Capturing Reservoir Heterogeneity in Reservoir Models – How Much Is Enough?*

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Abstract

As the cost of computing decreased and the sophistication of reservoir modeling software increased over the past decade or two, the ability to capture reservoir heterogeneity in reservoir models has increased significantly. This increase was augmented by the development of a variety of algorithms that enabled increased efficient use of data obtained at a variety of scales, from core plug to 3D seismic, to be used to constrain reservoir models. While these important advances clearly enabled very large and very detailed reservoir models to be constructed relatively simply, a robust debate within the industry as to the overall value of highly detailed reservoir models as the basis for dynamic models that are in turn used to produce the volumetric forecasts required to evaluate and ultimately justify project development decisions continues. This "debate" has been referred to by some as the "Frankenstein vs. Gilligan" model debate. Studies completed by the author and others over the past two decades suggest that a better frame for this discussion and evaluation of model-based workflows is "fit-for-purpose" or "fit-for decision" modeling. In other words, reservoir models should capture the level of reservoir heterogeneity needed to make project development decisions. Oftentimes, the level of geologically heterogeneity that needs to be incorporated in dynamic models used to justify project decisions is actually quite low. For example, once the reservoir net-to-gross ratio exceeds roughly 15-20%, the reservoir is essentially connected and increased model heterogeneity adds little value. This applies to both carbonate and clastic reservoirs. The impact of sparse data and the dynamic model size (as measured by number and/or dimension of grid cells) has greater influence on project decision-making than fully capturing detailed reservoir stratigraphy and/or reservoir property heterogeneity. Results of various studies on Permian Basin (USA) and large Middle East carbonate reservoirs, as well as clastic reservoirs in the San Joaquin Basin in California and the Maracaibo Basin in Venezuela, are used to support these conclusions.

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Heterogeneity “Controls” in Earth Models

1. Model Grid Size and Number of Cells
2. Stratigraphy – Detail and Continuity
3. Spatial Continuity as modeled by the semivariogram for point-based methods
4. Spatial Continuity as controlled by the geometry of objects in object-based algorithms

Heterogeneity “Controls” in Earth Models

1. Model Grid Size and Number of Cells
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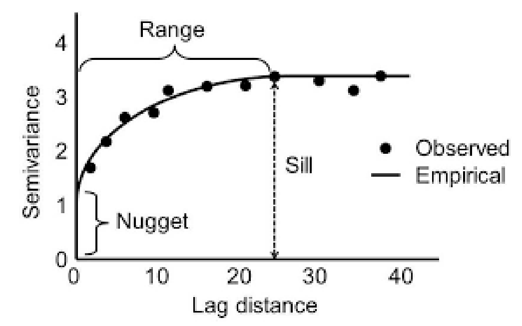
4. Spatial Continuity as controlled by the geometry of objects in object-based algorithms

Semivariogram - Basics

- Semivariogram (γ) – measure of spatial continuity or heterogeneity
- Range parameter increases as the spatial continuity of the property of interest (e.g., porosity) increases

$$\gamma^{*}(h)=\frac{1}{2N_h}\sum_{i=1}^{N_h}\left[Z(x_i+h)-Z(x_i)\right]^2$$

Z = Data Value at locations *x(i)* and *x(i+h)*
N = Number of sample pairs at separation distance ***h***



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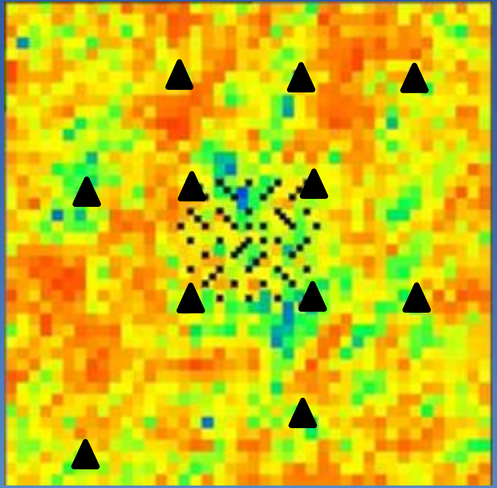
Impact of Semivariogram

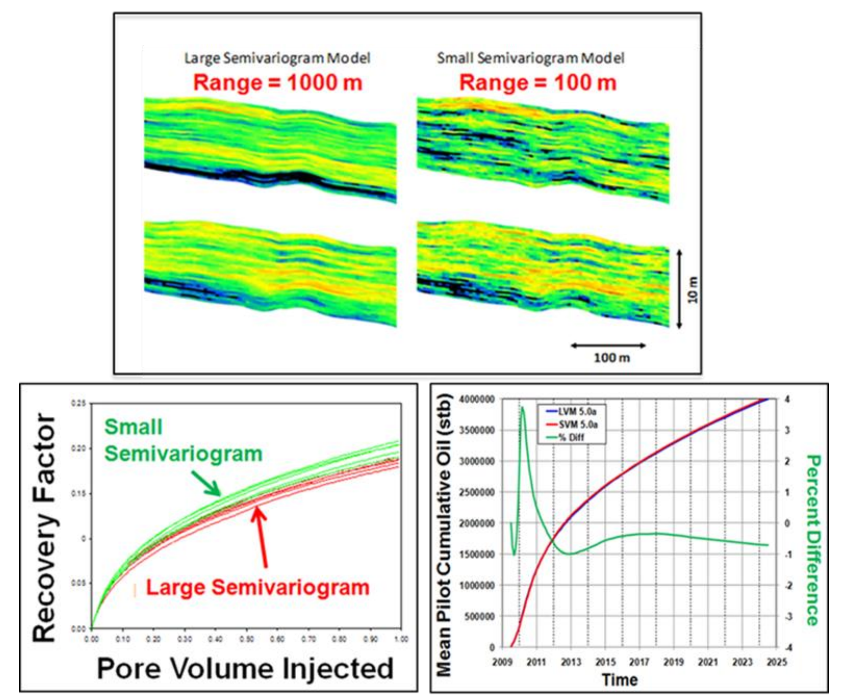
- Range is a function of the support (data density). Widely spaced data tends to provide larger values for the range whereas closely spaced data tends to provide smaller values for the range parameter
- Wafra First Eocene Example
  - Semivariogram analysis using only the full field development wells (1000-m spacing) gave a range of 1000 m
  - Semivariogram analysis using all wells in the steamflood pilot (~40-m spacing) gave a range of 100 m



▲ Full field wells
■ Pilot wells

Impact of Semivariogram

- Top – Cross sections through models generated with 1000-m range and 100-m range
- Bottom – Comparison of forecast recovery for waterflood and steamflood. Note small difference for waterflood and essentially no difference for steamflood



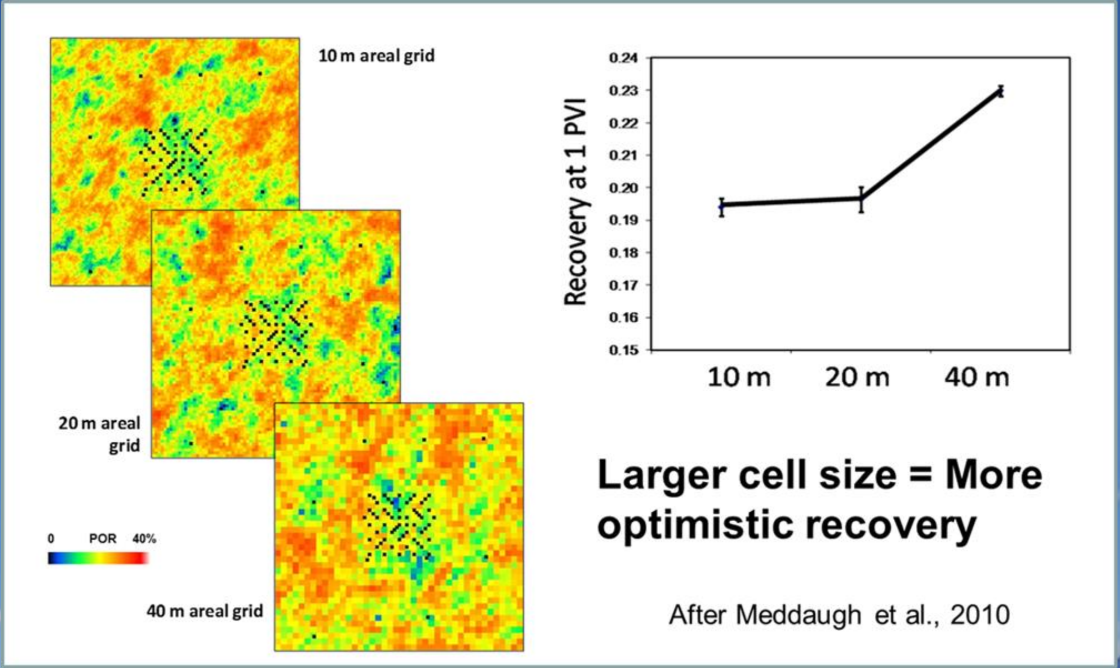
Waterflood

Steamflood

(Meddaugh et al., 2012)

Impact of Model Grid Size

- Recovery as a function of grid size
- Results for 10-m, 20-m, and 40-m areal grid size shown at right
- Grid size impact should be investigated via sensitivity studies

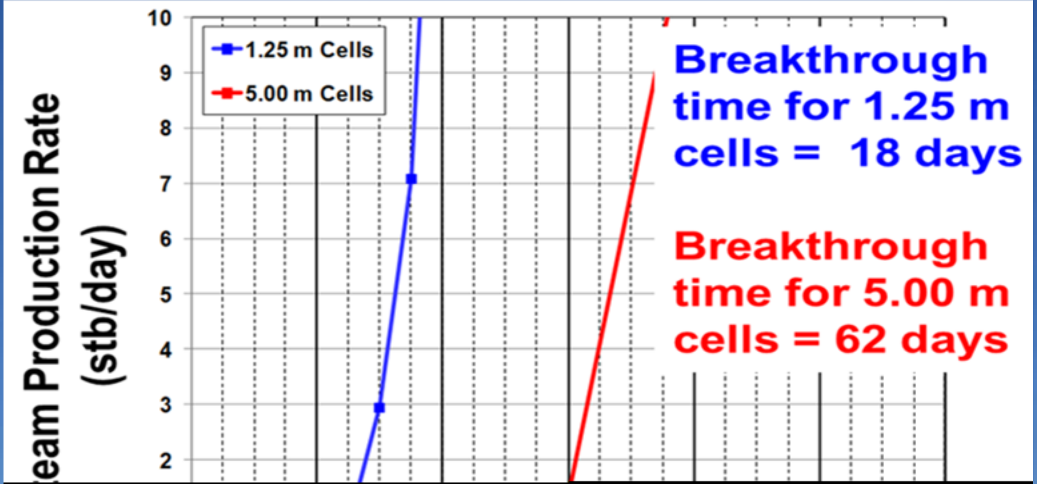


Larger cell size = More optimistic recovery

After Meddaugh et al., 2010

Impact of Model Grid Size

- Breakthrough (arrival of hot water, in this pilot project example) as a function of grid size
- Results for 1.25-meter and 5-meter grid size shown at right
- Pilot project wells showed large temperature increase within days



Breakthrough time for 1.25 m cells = 18 days

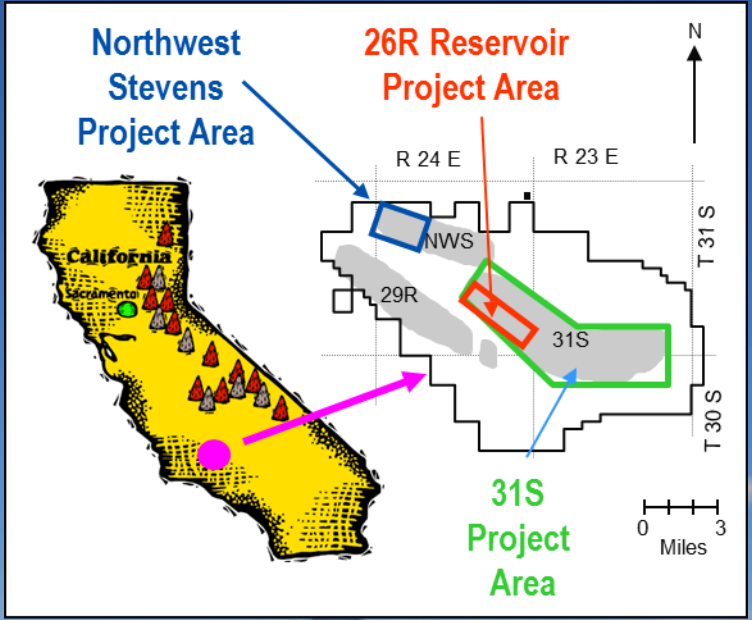
Breakthrough time for 5.00 m cells = 62 days

[redacted]

Meddaugh et al., 2012

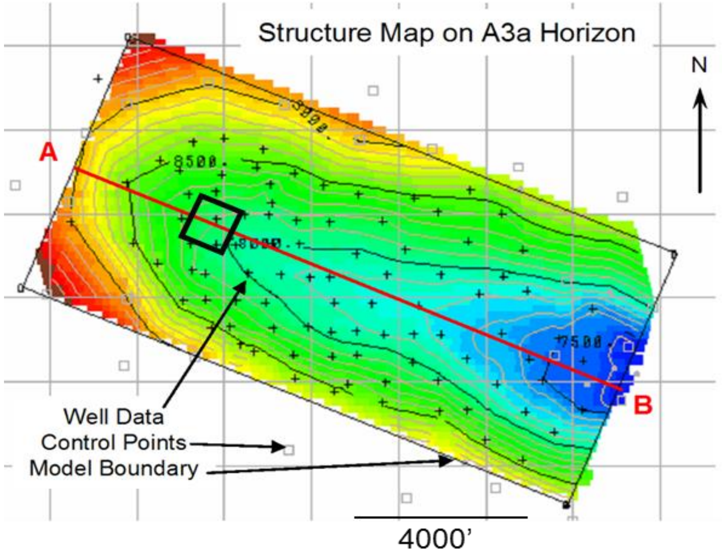
Impact of Stratigraphic Detail - 1

- Based on several studies of various Elk Hills reservoirs
- Examined impact of stratigraphic detail and up-scaling on recovery and breakthrough times



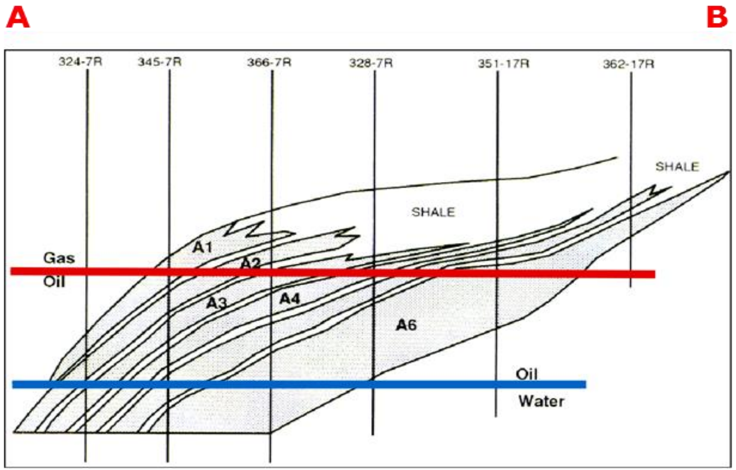
(Meddaugh, 2006)

Impact of Stratigraphic Detail - 1



Black square on west side of structure map shows the study area.

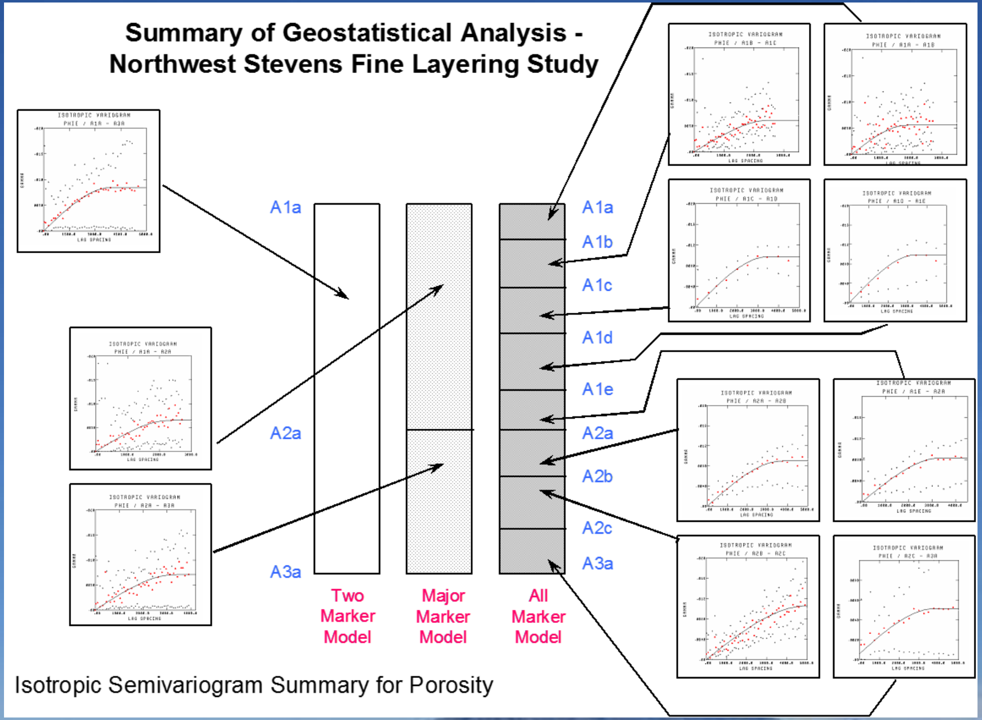
Northwest Stevens Reservoir



(Meddaugh, 2006)

Impact of Stratigraphic Detail - 1

- Cases studied:
  1. Two markers (top, bottom only)
  2. Three "major" markers
  3. Nine "detailed" markers



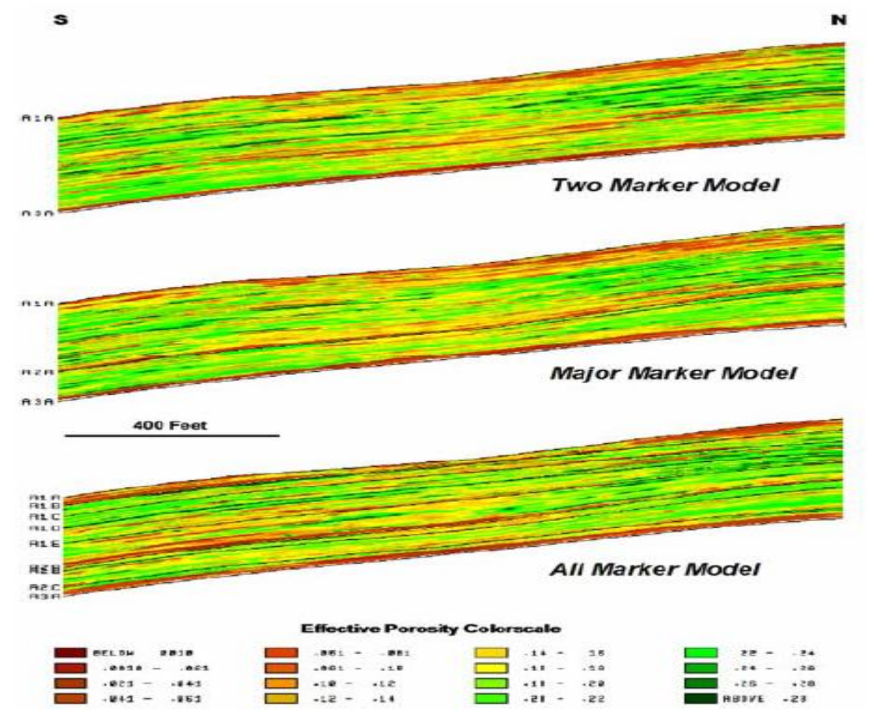
Summary of Geostatistical Analysis - Northwest Stevens Fine Layering Study

Isotropic Semivariogram Summary for Porosity

(Meddaugh, 2006)

Impact of Stratigraphic Detail - 1

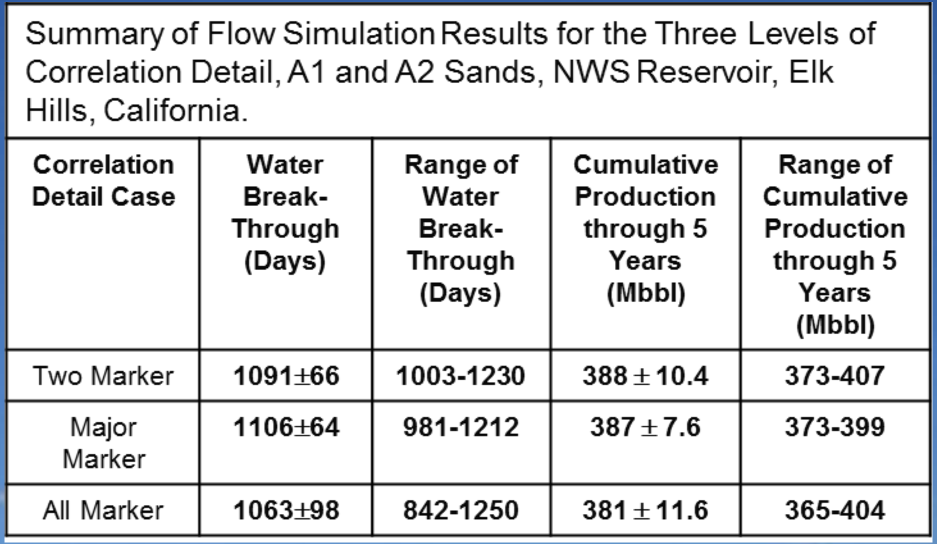
- Cases studied:
  1. Two markers (top, bottom only)
  2. Three “major” markers
  3. Nine “detailed” markers



(Meddaugh, 2006)

Impact of Stratigraphic Detail - 1

- Summary of fluid flow results obtained from twenty realizations for each of the three levels of stratigraphic detail
- Note that there is little difference for the three cases



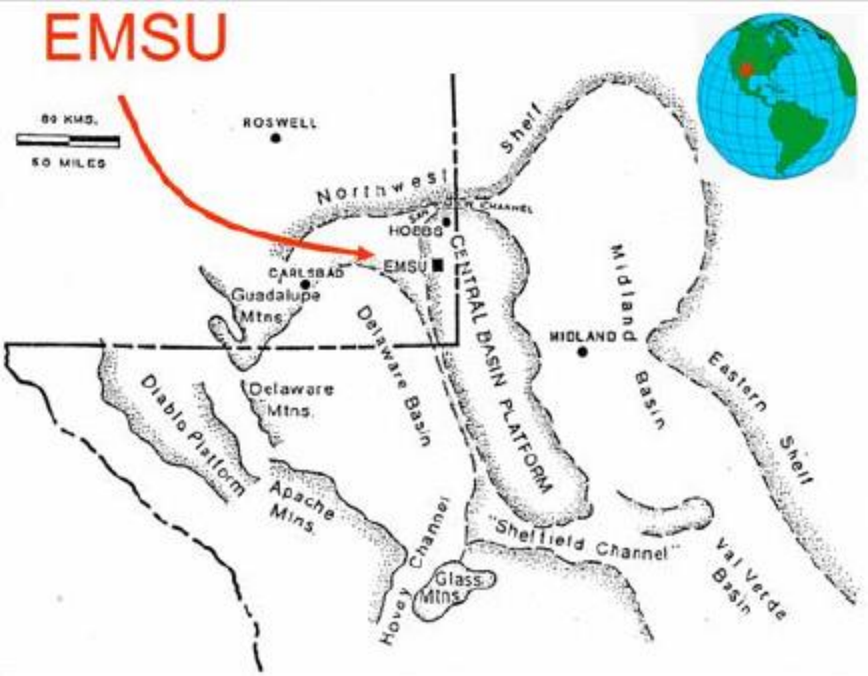
Summary of Flow Simulation Results for the Three Levels of Correlation Detail, A1 and A2 Sands, NWS Reservoir, Elk Hills, California.

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**

(Meddaugh, 2006)

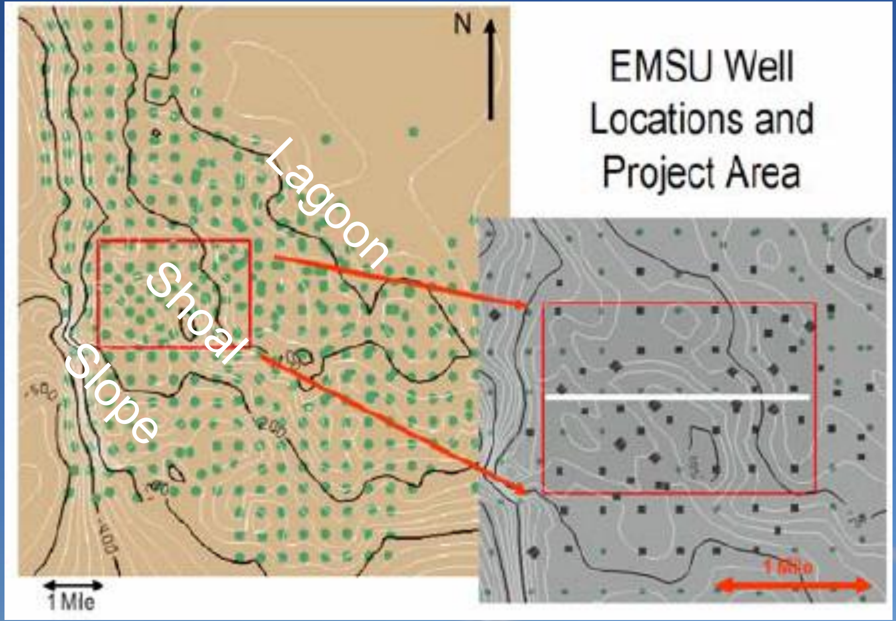
Impact of Stratigraphic Detail - 2

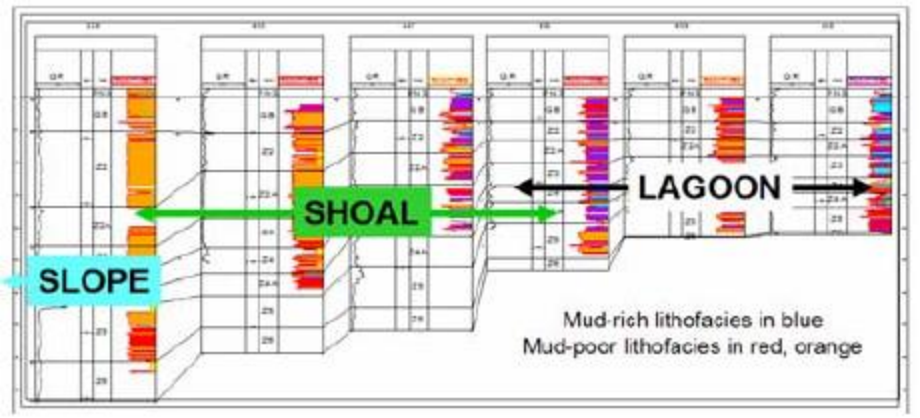
- Eunice Monument South Unit
- Carbonate reservoir in New Mexico



(Meddaugh, 2006)

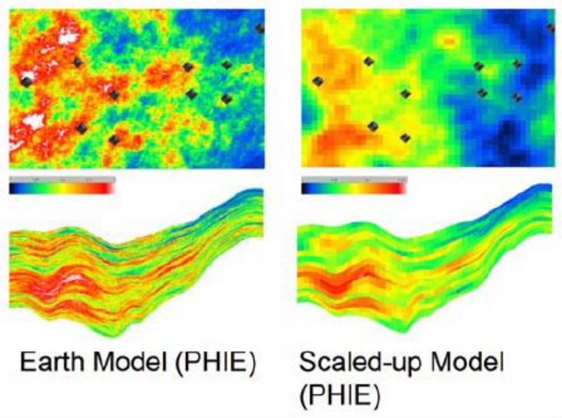
Impact of Stratigraphic Detail - 2



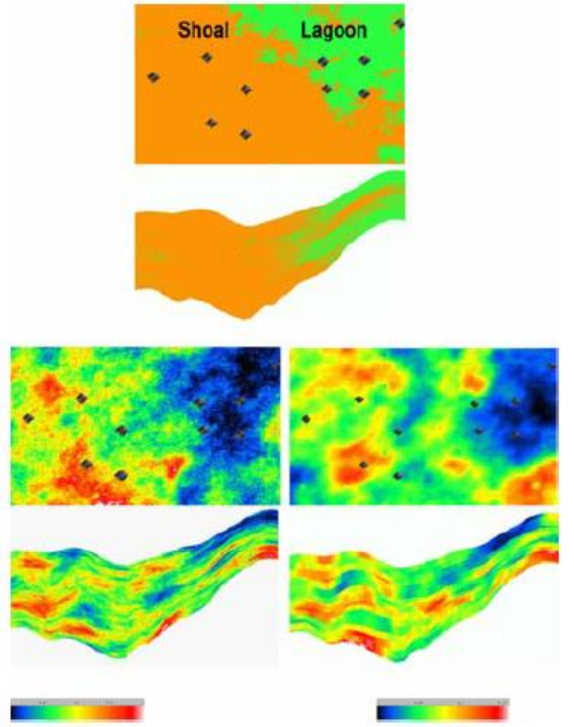


(Meddaugh, 2006)

Impact of Stratigraphic Detail - 2



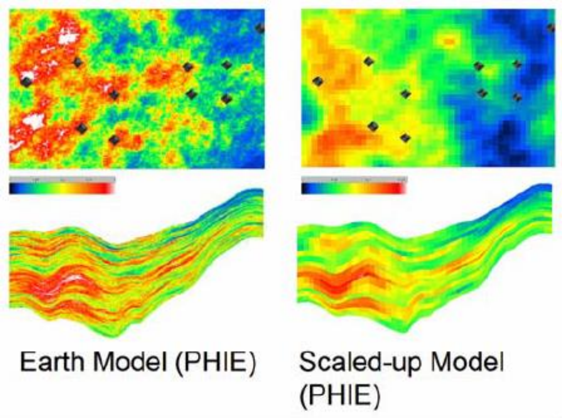
Simple Model – Well Data and Formation Tops



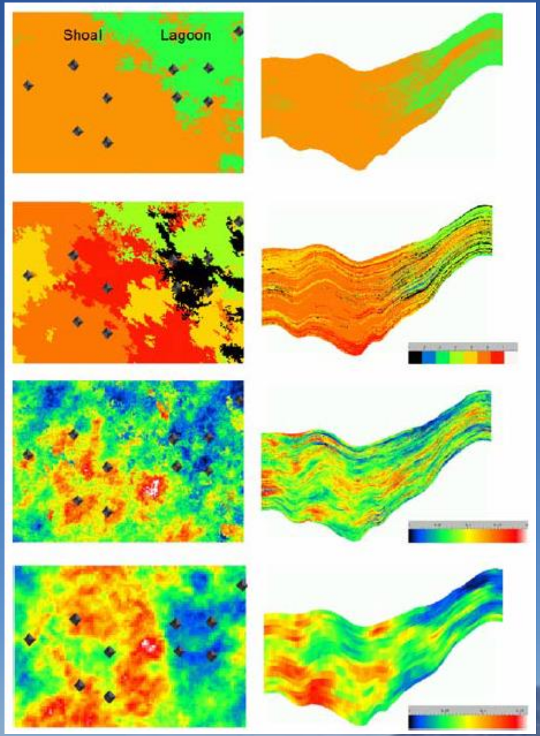
Facies Model – Well Data, Facies Regions, and Formation Tops

(Meddaugh, 2006)

Impact of Stratigraphic Detail - 2



Simple Model – Well Data and Formation Tops

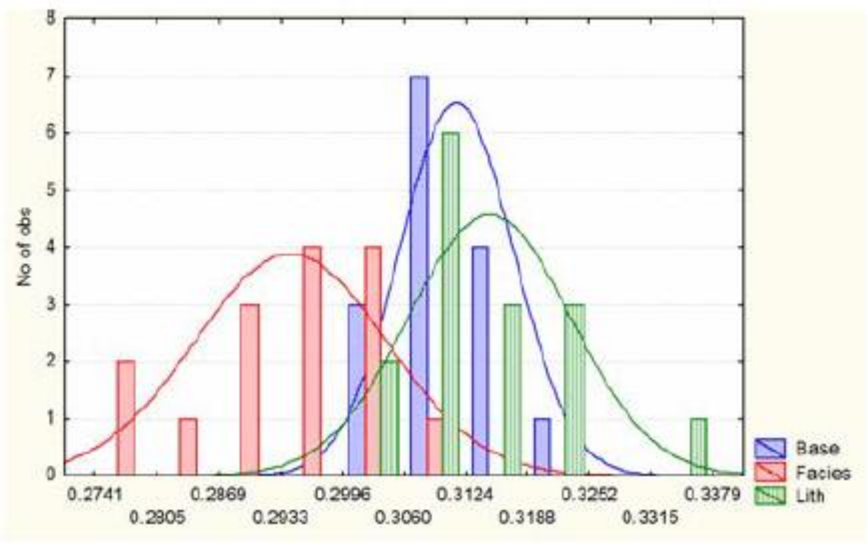


Lithofacies Model – Well Data, Facies Regions, Lithology Distribution and Formation Tops

(Meddaugh, 2006)

Impact of Stratigraphic Detail - 2

- Results showing the distribution of recovery factor (RF) overlap obtained from 15 realizations of each of the three workflows studied

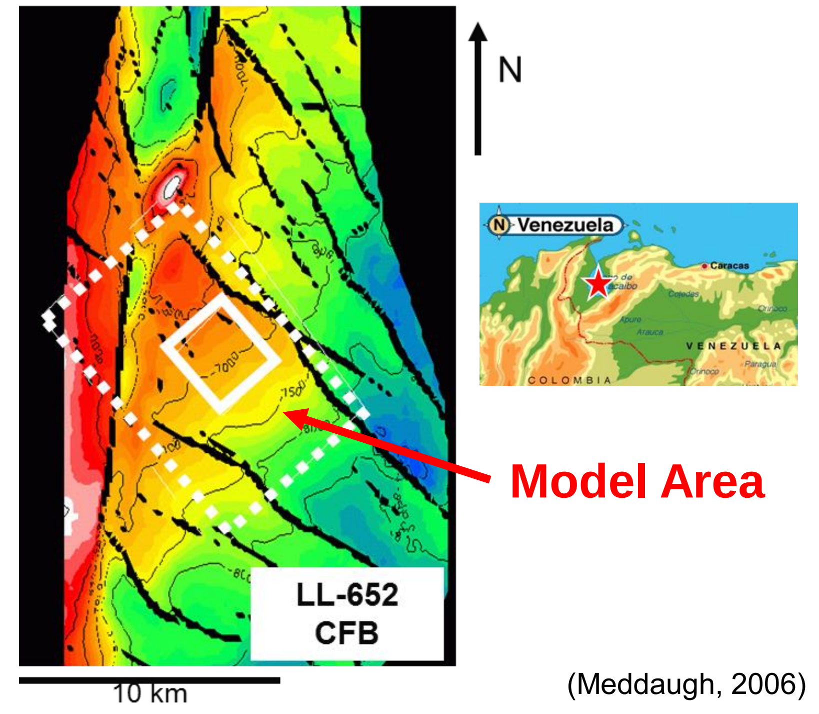


Workflow	Mean RF	RF Std. Dev.	RF Min.	RF Max.
Simple	0.311	0.006	0.303	0.324
Facies	0.294	0.010	0.274	0.308
Lithology	0.315	0.008	0.302	0.338

(Meddaugh, 2006)

Impact of Stratigraphic Detail - 3

- LL-652 reservoir is located in Venezuela
- Oil production from several Eocene sands
- Non-reservoir sands have a porosity about 4% and permeability less than 0.02 mD
- Reservoir sands have a porosity about 14% and permeability about 40 mD



(Meddaugh, 2006)

Impact of Stratigraphic Detail - 3

- Reservoir models were generated using four different workflows with increasing geological constraints:
  - **Simple** – Framework derived from structure maps for the five major stratigraphic picks (used on all the following except “complex facies mode”. Porosity distributed using SGS* constrained by stratigraphic layer. Permeability was added via collocated cokriging with SGS by stratigraphic layer using porosity as soft data.

Porosity Model

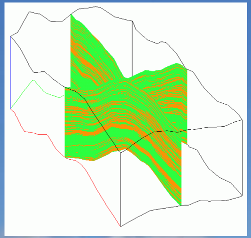
Up-scaled Model

*SGS = Sequential Gaussian Simulation

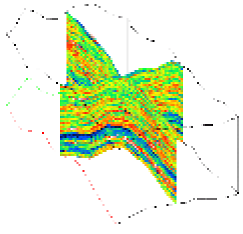
(Meddaugh, 2006)

Impact of Stratigraphic Detail - 3

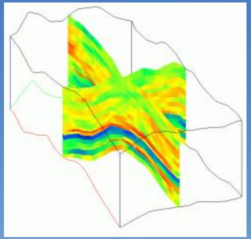
- Reservoir models were generated using four different workflows with increasing geological constraints:
  - **RnR** (Reservoir/non-Reservoir) – Reservoir and non-reservoir facies distributed using SIS*. SGS by facies region used to distribute porosity. Permeability was added via collocated cokriging with SGS by facies and stratigraphic layer using porosity as soft data.



RnR Model



Porosity Model



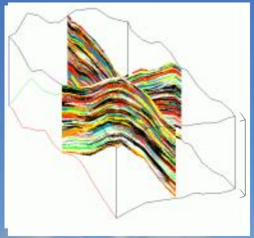
Up-scaled Model

*SIS = Sequential Indicator Simulation

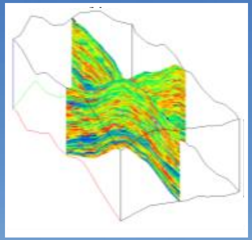
(Meddaugh, 2006)

Impact of Stratigraphic Detail - 3

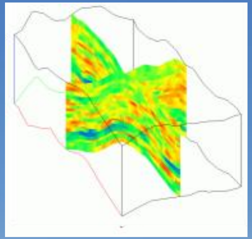
- Reservoir models were generated using four different workflows with increasing geological constraints:
  - **Lithofacies** – Seven lithofacies facies distributed using MBSIS*. SGS by lithofacies region was used to distribute porosity. Permeability was added via collocated cokriging with SGS by facies and stratigraphic layer using porosity as soft data.



Facies Model



Porosity Model



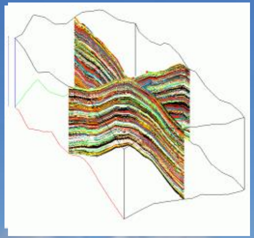
Upscaled Model

*MBSIS = Multi-Binary Sequential Indicator Simulation

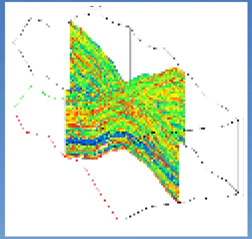
(Meddaugh, 2006)

Impact of Stratigraphic Detail - 3

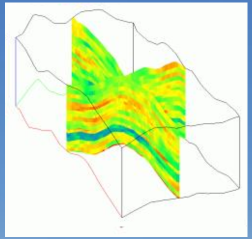
- Reservoir models were generated using four different workflows with increasing geological constraints:
  - **Complex Facies** – framework from surfaces for 16 "detailed" sequence stratigraphic picks. Lithofacies, porosity, and permeability distributed using the lithofacies workflow given above



Facies Model



Porosity Model

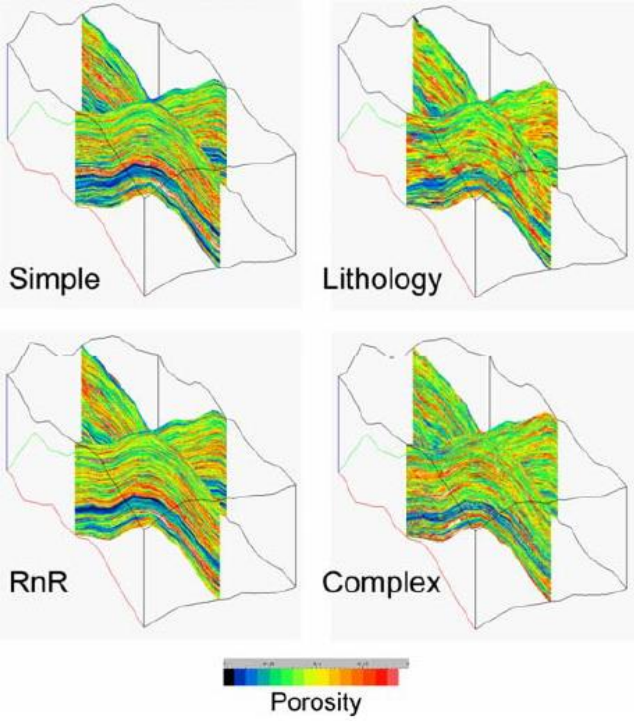


Up-scaled Model

(Meddaugh, 2006)

Impact of Stratigraphic Detail - 3

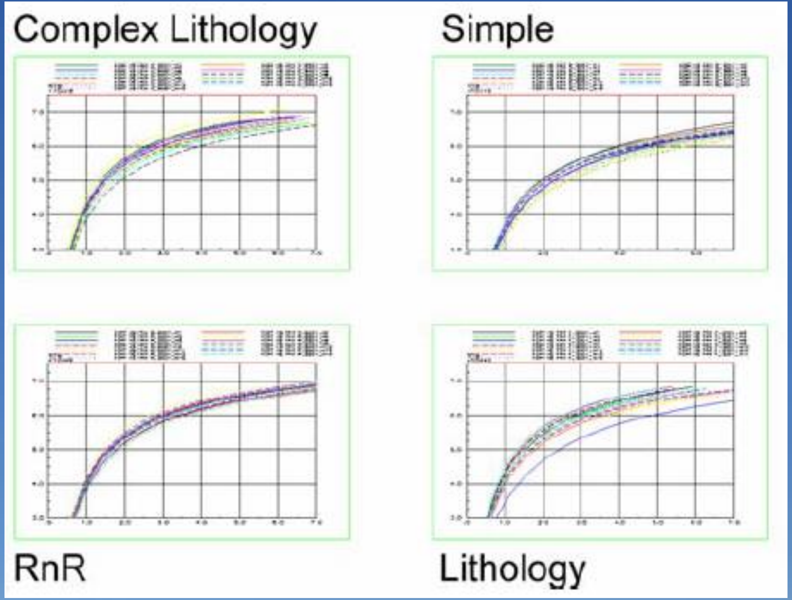
- Comparison of the porosity distribution obtained from the four LL-652 model workflows
  - Simple Stratigraphy
  - Reservoir, Non-Reservoir (RNR)
  - Lithofacies
  - Complex Stratigraphy and Facies



(Meddaugh, 2006)

Impact of Stratigraphic Detail - 3

- Similarity of cumulative oil versus pore volume water injected for the four LL-652 model workflows
  - Simple Stratigraphy
  - Reservoir, Non-Reservoir (RNR)
  - Lithofacies
  - Complex Stratigraphy and Facies



(Meddaugh, 2006)

Impact of Stratigraphic Detail - 3

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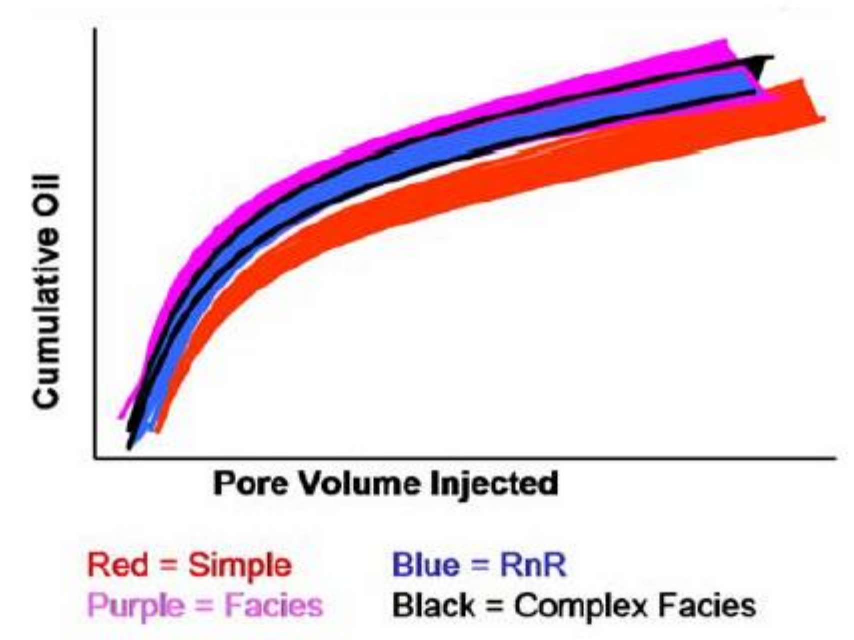
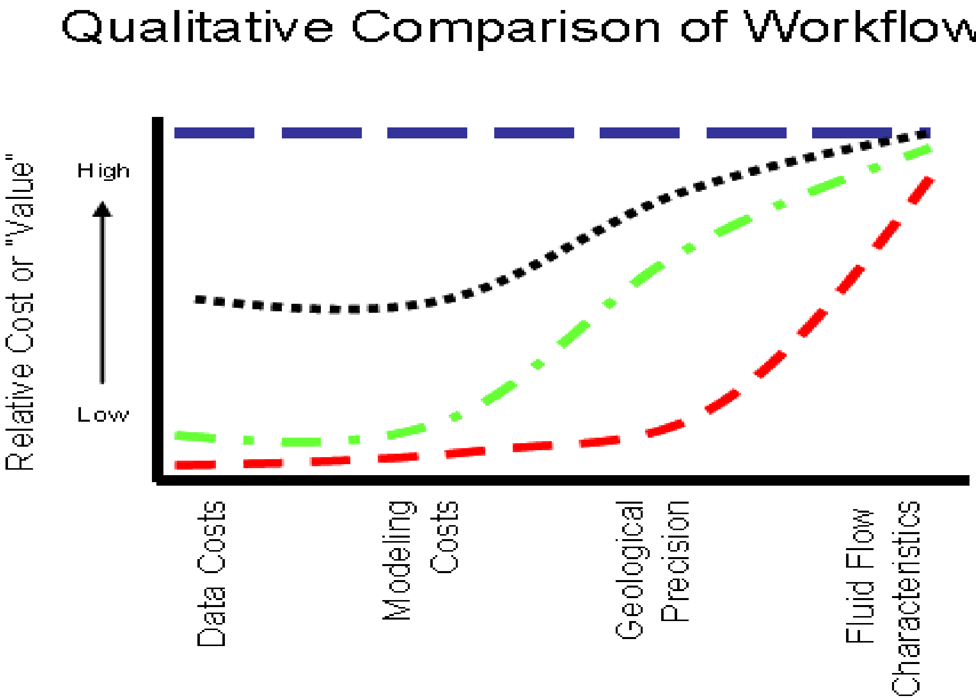


(Meddaugh, 2006)

Impact of Stratigraphic Detail - 3

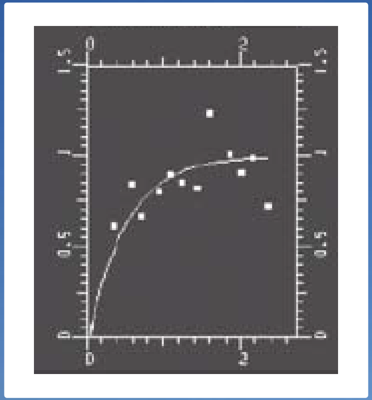

Qualitative Comparison of Workflows

1. **Complex Facies**
2. **Lithofacies**
3. **RNR**
4. **Simple**

(Meddaugh, 2006b)

Impact of Semivariogram Fit

- LL-652 Reservoir

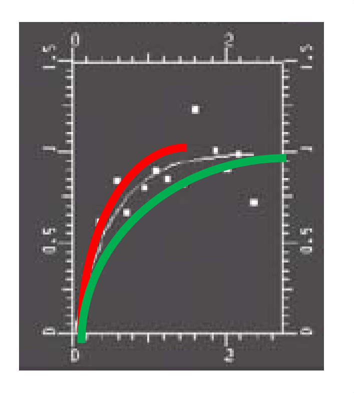


Semivariogram Case	Range 1 (m)	Range 2 (m)	Azimuth	Average Recovery Factor (15 Realizations)
Base Case (Data Driven Range Value)	2300	1400	N45E	46.2%

(Meddaugh, 2006b)

Impact of Semivariogram Fit

- LL-652 Reservoir



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%

Note: Longer Range = More Spatial Continuity

(Meddaugh, 2006b)

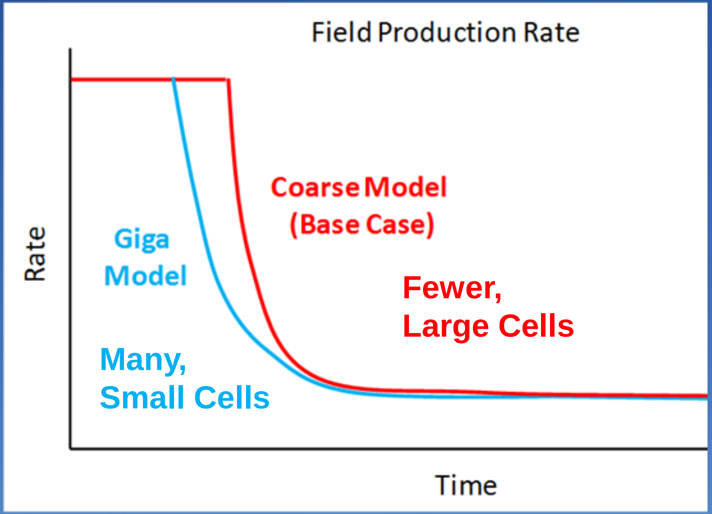
Summary 1

- Reasonable value ranges for various modeling parameters appear to have only a small effect on model-derived recovery

Summary 2

- However, reservoir models with larger number of smaller-sized grid cells give less optimistic (and more realistic) forecasts compared to models with fewer, larger-sized grid cells

Summary 2 - Illustration



10-15% Production Forecast Increase Predicted from Coarse Model Compared to Fine Grid, Giga-Cell Model. After Obi et al. (2014).

Thank You