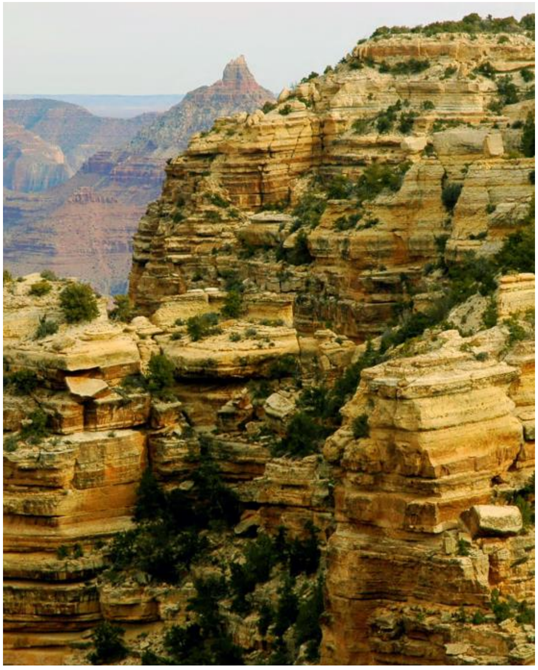
Geovariances
Where no one has gone before

White Paper



Geological Facies Simulations

Methodologies for stochastic simulations of geological facies and applications to resource estimation

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Whatever the resource involved - oil & gas, coal or metallic resources – capturing the variability of the geological parameters is essential at the modelling stage.

The characteristics of the distributions of key parameters conditioning the resource recovery (e.g. rock properties, grades, 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 supporting the estimation process before being populated by other parameters (e.g. grades or petrophysical properties). Besides, producing stochastic models using appropriate simulation techniques fully allow assessing the uncertainty attached to the resource estimates.

A large variety of 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: kimberlite pipes, turbiditic and carbonate reservoirs, porphyry copper and hydrothermal type deposits.

Aim of facies simulation

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

Resource recovery and uncertainty depends on geological heterogeneities:

- Petrophysical properties (porosity, permeability) in oil/gas reservoirs mainly depend on lithologies (shale/sand/sandstone/etc.). See an example Figure 1.

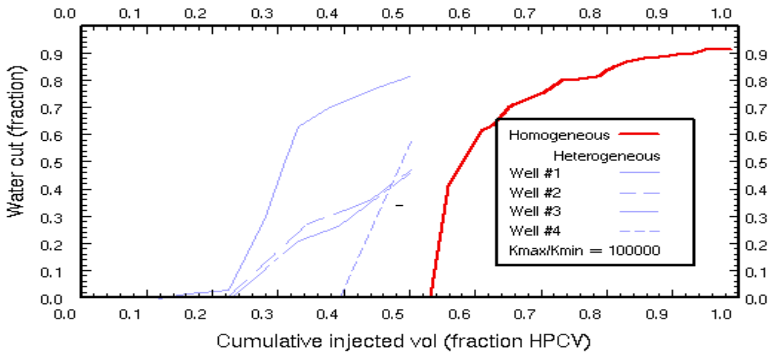

Figure 1: The water cut from a five spot scheme (water injection at the centre and recovery from four corner wells) is completely different if the area has a homogeneous permeability (red curve) or if the permeability is heterogeneous (blue curves). In the latter case the average water cut is NOT the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

- Ore grades with specific distributions conditioned by geological parameters have to be categorized to avoid modelling multi-modal histograms.

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

Methodologies

The main categories of simulation methods are:

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

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

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.

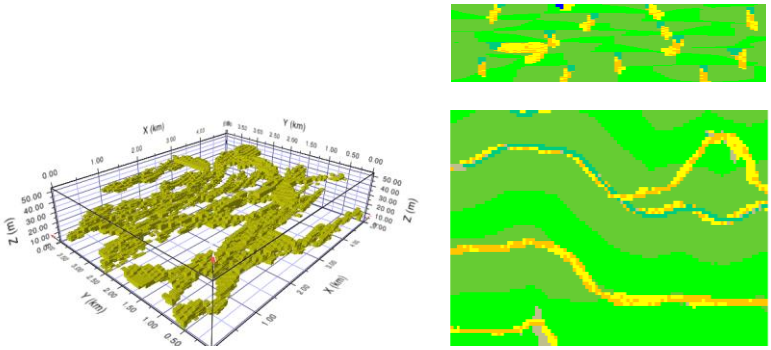

Figure 2: Example of simulated channels by process-based method FLUMY (Courtesy Mines ParisTech Geosciences Group)

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.

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.

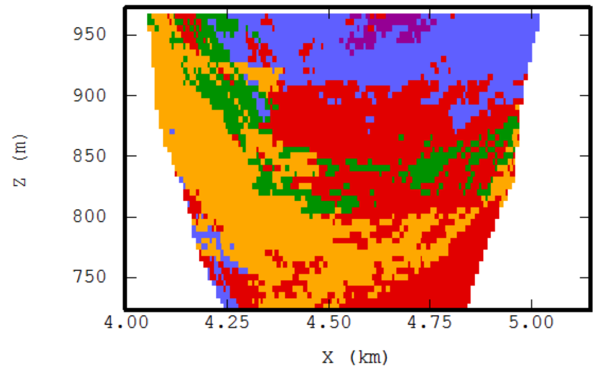

Figure 3: Example of SIS simulation of facies in a kimberlite pipe.

For TGS/PGS, a 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/drill holes vertical proportion curves (VPC) with a possible integration of seismic data or existing external geological model.

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

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.

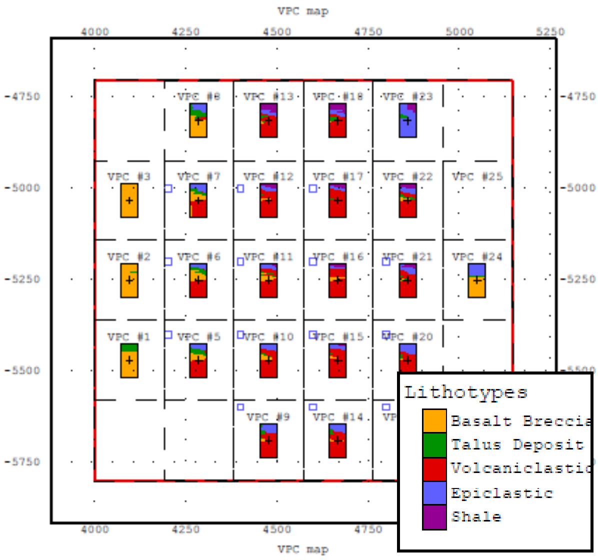

Figure 4: Vertical proportion curves grouping drillholes in regular cells.

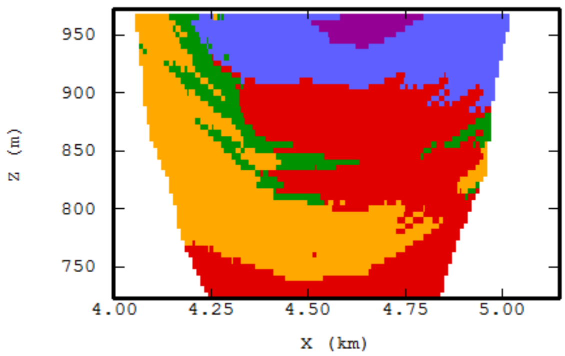

Figure 5: Same kimberlite pipe section as in figure 3 simulated by PGS.

Case Story for Orapa Kimberlite Mine

Plurigaussian simulations have been used to model the different sedimentary facies inside the crater zone. Results have been used to guide sampling programs to optimise sampling layouts and sample size and ensure that the goals of the sampling programs are attainable (Deraisme and al, 2004).

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

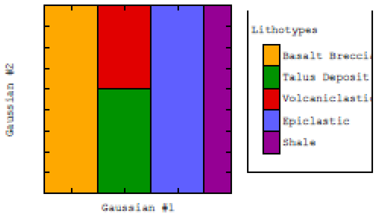

Figure 6: Lithotype rule (e.g. Basalt Breccia and Volcaniclastic facies cannot be in contact).

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

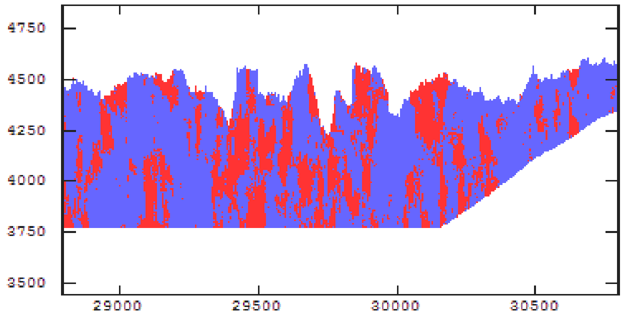

Figure 7: PGS of 2 facies of a volcano-sedimentary copper deposit.

In opposition to Process/Object based methods the variogram is a key input for these methods.

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).

Transforming the horizontal deposition of materials in a sedimentary process into vertical layering in a porphyry copper makes possible to apply TGS/PGS in a different context.

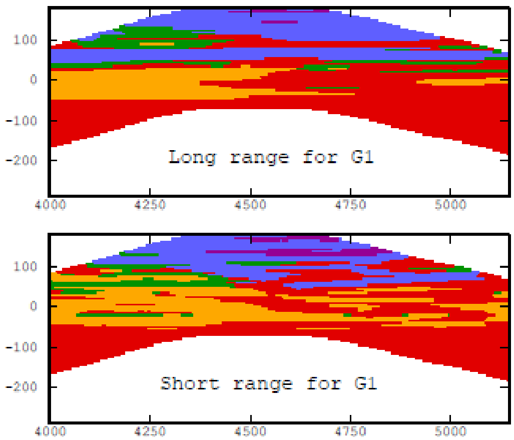

Figure 8: Comparison of two simulations based on two variograms used for the first Gaussian function of PGS

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.

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.

Multiple Point Statistics Simulations (MPS)

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

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 crux of the method is the training image and how to get it: from conceptual model, analogous orebody, geological model obtained after open pit exploitation and geological controls, etc.

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

Case Story: Modelling of mineralized zones in a hydrothermal deposit

A training image has been developed from abundant production data in order to provide an analogue to simulate deposits in similar geological settings in the context of Multiple-point Statistics Simulations (MPS). MPS have also been used to quantify the uncertainty with regard to different borehole drilling grids (Deraisme and al, 2013).

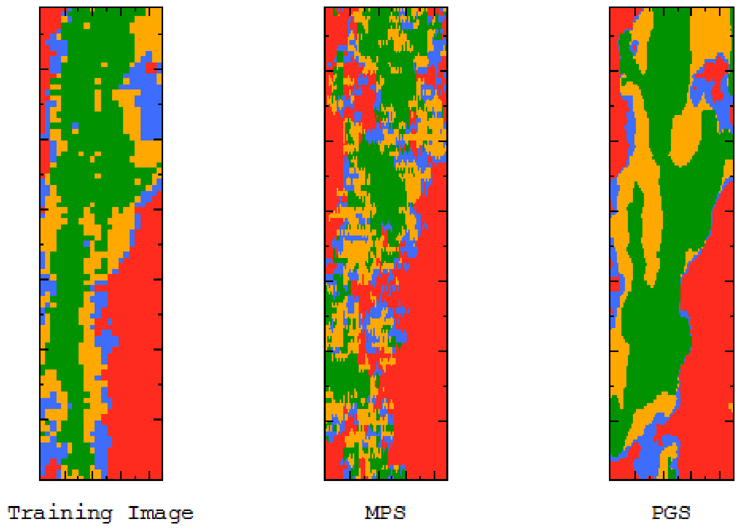

Figure 9: Training Image (TI) of a carbonate reservoir, one MPS simulation, one simulation from PGS with proportions calculated from the TI

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. As shown in the example of Figure 9, the combination of MPS and PGS may provide a good solution.

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.
- Uncertainty characterization on tonnage and grade after cutoff when grade AND geometry of mineralization are at stake. For instance, 100 simulations of facies are firstly generated, then 100 grade simulations are generated for each facies. Both facies and grades are combined to get 100 grade simulated models. An E-type estimate (i.e. the mean value of the *ccdf*) from these simulations will then provide a local estimation model.
- 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 as explained above. Even if the process is heavy and time consuming, it meets the goal with commonly available computing resources.

Perspectives

The Potential Field method provides new perspectives in geostatistical simulations.

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Who is Geovariances?

Geovariances is a specialist geostatistical consulting and software company. We have over 45 staff, including specialist mining and oil consultants and statisticians.

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 to mining operations or for oil reservoir modelling. We have gained trust from the biggest international companies.

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

The principle of the method is to derive the geometry of a domain from a 3D interpolation of a scalar field, known as the Potential Field. This is achieved by cokriging the information on contacts from drill holes and structural data linked with the gradient of the potential field.

The possibility to simulate the Potential Field is currently examined by a Research Consortium on Geological and Geostatistical Domain Modelling (G2DC) carried out by Geovariances and the Centre de Geosciences of Mines ParisTech with the sponsorship of five leading mining companies.

Our expertise

Geovariances has more than 15 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 mining industry with premium software and consulting solutions for more than 25 years. The company can provide a unique expertise through both its French and Australian offices.

For more information

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

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