Some Practical Aspects of Reservoir Modeling

- Laws of Heterogeneity / Why Build Geologic Models?
- Steps in a Geostatistical Reservoir Modeling Study
- Hierarchical Approach to Modeling
- Spatial Continuity
- Estimation / Mapping of Petrophysical Properties
- Stochastic Simulation / Modeling
- Issues and Concerns

Preliminaries (1)

- Laws or Heterogeneity:

1. All reservoirs are heterogeneous
2. All reservoirs are more heterogeneous than first imagined
3. The degree of heterogeneity is directly proportional to the amount of time allocated for the project and the project funding

- Why Build 3-D Geologic Models?
  - handle large amounts of data
  - consistent analysis in three dimensions
  - direct numerical input to flow simulation and pore volume calculation (reservoir management)
  - test / visualize multiple geologic interpretations
  - assess uncertainty

Preliminaries (2)

- Historical Perspective of *Geostatistical* Modeling:
  - Theory of probability (in its modern form) was formalized in the 1600's by Blaise Pascal and Pierre de Fermat. Others: Bayes, Gauss, **...**
  - The foundation for geostatistical techniques was established by people like Kolmogorov, Weiner, Matern, and Gandin in the early 1900's
  - *Geostatistics* was started in the 1960's by Krige and Sichel in South Africa and Matheron in France. Two of Matheron's first students (Journel and David) would start new centers of teaching and research in the USA and Canada
  - Application became popular in mining and meteorology. Now, these techniques are applied in many fields from fisheries, forestry, environmental remediation, and so on
  - Extensively used by major oil companies

Some of the Data Available for Reservoir Modeling

Data Integration is a fundamental principle of geostatistics / reservoir modeling; the goal is to explicitly account for all of the available data. A large part of the ongoing research in Geostatistical Reservoir Modeling is to devise techniques that can accommodate a greater variety of data. Following are some of the data that are considered:

- Well Log Data (surface tops, rock type, ϕ, K) by zone
- Core Data (ϕ and K by rock type) by zone
- Sequence Stratigraphic Interpretation / Layering (a definition of the continuity and trends within each layer of the reservoir)
- Trends and Stacking Patterns available from a regional geological interpretation
- Analog data from outcrops or densely drilled similar fields (size distributions, measures of lateral continuity)
- Seismic-Derived Attributes (vertically averaged rock type proportions and porosity)
- Well Test and Production Data (interpreted K • thickness, interpreted channel widths, connected flow paths, barriers)

This information is sparse relative to the size of the heterogeneities being modeled; therefore, there is always uncertainty in the geological model

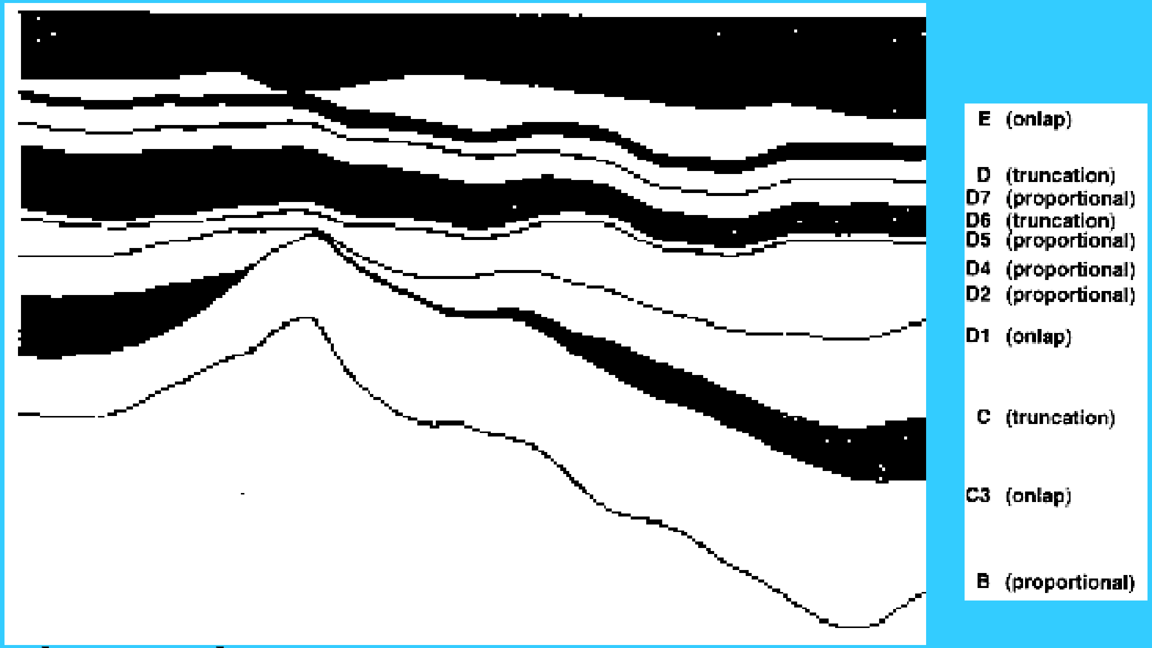
Constructing 3-D Models

The specific process employed for 3-D model building will depend on the data available, the time available, the type of reservoir, and the skills of the people available. In general, the following major steps are required:

1. Determine the areal and vertical extent of the model and the geological modeling cell size
2. Establish a conceptual geological model and define zones for modeling
3. For each zone:
    (a) define stratigraphic correlation
    (b) define the number of rock types, the rock type data, and the spatial correlation of the rock types
    (c) generate 3-D rock type model
    (d) establish the porosity and permeability values from core / log data and the spatial correlation
    (e) generate 3-D porosity models
    (f) generate 3-D permeability models
    (g) merge and translate back to real coordinate *space*
4. Verify the model
5. Combine zones into a single model

- Each of these steps is addressed during this lecture or course (to some extent)
- Uncertainty is assessed by deriving reasonable estimates of uncertainty for each input parameter and then generating multiple realizations

Conceptual Geological Model / Zone Definition



Select zones by considering:

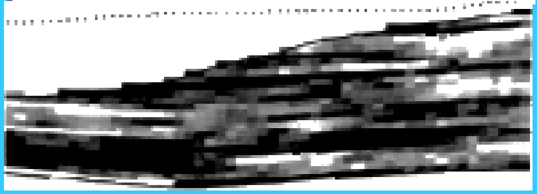
- sequence stratigraphic zonation
- keep geologically “homogeneous” rock together
- maintain a reasonable number of data per zone
- less resolution in water bearing formation

Geological Correlation Style

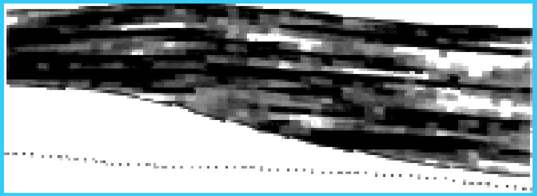
Each layer in the reservoir is classified as belonging to one of the following geological correlation styles. The existing grids defining the zone and the restored grids are used for modeling.

- Proportional (conforms to existing top and base):

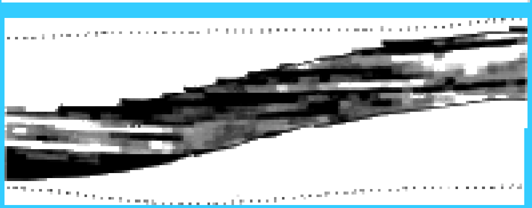
- Truncation (conforms to existing base):



- Onlap (conforms to existing top):



- Offlap (does not conform to existing top or base):

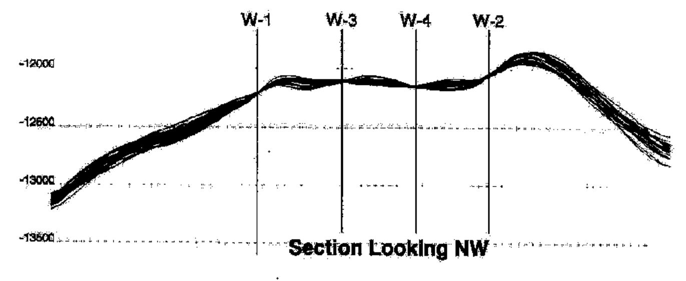


Stochastic Modeling of Surfaces

To assess uncertainty in pore volume or reservoir performance predictions requires adding uncertainty to the gridded surface elevations. Some characteristics of the uncertainty:

- essentially zero at the well locations
- varies smoothly away from the wells
- variance depends on the quality of the seismic and the distance from the wells

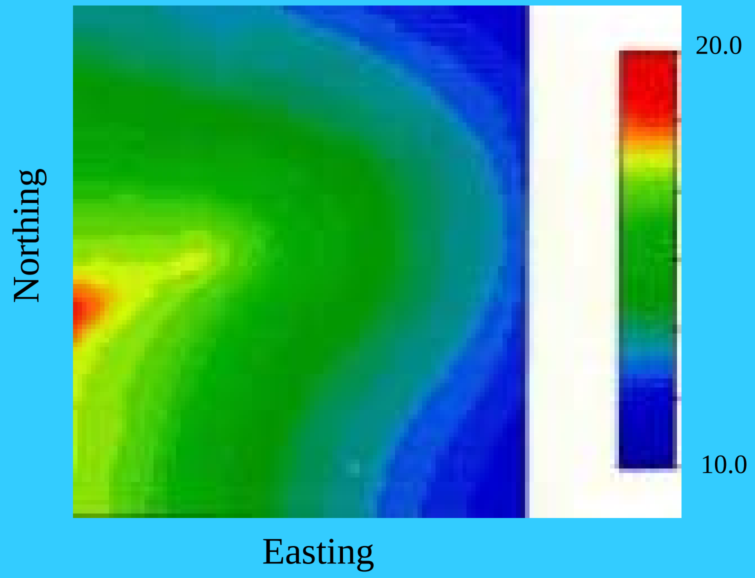
The following example was created by using sgsim to create a correlated Gaussian error. A section through four wells:

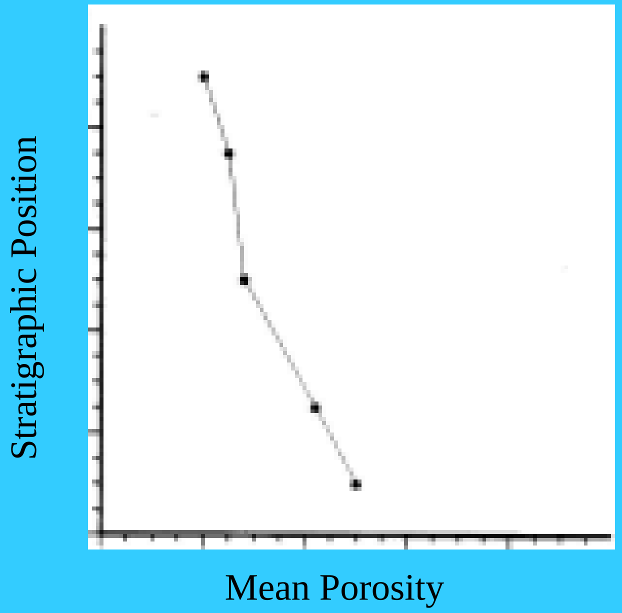


Multiple surfaces would be handled by constructing stochastic isochore maps and subtracting them from the top surface. The grids are constrained to honor the well data, not cross each other, and fall within realistic bounds of uncertainty.

Areal and Vertical Trends

- Often it is possible to infer areal or vertical trends in the distribution of rock types and/or petrophysical properties.



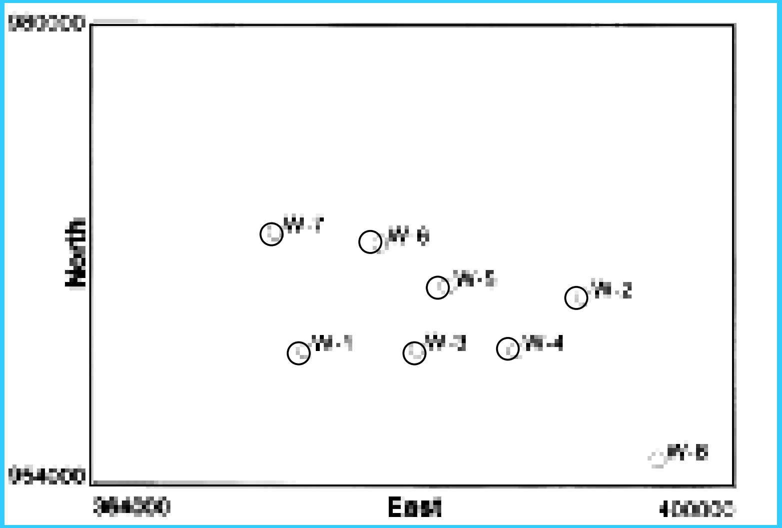


- These trend profiles/maps may be used in many geostatistical modeling programs
- Trends should be removed and residuals are modeled stochastically

Declustering

Data may be clustered in high pay zones or in certain areas; a declustering procedure is required to assign relative weights. These *declustering* weights can then be used when looking at histograms or summary statistics or when model building.

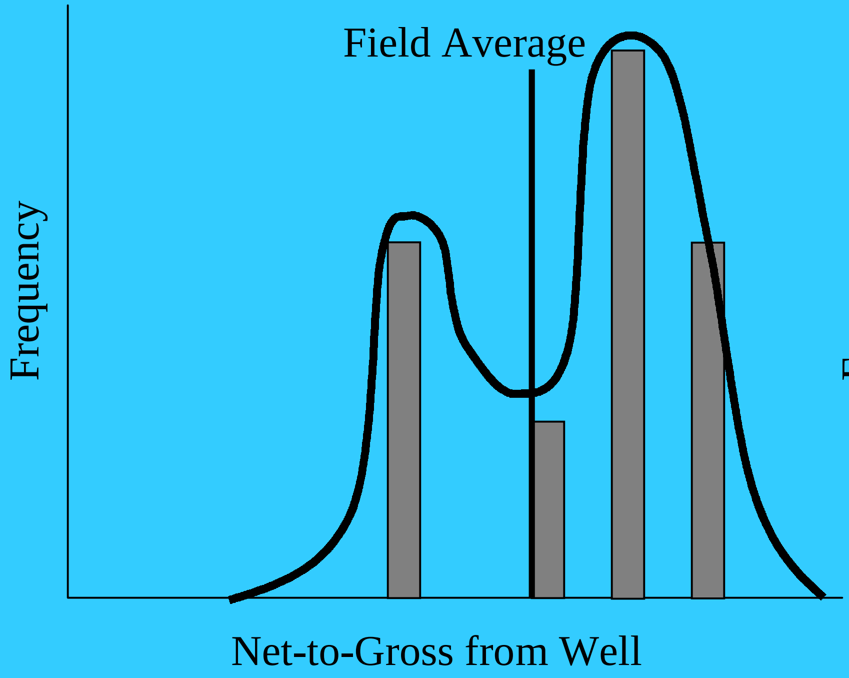
Given an example with eight values. With cell declustering, the relative declustering weight for each datum would be:

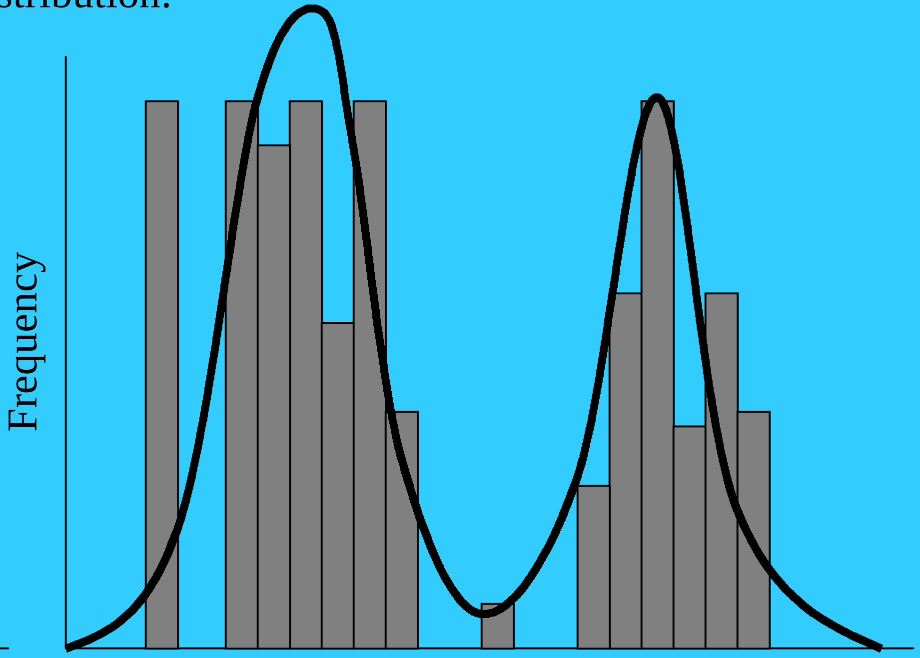


Well	Weight
W-1	1.2
W-2	1.13
W-3	0.8
W-4	0.85
W-5	0.74
W-6	0.93
W-7	1.1
W-8	1.26

Histogram Smoothing / Modeling

Sparse data may create a need to smooth or model the histogram of the attribute under consideration. Two examples, one with eight data values and an example with 243 core permeability measurements from a bimodal distribution:

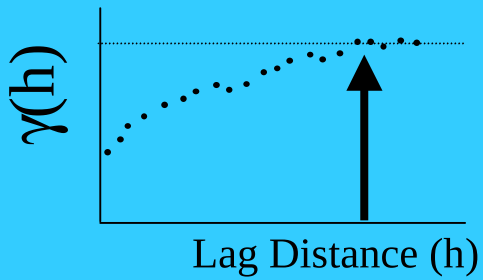




Definition of the Variogram

A quantitative measure of spatial variability/continuity is needed to characterize the detailed distribution of attributes within the reservoir; this measure must be customized for each field and each attribute (ϕ,K)

The variogram is one way to quantify spatial variability:



- The variogram for lag distance **h** is defined as the average squared difference of values separated approximately by **h**:

$$2\gamma(\mathbf{h}) = \frac{1}{N(\mathbf{h})}\sum_{N(\mathbf{h})}[z(\mathbf{u}) - z(\mathbf{u}+\mathbf{h})]^2$$

where N(**h**}) is the number of pairs for lag **h**.

- In probabilistic notation, the variogram is defined as:

$$2\gamma(\mathbf{h}) = E\{[Z(\mathbf{u}) - Z(\mathbf{u}+\mathbf{h})]^2\}$$

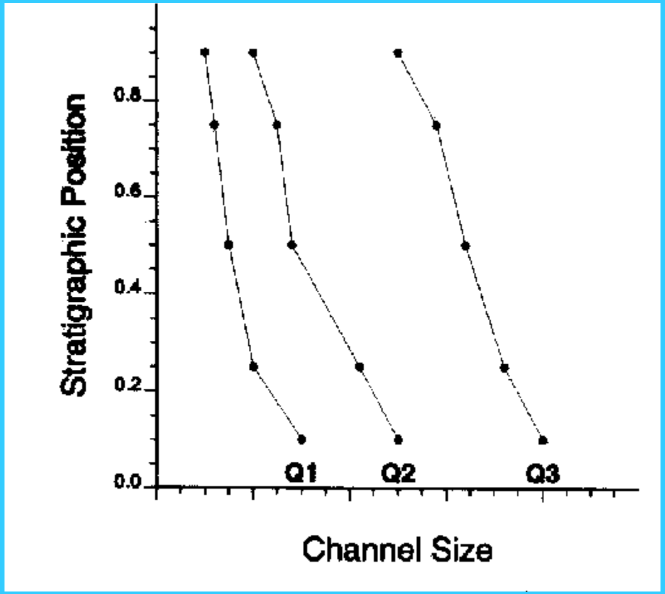
Spatial Information for Object-based Modeling (1)

Object-based modeling techniques require information on the size, shape, and relationship between the different objects. For braided fluvial reservoirs, some of the needed information includes:

- fraction of channel sand (could vary areally and vertically)
- width and thickness of channel sands (could vary vertically and follow a distribution of possible sizes)
- measures of channel sinuosity (depend on size of channel and vertical position)
- geometry of channel “families” or multi-story channels

Spatial Information for Object-based Modeling (2)

An example of how the channel size (say thickness) could be specified:



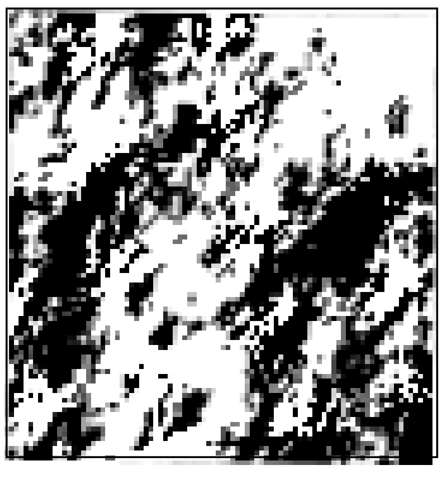
The vertical axis on this plot represents restored stratigraphic position and the horizontal axis is channel thickness. The Q1, Q2, and Q3 lines represent the quartiles (25%, 50% and 75%) values of the distribution. Note how the channels are smaller at the top of the zone.

Sequential Indicator Simulation

- Generate indicator-based realizations that reproduce local conditioning data, global proportions, local proportions (via locally varying proportions), and patterns of spatial correlation (variogram)
- Define an indicator transform:

$$i(u_\alpha;k) = \left\{ \begin{array}{l} 1, \quad if \quad lithosfacies \quad k \quad present \quad at \quad location \quad u_\alpha \\ 0, \quad if \quad not \end{array} \right\}$$

- Generate a 3-D realization of that indicator variable
- Example from the Ghawar field in Saudi Arabia:



Object-Based Modeling

- Simulate the deposition of the reservoir by stochastically positioning geometric shapes
- Start from the bottom and alternately lay down floodplain sediments and channel fill. Specify the distribution of channel sizes, spacing, and so on.
- Could additionally model crevasse deposits and point bar sands
- Honor limited well data by controlling the channel positions
- Commonly applied to fluvial reservoirs

Sequential Gaussian Simulation

- A technique that is robust and applicable for the generation of realizations of continuous variables. The realizations can be made to honor:
  - local conditioning data,
  - the global histogram (declustered and smoothed),
  - areal and vertical trends (via locally varying mean), and
  - patterns of spatial correlation (variogram)
- Works with a Gaussian or Normal transform of the data (see *Normal Scores Transformation*)
- Generate a 3-D realization of Gaussian variable and back transform
- Applied on a by zone and by rock type basis between the restored grids for geological correlation

Annealing Cosimulation

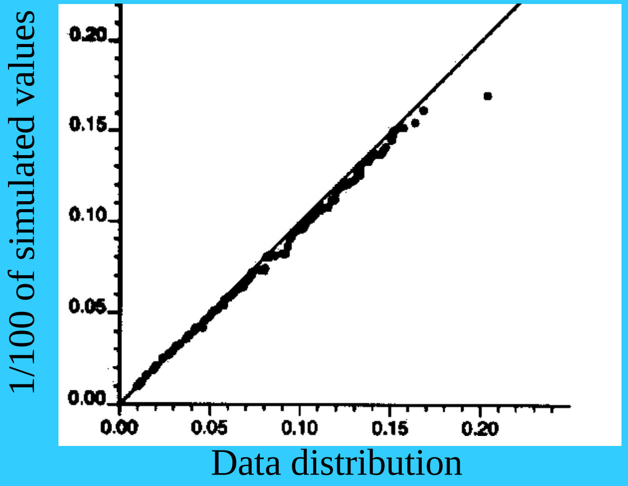
- A technique that is robust and applicable for the generation of realizations of continuous variables (specifically permeability). The realizations can be made to honor:
  - local conditioning data,
  - the global histogram (declustered and smoothed),
  - areal and vertical trends (via locally varying mean), and
  - patterns of spatial correlation (variograms and indicator variograms -- for special continuity of high and low values)
  - a cross plot of porosity and permeability
- The stochastic simulation problem is posed as an optimization problem and the simulated annealing algorithm is used to solve the problem, i.e., generate plausible realizations
- Applied on a by zone and by rock type basis between the restored grids for geological correlation

Criteria for Model Verification

- Many interdependent subjective decisions are made in the construction of a geostatistical reservoir model. Some things that should be checked:
  - does the model appear geologically plausible?
  - relative to other models, are the heterogeneities reasonably distributed?
  - are the porosity and permeability models consistent with the rock type model?
  - is the geological correlation style correct (mistake with Z_{rel})?
  - does the model present trends consistent with the regional geology?
- Does the model honor all of the input data?
  - local conditioning data (plot the results),
  - declustered histogram (Q-Q plot),
  - variograms,
  - cross plot between porosity and permeability,
- Do the techniques employed pass all of the cross-validation checks?
- Can the model be checked relative to data that were not used in the model building, e.g., well test or production history?

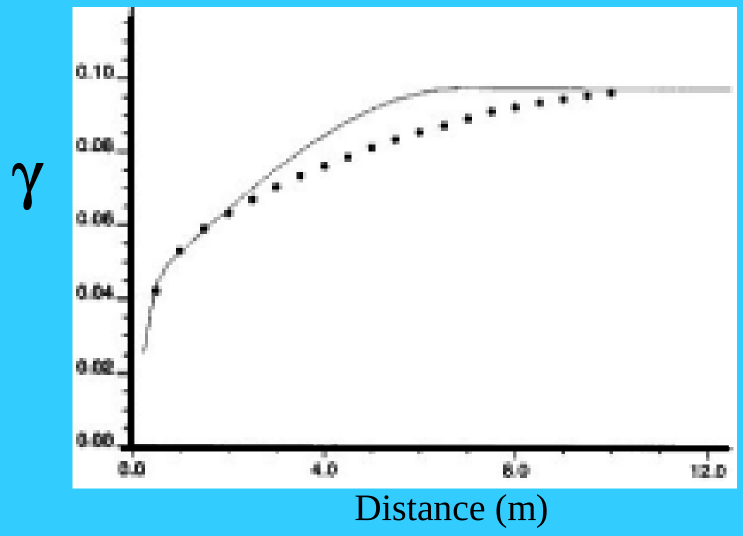
Q-Q Plots to Assess Histogram Reproduction

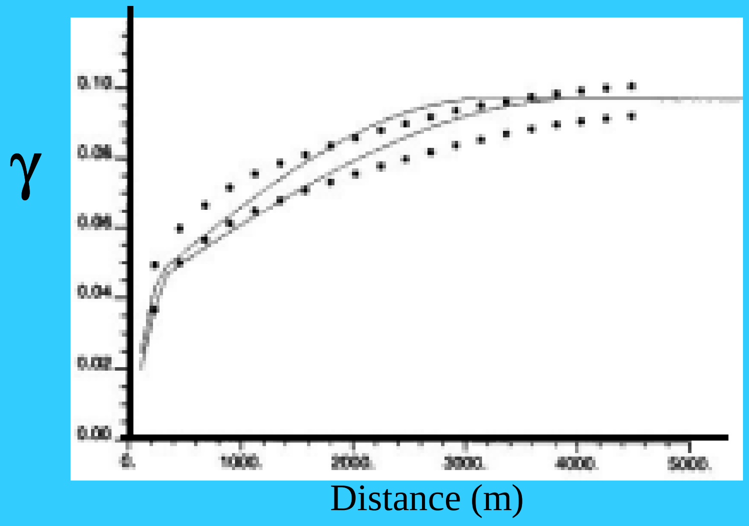
- A Q-Q plot is to compare two histograms or univariate distributions, e.g., the input declustered histogram of porosity for a specific rock type within a specific zone and the distribution from the final 3-D model
- A plot of the matching quantiles of two distributions. For example, one point on the plot is the median of the first distribution plotted against the median of the second distribution. If the points for many quantiles (1%, 2%, ..., 98%, 99%) fall on a straight line then the two distributions agree
- The two axes are in units of the data. The following is an actual example from one zone of a large clastic reservoir:



Assessing Variogram Reproduction

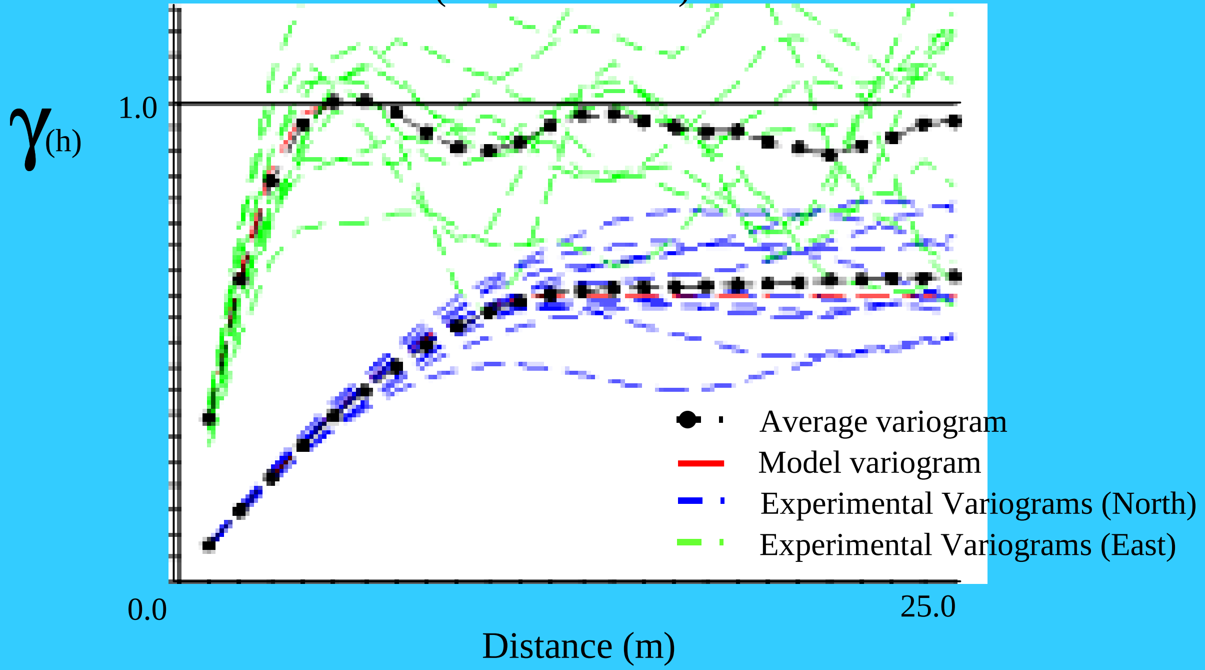
- Plot of the input variogram model (solid line) with the variogram from the 3-D realization (black dots) in three major directions:





Assessing Variogram Reproduction

- A 2-D example
- The variogram should be reproduced on average


Model, Average and Experimental Variograms (10 Realizations)

Summary

- All reservoirs are heterogeneous
- Reasons for building 3-D models (data integration, refine estimates of PV, quantify uncertainty, assess continuity, quantify uncertainty in predictions,**...**)
- Procedure for modeling:
  - geological zonation, layering, conceptual model
  - statistics: declustering, modeling, variograms
  - rock type modeling (indicator, object-based, hybrid)
  - porosity modeling
  - permeability modeling
  - model validation
- Issues that have been glossed over:
  - size scaling from core to geological modeling cell
  - faults and fractures
  - reliable inference of spatial statistics
  - hierarchical modeling