Application of a Training-Image Library to Reservoir Modeling Using Multi-Point Statistics Based on Quantitative Fluvial Facies Characterization*

Jose M. Montero1, Nigel P. Mountney1, Luca Colombera1, Na Yan1, and Alessandro Comunian2

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Abstract

Facies modelling seeks to reproduce the geometry and distribution of the reservoir-forming sedimentary bodies in three dimensions to provide a framework for the construction of property and flow models. However, variogram-based facies modelling techniques are not well suited to the reproduction of complex geological shapes (e.g., sinuous fluvial channels), whereas object-based simulations may fail to honour conditioning data (e.g., well data). New workflows have been developed for the generation of fluvial reservoir models with improved geological realism compared to outputs of conventional methods. These workflows are suitable for modelling reservoirs that comprise fluvial meander-belt deposits, and can therefore provide the models of spatial heterogeneity (training images) required to apply simulation techniques based on multi-point statistics (MPS), which are then useful to integrate complex geological patterns. A library of training images from which MPS modelling algorithms replicate geological patterns has been developed using quantitative information derived from a relational database of geological analogues (Fluvial Architecture Knowledge Transfer System, FAKTS), and a forward stratigraphic modelling tool that simulates fluvial meander-bend evolution and resulting point-bar facies organization (PB-SAND). The devised training images incorporate fundamental features of the facies architecture of fluvial point-bar elements and larger meander belts composed of these and related elements. The application of training images has been optimized to three widely used MPS algorithms: SNESIM, DEESSE and FILTERSIM. A quantitative and qualitative quality check of MPS realizations has been performed whereby facies proportions, facies relationships, element geometries, dimensions, control of non-stationarity and runtime are optimized for particular fluvial successions being modelled. The sensitivity of multiple simulation results to input parameters has been analysed to define preferred modelling recipes, paired to each training image and to each MPS modelling algorithm. Research outcomes are the development of an extensive library of training images for MPS simulations of the architecture of subsurface successions deposited by a variety of types of meandering fluvial systems. Devised workflows are applicable to multiple MPS algorithms, and enable off-the-shelf training-image selection for the effective establishment of a hierarchical approach to facies modelling.
Selected References


Application of a Training-Image Library to Reservoir Modeling Using Multi-Point Statistics Based on Quantitative Fluvial Facies Characterization

Jose M Montero, Dr. Nigel P. Mountney, Dr. Luca Colombera, Dr. Na Yan, Dr. Alessandro Comunian
MAIN POINTS AND AIM OF THE PROJECT

OUTLINE

1- What are facies models? Why do they need to be improved?

2- Multipoint statistical simulation introduction (MPS)

3- A novel facies modelling workflow for fluvial meandering system
   - FAKTS analogue database
   - PB-SAND program for forward stratigraphical models
   - Training Image Library

4- Applications to SNESIM and DEESSE (Multipoint Statistical simulation)

AIMS

- Deliver an effective and fast methodology by which training-image building can be informed quantitatively
- A workflow for facies modelling using MPS applicable in the oil and gas industry, geothermal and hydrogeology
WORKFLOW AND GEOSTATISTICAL METHODS

Why does facies modelling matter?

Facies models

Why do facies models need to be improved?

Lack of data (Well data, core data, seismic data)

Geostatistical methods “The need to fill the gaps”

1- Pixel-based methods (i.e., SIS)
- Does not reproduce curvilinear shapes
- Relies on variograms...

2- Object-based methods
- Not good at honouring hard data

Property models (Vcl, Φ, k, Sw…)

Flow Models

1.

Macnchuk et al. 2011
Multipoint statistical simulations combines both the capability of honouring hard data and the ability to reproduce complex geological shapes.

Needs a TRAINING IMAGE

The digital representation of the heterogeneities of the reservoir rock.

The training image substitutes the variograms.

Satellite image

Object-based generated 3D realization

Facies models based on outcrop studies

Need to be “stationary”

1: Patterns are reasonably homogeneous in the Training Image
2: Patterns should be repeated in the Training Image
3: Patterns should not be confined to specific locations in the Training Image
FORWARD NUMERICAL SIMULATION OF FLUVIAL POINT-BAR EVOLUTION

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Max</th>
<th>Min</th>
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</thead>
<tbody>
<tr>
<td>bar thickness (m)</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>channel width (m)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>thickness (m)</td>
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<td></td>
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<tr>
<td>length above accretion surfaces (m)</td>
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<td>spacing (m)</td>
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<tr>
<td>proctor (in the top) (m)</td>
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<td></td>
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<tr>
<td>proctor (in the top) (m)</td>
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</tr>
<tr>
<td>mudstone</td>
<td>30%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>facies</td>
<td>15%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>very fine sand</td>
<td>7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fine sand</td>
<td>37%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>medium sand</td>
<td>45%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Model Components:
- Morphological Evolution
- Vertical Cross-Sections
- Stacking Patterns
- Bounding surfaces

Model Outputs:
- Facies Transect
- High resolution morphology
- Prediction of 3D architecture
- Probability of possible scenarios

Training Image Components:
- Transects transformed from RGB to facies
- Stationary and non-stationary Training Images
- From .png to .gslib files.

COLLATION OF QUANTITATIVE DATABASE OF APPROPRIATE CASE STUDY EXAMPLE

COLLATION OF QUANTITATIVE DATABASE OF APPROPRIATE CASE STUDY EXAMPLE

TRAINING IMAGE IMAGE ASSEMBLY
LITERATURE AND FIELD STUDIES

FAKTS (Fluvial Architecture Knowledge Transfer System)

LITERATURE AND FIELD STUDIES

Facies Proportions

Facies Geometries

Facies transition statistics

Reservoir Modelling Constraints

(Faith, 2017)

(Colombera et al., 2013)

Width (m)

Thick (m)

10

100

1000

1000

10000

100000

Width (w) / Thickness (h) aspect ratios

N = 1446

Table 1: Transition statistics for channel-complexes

Yield (R²)

Model

Material-Unit Dimensions for the Given Direction:

Mean & Extension

Coefficient of Variation

Material-Unit Propositions

MORRISTON FORMATION

Yield: 0.42

Domain

DA

N = 42

N = 12

N = 10

Downstream

Upstream

In the Lower Snake, Kaysen’s Ferry, SE Utah

N = 137

Partial width (N = 132)

Unlimited width (N = 156)

Width (N = 503)

N = 1446

N = 156
FORWARD STRATIGRAPHIC MODELLING OF FLUVIAL POINT-BAR ELEMENTS USING PB-SANDS

EXPANSIONAL MEANDER EXAMPLE

Yan et al., 2017. Computers & Geosciences, 105, 65-80

<table>
<thead>
<tr>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>Std</th>
</tr>
</thead>
<tbody>
<tr>
<td>bar thickness (m)</td>
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<td>1.06</td>
<td>0.68</td>
</tr>
<tr>
<td>channel width (m)</td>
<td>74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>thickness (m)</td>
<td>0.20</td>
<td>0.06</td>
<td>0.68</td>
</tr>
<tr>
<td>length along accretion surfaces (m)</td>
<td>7.60</td>
<td>1.60</td>
<td>19.00</td>
</tr>
<tr>
<td>spacing (m)</td>
<td>5.74</td>
<td>1.90</td>
<td>10.20</td>
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<td>1.35</td>
<td>0.28</td>
<td>3.30</td>
</tr>
<tr>
<td>position (to the top)</td>
<td>23 %</td>
<td>5 %</td>
<td>55 %</td>
</tr>
<tr>
<td>mud drape</td>
<td>11 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>facies</td>
<td>very fine sand</td>
<td>7 %</td>
<td></td>
</tr>
<tr>
<td>medium sand</td>
<td>37 %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3D STRATIGRAPHICAL MODELS

-Deterministic-stochastic mixed
-Geometric-based
-Process-based
<table>
<thead>
<tr>
<th>EXPANSIONAL BAR</th>
<th>EXPANSIONAL BAR (Objects repetition)</th>
<th>OTHER TYPES OF MEANDER TRANSFORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Neighbouring Point Bars + Floodplain (Non-stationary)" /></td>
<td><img src="image2" alt="Channel-Belt Form + Bar Form (Partially stationary)" /></td>
<td><img src="image3" alt="Translational bar (Non-stationary)" /></td>
</tr>
<tr>
<td><img src="image4" alt="Single Point Bar + Floodplain (Non-stationary)" /></td>
<td><img src="image5" alt="Channel-Belt Form (Partially stationary)" /></td>
<td><img src="image6" alt="Rotational bar (Non-stationary)" /></td>
</tr>
<tr>
<td><img src="image7" alt="Point Bar (Non-stationary)" /></td>
<td><img src="image8" alt="Channel-Belt Form (Partially non-stationary)" /></td>
<td></td>
</tr>
</tbody>
</table>

**Legend:**
- Blue: Floodplain Facies
- Black: Bar Top Facies (Mud)
- Gray: Bar Top Facies (silt)
- Yellow: Point Bar (Fine sands)
- Orange: Point Bar (Medium sands)
- Red: Point Bar (Coarse sands)
- Brown: Channel-lag Facies
- Light Gray: Channel-Fill Facies
2 CASE STUDY (EXAMPLE 1 and 2)

2 algorithm will be tested and compared:

SNESIM (Strebelle, 2002)
- Search Template Geometry
- Number of nodes
- Number of replicates
- Servosystem
- Multigrids
- Subgrids

DEESSE (Mariethoz et al. 2010)
- Search Window
- Number of nodes
- Search distance
- Fraction
- Support Radius
- Deactivation Threshold

EXAMPLE 1
EXPANSIONAL BAR
(Partially STATIONARY EXAMPLE)

EXAMPLE 2
EXPANSIONAL BAR
(NON-STATIONARY EXAMPLE)

AUXILIARY VARIABLE MAPS
(Handling non-stationarity and include trends)

QUALITY CHECK:
- Geometries
- Proportions
- Trends

- Run-Time
- Noise
- Stationarity

Probability Rotation Scaling Regions
Songhua River, China (NASA)

ZONE 1: Main sand fairway
ZONE 2: Floodplain deposits
ZONE 3: Buffer or transitional zone

ZONE 1
ZONE 2
ZONE 3
3 km

AUXILIARY VARIABLE MAPS (PROBABILITY MAPS CONSTRUCTION)
AUXILIARY VARIABLE MAPS (PROBABILITY MAPS CONSTRUCTION)

ZONE 1: Main sand fairway
ZONE 2: Floodplain deposits
ZONE 3: Buffer or transitional zone

Songhua River, China (NASA)
**AUXILIARY VARIABLE MAPS (PROBABILITY MAPS CONSTRUCTION)**

**Facies 0**: Floodplain

**Facies 1**: Point bars

**Facies 2**: Shale plugs (Channel-fill deposits)

ZONE 1: Mostly Point-bars and channel-fill deposits

ZONE 2: Buffer with 50% probability of point-bar/Channel-fill and 50% of floodplain deposits

ZONE 3: 100% probability of floodplain deposits

---

<table>
<thead>
<tr>
<th>Zone</th>
<th>Floodplain</th>
<th>Point Bars</th>
<th>Ch-Fill</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
AUXILIARY VARIABLE MAPS (PROBABILITY MAPS CONSTRUCTION)

1- Based on SOFT DATA

Alqahtani A. et al. 2015. Sedimentology 62, 1198-1232
AUXILIARY VARIABLE MAPS (PROBABILITY MAPS CONSTRUCTION)

- Sedimentological analysis at a BIG SCALE required to interpret the fluvial geological setting.

- Channel-belt estimates can be easily obtained using FAKTS:
  - Facies Proportions
  - Geometries size
  - Net to gross (Shale/sand proportions)
  - Different solutions can be created stochastically with an object-based algorithm.

2- Based on FAKTS estimates (Channel-belt case)

Songhua River, China (NASA)
EXAMPLE-1: EXPANSIONAL BAR (STATIONARY EXAMPLE)

- Homogeneous Patterns
- Repeated objects
- Only One single channel belt
EXAMPLE-1. SIMULATION WORKFLOW

STEP 1: Category reduction (From 5 to 3 facies)

Facies 0  Facies 1  Facies 2
AREA 1     0.1    0.55   0.35
AREA 2     0.5    0.25   0.25
AREA 3     1      0      0

SNESIM (Strebelle, 2002)
- Search Template Geometry
- Number of nodes
- Number of replicates
- Servosystem

DEESSE (Mariethoz et al. 2010)
- Search Window
- Number of nodes
- Search distance
- Fractions

- TAU model probability for SNESIM
- Support radius and Deactivation threshold for DEESSE.
EXAMPLE-1. STATIONARY TRAINING IMAGE REALIZATIONS (3 facies)

**SNESIM**

- Runtime <2 min/realization

**DEESSE**

- Runtime <2 min/realization

**Parameters:**

- **Search Radius:** 4000x4000x15, N=70, Replicates=20, Serv=1, Multigrids=4
- **Condition to Auxiliary Probability (TAU MODEL 2 1)**

**SIMULATION GRID**

- X: 250
- Y: 250
- Z: 50

**TI Number of Cells**

- X: 90
- Y: 210
- Z: 33

**CELL SIZE**

- X: 20
- Y: 20
- Z: 0.25

**Parameters:**

- **Search Window:** 20x20x8, N=35, Distance=0.25, Radius=10, Deact. Threshold=5
- **Condition to Auxiliary Probability and Rotation map**
EXAMPLE-1. STATIONARY TRAINING IMAGE REALIZATIONS (5 facies)

Parameters:
Search Radius: 4000x4000x30, N=70, Replicates=20, Serv=1, Multigrids=4
Condition to Auxiliary Probability (TAU model 2 1)
## EXAMPLE-2. EXPANSIONAL BAR (NON-STATIONARY EXAMPLE)

### TRAINING IMAGE LIBRARY

<table>
<thead>
<tr>
<th>Expansional Bar</th>
<th>Expansional Bar (Objects repetition)</th>
<th>Other Types of Meander Transformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Image 1]</td>
<td>![Image 2]</td>
<td>![Image 3]</td>
</tr>
<tr>
<td>![Image 7]</td>
<td>![Image 8]</td>
<td></td>
</tr>
<tr>
<td>![Image 9]</td>
<td>![Image 10]</td>
<td></td>
</tr>
</tbody>
</table>

### EXPANSIONAL BAR CASE (NON-STATIONARY TRAINING IMAGE)

- No repetition of patterns
- Patterns confined to specific locations
EXAMPLE-2. SIMULATION WORKFLOW

STEP 1: Category reduction (3 facies)

STEP 2: Upscaling / Downscaling

SIMULATION GRID
- X: 250
- Y: 250
- Z: 50

Training Image
- Number of Cells
  - X: 128
  - Y: 144
  - Z: 39

CELL SIZE
- X: 20
- Y: 20
- Z: 0.25

STEP 3: Sensitivity Phase

SNESIM (Strebelle, 2002)
- Search Template Geometry
- Number of nodes
- Number of replicates
- Servosystem

DEESSE (Mariethoz et al. 2010)
- Search Window
- Number of nodes
- Search distance
- Fractions

STEP 4: Auxiliary Variable Maps

- TAU model probability for SNESIM
- Support radius and Deactivation threshold for DEESSE.
- Rotation Map (blue:0°, Red: 180°)

Grid TI

AREA 1
- Flood-plain deposits
- Point-Bar deposits
- Ch-Fill deposits

AREA 2
- Flood-plain deposits
- Point-Bar deposits
- Ch-Fill deposits

AREA 3
- Flood-plain deposits
- Point-Bar deposits
- Ch-Fill deposits

<table>
<thead>
<tr>
<th></th>
<th>Facies 0</th>
<th>Facies 1</th>
<th>Facies 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>AREA 1</td>
<td>0.1</td>
<td>0.55</td>
<td>0.35</td>
</tr>
<tr>
<td>AREA 2</td>
<td>0.5</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>AREA 3</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
EXAMPLE-2. NON-STATIONARY TRAINING IMAGE REALIZATIONS (3 facies)

Parameters:
Search Radius: 2000x2000x15, N=60, Replicates=20, Serv=1, Multigrids=4
Condition to Auxiliary Probability and Rotation map

Parameters:
Search Window: 25x25x10, N=35, Distance=0.25, Radius Threshold=4
Condition to Auxiliary Probability and Rotation map
EXAMPLE-2. NON-STATIONARY TRAINING IMAGE REALIZATIONS (5 facies)

SNESIM
Runtime <20 min/realization

SIMULATION GRID
| X: 250 |
| Y: 250 |
| Z: 50 |

TI Number of Cells
| X: 128 |
| Y: 144 |
| Z: 39 |

CELL SIZE
| X: 20 |
| Y: 20 |
| Z: 0.25 |

Parameters:
Search Radius: 2000x2000x15, N=60, Replicates=20, Serv=1, Multigrids=4
Condition to Auxiliary Probability and Rotation map

DEESSE
Runtime <20 min/realization

Parameters:
Search Window: 25x25x10, N=35, Distance=0.25, Radius=5, Deact. Threshold=4
Condition to Auxiliary Probability and Rotation map
Realizations performed following this workflow attempted to model the sedimentary architecture of fluvial meandering systems, at bar and facies scales. Training images with different levels of non-stationarity can be handled by the use of probability maps.

Apply the workflow to a real-case scenario where:

- Training images can be built based on analogue data;
- Well data can be used to define training-image lithotypes;
- Soft data (e.g., seismic attributes) can be used to create probability maps;
- A connectivity study can be performed to compare results with those of other pixel- and object-based methods.

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