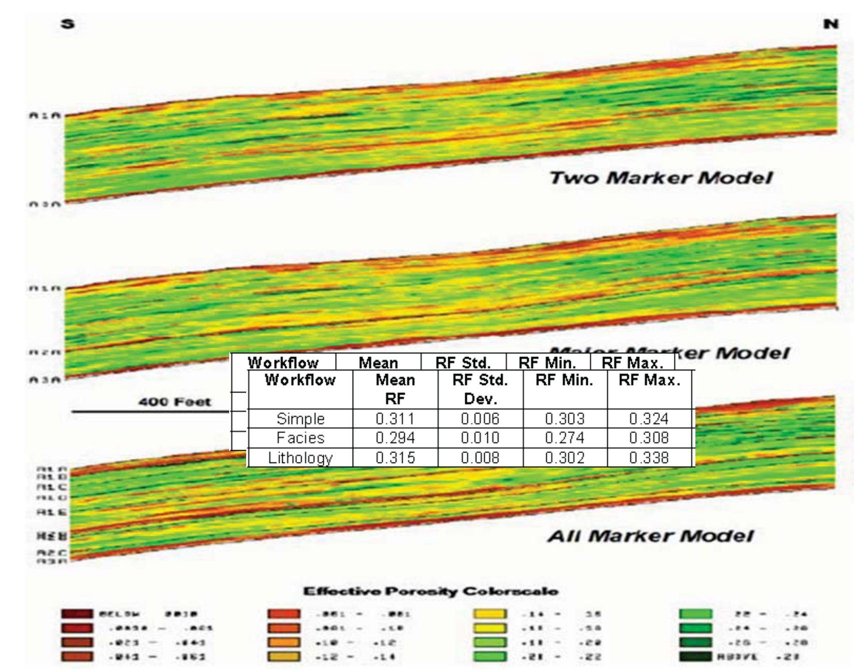


Figure 17. Porosity cross sections generated for the NWS Reservoir using varying levels of stratigraphic control

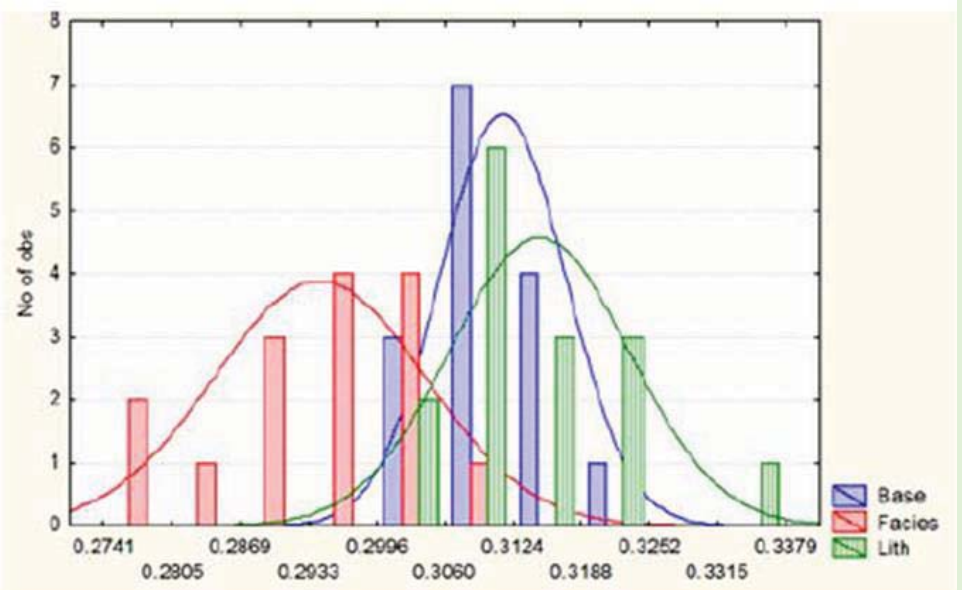
Summary of Flow Simulation Results for the Three Levels of Correlation Detail, A1 and A2 Sands, NWS Reservoir, Elk Hills, California.				
Correlation Detail Case	**Water Break-Through (Days)**	**Range of Water Break-Through (Days)**	**Cumulative Production through 5 Years (Mbbl)**	**Range of Cumulative Production through 5 Years (Mbbl)**
Two Marker	1091±66	1003-1230	388 ± 10.4	373-407
Major Marker	1106±64	981-1212	387 ± 7.6	373-399
All Marker	1063±98	842-1250	381 ± 11.6	365-404

Table 2. Summary of fluid flow results obtained from the three levels of stratigraphic detail used in the Northwest Stevens study. Note that there is little difference in recovery or breakthrough time for the three stratigraphic detail cases.

For the Eunice Monument South Unit (EMSU) the following stratigraphic control cases were investigated:

- Top/Bottom Markers Only; the Simple Case)
- Above plus Mapped Depositional Facies (Shoal, Lagoon)
- Above, plus Lithology

Figure 18 shows the similarity of forecast recovery for the three cases. ***Figure 19*** shows map and cross sections from the three cases investigated.



Workflow	Mean RF	RF Std. Dev.	RF Min.	RF Max.
Simple	0.311	0.006	0.303	0.324
Facies	0.294	0.010	0.274	0.308
Lithology	0.315	0.008	0.302	0.338

Figure 18. EMSU reservoir models recovery forecasts obtained for multiple realizations of the three "cases" investigated. Note that the spread of the recovery within and across the cases is quite small.

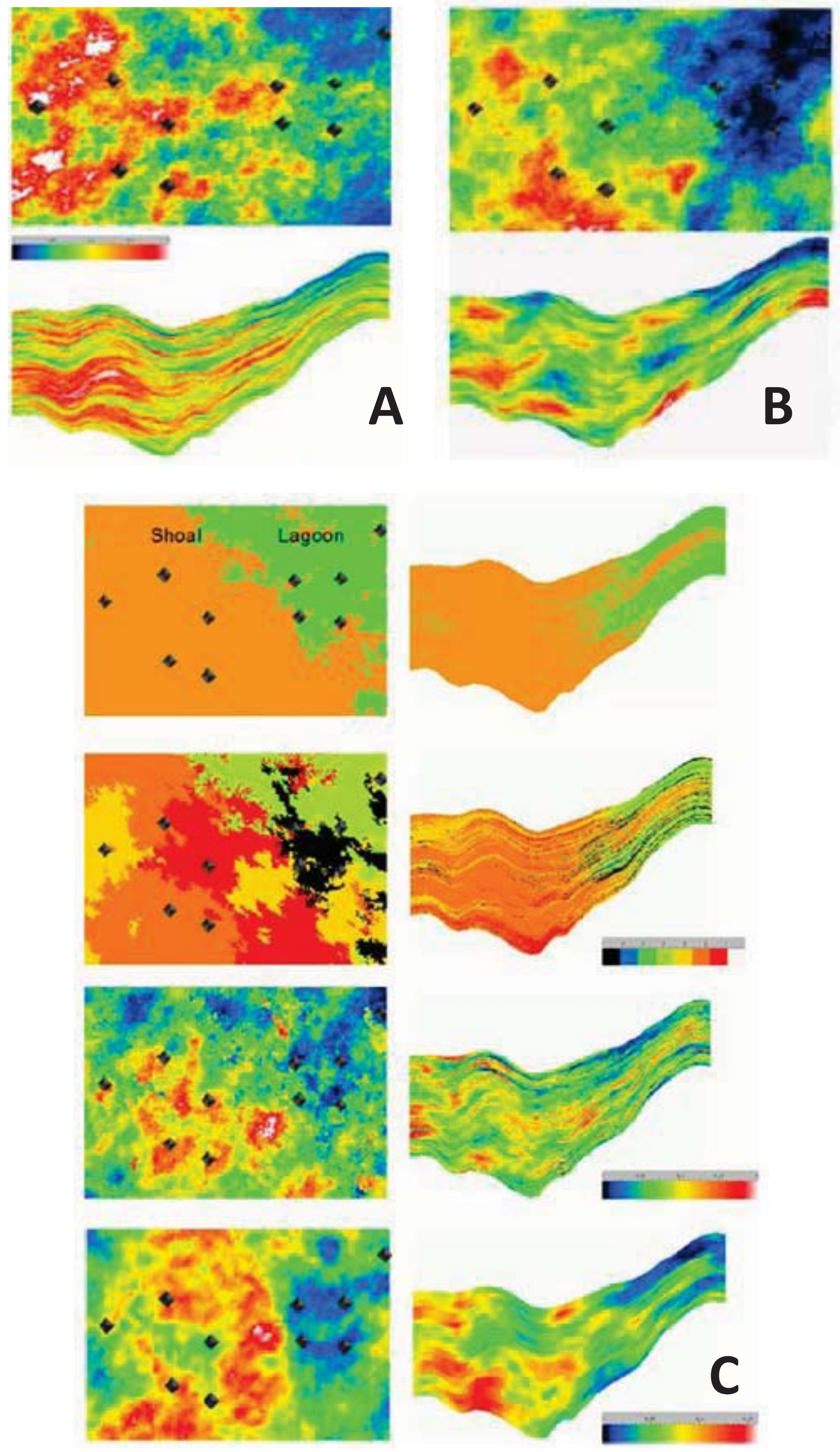


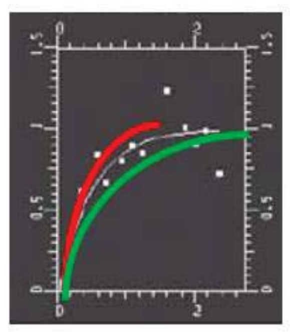
Figure 19. EMSU reservoir models with varying level of stratigraphic control: A – Top/Bottom only; B – Top/Bottom plus Shoal/Lagoon Facies; C – Top/Bottom, Facies, and Lithology

"Accuracy" of the Semivariogram Model

Meddaugh (2006) investigated the impact of the "Goodness" or "Accuracy" of the semivariogram fit to the available data. After establishing a "best fit semivariogram model", the best fit range parameter was arbitrarily altered to measured the impact of a "less than perfect fit" on the simulation-derived forecast recoveries. These results are summarized in ***Figure 20***. Note that significant changes in the semivariogram range parameter produced only a minor, and likely insignificant, change in forecast recovery.

Semivariogram Case	Range 1 (m)	Range 2 (m)	Azimuth	Average Recovery Factor (15 Realizations)
Base Case (Data Driven Range Value)	2300	1400	N45E	46.2%
Range Decreased 25%	1750	1050	N45E	46.3%
Range Decreased 50%	1150	700	N45E	46.3%
Range Increased 25%	2900	1800	N45E	46.7%

Figure 20. Increasing or decreasing the semivariogram range parameter by 25-50% had little impact on fluid recovery.



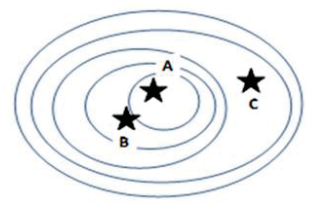
Sparse Data

Sparse data has a significant impact on production forecast accuracy. Consider the simple case shown in ***Figure 21***. Forecasts for this "Test" reservoir were generated from a set of 18 analog reservoirs (Meddaugh, 2015). Depending on drilling order and given that the forecast is a function of the 'Test" reservoir's average porosity, permeability, and net pay thickness, the forecast results are (depending on drilling order):

1. One well forecast recovery range is 27-51%
2. Two well forecast recovery range is 34-46%
3. Three well forecast is 40%

The impact of sparse data is much more significant than any of the factors previously discussed! Note that according to Meddaugh et al (2015) and Meddaugh and Meddaugh (2017), the impact of sparse data and human biases are roughly the same and both are the significant contributors to forecast optimism.

Table 1 - Well Properties for the "Test" Reservoir			
Well	Net Avg. Porosity %	Net Avg. Perm md	Net Pay feet
A	27	320	61
B	22	300	55
C	15	260	35



	"Test" Reservoir Forecast		
Drilling Order	*1 Well*	*2 Wells*	*3 Wells*
ABC	41.7	46.2	39.8
BAC	50.6	46.2	39.8
CBA	27.0	38.8	39.8
ACB	41.7	34.3	39.8
BCA	50.6	38.8	39.8

Figure 21. Simple demonstration of the significant impact of sparse data on forecast recovery using a synthetic data set and forecasts derived from appropriate analogs (Meddaugh et al., 2015)

Summary

Reservoir modeling parameters do impact forecast recoveries and contribute to forecast optimism. The impact, however, is relatively small compared to the impact of sparse data and human biases. The table below summarizes the contributions of the various sources of forecast bias (Meddaugh, 2018)

Bias Source	Magnitude in Recovery Factor Units (RFUs)	Direction of Bias – Optimistic, Pessimistic, or Either
Reservoir Modeling Parameters	Small, less than 5 RFU.	Either
Vertical Upscaling	Small, less than 5 RFU.	Optimistic
Horizontal Upscaling, Areal Cell Size	Small to Large, likely between 5-15 RFUs	Optimistic
Well Location Optimization	Large, likely between 5 -15 RFU. May tend to be larger for strongly anisotropic reservoirs (e.g. channelized)	Optimistic though additional study is much needed.
Sparse Data	Large, likely between 10-15 RFUs	Either; will be optimistic if early wells sample higher quality reservoir volume as is the "usual" case
Human Decision Bias	Moderate, likely between 5-10 RFUs	Either; will almost certainly be optimistic given the typical "need" to move projects towards sanction

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