PGE 338 Data Analytics and Geostatistics

Lecture 15: Facies Simualtion

Lecture outline . . .

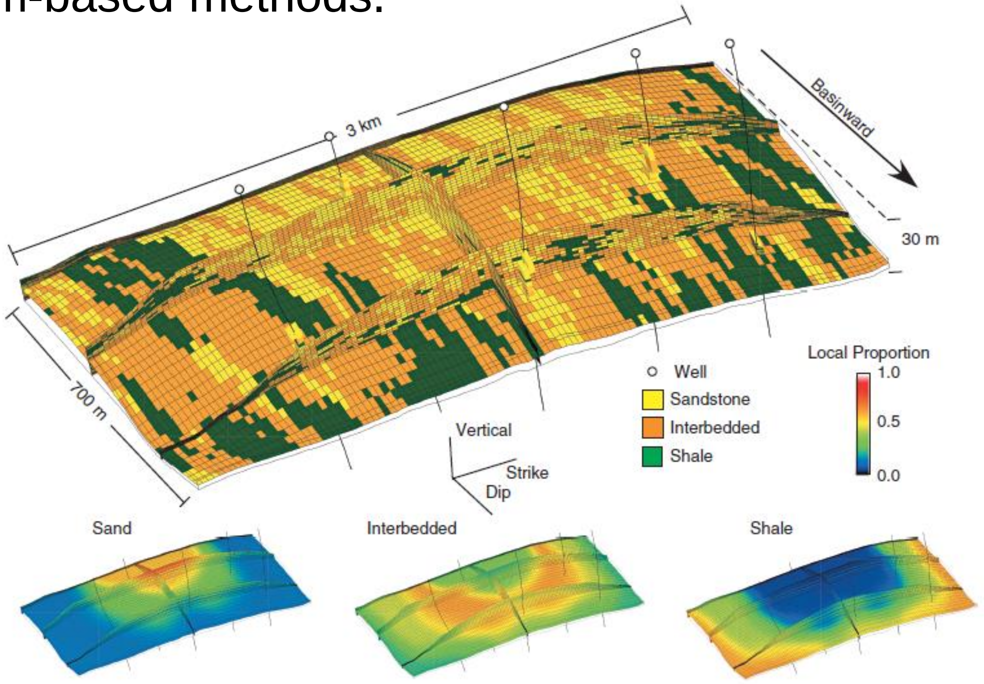
- Facies
- Multiple-point Simulation
- Object-based Simulation

Michael Pyrcz, The University of Texas at Austin

Motivation

Facies modeling is important. Awareness.

- The most important reservoir heterogeneity is captured with facies models.
- There are other, non-variogram-based methods.



Example of a categorical facies model by multiple point simulation.

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Lecture 15: Facies Simualtion

Lecture outline . . .

- Facies

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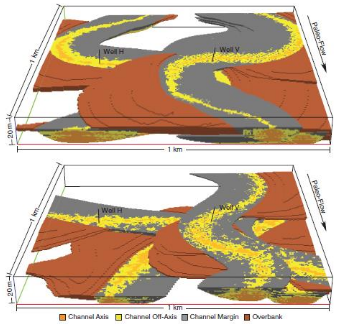
The Subsurface Modeling Workflow

Facies Categorical, Porosity Continuous then Permeability Cosimulation – here's Some Context!

Categorical Simulation

Models Facies PDF, Trends and Spatial Continuity

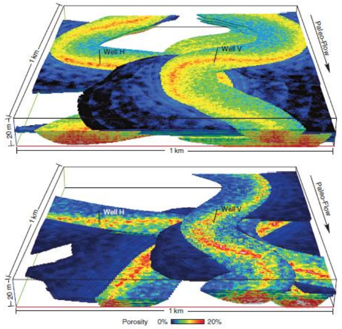
Multiple Facies Realizations



Continuous Simulation

Models Porosity PDF, Trends and Spatial Continuity within each facies

Multiple Porosity By-facies Realizations

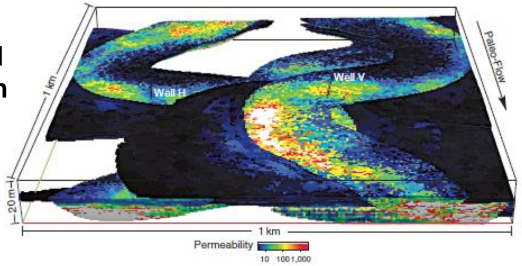


Continuous Cosimulation

Models Permeability PDF, Trends and Spatial Continuity and Porosity Relationship within each facies

Multiple Permeability By-facies Realizations Correlated with Porosity

Note: only had 1 realization on hand (should be two in figure).

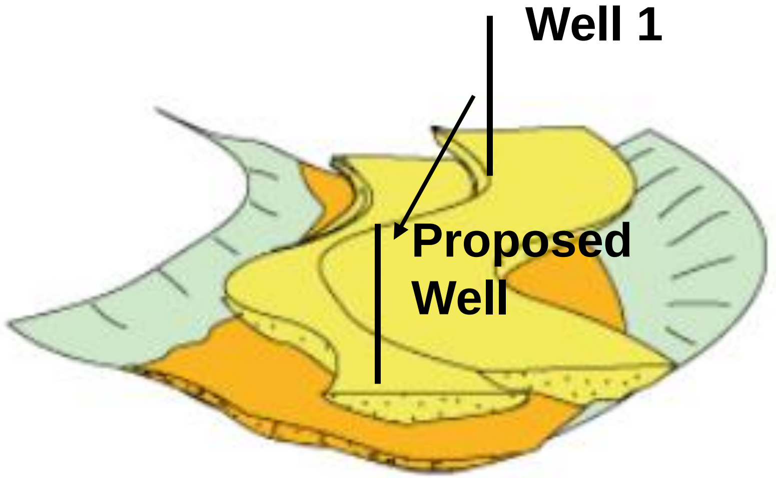


Reservoir modeling workflow with categorical facies modeling followed by continuous porosity and permeability modeling.

Facies Definition

What Are Facies?

- Grouping rock into discrete groups, a new categorical feature.
- Method to categorize rock in a useful manner that aids:
  - characterization through statistics, e.g. distributions and variograms
  - Prediction of features, e.g. porosity and permeability away from wells



Channel faceis model to assist with well location selection.

Figure modified from Kendall and Haughton (2008).

Facies Definition

What Are Facies?

Different types depending on the scale and modeling goals

1. **Lithofacies** – small scale porosity and permeability clusters and sedimentary structures

- E.g. shale, sandstone, dolomite, limestone, laminated sandstone, hummocky cross stratification.

Tabular mudstone, sandstone (red) and gypsum (white) layers of Permian redbeds, Caprook Canyons State Park, Texas.

Hummocky cross-stratification, Eocene Coaledo Formation, Oregon.

Triasic turbidite parallel liminated sandstone, Karoo Basin, South Africa (Hansen et al., 2019).

https://geologypics.com/hummocky-cross-stratification/

https://gjmnaturemedia.com/permian-redbeds-with-alternating-gypsum-layers/

https://www.frontiersin.org/articles/10.3389/feart.2019.00012/full

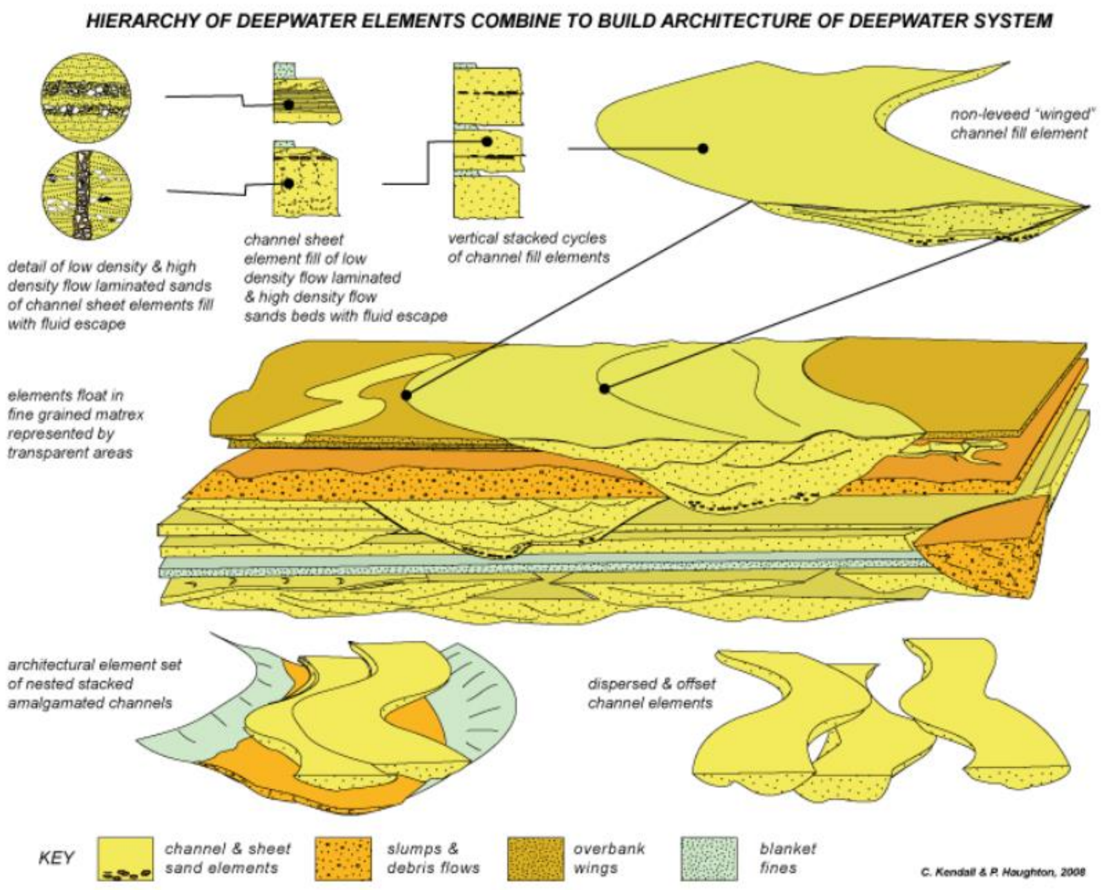
Facies Definition

What Are Facies?

Different types depending on the scale and modeling goals

2. **Depofacies** – mixtures of lithofacies and consideration for 3D shape and geometry away from the wells, reservoir flow units

- Integrated as the reservoir significant scale, impacts reservoir flow, well connectivity.
- E.g. channel axis, outer sheet



Depofaceis for deepwater reservoirs (Kendall and Haughton, 2008)

Facies Definition

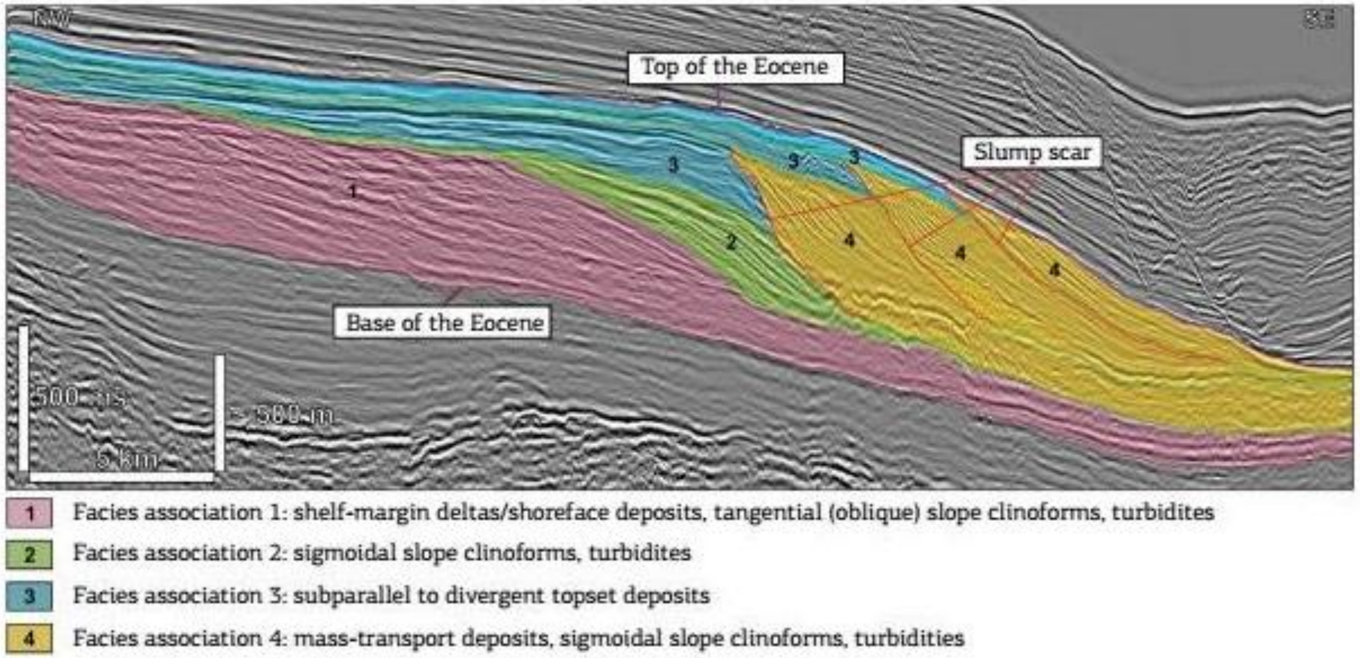
What Are Facies?

Different types depending on the scale and modeling goals

3. **Seismic Facies** – large-scale distinct acoustic and elastic property and seismic geomorphological expressions

- Integrated as the large-scale reservoir framework

- E.g., parallel continuous high amplitude, chaotic amplitudes, mounded discontinuous low amplitudes, truncation, onlap, offlap



Prograding shelf of Santos Basin, Brazil

Image from https://wiki.seg.org/wiki/File:Prograding_Shelf_in_Santos_Basin_Brazil.jpg

Facies and Facies Simulation

First some general comments:

1. **Facies / Rock type** is an important decision for subsurface modeling. It should remain a collaborative decision integrating expertise from the project team (Geologists, Reservoir Modelers, Reservoir Engineers, Petro- and Geophysicists).

2. Facies / Rock types **must improve subsurface prediction** away from the data or they do not add value.

3. **Number of facies** is a balancing act between accuracy of geological concepts and statistical inference, and modeling effort

Facies and Facies Simulation

First some general comments:

4. Reservoir modeling is often **hierarchical**,
   - units *contain* depofacies *contain* lithofacies *contain* por/perm

5. 80-90% of **flow heterogeneity** is captured in the facies models.

6. Three main approaches to simulate reservoir facies are:

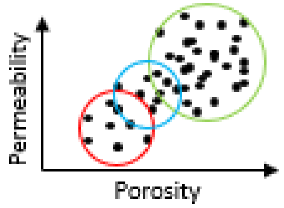
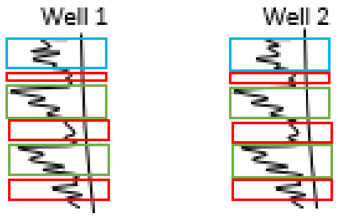
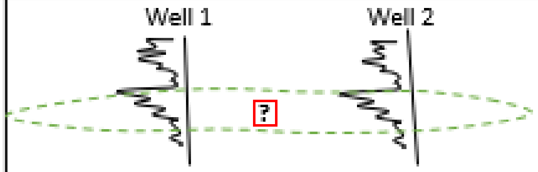
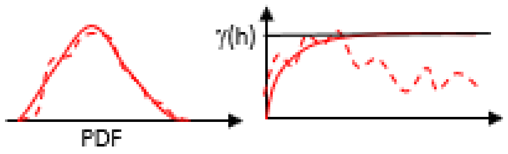
i. Variogram-based, sequential indicator simulation

ii. Image-based, multiple point simulation

iii. Object-based

What are the Criteria for Facies?

These are the **criteria for facies** (or any categories in reservoir models).

Criteria	Considerations	Example
Separation of Rock Properties	Facies must divide the properties of interest that impact subsurface environmental and economic performance (e.g. grade, porosity and permeability).	
Identifiable in Data	Facies must be identifiable with the most common data available. e.g. facies identifiable only in cores are not useful if most wells have only logs.	
Map-able Away from Data	Facies must be easier to predict away from data than the rock properties of interest directly, facies improves prediction.	
Sufficient Sampling	There must be enough data to allow for reliable inference of reliable statistics for rock properties for each facies.	

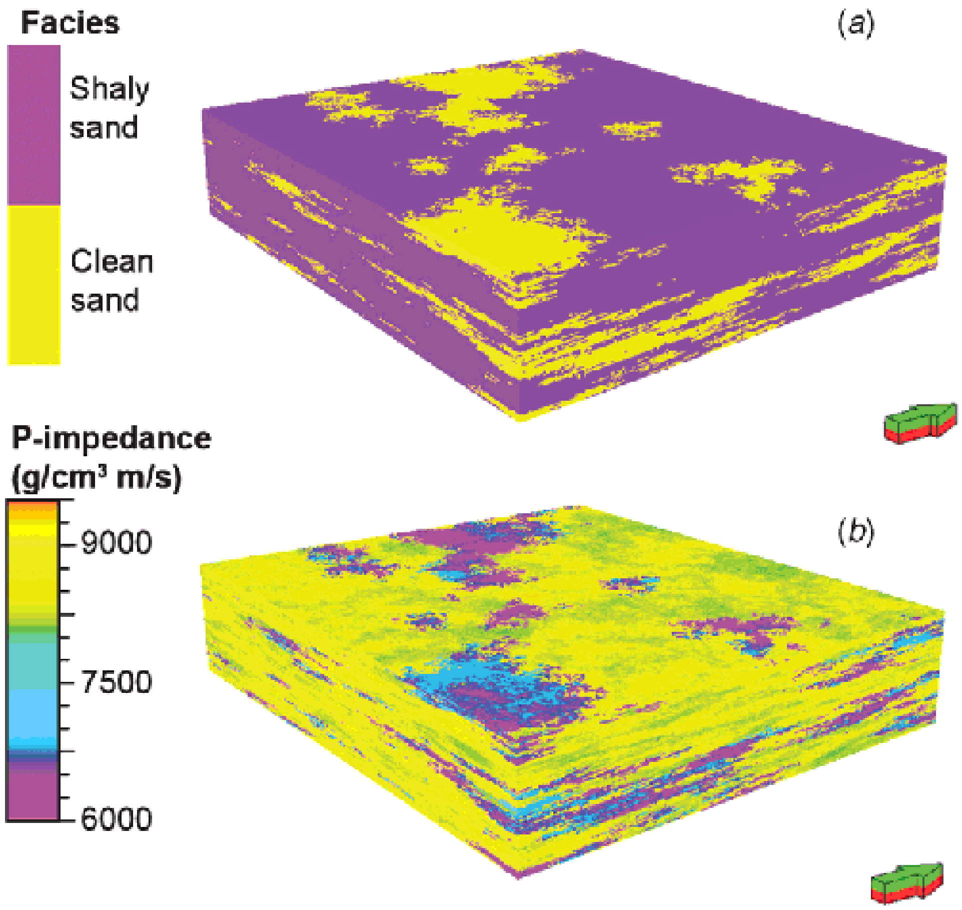
Dr. Pyrcz's criteria for selecting facies for a subsurface model.

Facies Model Examples

Categorical indicator simulation

Variogram-based, 2 point statistics

- captures only linear spatial structures
- does not capture facies ordering relationships, e.g., facies 1 only contacts facies 2 and not facies 3



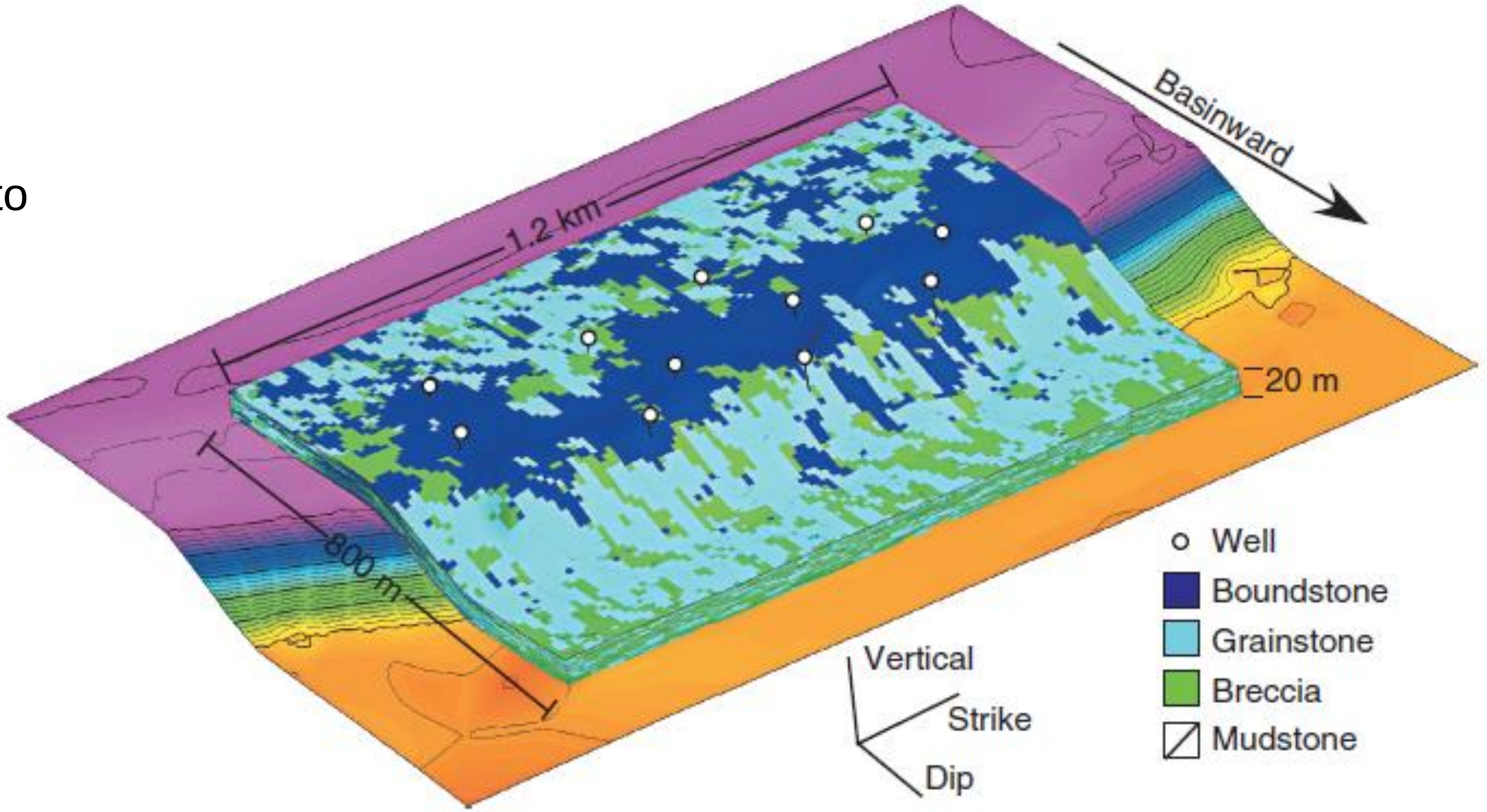
Categorical indicator simulation and sequential Gaussian simulation by-facies (Niri, Lumley, 2015).

Image from https://www.publish.csiro.au/EG/fulltext/EG15013

Facies Model Examples

Categorical indicator simulation

- May use a trend model
- Locally variable facies proportions to impose trends and 'facies ordering'

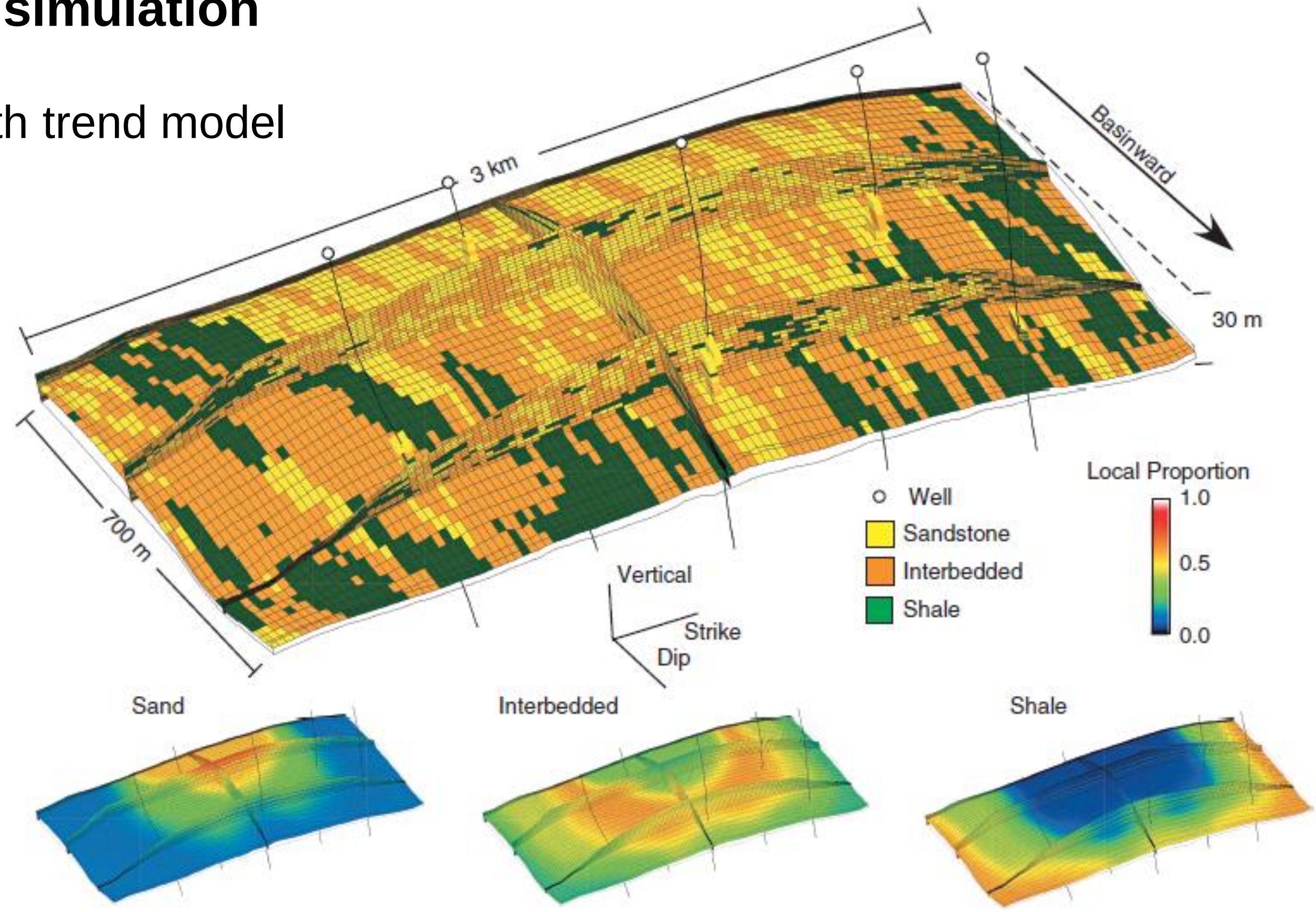


Categorical carbonate reservoir facies indicator simulation with locally variable proportions (Pyrcz and Deutsch 2014).

Facies Model Examples

Categorical indicator simulation

- Indicator simulation with trend model shown.

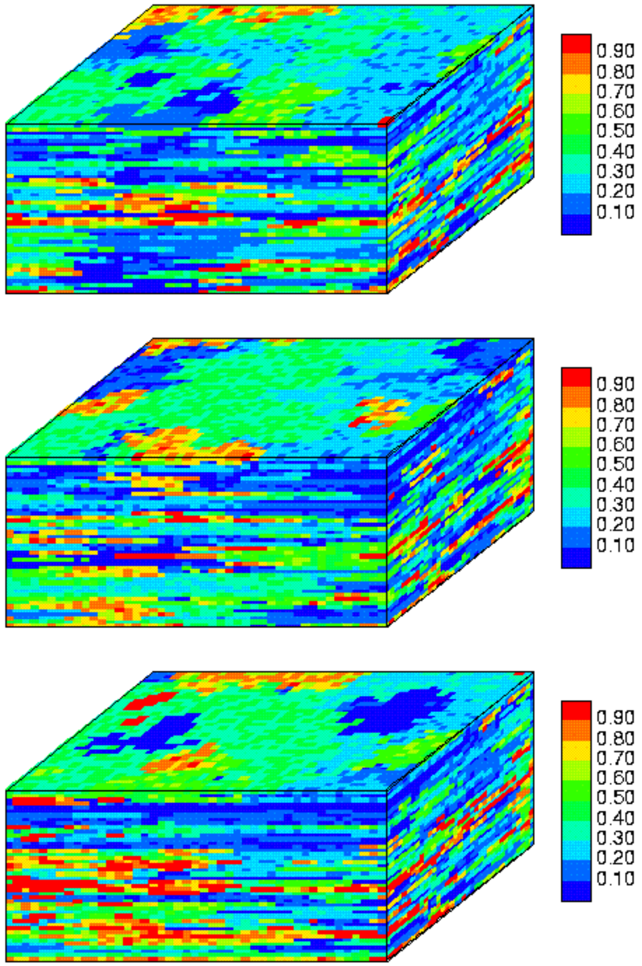


Categorical clastic deltaic reservoir facies indicator simulation with locally variable proportions (Pyrcz and Deutsch 2014).

Facies Model Examples

Continuous indicator simulation

- See the discontinuity across the continuous thresholds?
- Likely 0.7, 0.5, 0.3 and 0.1 were used as thresholds (my estimate from ocular inspection).



Three faction of shale continuous indicator simulations (Meehan and Verma, 1994).

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Lecture outline . . .

- Multiple-point Simulation

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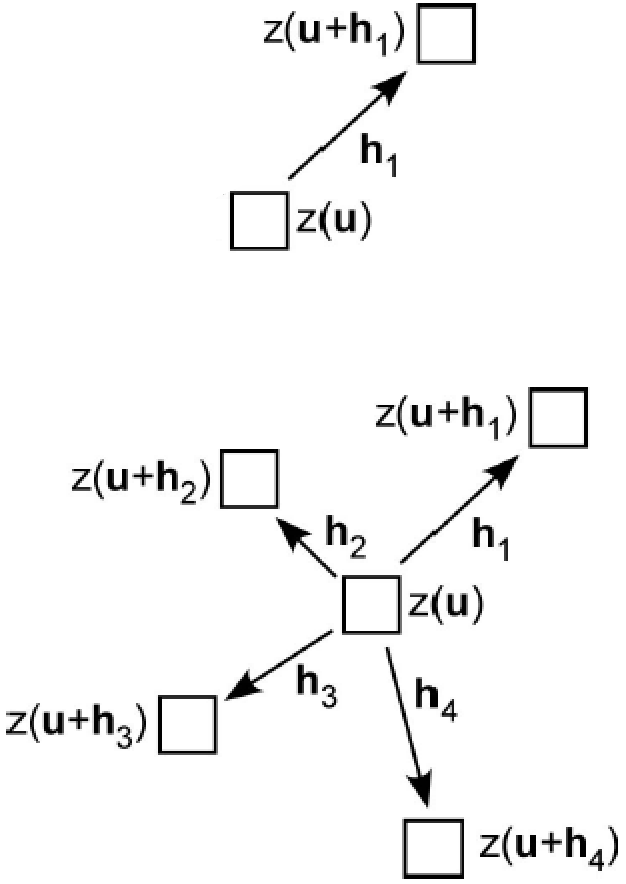
Multiple Point Simulation (MPS)

Multiple Point Simulation (MPS)

The concept of a variogram may be extended to > two points.



Variogram (above) vs. multiple point template (below) (Pyrcz and Deutsch, 2014).

Only practical for:

- categorical variables
- limited number of points

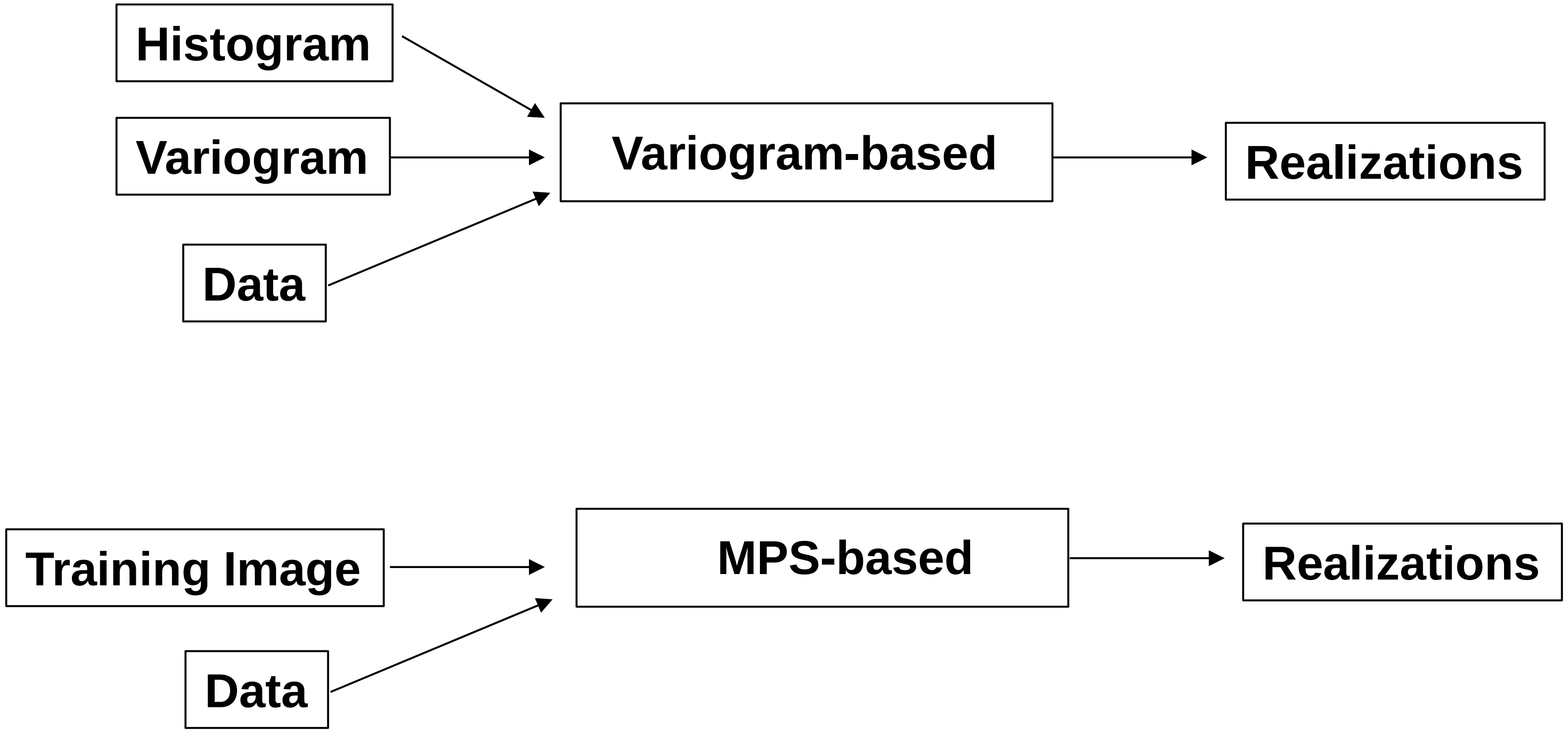
$$P\{Z(\mathbf{u}) = z_k \mid d_n\} = \frac{P\{\, Z(\mathbf{u}) = z_k \,,\, Z(\mathbf{u} + \mathbf{h}_1) = z_{k1} ,\ldots,\, Z(\mathbf{u} + \mathbf{h}_n) = z_{kn} \,\}}{P\{\, Z(\mathbf{u} + \mathbf{h}_1) = z_{k1} ,\ldots,\, Z(\mathbf{u} + \mathbf{h}_n) = z_{kn} \,\}}$$

- still not practical to calculate from data.
- paradigm shift, design a training image and borrow spatial statistics from the training image
  - **image reproduction vs. statistical analysis of data**

Multiple Point Simulation (MPS)

Variogram-based vs MPS Inputs and Outputs

Spatial continuity model is from an image! We are now doing image reproduction.



Subsurface model inputs and outputs for variogram-based (above) and MPS (below).

Multiple Point Simulation (MPS)

Example of Calculating a Multiple Point Statistic

Set of conditional probabilities

- Frequentist approach by scanning the training image with a data template,

$$Z(\mathbf{u} + \mathbf{h}_1) = z_{k1}, \ldots, Z(\mathbf{u} + \mathbf{h}_n) = z_{kn}$$

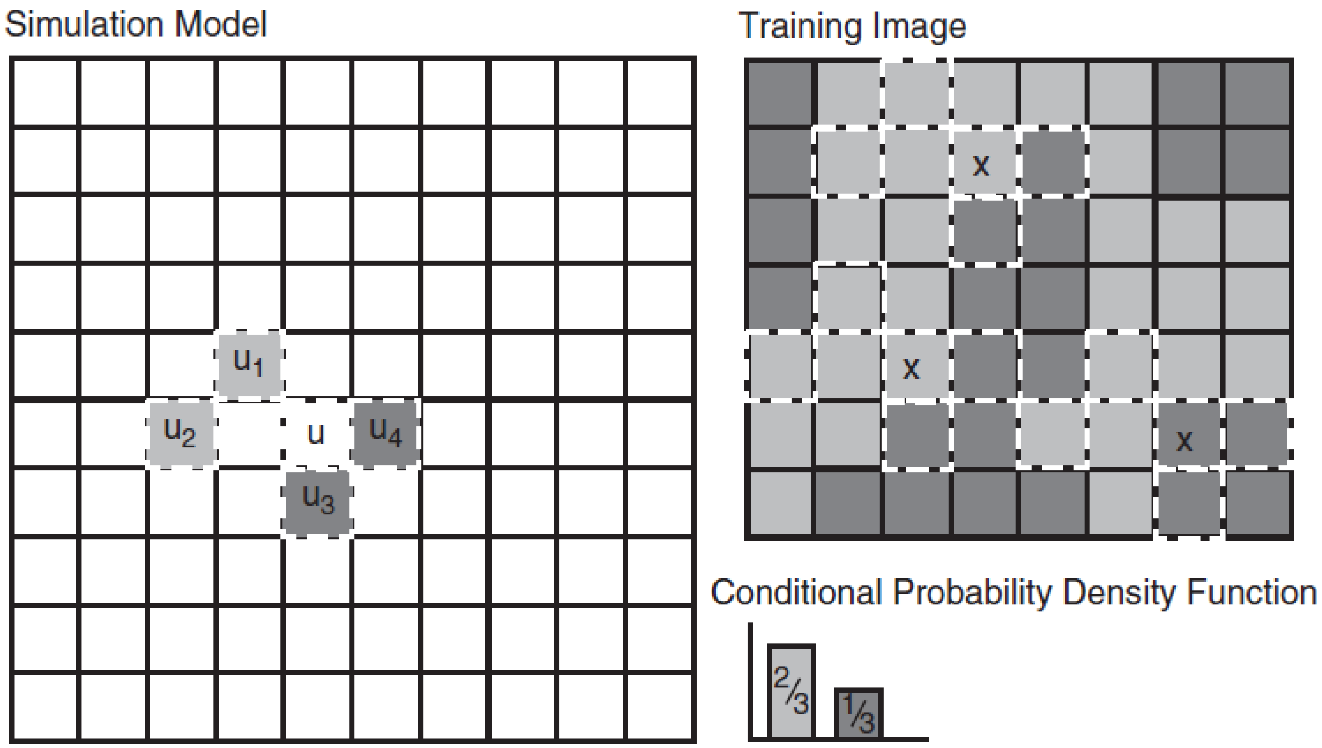


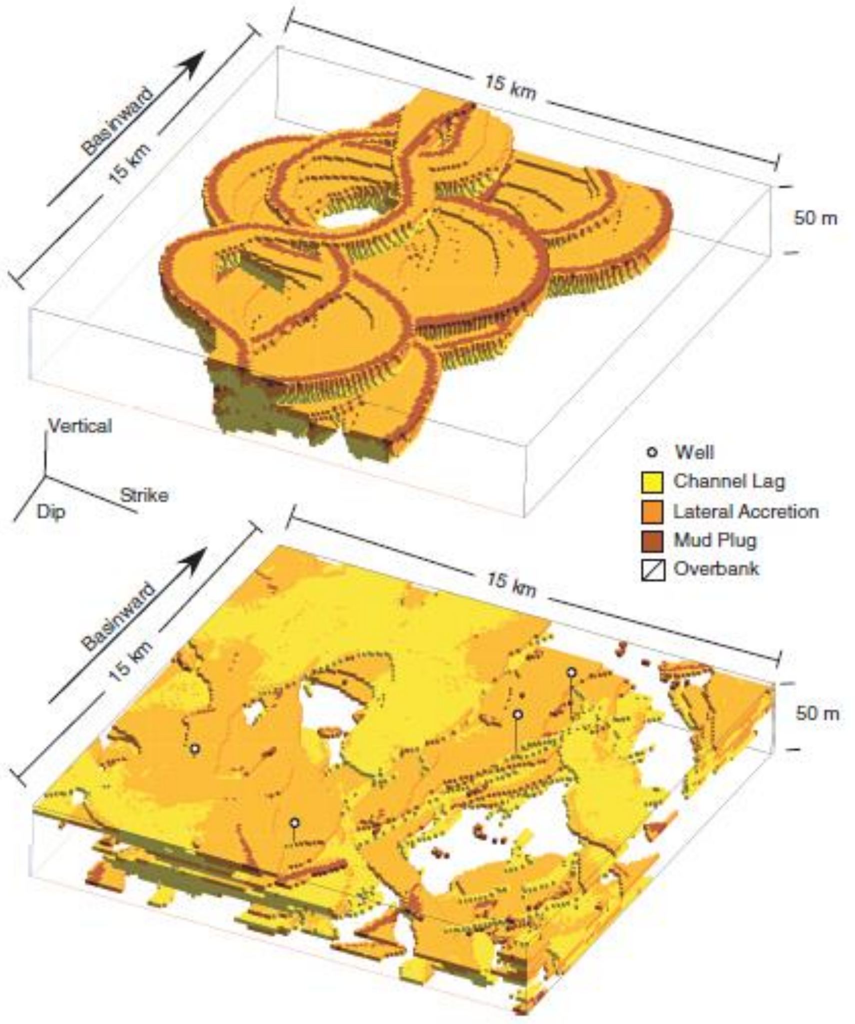
FIGURE 4.30: Simulation at Location **u** Given Four Points in a Local Search Neighborhood. The conditional probability is sampled by scanning the training image for the frequencies of facies at location **u** divided by the total number of occurrences. In this case, $\frac{2}{3}$ for light gray and $\frac{1}{3}$ for dark gray.

MPS conditional probabilities by frequencies (Pyrcz and Deutsch, 2014).

Multiple Point Simulation (MPS)

Training Image

1. Unconditional
   – No data constraints
2. Stationary
   – Nonstationary with auxiliary variables? Multiple training images?
3. Regular Grid
   – Same as any cell-based
4. No Location Information
   – Box in space, not georeferenced
5. Only Simulated Categories
   – Must be consistent

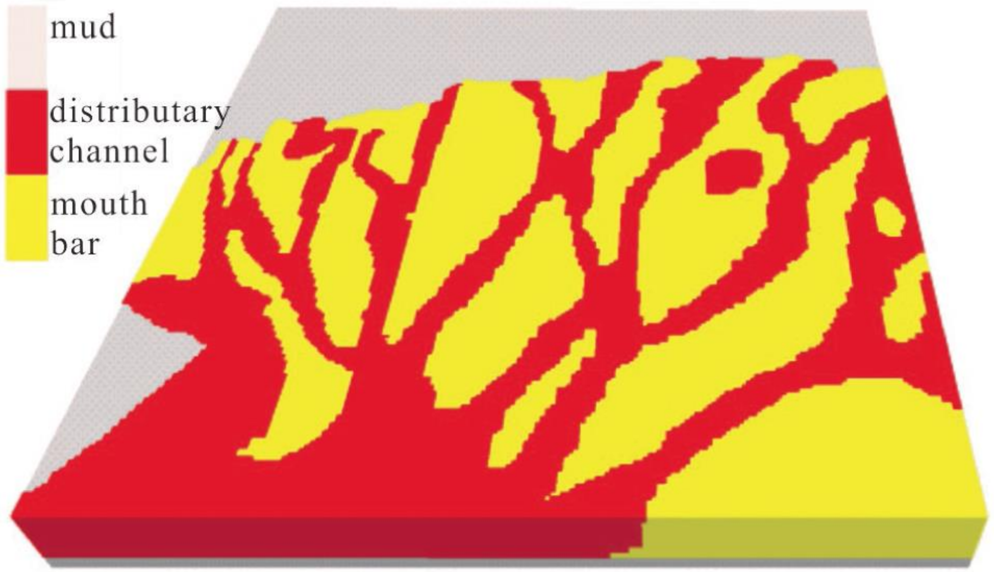


Impact of nonstationary training image + stationary simulation (Pyrcz and Deutsch, 2014).

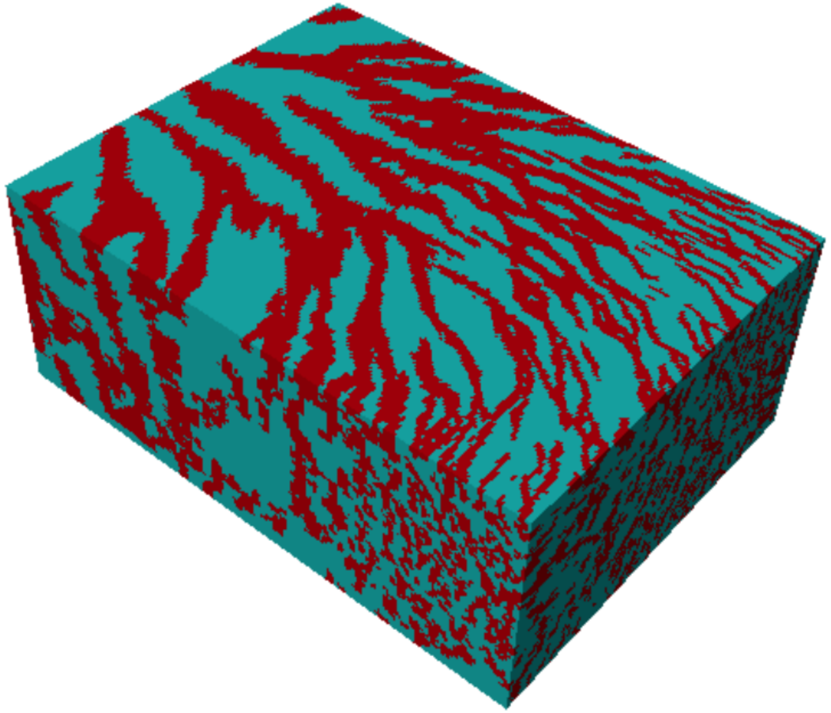
Multiple Point Simulation (MPS)

MPS Examples

- MPS simulation with non-linear spatial structure
- Locally variable azimuth model by rotating the training image at each location.



Three facies delta multiple point simulation (yin and Feng, 2017).

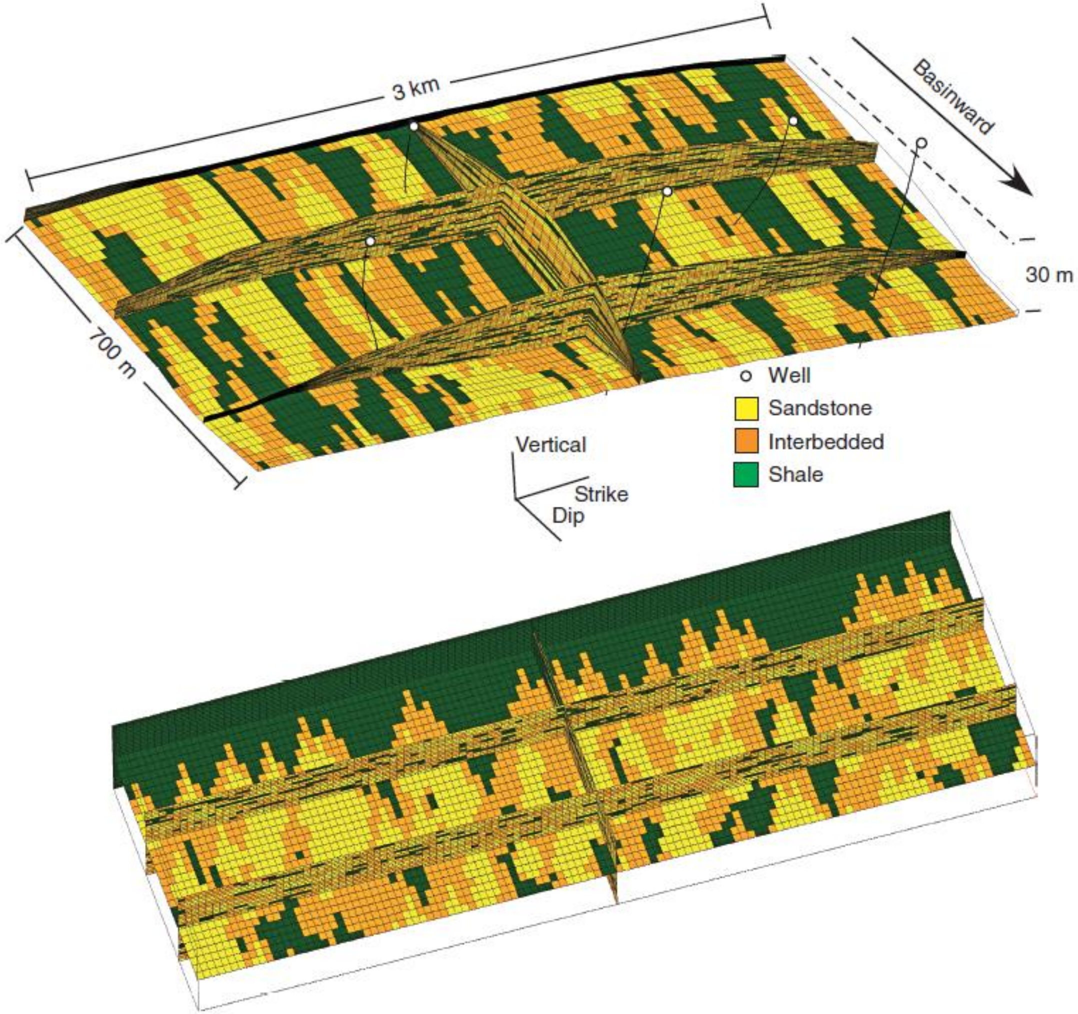


Two facies, channel and overbank multiple point simulation and locally variable azimuth (Zhang, 2008).

Multiple Point Simulation (MPS)

MPS Example

- MPS for a deltaic depositional setting
- Training image



Example of MPS simulation, training image is below (Pyrcz and Deutsch, 2014).

Multiple Point Simulation (MPS)

MPS Example

- MPS for a deltaic depositional setting
- Training image
- Locally variable scale
- Locally variable azimuth

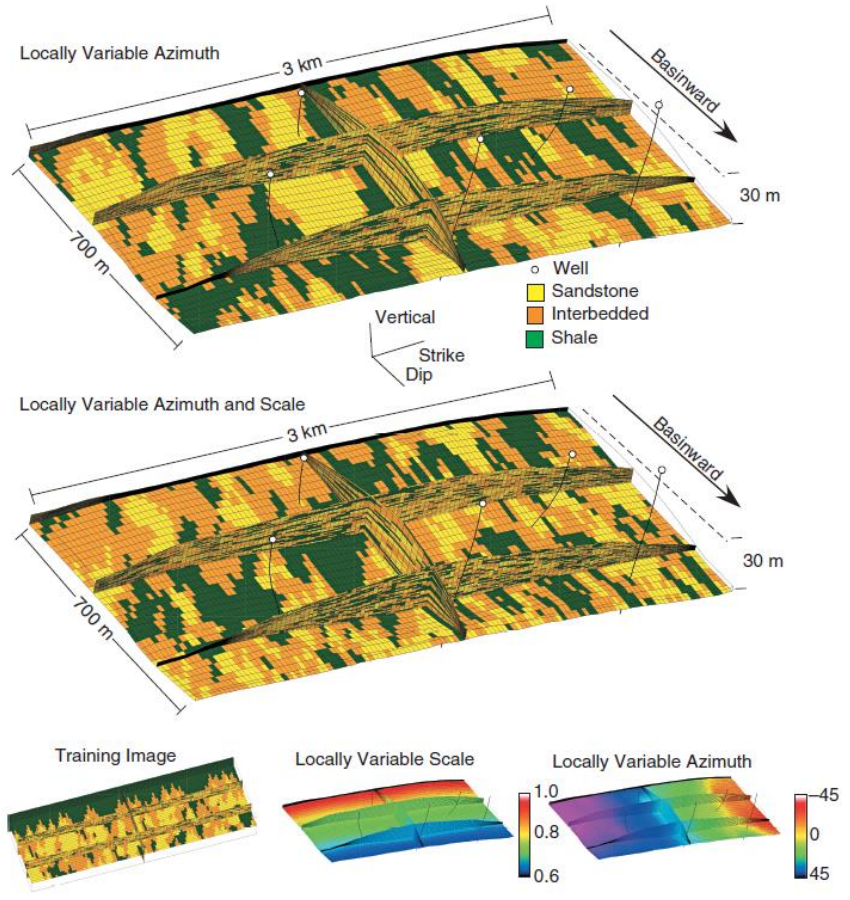


FIGURE 4.33: Single Realization of the Delta Reservoir Simulated with MPS with the Indicated Training Image, Wells, and Locally Variable Azimuth (Upper) and Locally Variable Azimuth and Scale (Lower). Note the distributary pattern and the decrease in lobes size distally. Compare to the same model constructed with MPS and without locally variable constraints in Figure 4.29.

Example of MPS simulation with locally variable azimuth and scale (Pyrcz and Deutsch, 2014).

Multiple Point Simulation (MPS)

MPS Example

- MPS for a deltaic depositional setting
- Training image
- Locally variable / nonstationary scale
- Locally variable / nonstationary azimuth
- Locally variable / nonstationary facies proportions

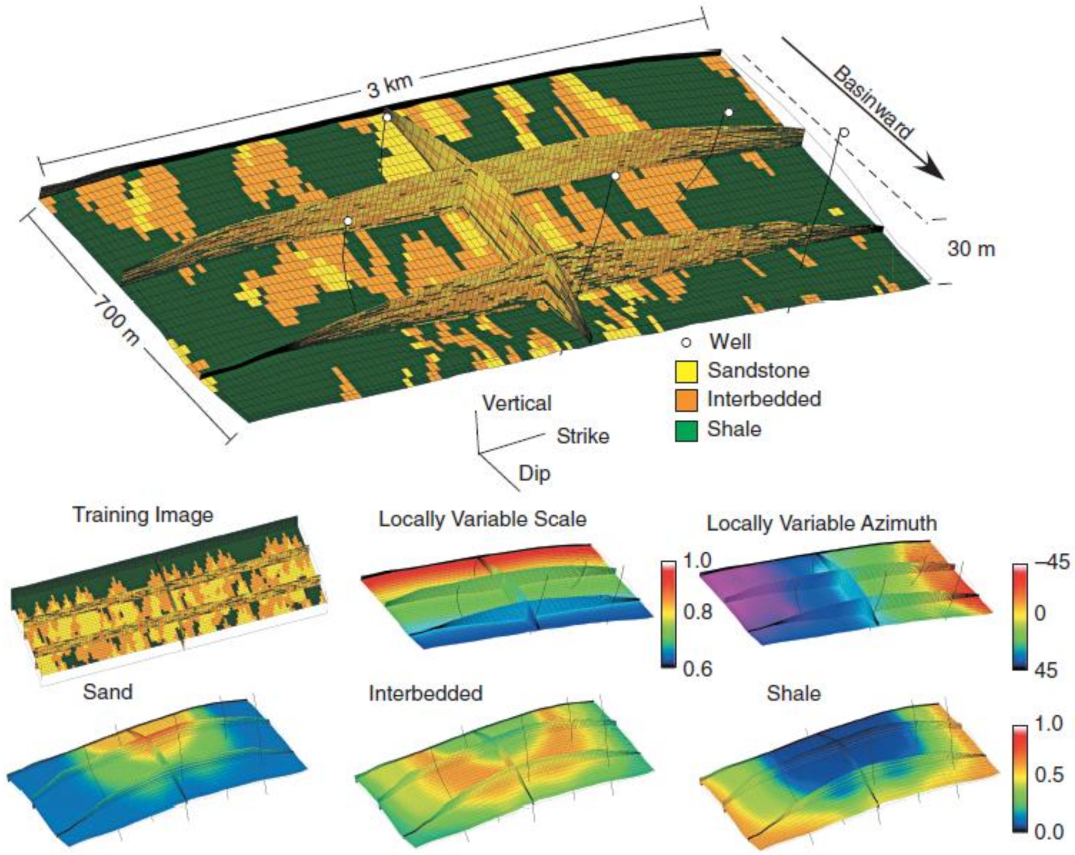


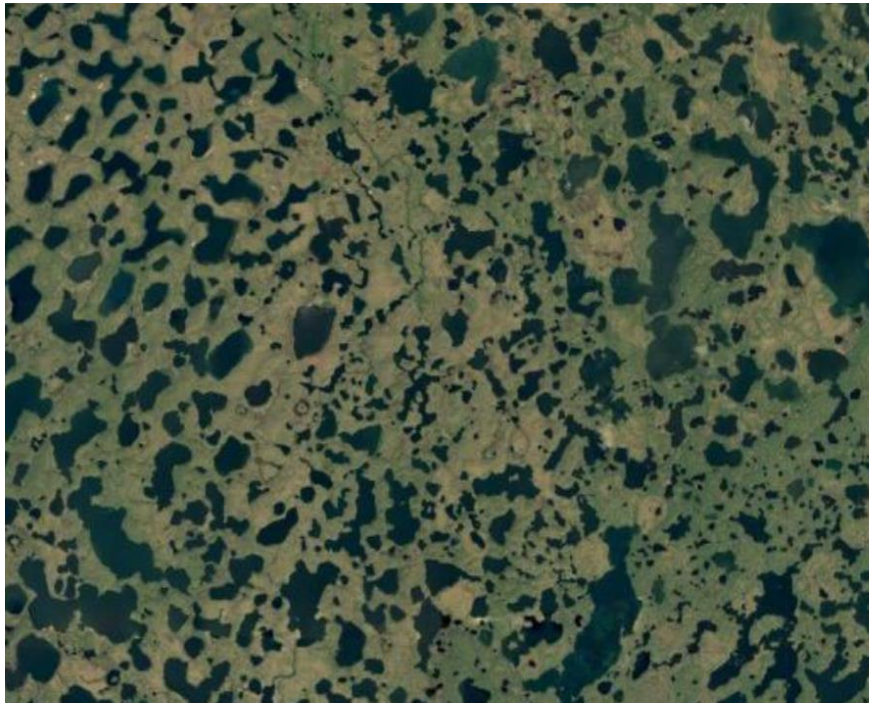
FIGURE 4.34: Single Realization of the Delta Reservoir Simulated with MPS with the Indicated Training Image, Wells, and Locally Variable Azimuth (upper) and Locally Variable Azimuth and Scale (Lower) and Locally Variable Proportions for Each Facies. Note distributary pattern and the decrease in lobes size distally and the transitions from sand to interbedded sand and shale and shale from proximal to distal. Compare to the same model constructed with MPS and without locally variable facies proportions in Figure 4.33.

Example of MPS simulation with locally variable azimuth, scale and proportions (Pyrcz and Deutsch, 2014).

MPS Training Image Construction

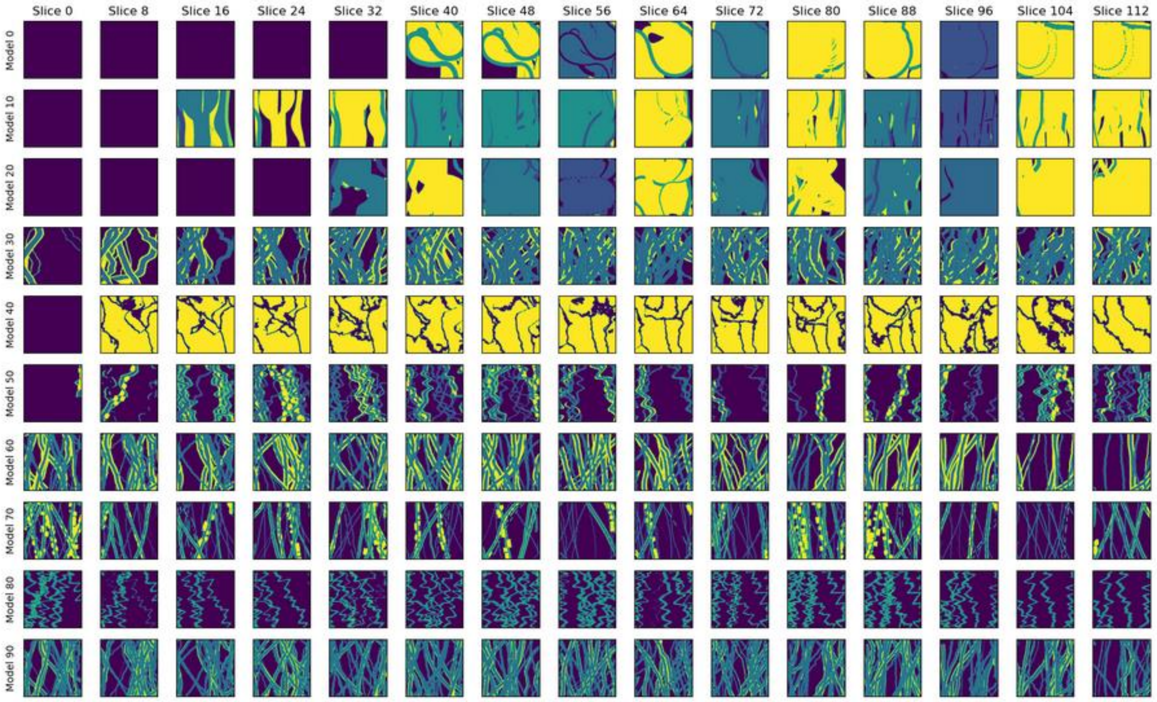
Sources / methods to make training images, e.g.:

- Hand drawn / tedious
- 2D satellite / outcrop
- Geophysical information



Satelite imagery of Mackenzie Delta, Yukon, Canada.

Hand drawn channel training image (Strebelle, 2001).

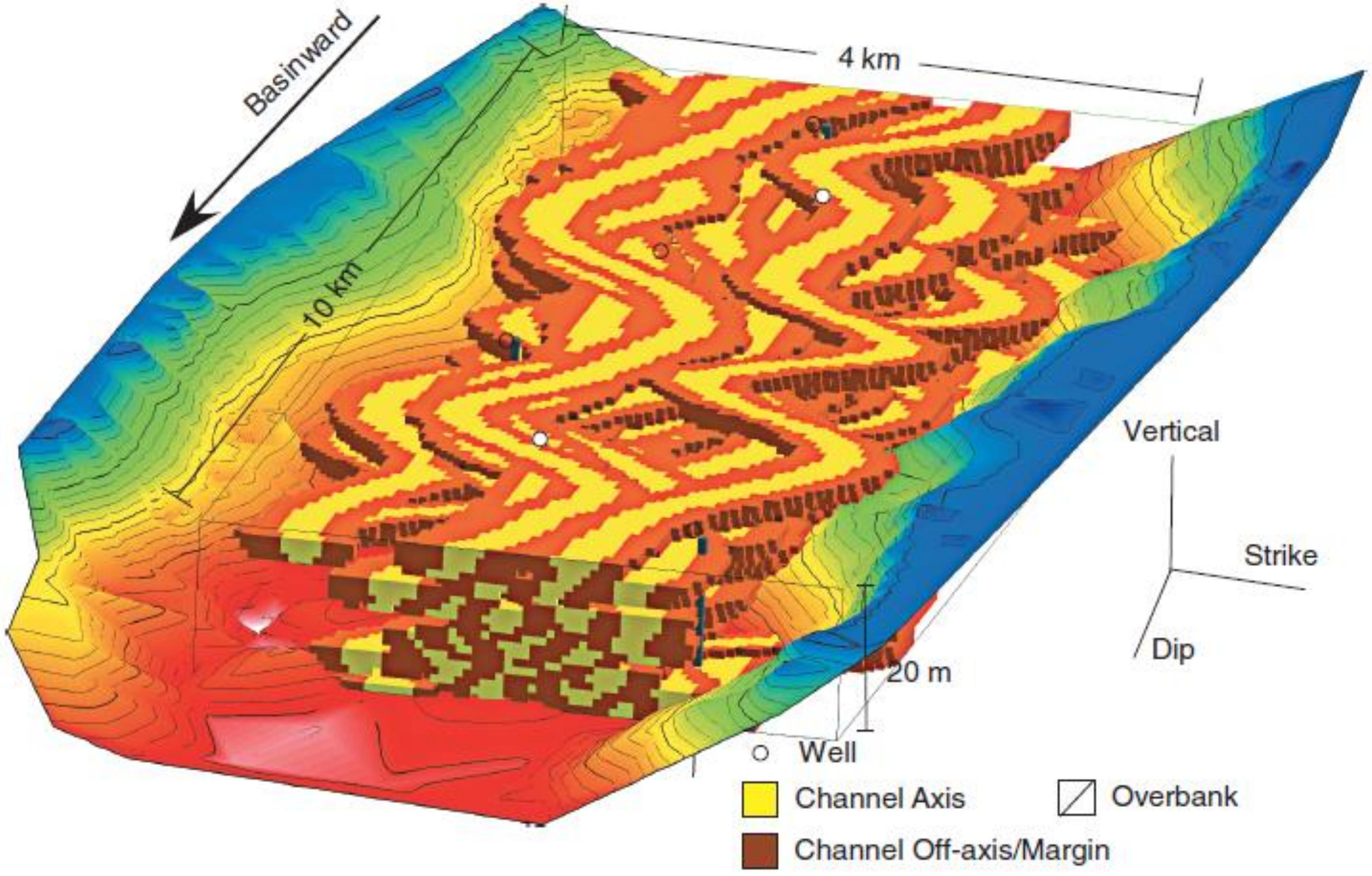


Training image library (Pyrcz and Morales, 2023).

MPS Training Image Construction

Sources / methods to make training images, e.g.:

- Unconditional (not matching data at data locations) object-based models

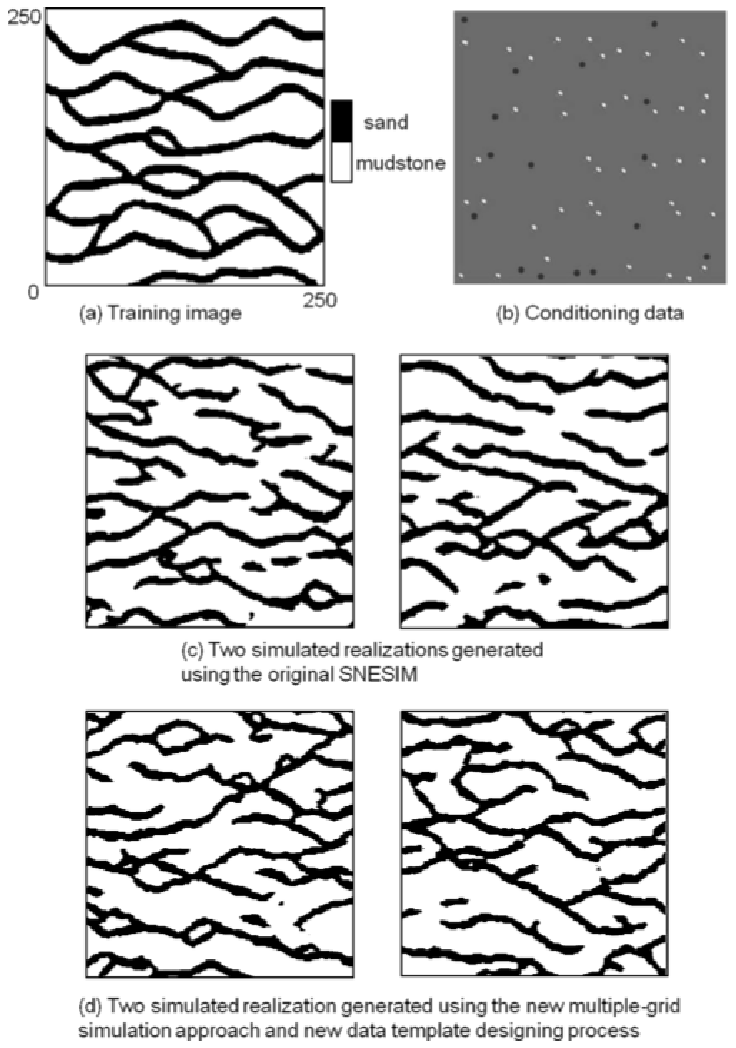


Example object-based model (Pyrcz and Deutsch, 2014).

MPS Issues

Potential discontinuities

- Likely due to the random path and Monte Carlo simulation at each model cell.
- Exists in other simulation methods, not as obvious as the simulated patterns are simpler and have more short scale discontinuity.



2D channel example with discontinuity issue shown (Cavelius and Strebelle, 2013)

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Lecture 15: Facies Simualtion

Lecture outline . . .

- **Object-based Simulation**

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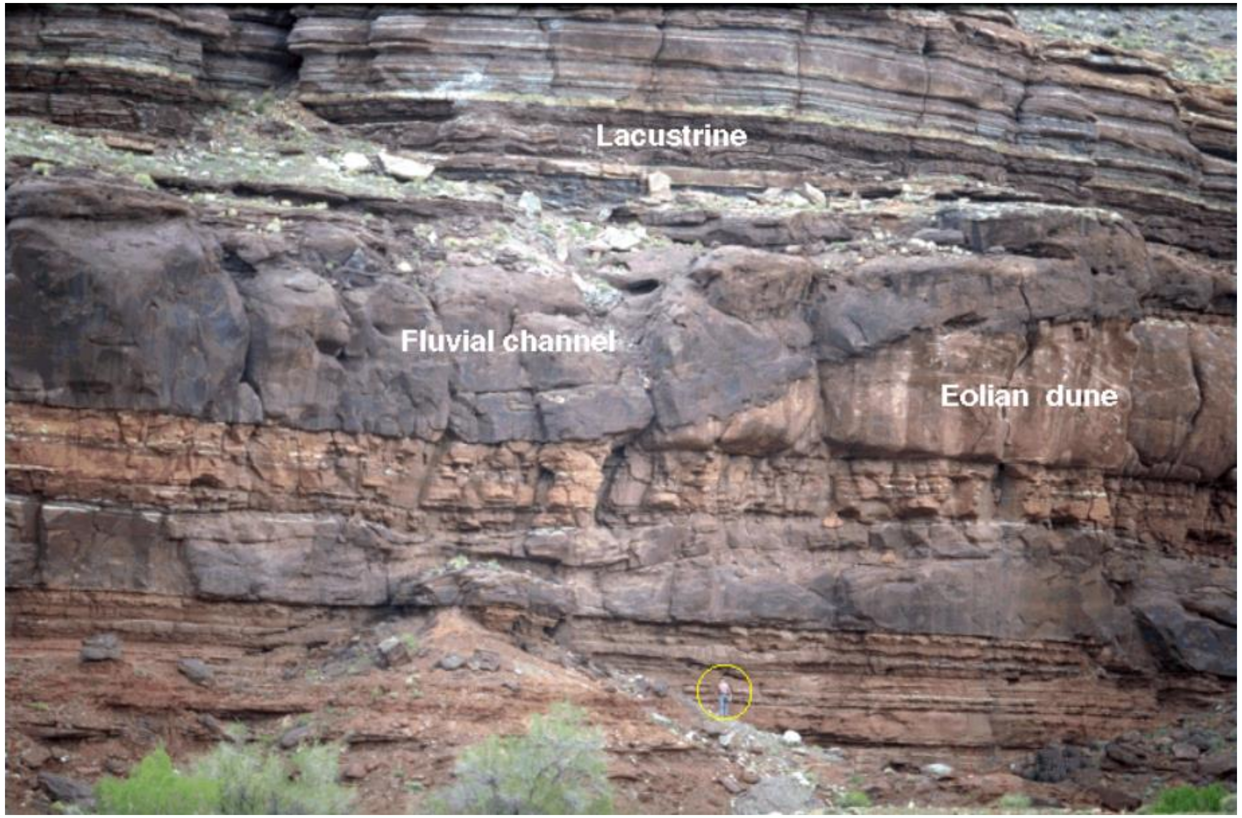
Object-based Modeling

Geological Shapes

Commonly, our reservoirs our constructed of predictable geologic units with common, parameterizable geometries



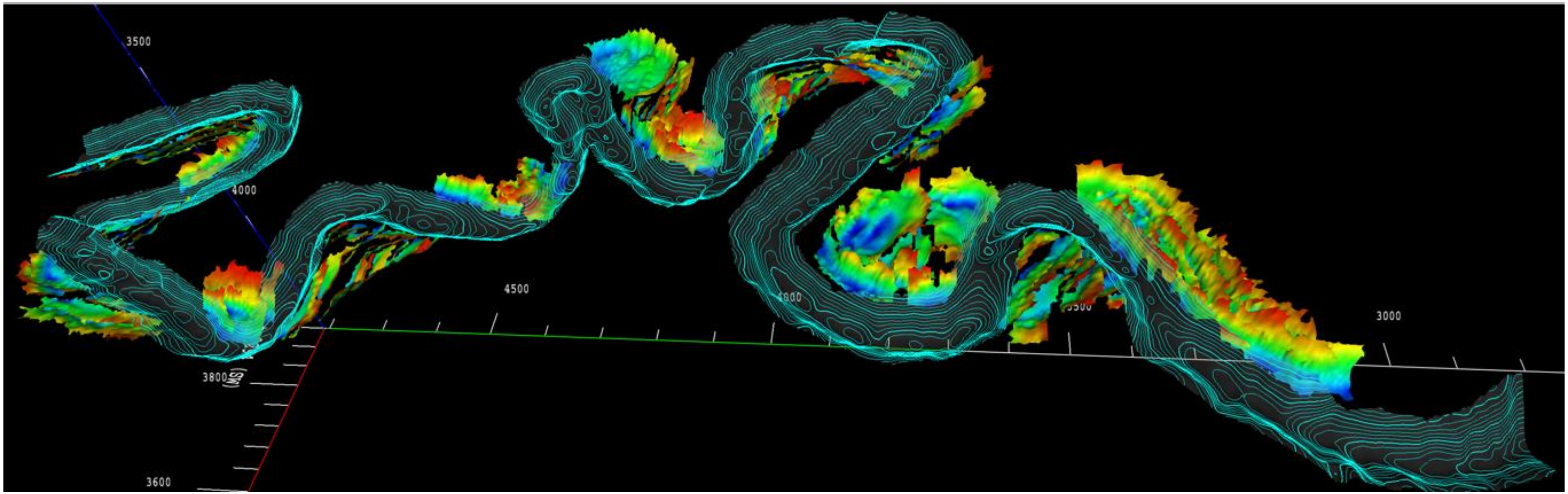
Channels, dunes and tabular lake fill in outcrop (Doligez and Beucher, 2002).

Object-based Modeling

Geological Shapes

They are explainable form our knowledge about depositional processes

- mass flow, fluvial processes, deepwater turbidity currents



Lateral accretion packages in submarine channels: occurrence, geometry, and depositional processes from 3D seismic (Fernandes, Mohrig, Buttles, Petter, Steel,).

Image from https://steelresearch.geo.utexas.edu/Project_pages/Anjali_LAPs.htm.

Object-based Modeling

Geological Shapes

The shapes, heterogeneity within the shapes and the relationships (stacking) of the shapes impact flow response.

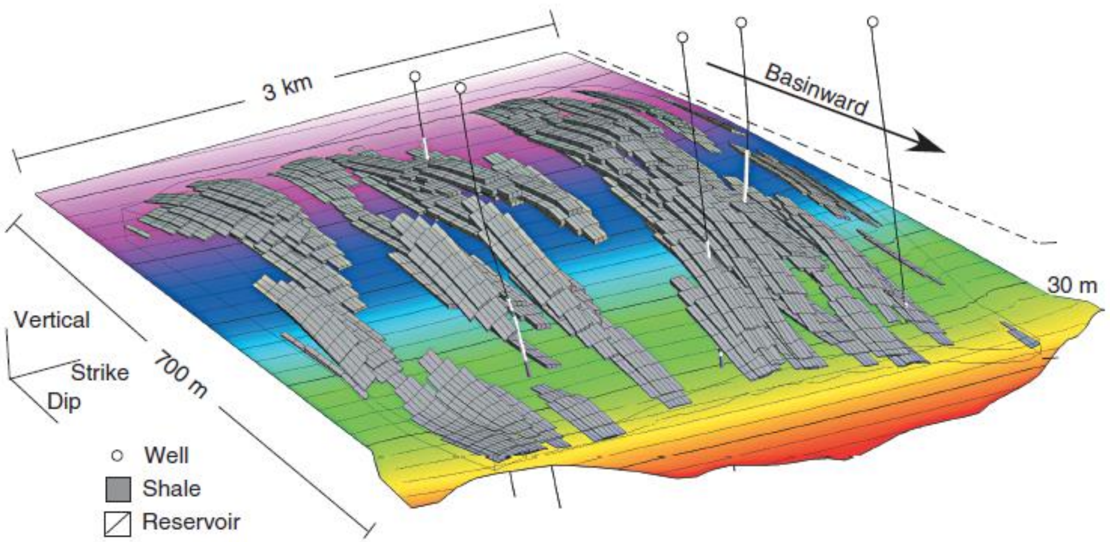
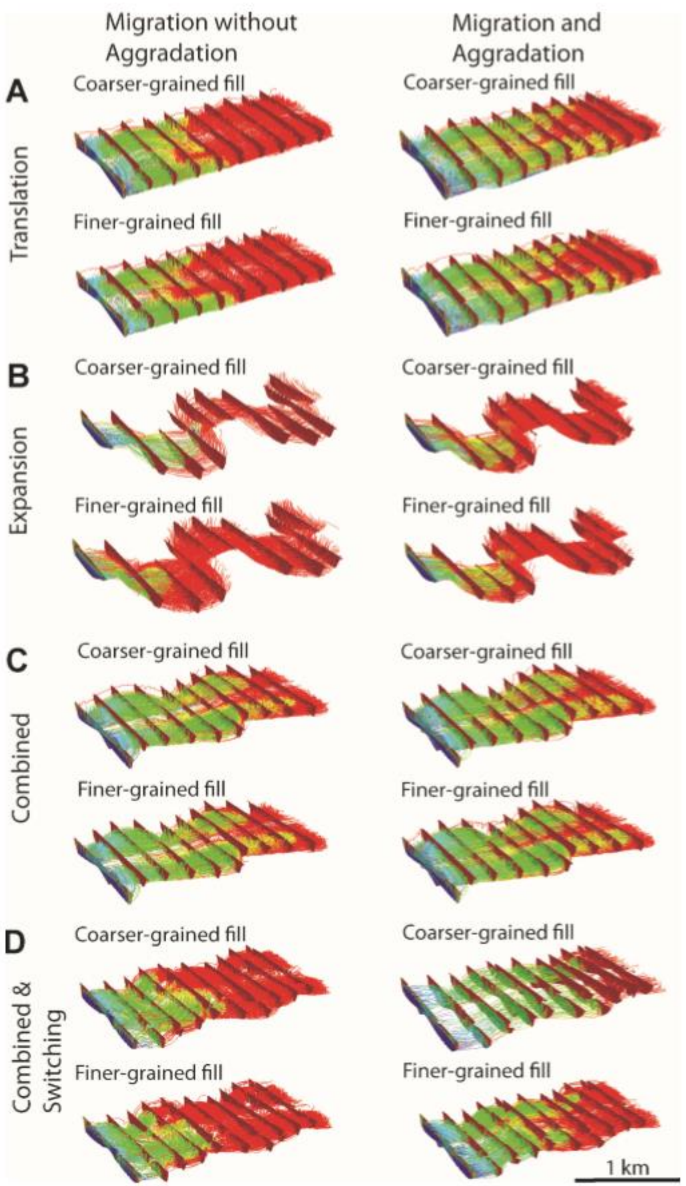


FIGURE 4.41: Shale Object-Based Realizations for the Delta Reservoir. Note the dip axis is lengthen due to the oblique projection. The reservoir facies is hidden to expose the shale objects.

Object-based shales (Pyrcz and Deutsch, 2014).



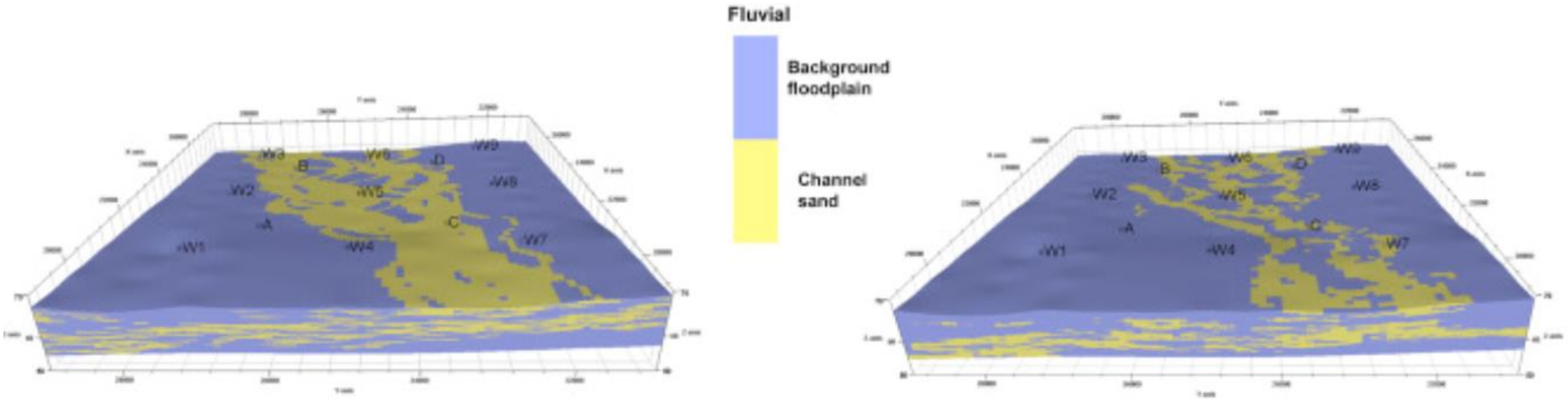
Fluvial channel types and streamline-based simulation to analyze sweep efficiency (Willis and Tang, 2009).

Object-based Modeling

Geological Shapes

MPS is pixel-based, these methods are limited in their ability to capture object geometries.

- they trend to be 'pixelated'
- MPS improves of variogram-based, that results in linear / blobs.



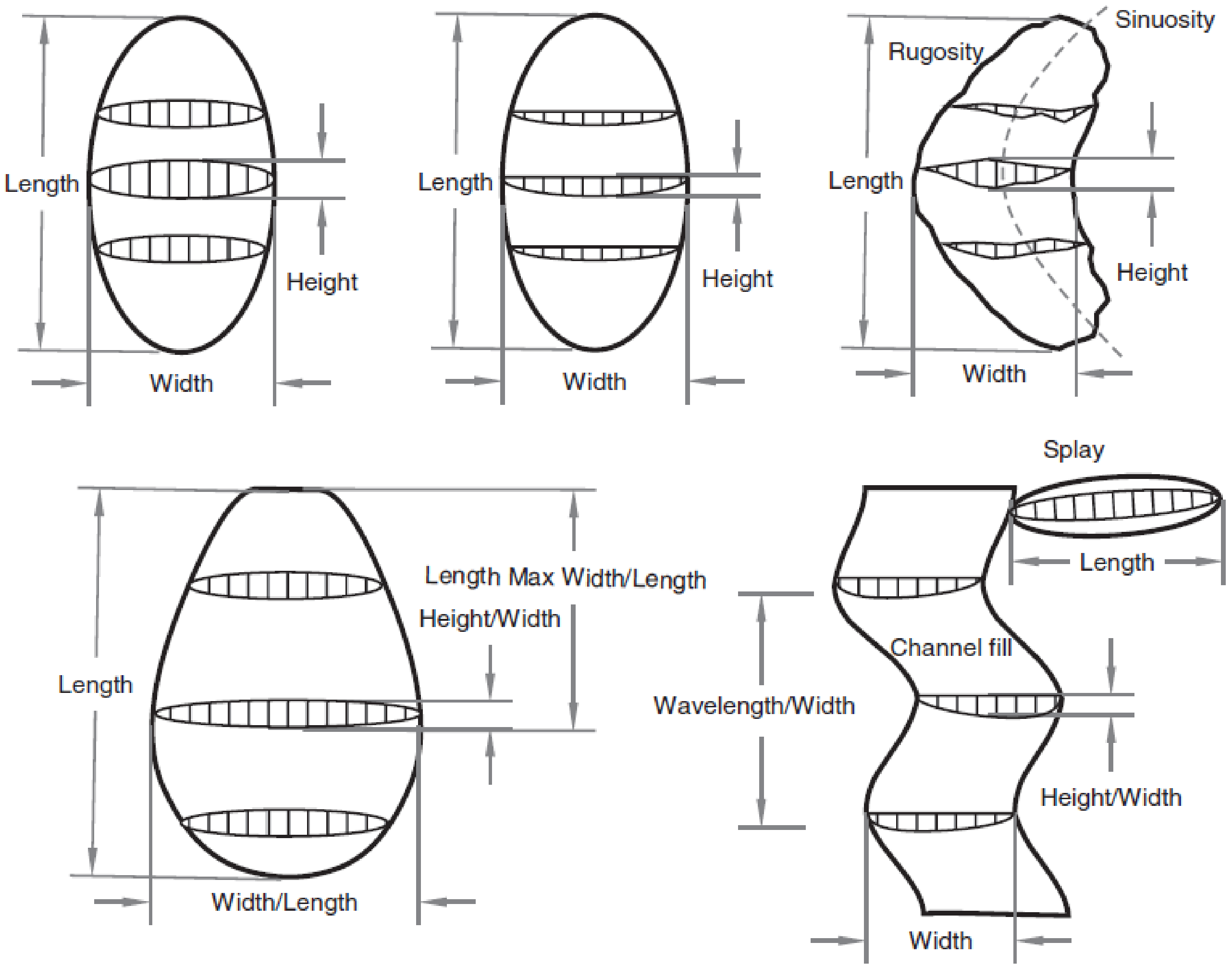
Object-based (left) vs. MPS with significant trend control (right) (Sacchi et al., 2016).

Object-based Modeling

Geological Shape

Parametric representations of objects.

- lobes, channels, bars, beds, dunes, levees, shale drapes etc.
- extent, ratios, shape
- connections
- undulations
- internal trends



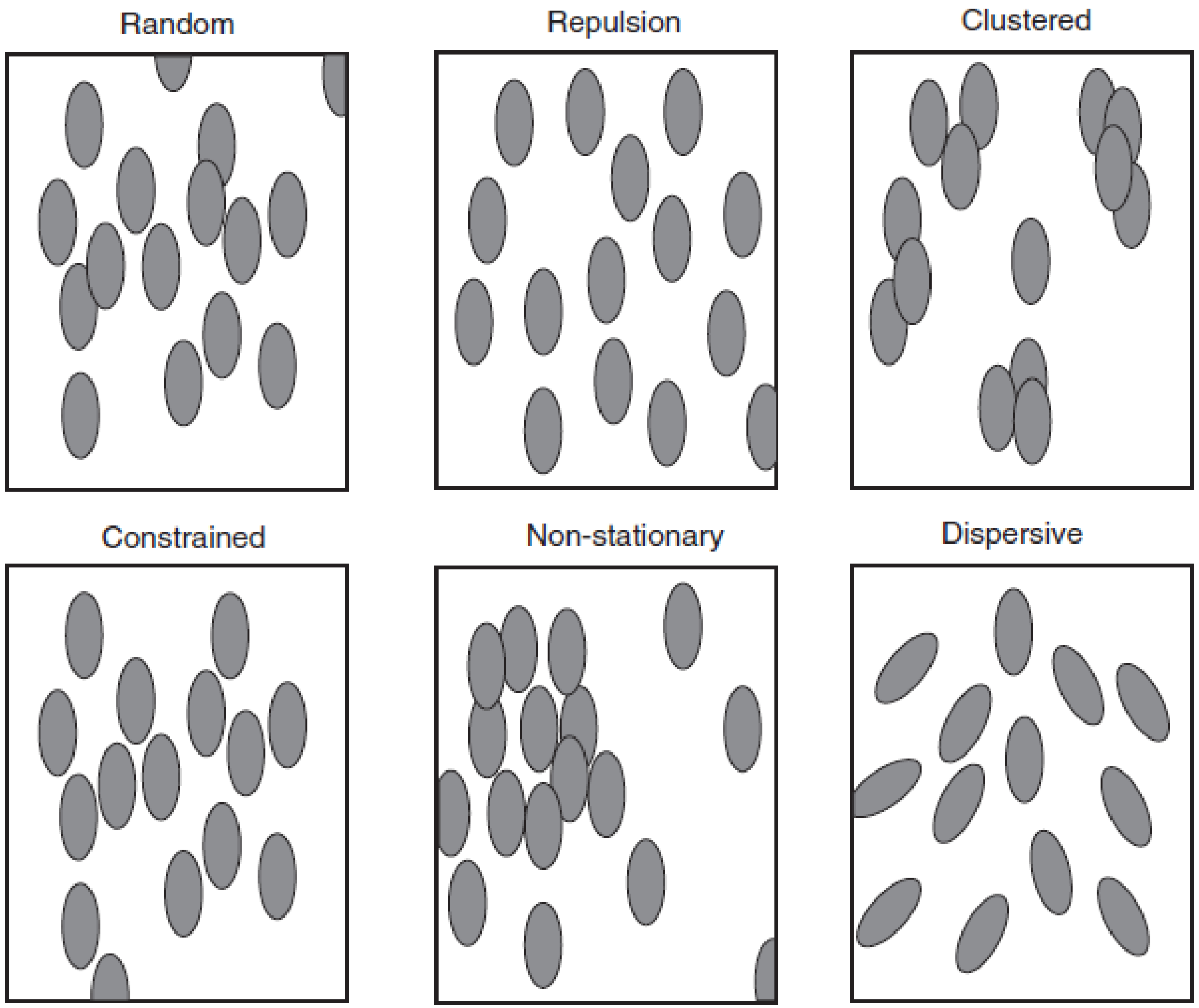
Example geometric parameterizations (Pyrcz and Deutsch, 2014).

Object-based Modeling

Geological Stacking

Parametric representations of object relationships.

- random
- repulsion
- clustered
- constrained
- nonstationary
- dispersive



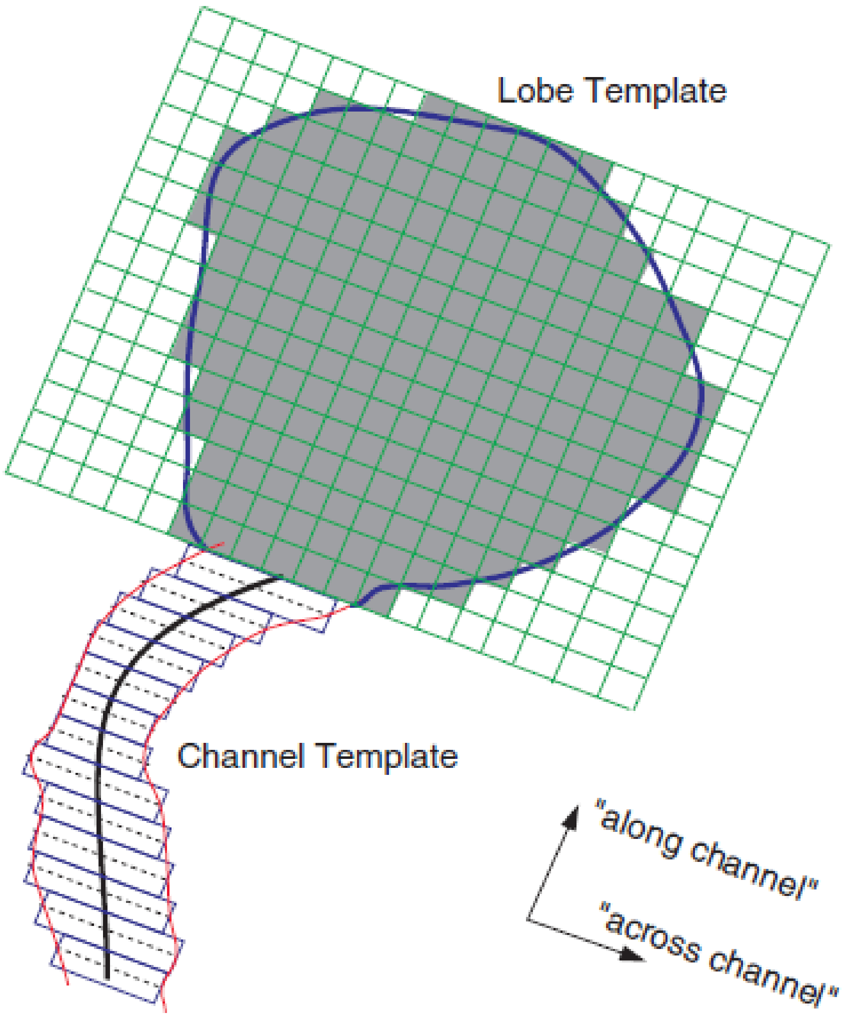
Relationships / stacking parameters (Pyrcz and Deutsch, 2014).

Object-based Modeling

Object-based Raster Templates

Numerical efficient representations

- fast placement, movement / iterations



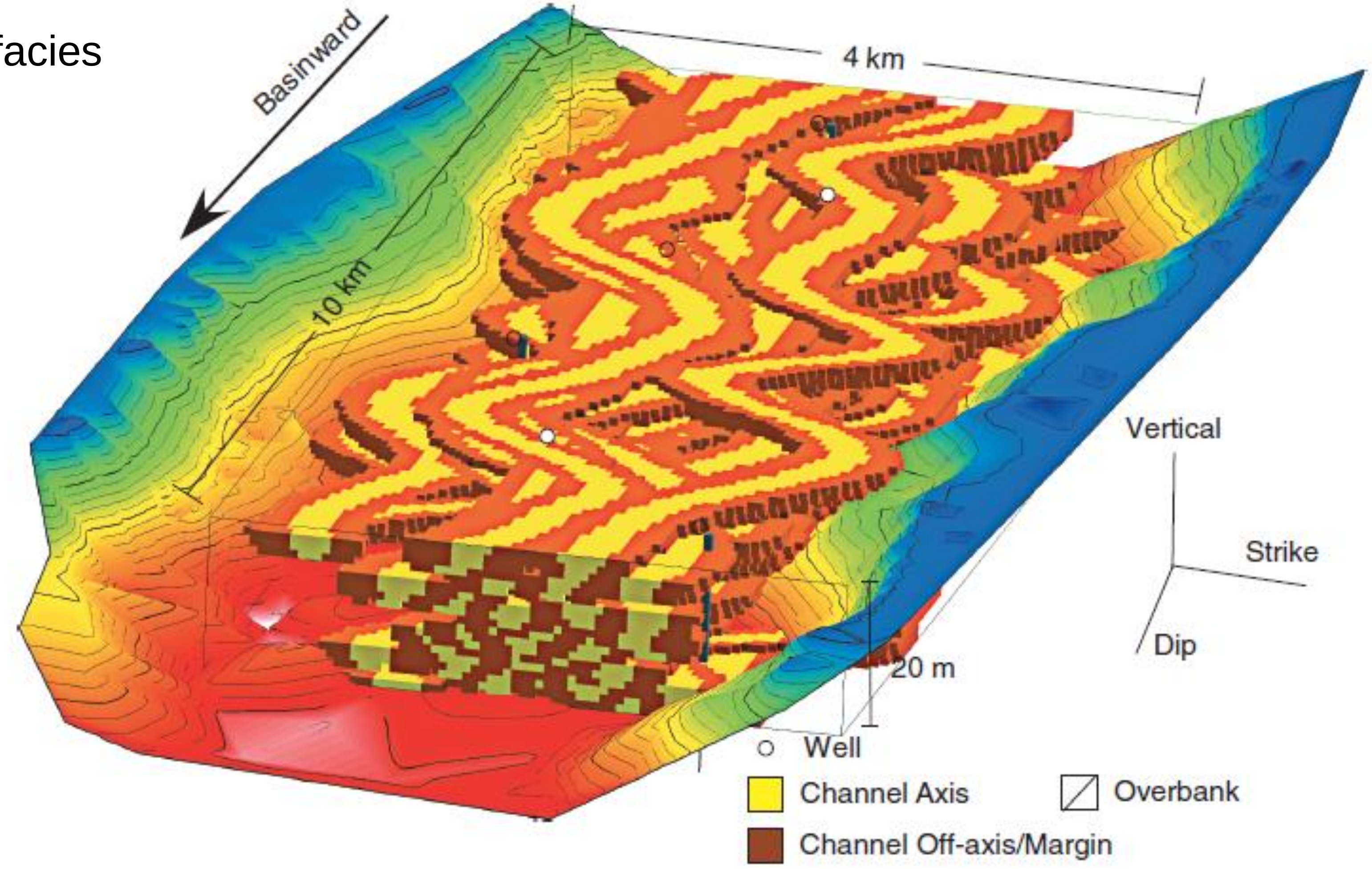
Object-based raster templates for channels and lobes (Pyrcz and Deutsch, 2014).

Object-based Modeling

Example Deepwater OBM

Stationary channels with 2 internal facies

- axis and margin
- cookie cutter approach



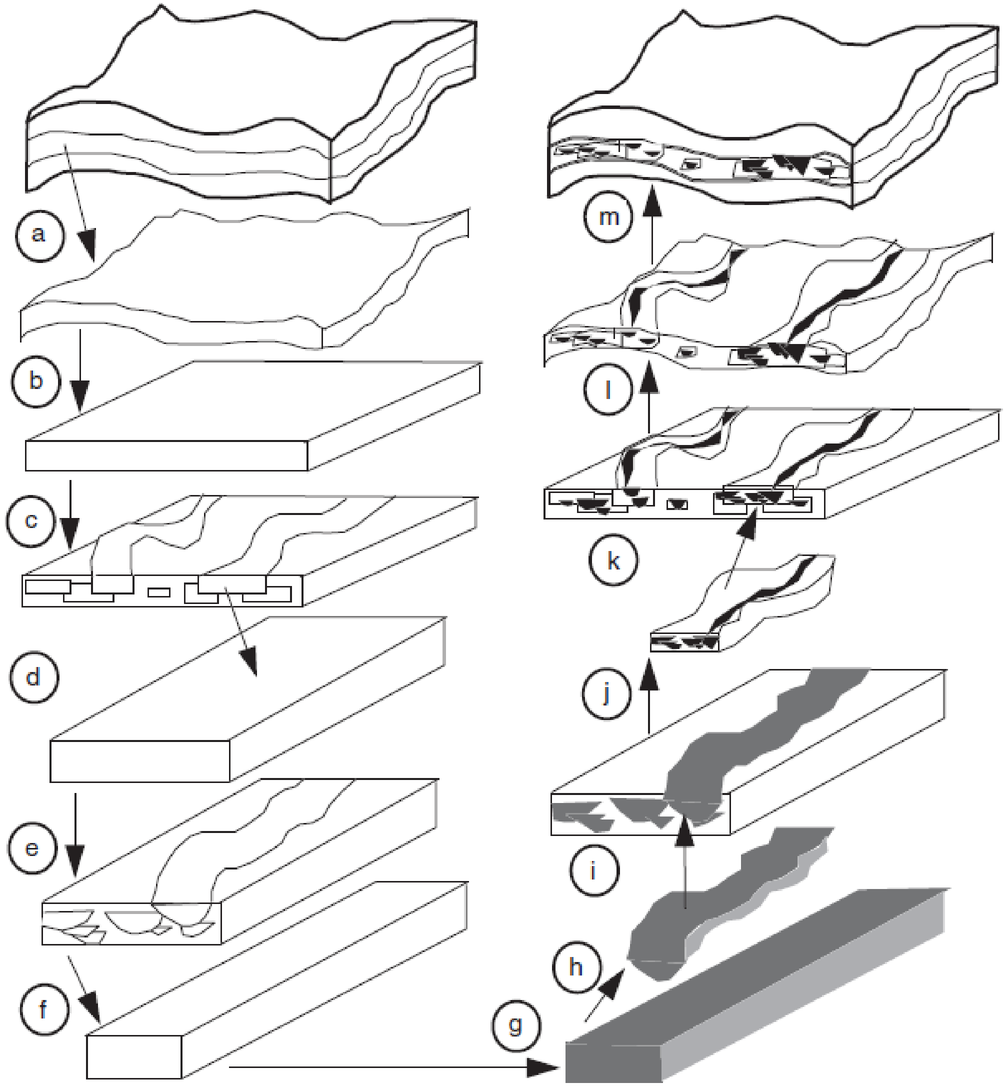
Example object-based model (Pyrcz and Deutsch, 2014).

Object-based Modeling

Hierarchical Object-based Models

Possibility to build models with nested, hierarchies.

- objects within objects within objects …
- beds within elements, elements within complexes, complexes within complex sets, etc.,



Hierarchical object-based models (Pyrcz and Deutsch, 2014).

Comparison of Facies Modeling Methods

Comparison of Facies Modeling Methods

Here's some general comments for comparison of various aspects of each.

	Indicator	MPS	Object-based
Spatial Continuity Inputs	Indicator Variogram	Training Image	Geometric Parameters
Well Data Conditioning	Unlimited	Unlimited	Limited
Heterogeneity	Pixelated, Linear	Pixelated, Some Non-linear and Ordering	Crisp, Geometric Shapes
3D Trend Integration	Unlimited	Unlimited	Limited
Computational Time	Very Fast	Slow with Many Points	Slow with Dense Data

Comparison between the three most common categorical, facies modeling methods.

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