# [PS]Comparison of Methodologies and Geostatistical Approaches for Diagenesis Quantification*

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## Abstract

Diagenesis changes the original relationship between the facies and the distribution of the petrophysical properties. The objective of this work is to compare several methods to integrate diagenetic constraints into geostatistical models using new methodological workflows. The main objective is to define rules and to acquire know-how in order to recommend one methodology or another, depending on the geological environment, the context of diagenesis, and the available data.

On a real dataset of a fluvial environment, a relationship has been quantified between the pore chlorite filling and the grain size, which allowed definition of several degrees of diagenesis in the reservoir. Several alternative methods have been used to create a geological model of this reservoir with properties in terms of sedimentary facies and diagenetic class, as nested simulations, plurigaussian simulations and bi-plurigaussian simulations.

In the nested simulations workflow, each step is done sequentially: simulation of sedimentary facies, simulations of the classes of diagenesis within each sedimentary facies, then reconstitution of the final model. The simulation parameters are specific for each property, sedimentary facies and class of diagenesis. This method allows uncoupling of the constraints in terms of conditioning wells

and parameters, for each simulated property. In return, it will not be possible to use a correlation between sedimentation and diagenesis.

The direct plurigaussian simulation (PGS) method has several strong points: a unique simulation is launched globally and a correlation coefficient may be used between the two Gaussian functions, which could translate the relationship between sedimentation and diagenesis. But the method is applied to only one global variable, and will be constrained only with the wells owning the two types of information, sedimentary facies and diagenesis.

A new model, the Bi-PGS model has been developed that provides a sound basis for bivariate categorical simulation. It is flexible, as each physical process is associated with a complete PGS (possibly using two underlying Gaussian random functions). A further possible development is to introduce a correlation between the two PGS. The Bi-PGS technique can cope with non-stationarity by using proportions for each sedimentation and diagenetic class that varies in space. It would also be possible to use the Bi-PGS technique for processing two categorical data sets of different qualities.

# Comparison Of Methodologies And Geostatistical Approaches For Diagenesis Quantification

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## Abstract

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The objective of this paper is to compare several methods to integrate diagenetic constraints into geostatistical models using new methodological workflows. The main objective is to define rules and to acquire know-how in order to recommend one methodology or another, depending on the geological environment, the context of diagenesis, and the available data.

On a real dataset in fluvial environment, a relationship between the pore chlorite filling and the grain size has been quantified which allowed to define several degrees of diagenesis in the reservoir. Several alternative methods have been used to create a geological model of this reservoir with properties in terms of sedimentary facies and diagenetic class, as nested simulations, plurigaussian simulations and bi-plurigaussian simulations.

In the nested simulations workflow, each step is done sequentially: simulation of sedimentary facies, using a matrix of proportions in terms of sedimentary facies, simulations of the classes of diagenesis within each sedimentary facies, then reconstitution of the final information using logical rules to combine the different realizations. The simulation parameters are specific for each property, sedimentary facies and class of diagenesis. This method allows to uncouple the constraints in terms

of conditioning wells and parameters, for each simulated property. In return, it will not be possible to use a correlation between sedimentation and diagenesis. Moreover, there will be no continuity in the diagenetic property from one cell to another one, if the sedimentary facies changes between these cells.

The direct plurigaussian simulation (PGS) method has several strong points: a unique simulation is launched globally and a correlation coefficient may be used between the two Gaussian functions, which could translate the relationship between sedimentation and diagenesis. But the method is applied to only one global variable, and as illustrated with this example will be constrained only with the wells owning the two types of information, sedimentary facies and diagenesis.

A new model, the Bi-PGS model has been developed that provides a sound basis for bivariate categorical simulation. It is flexible as each physical process is associated with a complete PGS (possibly using two underlying Gaussian random function). A further possible development is to introduce a correlation between the two PGS. The Bi-PGS technique can cope with non-stationarity by using proportions for each sedimentation class and chemical level that vary in space. It would also be possible to use the Bi-PGS technique for processing two categorical data sets of different qualities.

## Introduction

### Preamble :

*This work is part of a common research project between ENI, MinesParisTech and IFP.*

*The objectives of this project are to obtain a more accurate and less uncertain prediction of the fluid flow behavior in reservoirs where the diagenesis has changed the original relationship between the facies and the distribution of the petrophysical properties.*

*The main objective of this part of the work is to improve methodologies, to define rules and to acquire know-how in order to recommend one simulation methodology or another, depending on the geological environment, the context of diagenesis, the available data.*

*This presentation is only a summary of some tests, the integrality of the results being ENI property.*

### The heterotopic problem :

Two types of properties/variables have to be simulated:

- sedimentary facies (4 classes)
- diagenetic index (4 index) which can be derived from continuous property (Chlorite Pore Filling,...)

These two variables are not systematically known at the same locations : heterotopic dataset

Additional information :

- Qualitative or quantitative information giving trends for the spatial distribution of the different classes.
- Correlations between the diagenetic index from one facies to another: continuity or independence ?

## Short presentation of the dataset

### The sedimentary problem:
- clastic sedimentary environment.
- reservoir : transgressive sequence, fining upwards.

### Dataset:
- Top and bottom structural surfaces from seismic picking
- 13 wells (3 vertical and 10 deviated) available.
- Well logs (NPHI, SGR, RHOB, DT) used in cluster analysis for facies definition,
  ⇨ initial interpretation in terms of 7 facies regrouped in 4 classes for the study.

### The diagenetic problem :

Five wells (W1 to W5) have been studied in a detailed petrographic analysis.
⇨ the "Chlorite Pore Filling" component is the element that gives a direct impact on permeability.
From sedimentological analysis of the cores sampled in the wells, a Core Grain Size Log has been built.
Finally four classes of diagenetic index or level have been defined from this continuous information, each of them with specific petrophysical properties definition
The database includes 13 facies, see the couplet facies-diagenesis combining 4 sedimentary facies and 4 levels of diagenesis (only one class for shale).

From field observations, Chlorite content is higher in the northern area (well W5), based on the information known by means of sedimentological models.

the couplet facies-diagenesis
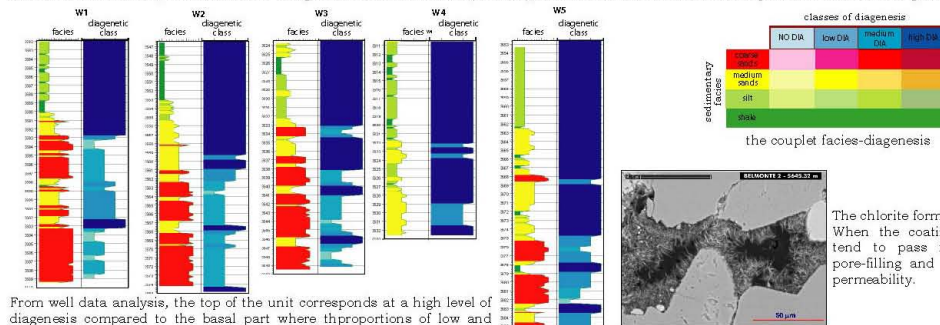
From well data analysis, the top of the unit corresponds at a high level of diagenesis compared to the basal part where theproportions of low and medium classes of diagenesis are important.

The chlorite forms coatings on grains. When the coatings are thick, they tend to pass from pore-lining to pore-filling and to heavily influence permeability.

From seismic interpretation, and computed from a correlation with porosities, four 3D grids of probabilities are available, one for each class of sedimentary facies, which have been combined into one 3D grid of proportions/probabilities of facies (MPC).

### "Non Specialist Area"
#### What are VPC and MPC ?

The VPC (vertical proportion curve) represents a cumulative histogram of the proportions of the facies present in the gridded wells. It is computed at each stratigraphic level, parallel to the reference level of the studied unit. It characterizes the vertical sequence and distribution of the facies in the reservoir unit from the available well data. (see Ravenne et al.for more details)
When the VPC is used as a parameter for the geological simulations, the facies proportions are considered to be constant in average for each horizontal level (stationarity).

The MPC (matrix of proportion vertical curves) corresponds to the cases when proportions vary also laterally (non stationarity). These proportions integrate qualitative or quantitative interpretations from geological and seismic data. The MPC is drawn as a 2D grid, each cell of which being a local vertical proportion curve.

**VPC or MPC are key parameters for the geostatistical facies simulations**

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## Nested simulations
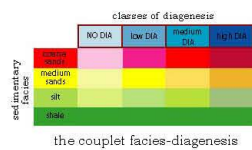
In this workflow, each step is done sequentially:
1. simulation of the 4 sedimentary facies,
2. simulations of the classes of diagenesis within each sedimentary facies which are concerned

(coarse sands, fine sands, silts); each simulation is done independently

### 1 The sedimentary simulation :

Truncation rule



13 wells conditioning the first PGS
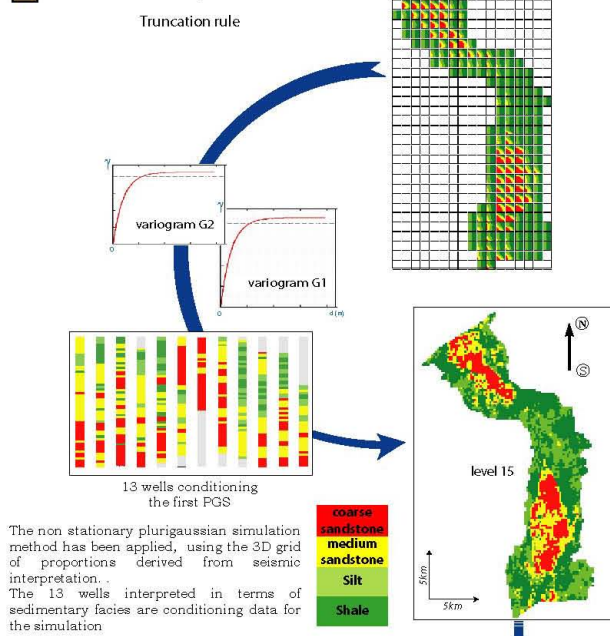
The non stationary plurigaussian simulation method has been applied, using the 3D grid of proportions derived from seismic interpretation..
The 13 wells interpreted in terms of sedimentary facies are conditioning data for the simulation

coarse sandstone
medium sandstone
Silt
Shale

level 15

level 15 diagenesis in coarse

5 conditioning wells

classes of diagenesis

NO DIA | low DIA | medium DIA | high DIA

### 2 The diagenetic simulation :

Sub-groups are defined within each sedimentary facies corresponding to the different levels of diagenesis
Then the diagenetic classes are simulated within each sedimentary class using specific method and parameters for each case :
- coarse sands : non stationary truncated Gaussian simulation method, and matrix of proportions obtained by kriging from the 5 wells diagenetic data for coarse sands,
- medium sands and silts : stationary truncated Gaussian simulation method.
These diagenetic simulations can be conditioned only to the 5 wells with diagenetic information

G1

K index

%

variogram G1

variogram G2

level 15 diagenesis in fine sands

5 wells conditionning the second PGS

+ level 15 diagenesis in silts
+ level 15 diagenesis in shales

### 3 

The final result (simulation combining sedimentary and diagenesis information) is finally computed using logical rules to combine the different realizations and using the couplet facies -diagenesis
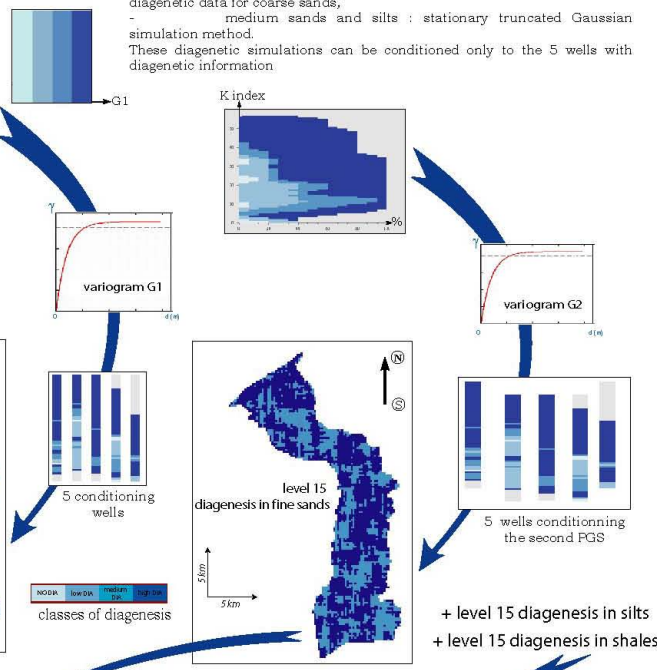
classes of diagenesis
NO DIA | low DIA | medium DIA | high DIA

the couplet facies-diagenesis

level 15

level 30

## Plurigaussian simulations

In this "direct workflow", one of the Gaussian functions, G1 is used to simulate the 4 classes of sedimentary facies, and the second one G2 is used to simulate the classes of diagenesis.
This direct approach allows to simulate directly the 13 classes of facies-diagenesis but in return, the constraints and parameters for the simulation have to be defined in terms of 13 classes of facies-diagenesis. The matrix of proportions, and the conditioning wells will also need to have the two types of information, sedimentary facies and diagenesis.
The method needs isotopic dataset for the two Gaussian and the result will be conditioned only by the 5 wells owning the two data.

### Transformation of the grid of % of sedimentary facies into a grid of % of "facies-diagenesis" :

proba high coarse | proba high diagenesis / coarse | proba high diagenesis and coarse
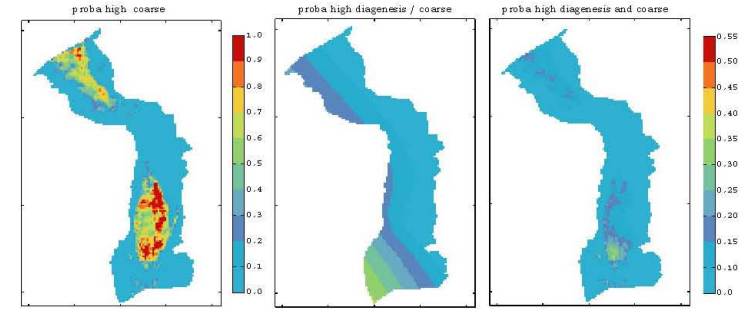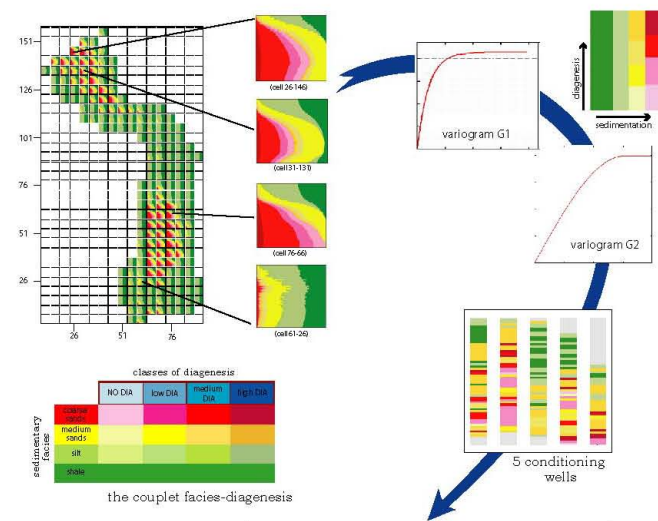
The probability matrix of the couplet facies-diagenesis has been computed combining these 2 types of properties, which can be expressed in terms of bivariate probabilities, as p(di∩fj)
In other words, the parameters combined in the matrix are:
p(coarse ∩ no diagenesis) = p(coarse) x p(no diagenesis / coarse)
p(coarse ∩ low diagenesis) = p(coarse) x p(low diagenesis/ coarse)
p(coarse ∩ medium diagenesis) = p(coarse) x p(medium diagenesis / coarse)
p(coarse ∩ high diagenesis) = p(coarse) x p(high diagenesis/ coarse)
p(fine ∩ no diagenesis) = p(fine) x p(no diagenesis/ fine)
- - - - - -
In order to take account for the non stationarity in the domain, the conditional probabilities, p(di / fj) terms, have been computed as 2D maps by spline interpolation of the data (mean values of proportions of each class of diagenesis in each class of facies) from the 5 wells where the diagenetic information is known.
These map have been normalized in order to keep the distribution of the values within [0, 1] and combined with the local proportion of sedimentary facies known in the matrix of proportions from seismic.

### Direct Conditional simulation in terms of "facies-diagenesis" but conditioning only by wells owning both properties (facies AND diagenesis)



diagenesis
sedimentation

variogram G1

variogram G2

(cell 26-146)
(cell 31-131)
(cell 76-66)
(cell 61-26)

5 conditioning wells

classes of diagenesis
NO DIA | low DIA | medium DIA | high DIA

sedimentary facies: coarse sands / medium sands / silt / shale

the couplet facies-diagenesis

level 15

level 30

## "Non Specialist Area" : (Pluri) Truncated Gaussian simulation ? How does it work ?

The truncated Pluri - Gaussian (PG) method is a generalization of the Truncated Gaussian model: the thresholds are defined according to two different Gaussian random variables (correlated or not).
The qualitative relationship between the different facies is summarized in a lithotype rule, giving their arrangements. In this illustration the green facies erodes the yellow and orange ones.

Z(x)
Threshold
Z<cutoff

Simulated lithofacies
(proportions $p_A$ / covariance $K(h)$)
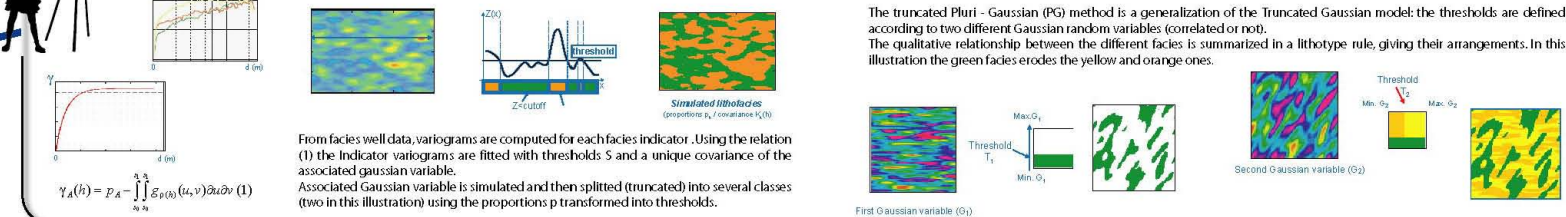
From facies well data, variograms are computed for each facies indicator .Using the relation (1) the Indicator variograms are fitted with thresholds S and a unique covariance of the associated gaussian variable.
Associated Gaussian variable is simulated and then splitted (truncated into several classes (two in this illustration) using the proportions p transformed into thresholds.

$$\gamma_A(h) = p_A - \int\int_{h_1}^{h_2}\int \mathcal{E}_{\bar{p}(h)}(u,v)\partial u\partial v \ (1)$$

First Gaussian variable (G1)

Threshold T1
Min. G2

Second Gaussian variable (G2)

Threshold T1
Min. G2 | Max. G2

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## Bi- Plurigaussian simulations



variogram G1

MPC in 4 classes of diagenesis

MPC in 13 classes of facies-diagenesis

MPC in 4 sedimentary facies

variogram G1

variogram G2

G2

| coarse sandstone |
| medium sandstone |
| Silt |
| Shale |

Truncation rule

classes of diagenesis

5 wells conditionning the second PGS

13 wells conditioning the first PGS
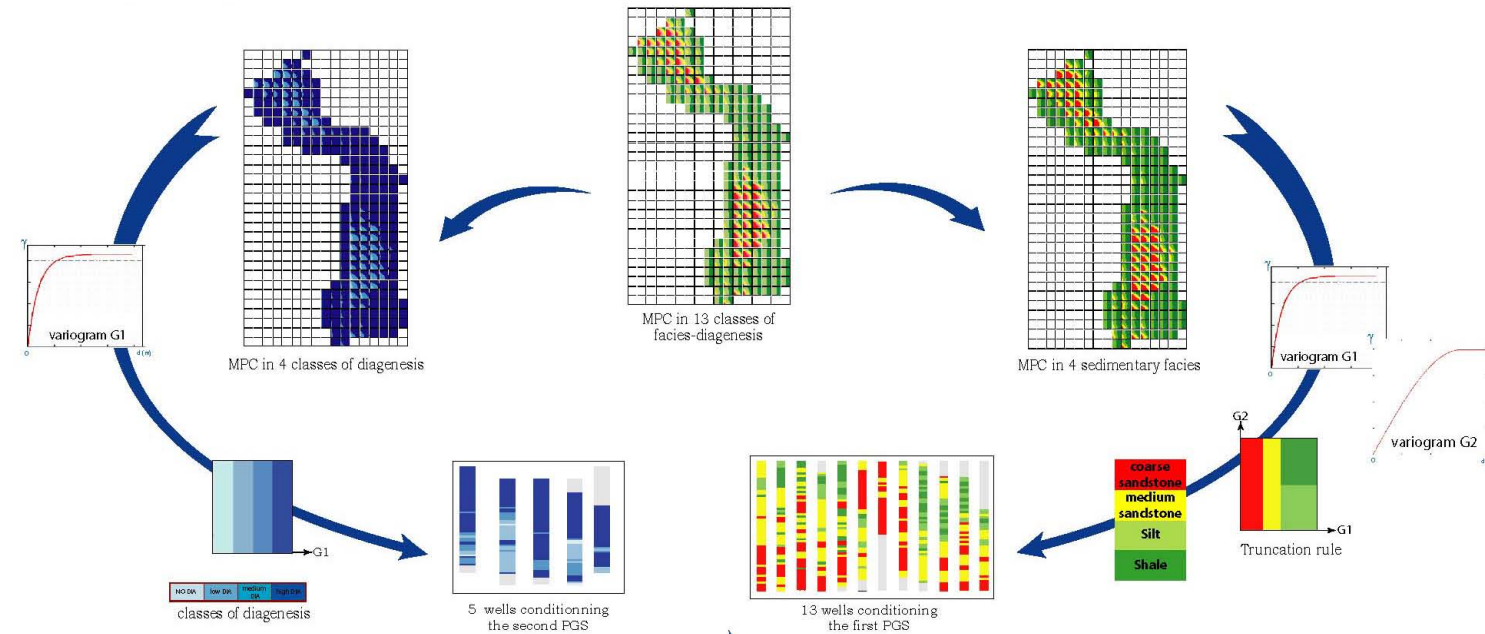
A new model, the Bivariate PluriGaussian (Bi-PGS), has been developed to address the problem of heterotopic bivariate conditional simulation.

The sedimentation process is governed by a complete PGS model, classically characterized by the number of GRF (Gaussian Random Function), their models and possible correlation, the proportions of the different sedimentation categories.

The diagenetic process is governed by a second complete PGS model.

The link between the two PGS is given through the proportions of all the associations of a sedimentation class with a diagenetic class, the previous MPC.

For the conditioning step, all heterotopic data are now included. For example, a grid cell, which belongs to a given sedimentation class, but has no measured diagenetic properties is used as a conditional information in the first PGS and will not constrain the second PGS.

An analogous situation would pertain for a sample with a recorded diagenetic class but no sedimentation information.

level 15

level 30

5km

### And so what ??

Nested :
- no continuity / correlation in the diagenesis

Bi-PGS :
- all data are conditioning
- continuity in the diagenesis

PGS
Wells without diagenesis are not used in the conditioning, thus are not honoured

## Pros and Cons of the nested method

As shown on this example, the 13 wells informed in terms of sedimentary facies are conditioning for the plurigaussian simulation of sedimentary facies.

The data for diagenesis are available on 5 wells only which have been used for conditioning the simulation of diagenetic classes.
The proportion matrix, variogram models, external constraints are specific for each property, sedimentary facies and class of diagenesis.

- This method allows to uncouple the constraints in terms of conditioning wells and parameters, for each simulated property. It would thus be possible to give different trends for diagenesis depending on the considered facies.

- In return, it will not be possible to use a correlation between sedimentation and diagenesis as it is in a plurigaussian simulation,

- Moreover, there will be no continuity in the diagenetic property from one cell to another one, if the sedimentary facies changes between these cells (in other words, a coarse sand with a high level of diagenesis could be close to a sand with no diagenesis for example).

## Pros and Cons of the direct plurigaussian method

This direct method has several strong points:
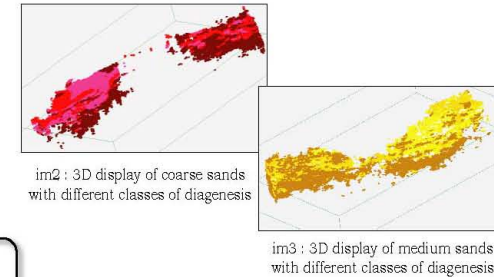- A unique simulation is launched globally

- A correlation coefficient may be used between the two Gaussian functions, which could translate the relationship between sedimentation and diagenesis

but also some constraints:

- The method is applied to only one global variable, and, as illustrated with this example, will be constrained only with the wells owning the two types of information, sedimentary facies and diagenesis.

and difficulties:

- The method needs the computation of the proportions of this global variable representing both sedimentary facies and diagenetic class. The computation should take into account the relationships between the two underlying physical processes, sedimentation and diagenesis.

## Synthesis - Discussion

im2 : 3D display of coarse sands with different classes of diagenesis

im3 : 3D display of medium sands with different classes of diagenesis

## Pros and Cons of bi-plurigaussian simulation (bi-PGS)

This method gives a large flexibility in the choice of parameters characterizing each type of variables, and allows to take into account heterotopic variables, meaning with different supports.

The Bi-PGS model is a new model that provides a sound basis for bivariate categorical simulation. It is flexible as each physical process is associated with a complete PGS (possibly using two underlying GRF). A further possible development is to introduce a correlation between the two PGS, but this option still has to be specified more precisely.

- The difficulty will be to compute the 3D matrix of proportions combining the rules and physical laws between sedimentation and diagenesis.

## Conclusions - Perspectives

Other simulation methods as multipoints statistics simulations, object based approaches and SIS have also been tested to generate the sedimentary model. Diagenesis classes have then be simulated inside this model.

The different simulations are being processed by reservoir engineers specialists of the field. Their simulated permeabilities have been compared by well test permeabilities which have not been used in the process (blind tests).
Final petrophysical realisations have been ranked in terms of history matching results considering different parameters, as oil rate and water production, or bottom hole and tubing head pressure, and rated.

Results change depending on the methods, but are globally satisfactory in terms of history matching.

Some sensitivity analyses have been carried out, in particular on the impact of the MPC which is a key parameter for geostatistical simulation. This MPC can be obtained using different approaches, and integrating different types of constraints, qualitative and quantitative. It is also linked to hypotheses made on the links between facies and diagenesis. Different matrix of proportions have been computed and used as alternative parameters for the simulations.