Geovariances
Where no one has gone before

White Paper

Geological Facies Simulations

Stochastic methods for geological modeling and links with fluid flow simulations

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Stochastic Methods for geological modeling and links with fluid flow simulations

Whatever the application domain - oil & gas production, aquifer pollution characterization, uranium production by lixiviation – characterizing the geological parameters and capturing their variability is essential to ensure realistic flow modeling.

Each time fluid movements in porous and permeable rocks must be modelled, it is of primary importance to build an accurate model of the geological facies distribution in the sub-surface. For example, in the Oil & Gas industry, Production History Match optimization and improvement of reservoir models prediction capability require a good consistency between geological static model and dynamic model. Similar issues exist in hydrogeology and in aquifer pollution control. If the uncertainty on flow models must be quantified, then it is necessary to build several realistic 3D images of the geological facies distribution, which is one of the main contributors to the flow behaviour uncertainty. Such images can be generated by using stochastic simulations methods.

The characteristics of the distributions of key parameters conditioning the flow behaviour in porous media (e.g. porosity, permeability, etc.) are informed by the geological context. An intuitive way to represent and thus characterise that geological framework is to use categorical variables, a common example being lithological facies coding.

The geological heterogeneity of the facies has to be reproduced in the model before being populated by other parameters (e.g. petrophysical properties). Besides, producing stochastic models using appropriate simulation techniques contributes to assess the uncertainty attached to fluid movements in the sub-surface.

A large variety of facies simulation techniques is available. They are not all similar and they have to be chosen according to the specific geological depositional environment. For instance, methods for deposits of sedimentary origin have been particularly developed to best represent a deposition sequence.

Over the last decade, Geovariances has gained expertise in developing successfully simulation strategies for different geological environments: fluvio-deltaic deposits, turbiditic and carbonate reservoirs or aquifers, karstic environments.

Aim of facies simulation

Simulations of facies and petrophysical properties (porosity, permeability) are the basis for analysing the dynamic performance of an aquifer or of a hydrocarbon reservoir as these latest mainly depend on lithologies (shale/sand/ sandstone/etc.). See an example Figure 1.

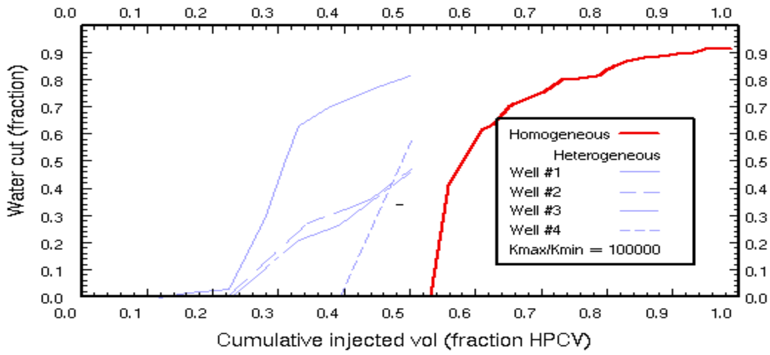

Figure 1: The water cut from a five spot scheme (water injection at the centre and recovery from four corner wells) is completely different if the area has a homogeneous permeability (red curve) or if the permeability is heterogeneous (blue curves). In the latter case the average water cut is NOT the water cut from a homogeneous averaged permeability.

Applying complex process (fluid flow or selective mining) must be supported by a geological model reproducing the variability and heterogeneity of the key parameters.

It is recommended to achieve simulations of properties using a two-step procedure to better ensure geological realism:

1. Simulation of geological parameters (facies) by an appropriate method dealing with categorical variables. In each facies, petrophysical properties should be quite homogeneous and significant contrasts are expected from one facies to another.

2. Population of the model with given properties (petrophysical parameters).

Methodologies

The most common methods are presented below. For clarity, they can be regrouped into few categories:

The main categories of simulation methods are:

- **Process based**
- **Object based**
- **Pixel based: SIS, TGS/PGS.**
- **Pattern based: MPS.**

Process-based methods

These methods are not generic but specific to the type of geological environment. They aim at reproducing the deposition of different materials over the geological times. An example is given by the simulation of fluvio-deltaic sediments using FLUMY, a model developed by Mines ParisTech Geosciences Group.

Advantages – As the simulation of the facies is guided by geological controls over time, the resulting image looks realistic.

Drawbacks - The conditioning to the data is difficult to achieve for a large number of data.

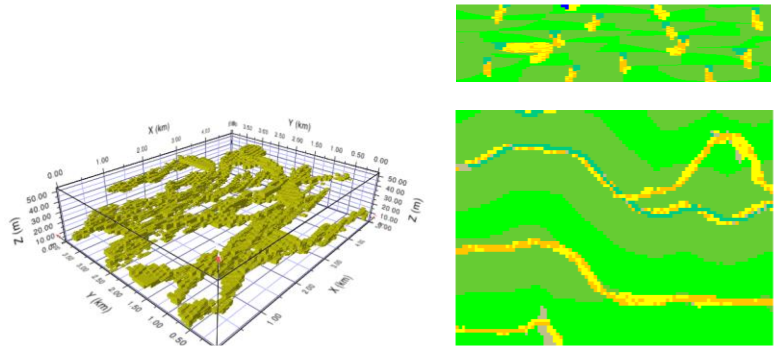

Figure 2: Example of simulated channels by process-based method FLUMY (Courtesy Mines ParisTech Geosciences Group)

Object-based methods (e.g. Boolean)

The method aims at describing the geology with "geometrical" objects or combinations of objects.

A first step consists in randomly selecting points in the 3D space (e.g. according to a Poisson process). A second step anchors the gravity centre of simple shaped objects on the previously selected points. As several objects can overlap the same node, a value is attached to each node by applying an operator (like sum, maximum, etc.) to the objects covering that node. This is done for each node of the grid.

Advantages - Resulting images show continuity, they are not "pixelated" and give an impression of geological realism in simple cases.

Drawbacks – Difficulty to quantify input parameters; simulations depending on a limited list of simple shapes; conditioning to wells may be tedious.

Pixel-based methods (SIS, TGS/PGS)

Sequential Indicator Simulations (SIS) or Truncated Gaussian/PluriGaussian Simulations (TGS/PGS) are based on stochastic modelling of facies indicators.

In the case of SIS, the facies outcomes are obtained after an iterative indicator kriging process of each facies indicator performed along a random path. A random number is generated from a uniform distribution, the facies is chosen by comparison with the kriged indicators.

SIS or PGS are not just two algorithm options. They are linked to conceptual interpretation of the transitions between facies.

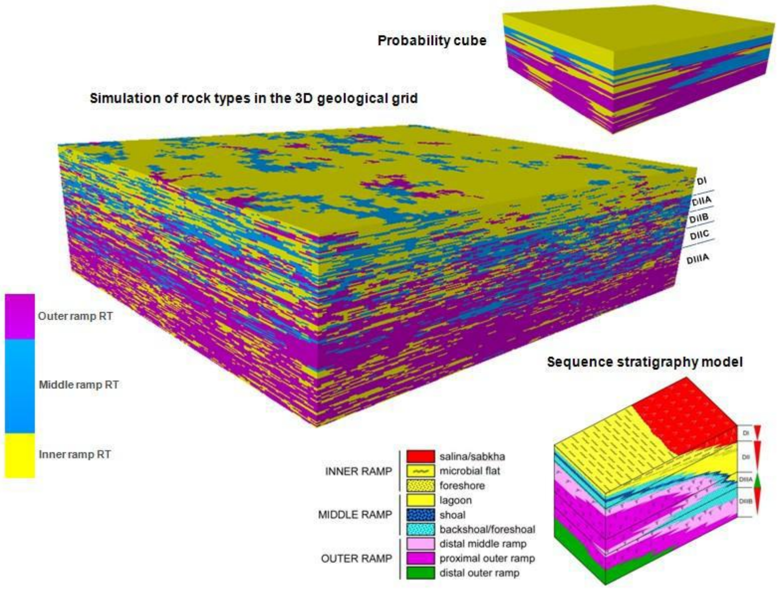

Figure 3: Example of SIS simulation of a carbonate formation (from Al Emadi et al., 2009).

For TGS/PGS, facies is obtained by applying thresholds to a simulation of one (TGS) or two or more (PGS) underlying Gaussian random function(s) characterized by a variogram model. In that method, facies proportions play an important role. These proportions are derived from wells/drillholes vertical proportion curves (VPC) with a possible integration of seismic data or existing external geological model.

The VPCs are used to estimate the facies proportions: either as local mean in simple kriging used in SIS, or to derive thresholds applied to get facies from simulated Gaussian functions in PGS.

Note that these VPC are also used as local mean in SIS.

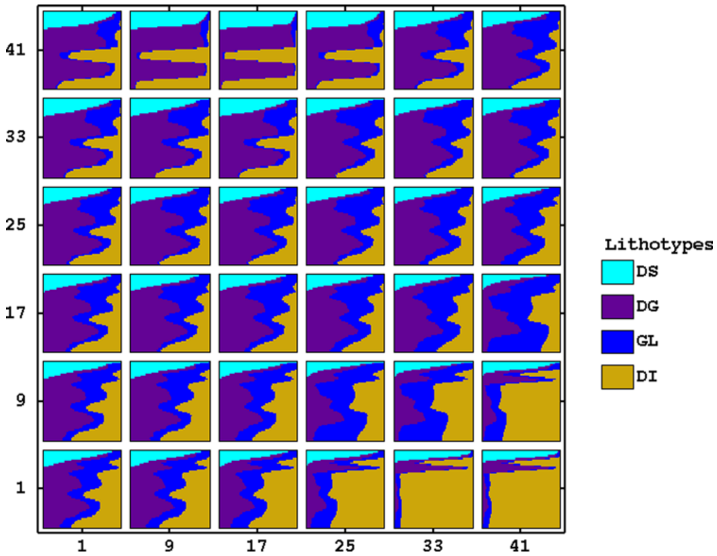

Figure 4: Vertical proportion curves grouping Glacier Bonnard boreholes in regular cells (from Jeannée et al., 2013).

In PGS, transitions between facies are controlled by the "lithotype rule". This is done graphically to give the user as much control as possible.

Case Study for Glacier Bonnard (Switzerland)

Plurigaussian simulations have been used to model the glacier’s internal structure in terms of ice content. Results have been used to evaluate the glacier’s current global dynamic and future evolution, in order to anticipate its constant creep over a settlement and control the environmental hazard. (Jeannée et al, 2013).

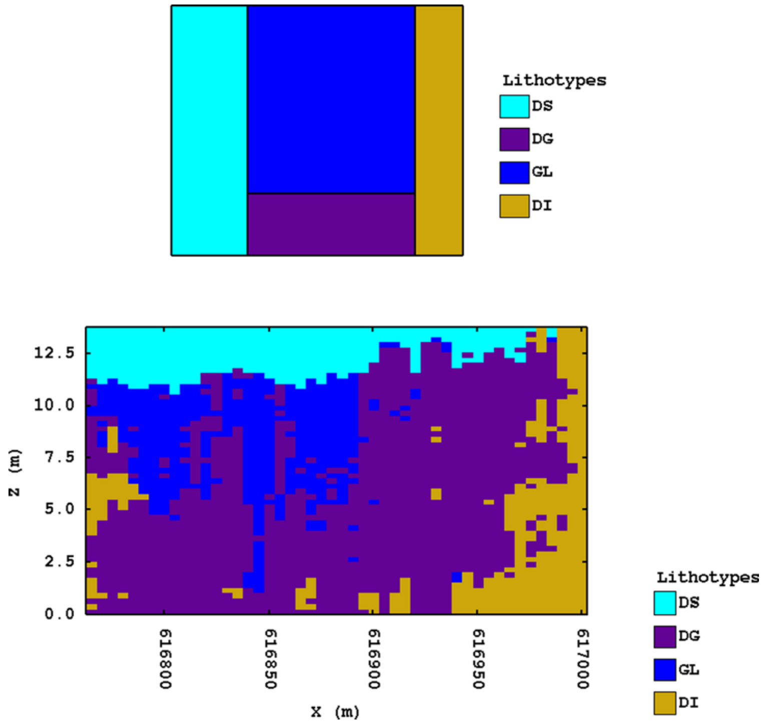

Figure 5: Top: Lithotype rule displaying authorized transitions between the facies. Bottom: cross-section example of a lithotype simulation using the plurigaussian approach. DS: Superficial diamict, DG: Glaciated diamict, GL: Ice and DI: Diamict (from Jeannée et al., 2013)

Although TGS/PGS has been originally developed for simulating oil & gas reservoirs resulting from a sedimentation process, it has wider applications in hydrogeology and in mining industry.

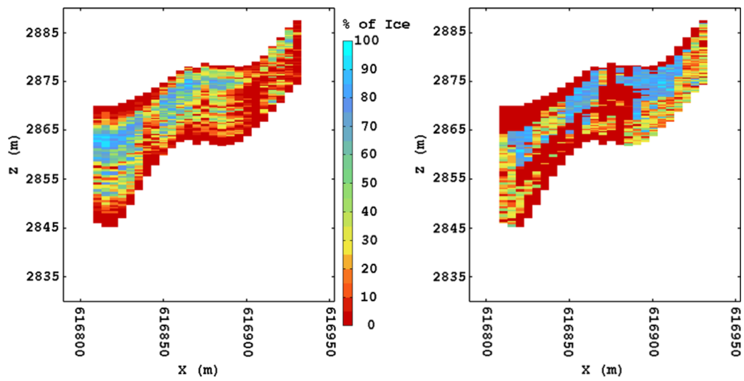

Figure 6: Cross-section of the ice content simulations using turning bands (left) or indirectly via plurigaussian (right) - (from Jeannée et al., 2013).

In opposition to Process/Object/Pattern-based methods, the variogram is a key input for SIS and TGS/PGS.

In addition, PGS offers more flexibility than SIS for two reasons:

- The number of combinations resulting from different structures of spatial correlation is increased by using two random functions.

- Variograms of indicators used in SIS are restricted to models less continuous than spherical models (e.g. exponential structures).

Advantages - Pixel-based methods are controlled by geostatistical parameters that can be inferred from the data and checked on the results. The conditioning is fully guaranteed whatever the number of data.

Drawbacks - The resulting images are "pixelized" departing from geological realism.

Pattern-based method: Multiple Point Statistics Simulations (MPS)

This method has been proposed in the 2000's with the objective of combining advantages of object and pixel-based methods.

The same training image may be used in MPS or for calculating proportions in PGS.

By choosing the variogram ranges, the continuity of the facies can be better adjusted in PGS than in MPS.

The central idea is to assume that the geological environment is described through a training image capturing the main features to be reproduced by the simulation at different scales.

The facies at a given point is derived from statistics of higher order than just the variance computed from pairs of points (variograms). The outcomes are obtained from the probability of having a facies given a similar configuration of neighbours calculated from the training image (TI). The configuration of neighbours is defined by a geometric pattern used for scanning the training image and for simulations.

The crux of the method is the training image and how to get it: from conceptual model, analogs, geological controls, etc.

The basic algorithm can be made more complex, for instance by adding information on local proportions to account for non-stationarity.

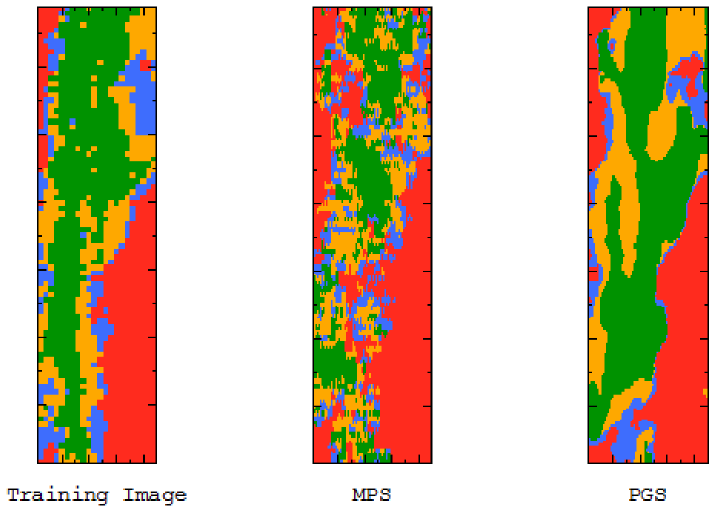

Figure 7: Training Image (TI) of a carbonate reservoir, one MPS simulation, one simulation from PGS with proportions calculated from the TI

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Advantages - The facies organization, even complex, is kept with a high level of details without requiring the simplification introduced by a variogram model.

Drawbacks - How to get the training image and its level of confidence is the main issue.

Applications

Among many practical applications of simulations of categorical variables, we can mention:

- From n facies simulations, a simple statistical analysis provides a local estimate of the probability to meet a given facies. An appropriate methodology also allows getting one geological model interpreted as a **probable model** from the analysis of several simulations.
- **Sampling optimization applied to complex models of geology and properties** is another powerful application:
    - In case of continuous properties, simulated samples extracted from a simulated grid can be used for kriging these properties. The difference between the simulated values and the kriged estimates is an outcome of the estimation error. Statistics can be derived from the distribution of n simulated errors and compared with the statistics obtained by modifying the sampling pattern used to extract samples.
    - In case of categorical variables, this approach cannot be applied because the simulated value is a facies code while the kriged estimate is a probability. The solution consists in performing for each facies simulation a second set of facies simulations that will be again populated by simulations of the continuous properties for generating an E-type estimate (i.e. the mean value of the *ccdf*). Even if the process is heavy and time consuming, it meets the goal with commonly available computing resources.

Link with flow simulations

Facies and petrophysical properties simulations are the basis for analysing the dynamic performance of an aquifer or of a hydrocarbon reservoir. The fluid flow behaviour is usually studied by mean of flow numerical simulations, using the geological model as a representation of rock properties distribution, and calibrated on well test data and/or production data. Such numerical simulations can properly predict the fluid movements in the sub-surface if and only if the geological static model on which they are based is realistic enough.

In particular, the geological static model must be constrained, as much as possible, with information coming from the analysis of

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Flow numerical simulations can properly predict the fluid movements in the sub-surface if and only if the geological static model on which they are based is realistic enough.

dynamic parameters measurements. Such information is, for example: hydraulic connections between perforations in different wells, average permeability around a well, presence of sealing faults, of permeability barriers or drains, fractures density and impact.

The presence of a permeable pathway between two wells is one of the most critical parameters for the fluid flow in the porous rocks, but it is not an input parameter for the different facies and properties simulation methods. Nevertheless, there are some ways to force the geological models to honor such constraints.

First, it is easy to check the presence of a permeable pathway between selected points in a geological model by calculating **Connected Components**. A Connected Component is a group of contiguous cells sharing the same facies (or group of facies), defining a continuous geobody. If the selected points are in the same geobody made of permeable rocks, then they can be considered as connected.

The simplest approach to force a geobody to include different wells consists in increasing the amount of the permeable facies which establishes the physical connection in the interwell space.

If it is not sufficient, it is possible to test the connection between wells on several stochastic realizations of the same model and to calculate, for each cell of the geological model, the percentage of realizations in which the cell belongs to a connecting geobody. Selecting randomly in the interwell space some cells corresponding to a high percentage allows defining additional control points used in further calculations of enhanced geological model realizations. Connections are always established in such realizations. This approach works with any simulation technique.

Permeable pathways between points in a geological model can be identified by calculating Connected Components.

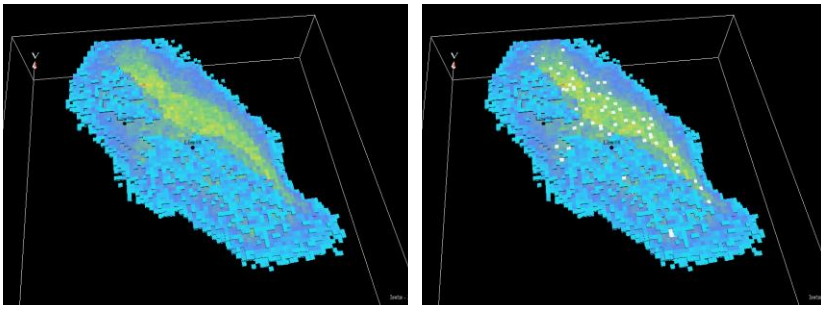

Figure 8: Left side = Probability of presence in connecting geobody; Right side = Probability of presence in connecting geobody + Additional random conditioning data (in white) - (from Chautru et al., 2015)

Who is Geovariances?

Geovariances is a specialist geostatistical consulting and software company. We have over 40 staff, including consultants and statisticians specialized in mining, oil & gas contaminated sites and hydrogeology.

Our software, Isatis, is the accomplishment of 25 years of dedicated experience in geostatistics. It is the global software solution for all geostatistical questions.

Other technical specialties

Geovariances are world leaders in developing and applying new and practical geostatistical solutions. We have gained trust from the biggest international companies and geological surveys.

Our expertise is in applying geostatistics to resource evaluation or geological modelling. Our services are through consulting, training, and software.

Our expertise

Geovariances has more than 20 years of experience in developing simulations methods into Isatis, its leading-edge geostatistical software solution, and in applying them in reservoir and orebody modelling worldwide. Isatis is unique in providing all the methodologies described earlier.

Geovariances collaborates with worldwide research leaders to develop innovations in Isatis. In particular, the TGS/PGS methods have been implemented after research works achieved by **Mines ParisTech Geostatistics Group** and **IFP** (French Institute of Petroleum). Isatis MPS implementation is based on the **IMPALA** high performance algorithm developed by the **University of Neuchâtel** and **Ephesia Consult**© (IMPALA stands for **I**mproved **M**ultiple-point **P**arallel **A**lgorithm using a **L**ist **A**pproach).

Geovariances is dedicated to applied geostatistics and has set the standards in geosciences, providing the industry with premium software and consulting solutions for more than 25 years. The company can provide a unique expertise through both its French, Australian and Brazilian offices.

For more information

Let us help you design your tailored simulation workflow for a better quantification of your uncertainties.

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