Overview

- Objectives of the Course
- What is Geostatistics?
- Why Geostatistics / 3-D Modeling?
- Uncertainty Quantification and Decision Making
- Heterogeneous Reservoir Modeling
- An Example / Limitations / Future

Objectives of the Workshop

- Increase awareness of geostatistics and the situations where the application of geostatistical techniques could add value
- Learn how to assemble the required data for geostatistical techniques
- Introduce statistical and geostatistical techniques available in GSLIB
- Provide some statistical / geostatistical tools that will help with specific tasks (core - log data, permeability prediction, 3-D model building, and uncertainty assessment)
- Step through major components of a reservoir modeling study (layering, rock type modeling, porosity modeling, permeability modeling)
- Understand the limitations of the resulting numerical models and the geostatistical techniques
- Note: while the context and examples in this workshop are specific to the petroleum field, these tools and techniques can be applied in similar manner to other areas which encounter geostatistical problems (i.e. mining)

Historical Perspective

- Theory of probability (in its modern form) was formalized in the 1600's by Blaise Pascal and Pierre de Fermat (Gauss and Bayes were more recent players)
- 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 leave for the USA and Canada and start new centers of geostatistical research
- The application of geostatistical techniques became popular in the mining industry and meteorology. Now, these techniques are applied in many diverse applications from fisheries, forestry, environmental remediation, and so on
- Extensively used by major oil companies
- Centers for research are numerous, including Stanford, Fountainbleau, and others such as the University of Alberta

Geostatistics for Reservoir Characterization (1)

- *Business Need*: make the best possible reservoir management decisions in the face of uncertainty. One of the biggest uncertainties is the numerical description of the reservoir.
- *Statistics* is concerned with scientific methods for collecting, organizing, summarizing, presenting and analyzing data, as well as drawing valid conclusions and making reasonable decisions on the basis of such analysis.
- *Geostatistic*s is a branch of applied statistics that places emphasis on (1) the geological context of the data, (2) the spatial relationship between the data, and (3) data measured with different volumetric support and precision.
- Geostatistics is sometimes referred to as stochastic modeling, geostatistical reservoir characterization, conditional simulation

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Geostatistics for Reservoir Characterization (2)

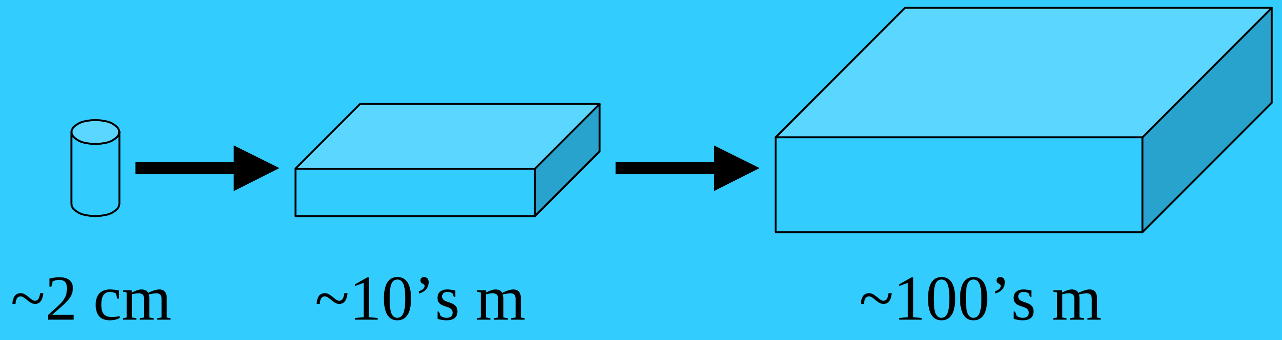
- Basic Principles:
  - work within all known geological (physical) constraints (sequence stratigraphic framework, …)
  - provide tools to quantify and exploit spatial correlation
  - algorithms for numerical geological modeling (heterogeneity modeling) and uncertainty quantification
- Doesn't make reservoir modeling any easier; just better (if correctly applied)

Motivation for Reservoir Models

- There is a need for reliable estimates of the original volume of hydrocarbon in the reservoir. These insitu volumes are important to (1) determine the economic viability of producing a given reservoir, (2) allocate equity among multiple owners, (3) compare the relative economic merits of alternative reservoirs, and (4) to determine the appropriate size of production facilities.
- Well locations must be selected to be economically optimal and robust with respect to uncertainty in the reservoir description. What type of wells (horizontal, vertical, multilateral, ...? How many wells?
- Reconcile an abundance of soft data (say, from a 3-D seismic survey or historical production data) with a limited amount of hard well data.
- Assess the potential for bypassed oil and the value of infill wells
- Flow simulation predicts reservoir performance with different production scenarios. The use of flow simulation was initially hampered by the limited resolution of flow models (primarily a computer hardware consideration) and simplistic geological input.
- Modern decision analysis tools require an assessment of the uncertainty in future production. One of the greatest sources of uncertainty is uncertainty is the geological inputs.

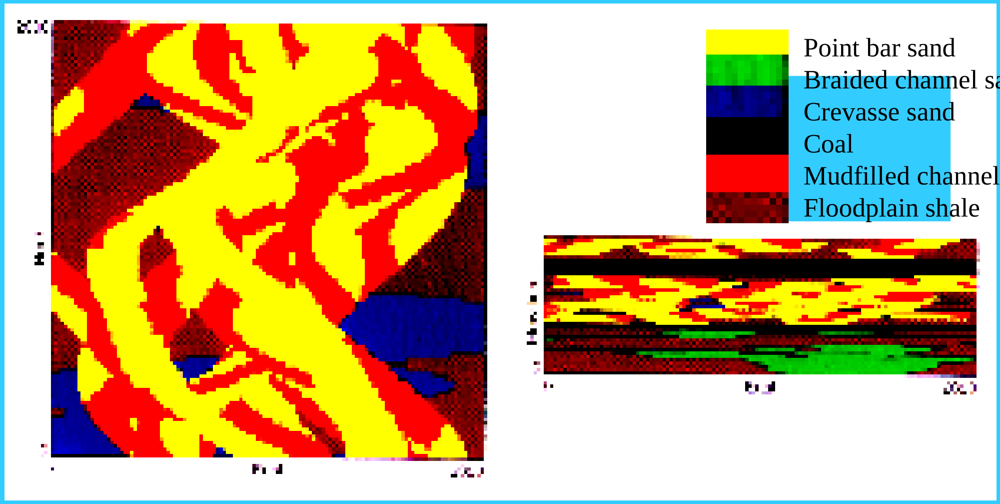
Key Geostatistical Concepts (1)

- **Petrophysical Properties:** concerned with constructing high resolution 3-D models of <u>lithofacies types</u>, <u>porosity</u>, and <u>permeability</u>.
- *Hard* truth measurements are the lithofacies assignments, porosity,and permeability observations taken from core (perhaps log) measurements. All other data types including well logs and seismic are called *soft* data and must be calibrated to the hard data.
- **Modeling Scale:** It is not possible nor optimal to model the reservoir properties at the resolution of the *hard* core data. The core data must be scaled to some <u>intermediate</u> resolution, models are generated at that intermediate geological modeling scale, and then the geological model is possibly scaled to an even coarser resolution for flow simulation



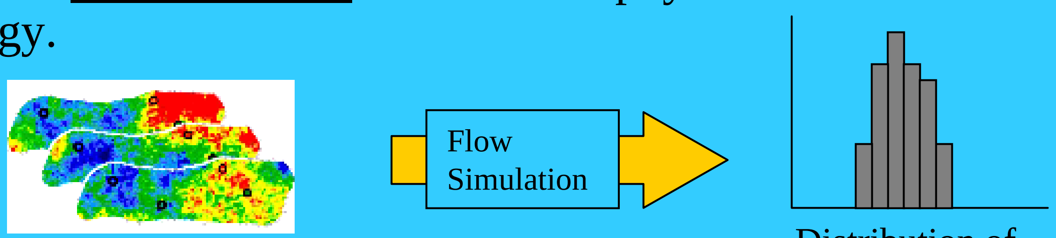
Key Geostatistical Concepts (2)

- **Numerical Modeling:** At any instance in geological time, <u>there is a single true distribution</u> of petrophysical properties in each reservoir. This true distribution is the result of a complex succession of physical, chemical, and biological processes. Although some of these depositional and diagenetic processes may be understood quite well, we do not completely understand all of the processes and have no access to the initial and boundary conditions in sufficient detail to provide the unique true distribution.



Key Geostatistical Concepts (3)

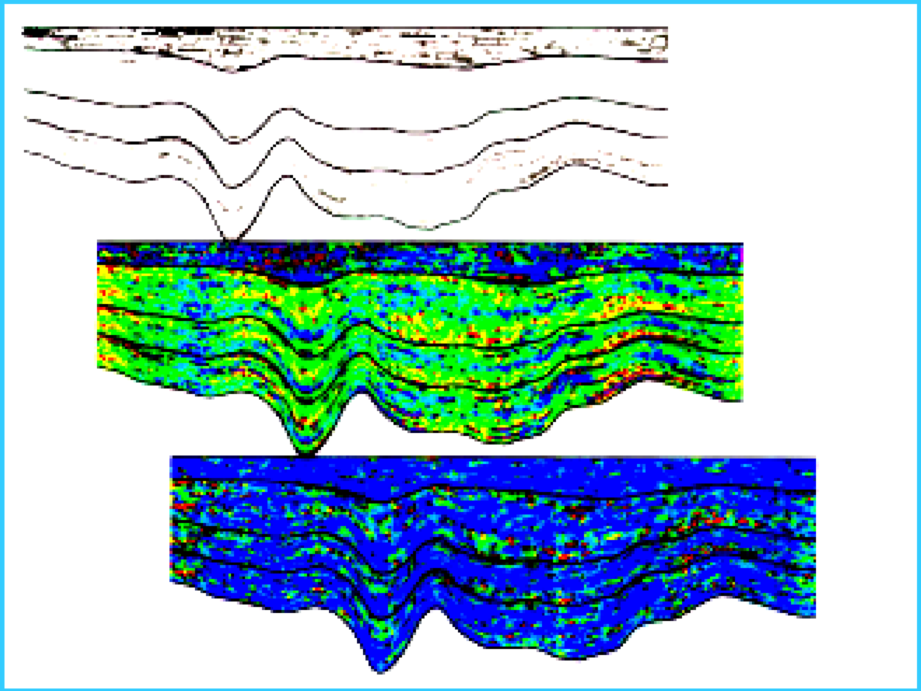
- **Uncertainty:** All numerical models would be found in error if we were to excavate that interwell volume and take exhaustive measurements: There is uncertainty. This uncertainty exists because of our ignorance/lack of knowledge. It is not an inherent feature of the reservoir.
- **Uniqueness and Smoothing:** Conventional mapping algorithms were devised to create smooth maps to reveal large scale geologic trends; for fluid flow problems, however, the extreme high and low values often have a large affect on the flow response.
- **Analogue Data:** There are rarely enough data to provide reliable statistics, especially horizontal measures of continuity. For this reason, data from analogue outcrops and similar more densely drilled reservoirs are used to help infer spatial statistics that are impossible to calculate from accessible subsurface reservoir data.
- **Dynamic Reservoir Changes:** Geostatistical modeling provides static descriptions of petrophysical properties. Time dependent changes in pressure and fluid saturations are best modeled with a flow simulator that encodes physical laws such as the conservation of mass and energy.



Multiple stochastic models

Distribution of possible responses

Cell-Based Modeling



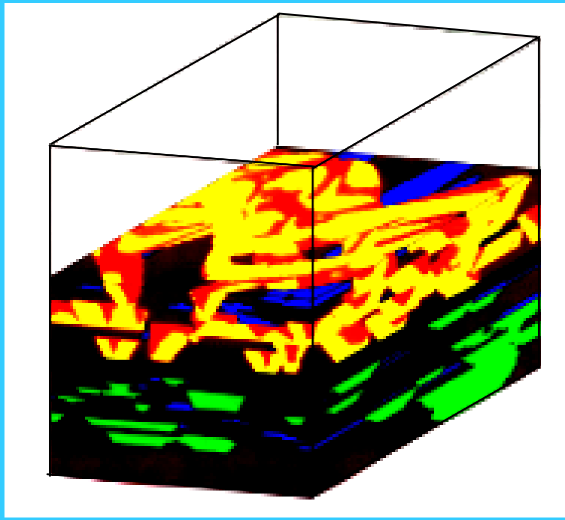
Lithology

Porosity

Permeability

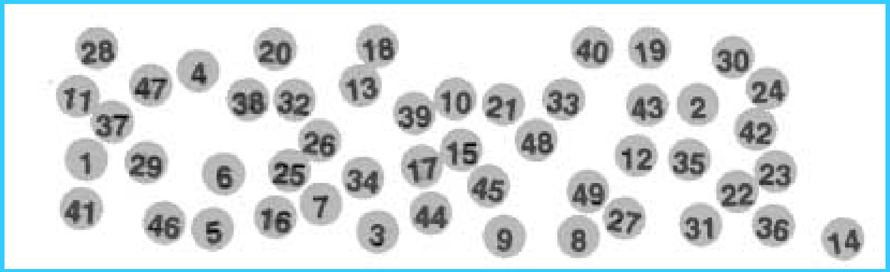
- Cell-based, stochastic, 3-D modeling of lithology, porosity and permeability in a sequential order
- Preserves major heterogeneities and statistical features
- Statistical control is obtained from cores, logs, seismic and outcrops

Object-Based Modeling



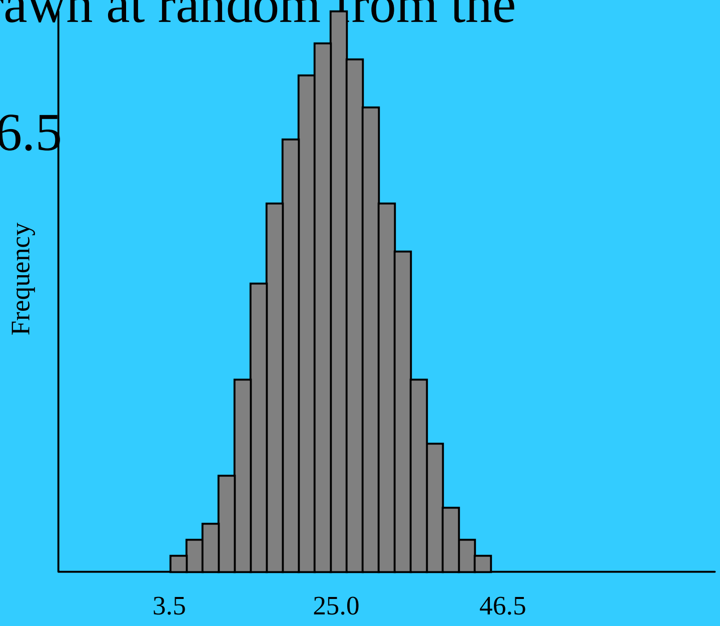
- Object-based, stochastic, 3-D modeling of well defined geometric objects
- Pseudo genetically simulate depositional history
- Statistical control is obtained from cores, logs, seismic and outcrops

Decision Making in the Face of Uncertainty

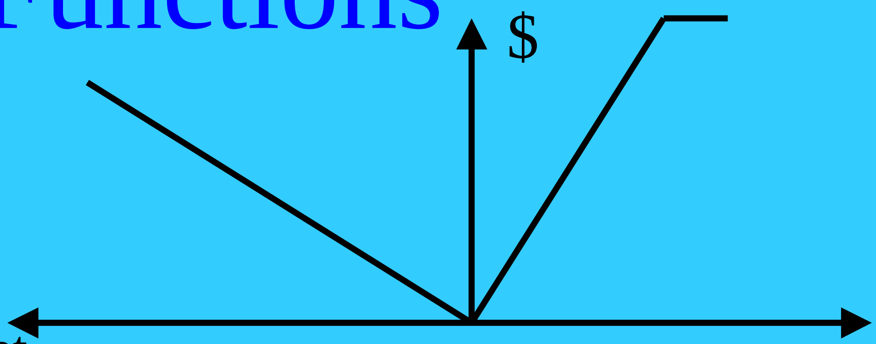


Given 49 balls numbered consecutively from 1 through 49, what is the **average** of the numbers showing on six balls drawn at random from the 49?

- The *honest* answer is somewhere from 3.5 to 46.5 (13,983,816 combinations)
- The *most likely* value is 25
- The *optimal* answer depends on two things:
  1. the uncertainty in the average, and
  2. the impact of making a mistake
- Stochastic simulation quantifies uncertainty⇒ in a distribution of uncertainty



Impact of Making a Mistake: Loss Functions



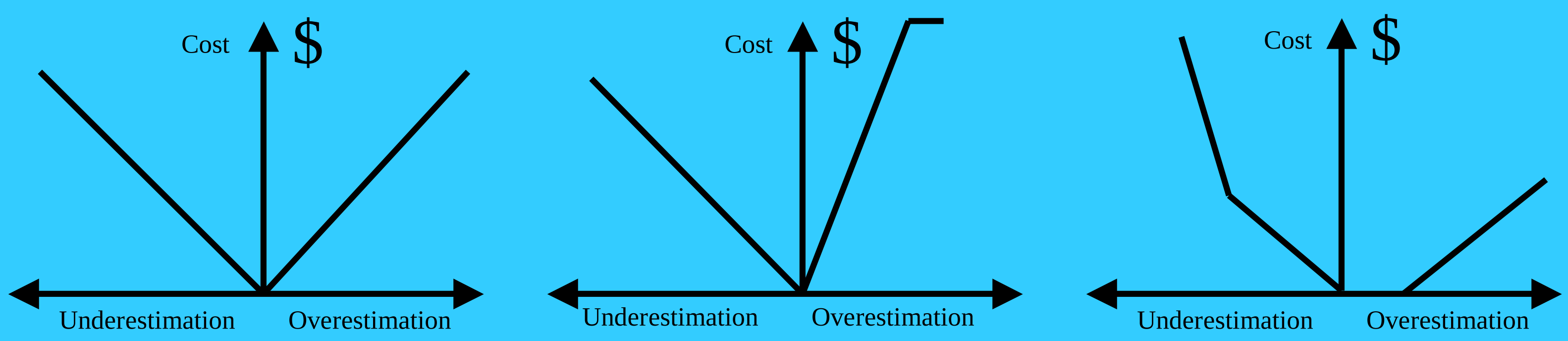
An Example Decision:

- Do we carry an umbrella?
  - Uncertainty: will it rain?
  - Impact of an underestimate: get wet
  - Impact of an overestimate: carry it around for nothing
- How tall should we design a dam?
  - Uncertainty: what is the largest rainfall in the lifetime of the dam?
  - Impact of an underestimate: failure of dam and loss of property
  - Impact of an overestimate: additional material and labor cost
- Do we clean a potentially contaminated site?
  - Uncertainty: what is the contaminant level?
  - Impact of an underestimate: insurance claims/lawsuits due to health problems
  - Impact of an overestimate: cost of unnecessary cleaning

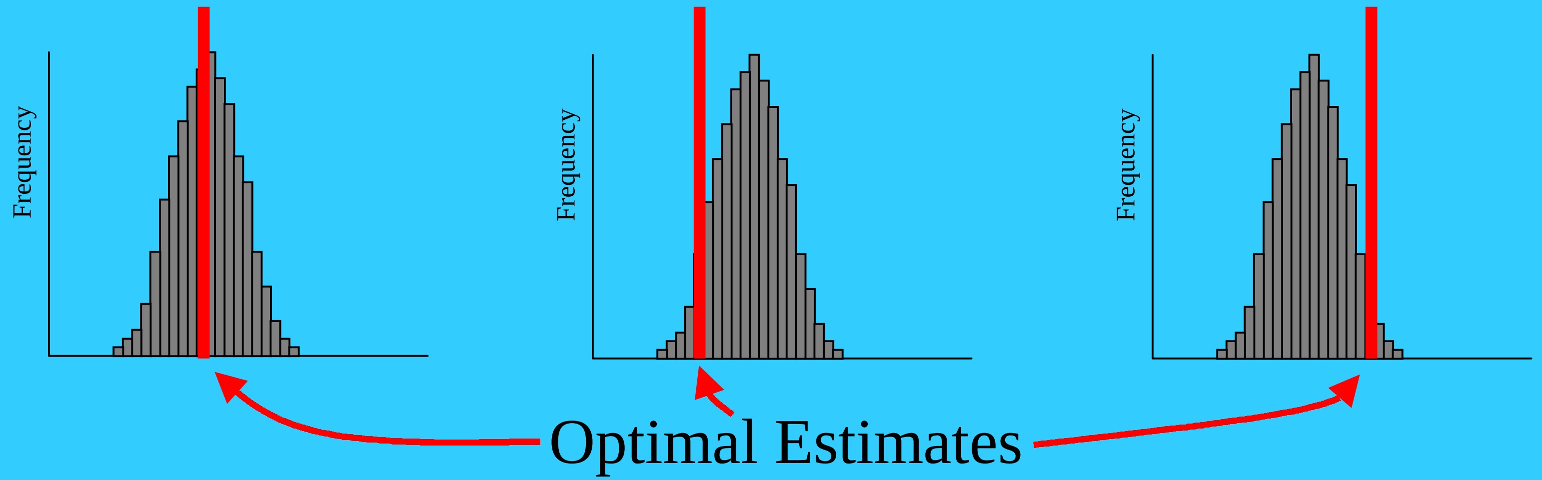
Optimal Estimates

(depend on the uncertainty and the impact of an mistake)

Loss function quantifies the impact of an mistake:



The distribution of uncertainty quantifies the uncertainty:

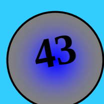


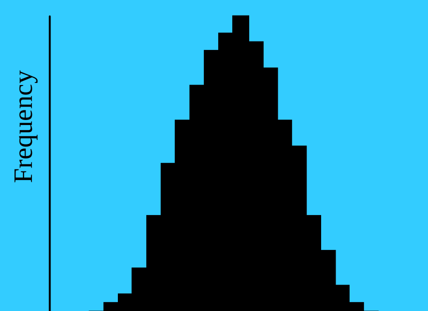
Uncertainty

(decreases as more data becomes available)

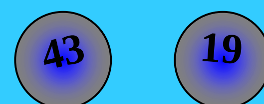
Returning to the previous example, what would be the **average** of six balls drawn from 49 balls, numbered 1 to 49?

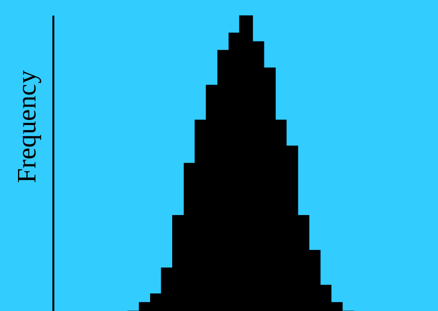
Knowing the outcome of one ball:



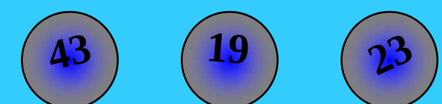


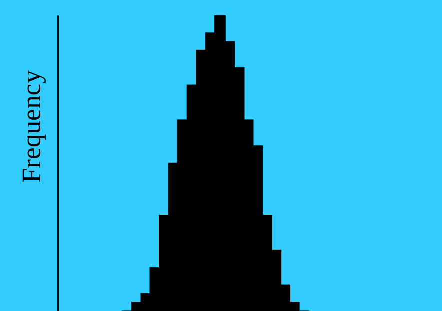
Knowing the outcome of two balls:





Knowing the outcome of three balls:





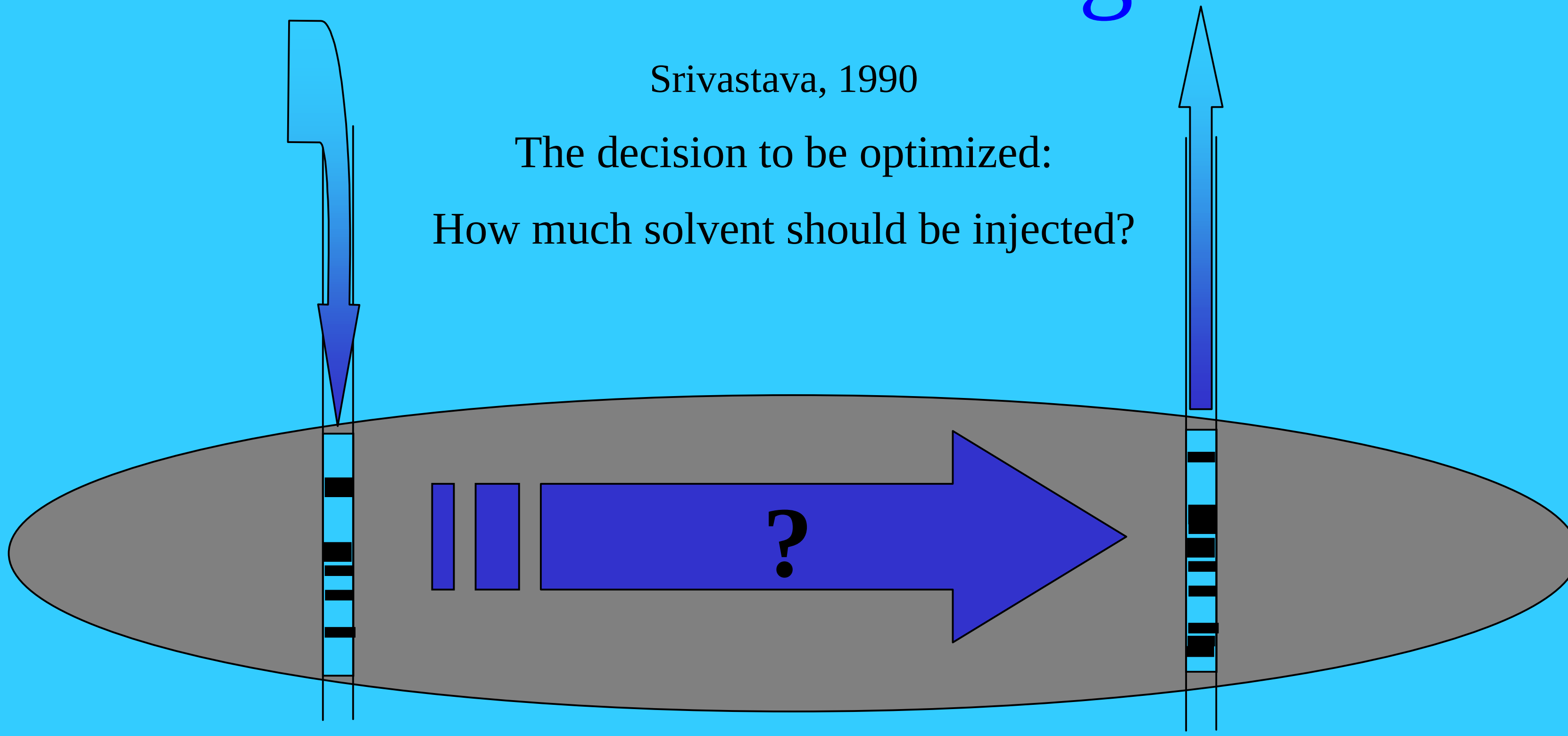
Note the decrease in uncertainty

An Application to Miscible Flood Design

Srivastava, 1990

The decision to be optimized:

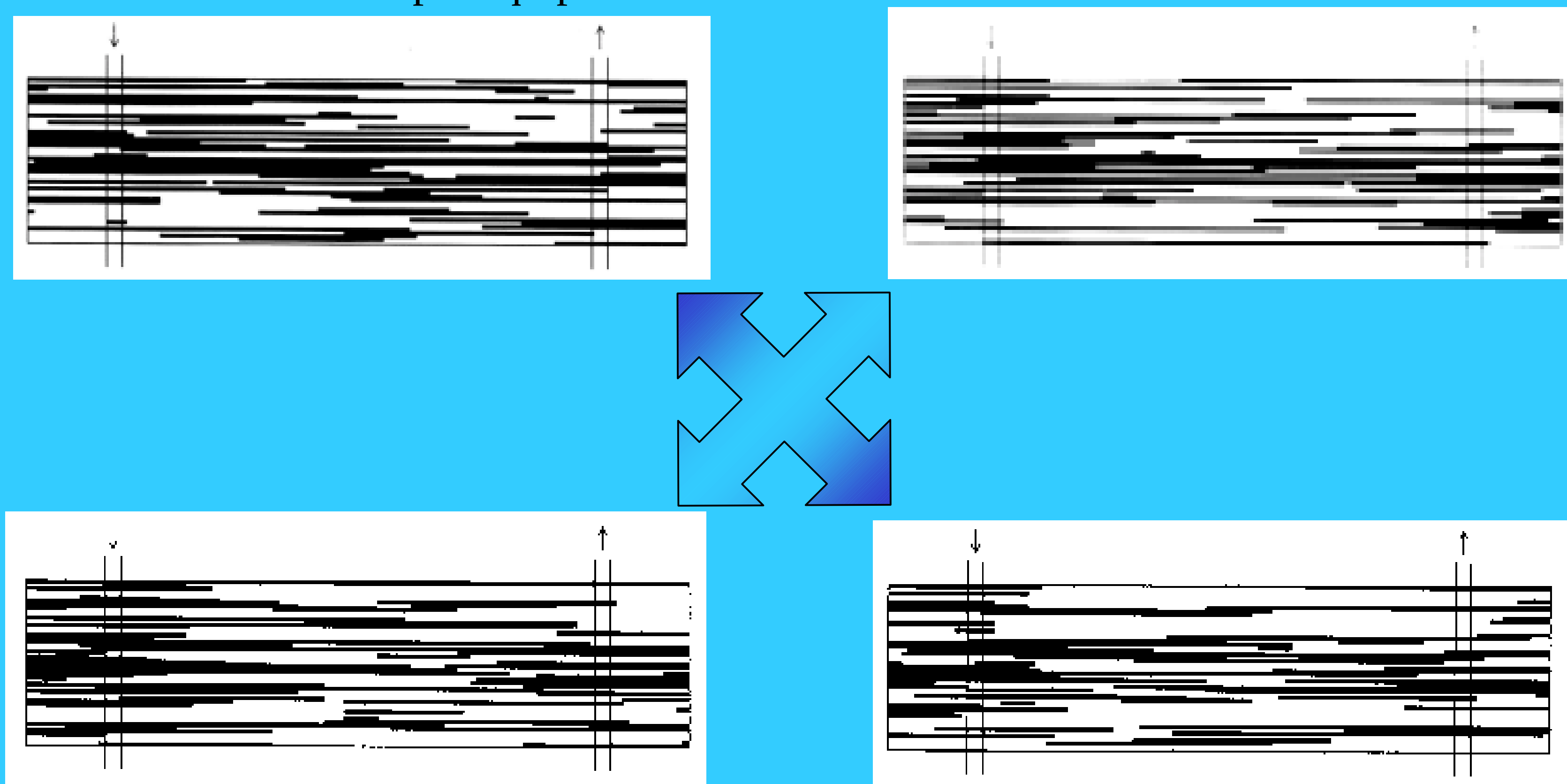
How much solvent should be injected?



- The answer depends on the connected pore volume.
- The uncertainty in the connected pore volume can be quantified with geostatistical simulation.
- The loss function is a function of the cost of solvent and the oil price.

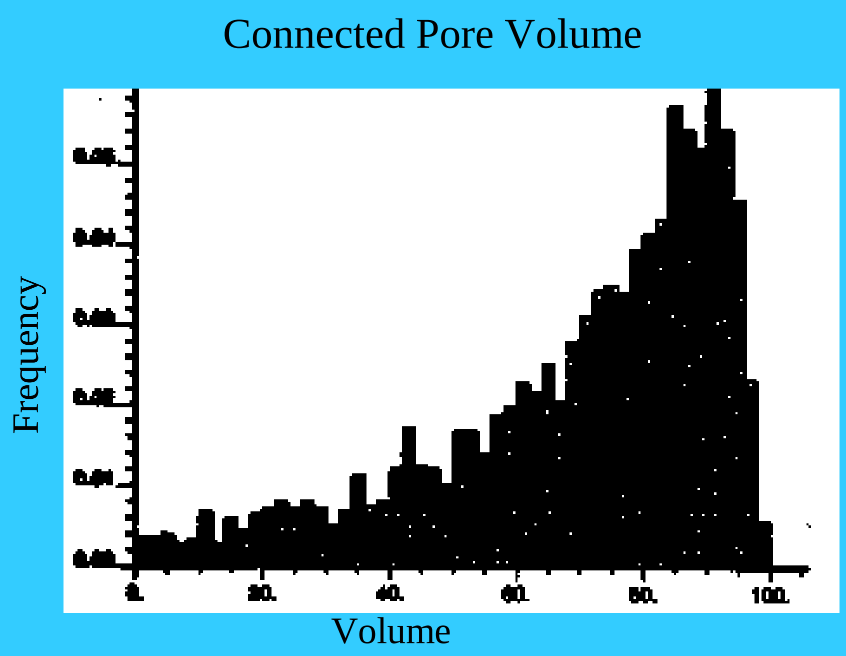
Geostatistical Simulation

Multiple equiprobable realizations of the reservoir



Uncertainty in Connected Pore Volume

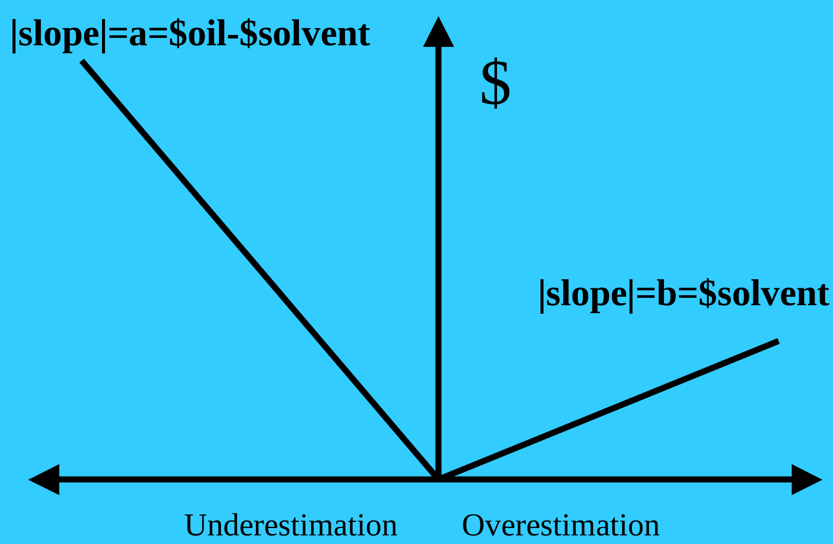
Running a random-walk sweep program on each geostatistical simulation realization provides a distribution of the connected pore volume:



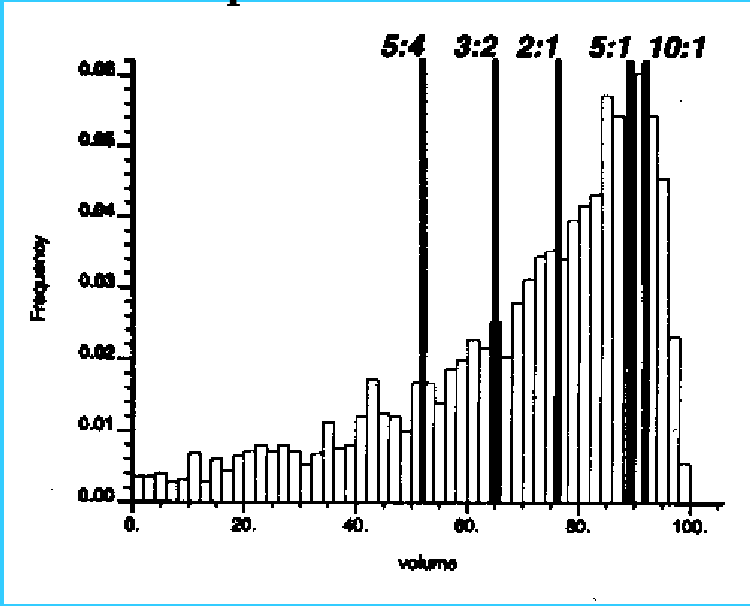
Now, apply loss function and compute how much solvent to inject

Decision Making in the Face of Uncertainty

Loss Function



Distribution of Uncertainty and Optimal Decisions



The optimal decision are indicated for various oil to solvent cost ratios.

Single answer integrates uncertainty and the impact of a mistake

Decision Making in the Face of Uncertainty

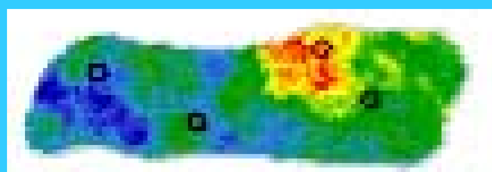
- Stochastic simulation is used to generate plausible realizations of what reality might be like
- Stochastic simulation is also used to *quantify* uncertainty
- Loss functions are appropriate for quantifying the impact of making a mistake
- Together, simulation and decision analysis tools, are appropriate for reservoir management
- This workshop will focus on stochastic simulation as applied to create plausible reservoir models

Stochastic Reservoir Modeling

A comparison between reality and a numerical model

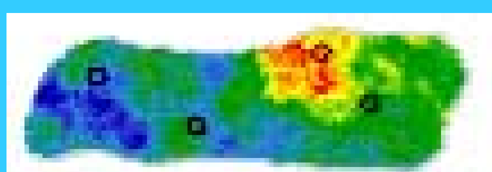
Reality

Distribution of Rock/Fluid Properties



single true distribution

Recovery Process



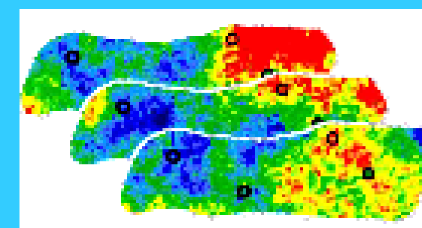
actual process implement

Field Response

Single true response

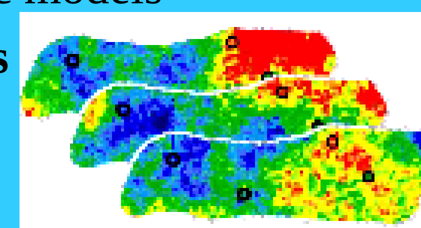
Model

Distribution of the Rock/Fluid Properties



multiple stochastic models

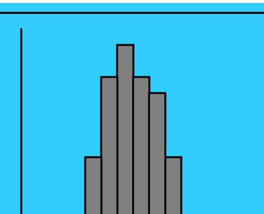
Recovery Process



numerical model

of process

Field Response



Distribution of possible responses

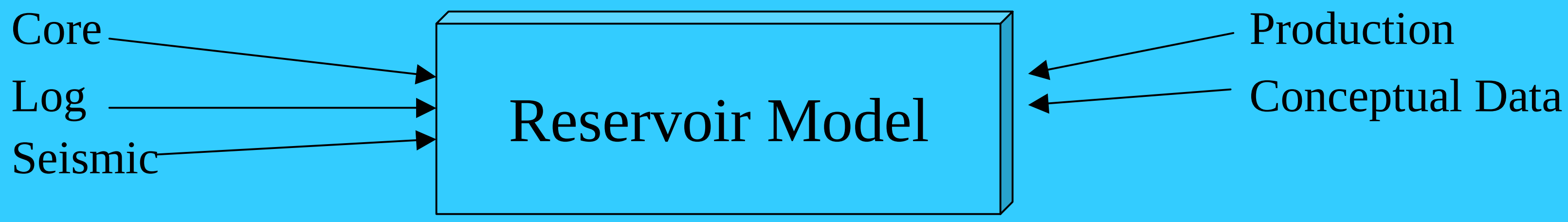
Constructing 3-D Models

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 data, and the spatial correlation
   c) Generate 3-D rock type model
   d) Establish porosity and permeability values and the spatial correlation
   e) Generate 3-D porosity models
   f) Generate 3-D permeability models
   g) Merge and translate back to real coordinates
4. Verify the model
5. Combine zones into a single model

Each of these steps is addressed to some extent in this workshop

Data for Reservoir Models



- **Core data** (ϕ and K by lithofacies)
- **Well log data** (stratigraphic surfaces, faults, measurements of petrophysical properties)
- **Seismic-derived structural data** (surface grids / faults)
- **Seismic-derived attributes** (vertically averaged facies proportions and ϕ)
- **Well test and production data** (interpreted K •thickness,channel widths, connected flow paths, barriers)
- **Sequence stratigraphic interpretation / layering** (a definition of the continuity and trends within each layer of the reservoir)
- **Spatial patterns** from regional geological interpretation
- **Analogue data** from outcrops or densely drilled similar fields (size distributions, measures of lateral continuity)
- **Knowledge of geological processes / principles** established through widely accepted theories (forward geologic modeling)

Recall of Geological Gridding (1)

- Triangular facets allow flexible modeling of surface grids and have some significant advantages:
  - handle multiple Z-valued surfaces
  - natural surface gridding for tetrahydra-based volume gridding
- In general, however, we prefer regular $n_x \bullet n_y$ Cartesian grids:
  - easier to work with cells that have the same volume
  - tetrahydra topology not commonly accepted by finite-difference scale-up and flow simulation programs
  - most visualization and mapping programs have been designed for either corner-point or block-centered Cartesian grids.

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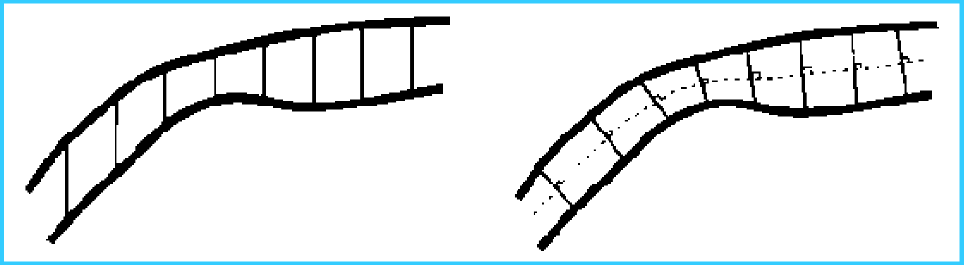
Recall of Geological Gridding (2)

•Also prefer a vertical Z coordinate, i.e.,



Two approaches to establish areal gridding: (1) on the left, the cells/nodes are stacked vertically, and (2) on the right, the cells/nodes are aligned on lines perpendicular to the bounding surfaces. The first approach, with a universal vertical coordinate, is preferred because of computational simplicity.

- Work within "stratigraphic layers" defined on the basis of:
  - sequence stratigraphic zonation
  - keep geologically "homogeneous" rock together
  - maintain a reasonable number of data per zone
  - less resolution outside the volume of interest

Stratigraphic Layers for Modeling(1)

- One example using top surface as datum (total vertical extent about 200 meters, horizontal extent about 15 kilometers):

Surface Type:

E (onlap)

D (truncation)
D7 (proportional)
D6 (truncation)
D5 (proportional)
D4 (proportional)
D2 (proportional)
D1 (onlap)

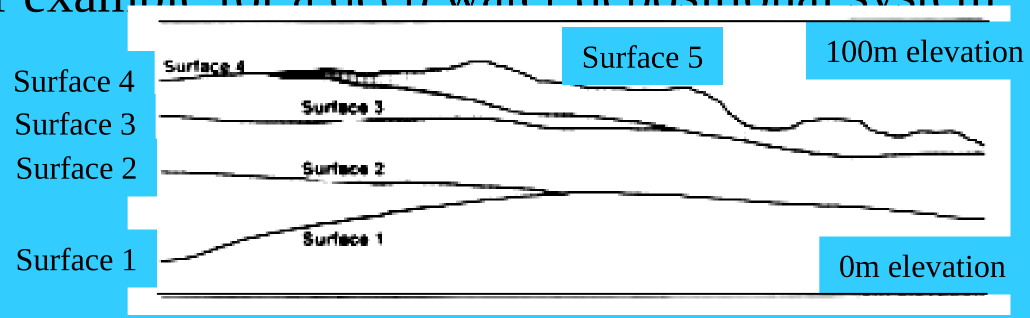
C (truncation)

C3 (onlap)

B (proportional)

Stratigraphic Layers for Modeling(2)

- Another example for a deep water depositional system:

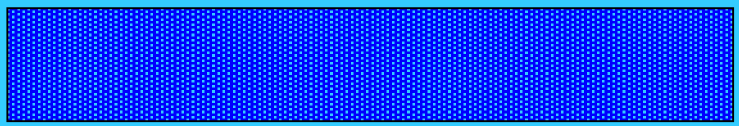


- Another example:

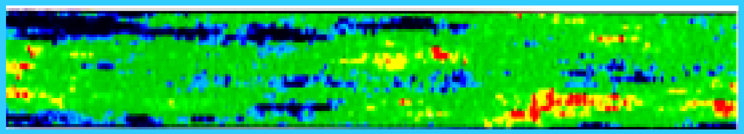
Stratigraphic Coordinates in Presence of a Fault

Pre-disturbance Stratigraphic Space

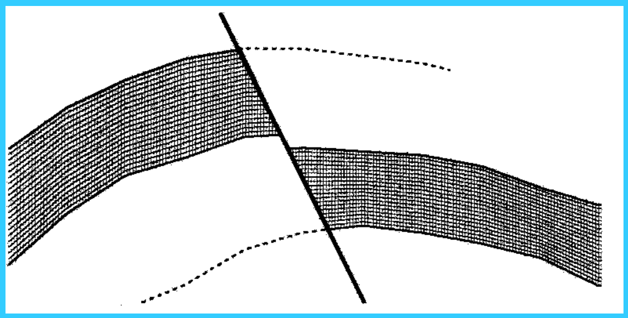
Grid

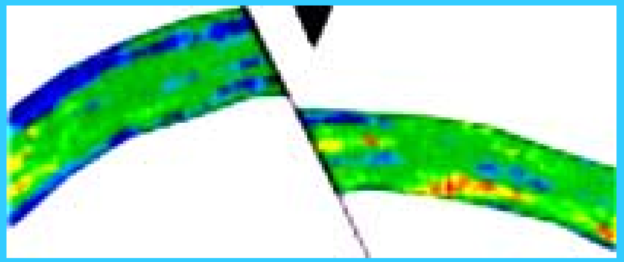


Model



Post-disturbance Stratigraphic Space





Grid translations may be applied to “remove” faults and tilting in order to work in the predisturbance stratigraphic setting.

Advantages of Geostatistics

- Intellectual integrity (?) Mathematical consistency (?)
- 3-D models lead to better volumetrics
- Better modeling of heterogeneity
  - no need for pseudo wells
  - controllable degree of spatial variability
  - flow models are more reliable
- Framework to integrate data
  - geological interpretation
  - core and log data
  - seismic data
  - production data
- Assessment of uncertainty in process performance due to uncertainty in geological model