Reservoir characterization

This paper gives an overview of the activities in geostatistics for the Petroleum industry in the domain of reservoir characterization. This description has been simplified in order to emphasize the original techniques involved.

The main steps of a study consist in successively building:

- the reservoir architecture where the geometry of the units is established,
- the geological model where each unit is populated with lithofacies,
- the petrophysical model where specific petrophysical distributions are assigned to each facies.

When the 3-D block is completely specified, we can calculate the volumes above given contacts and perform well tests.
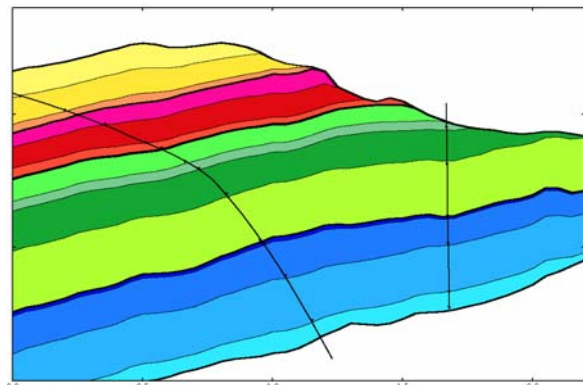
The reservoir architecture

The aim is to subdivide the field into homogeneous units which correspond to different depositional environments. The main constraints come from the intercepts of the wells (vertical or deviated) with the top and the bottom of these units.
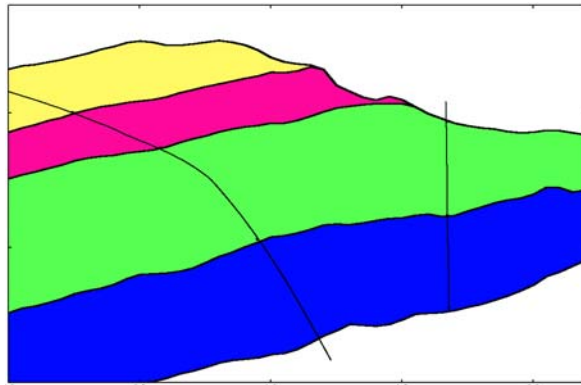
Layers constrained by well intercepts

The procedure can also be enhanced by the knowledge of seismic markers (in the time domain) strongly correlated to these surfaces. The seismic markers also reflect the information relative to the faulting. The time-to-depth conversion involved must be performed while still honoring the true depth of the intercepts.


Layers divided into sub-units

Finally each unit can be subdivided into several sub-units if we consider that the petrophysical parameters (porosity for example) only vary laterally and are homogenous vertically within each sub-unit. In this case, the constraints are provided by the intercepts of the wells and no seismic marker can be used to reinforce the information.

The geometry model makes it possible to evaluate the gross rock volume, or when the main petrophysical variables are informed, it can even lead to the computation of the fluid volume.

In terms of geostatistics, the layer surfaces or the petrophysical quantities are defined as random variables. The aim is to produce the estimation map constrained by the well information, and its confidence map as a side product. Each random variable is characterized by its spatial behavior established by fitting an authorized function on the experimental **variogram** computed from the data. This fitted variogram, called the **model**, quantifies the

correlation as a function of the distance and reflects the continuity and smoothness of the variable.
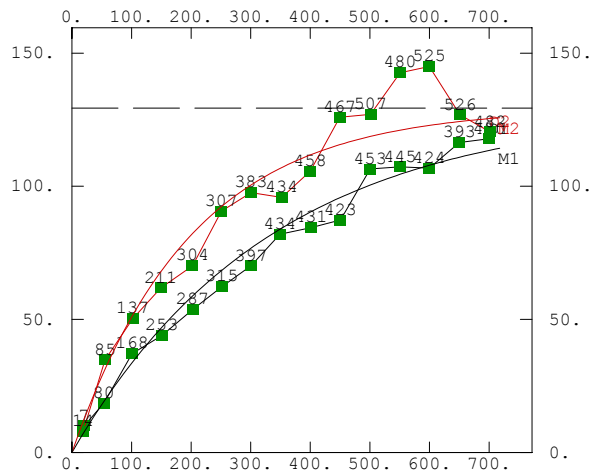
Experimental variograms calculated in two directions and the corresponding anisotropic model

The model is the main ingredient required by the estimation procedure (called **kriging**) which produces the most probable smoothed map constrained by the data.

When looking for volumes (i.e. quantity contained in a unit between the top reservoir and a contact surface) a non-linear operation is obviously involved. The results will be biased if the calculation is applied to the top surface produced by a linear technique (such as kriging or any other usual interpolation method).
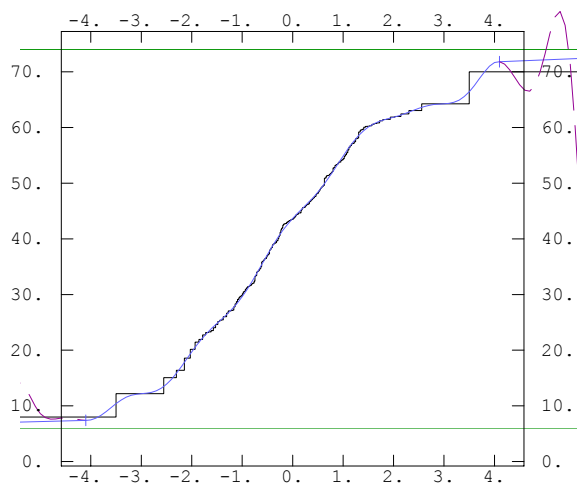
Instead the **simulation** technique must be used which produces several possible outcomes: each outcome reproduces the characteristics of the input variable (which is certainly not the case for the result of an interpolation method). Finally each simulated outcome must still honor the constraining data.

Most of the simulation procedures rely on the (multi-) gaussian framework and, therefore, require a prior transformation of the information (from the raw to the gaussian space) as well as a posterior transformation of the gaussian simulated results to the raw scale. This transformation is called the gaussian **anamorphosis** fitted on the data.

*Anamorphosis function used for conversion between raw and gaussian space*

The simulation of a continuous variable can be performed using various methods such as the turning bands, the spectral or the sequential methods: the choice is usually determined by the variogram model and the size of the field (count of constraining data and dimension of the output grid).
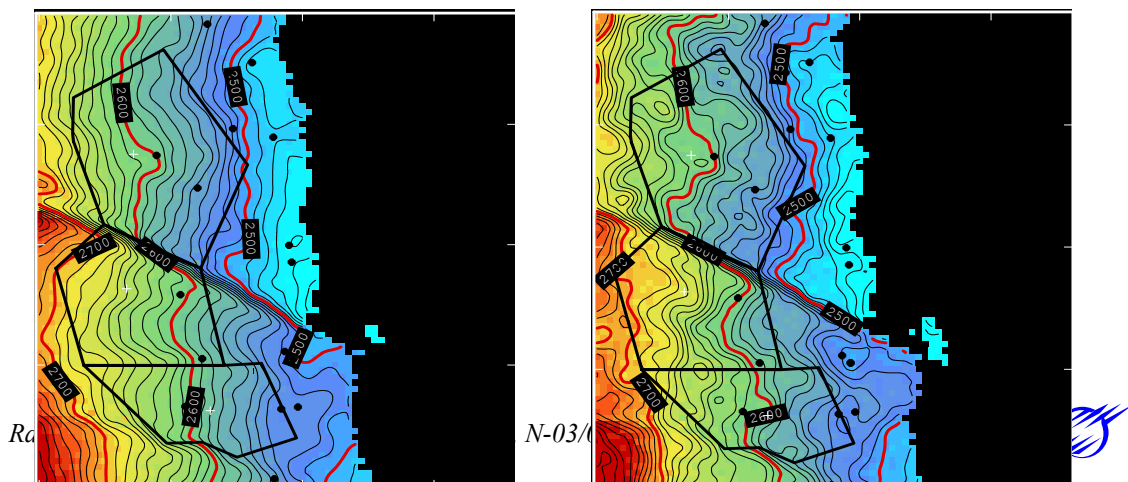
Comparison between the depth surface interpolated by kriging (left) and simulated (right)
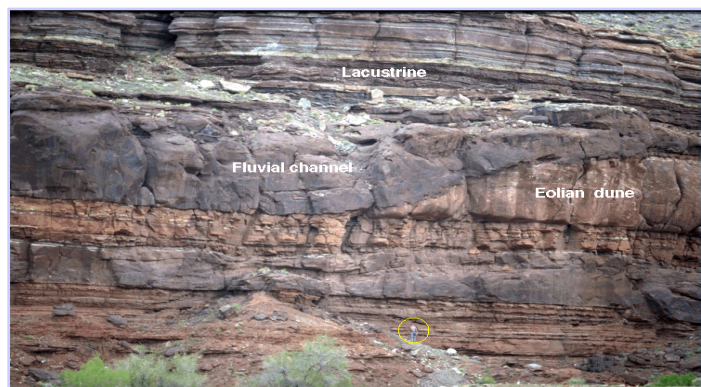
The geological model

This step consists in populating a litho-stratigraphic unit with facies using a categorical simulation. The simulations of **categorical** random variables have been mainly developed in collaboration with the Institut Français du Pétrole (IFP).
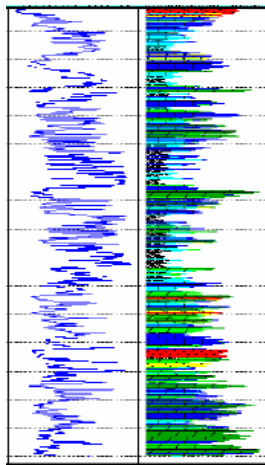

Well log and lithofacies

The information that must be taken into account is the data gathered along the well logs. This continuous information (gamma ray, density, ...) is first converted into a categorical information called **lithofacies**.

Due to the large degree of freedom in this technique, we often benefit from an exhaustive information collected from outcrops with the same depositional environment: they usually serve to tune the parameters used by the geostatistical techniques.

Finally, we may also account for constraints derived from seismic attributes, according to the relationship between the seismic attribute and the proportion of the sand facies for example.
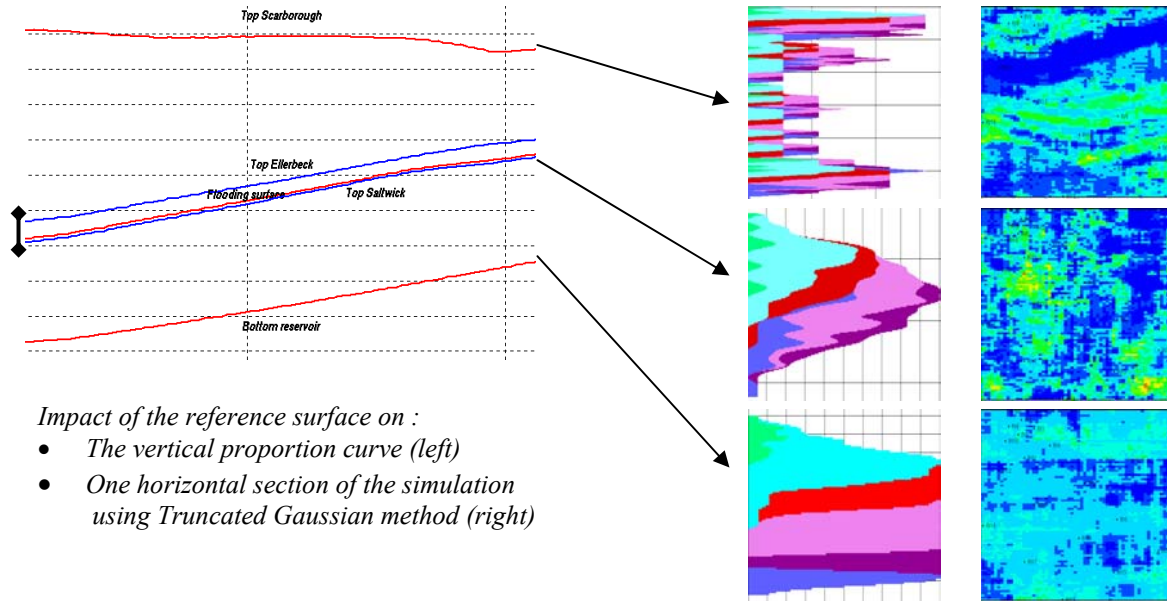

Outcrop used for geological interpretation
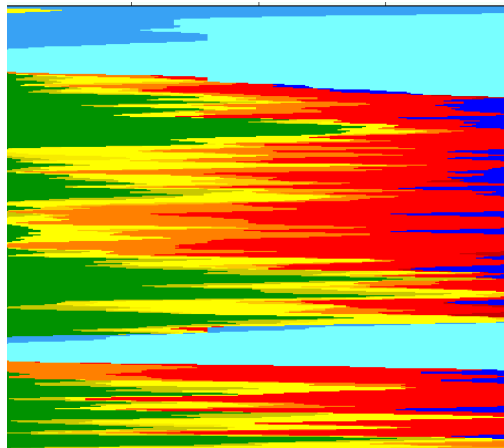
Vertical Proportion curve

This type of categorical simulation first requires a **flattening** step which places the information back in the sedimentation time where correlation can be calculated meaningfully.

For the categorical simulations, the first basic tool is the **vertical proportion curve** which simply counts the number of occurrences of each lithofacies along the vertical for each regular subdivision of the unit. This curve helps in characterizing the lithotype distribution and validating the sedimentology interpretation.

The proportion curve is obviously related to the choice of the reference level used for the flattening step as demonstrated in the next illustration. Three different surfaces are used as reference surface for the flattening step. The first choice leads to an erratic proportion curve which does not make sense in terms of geology. The next two reference surfaces are almost parallel, hence the large resemblance between the resulting proportion curves. However, the facies cycles in the middle proportion curve produce unrealistic patches in the simulated section, which contradicts the geological hypothesis of no oscillation of the sea level. For that reason, the correct choice of the reference surface is the bottom one.

Impact of the reference surface on :
- *The vertical proportion curve (left)*
- *One horizontal section of the simulation using Truncated Gaussian method (right)*

Using a pie representation, we can also check whether the facies proportions vary horizontally or not. In the following example, we can see that the green facies is more abundant in the Northern part, the orange facies has an isolated high value in the center part and finally the red facies is more homogeneous. This lack of homogeneity is referred to as the (horizontal) **non-stationarity**.
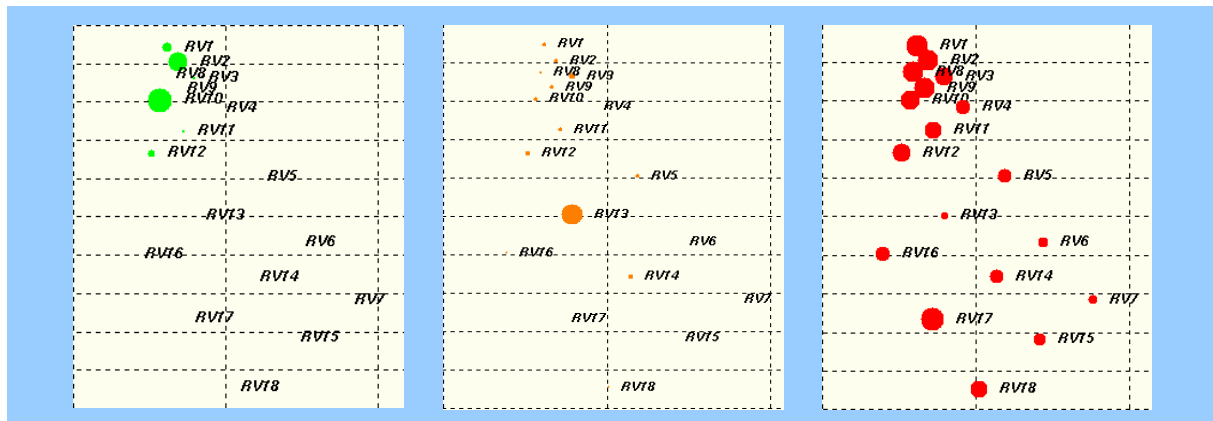
Pie representation of the facies proportion for three facies

The following figures show the facies proportions interpolated between the well projected along two sections. The North-South section confirms the non-stationarity whereas the East-West one is more stationary.
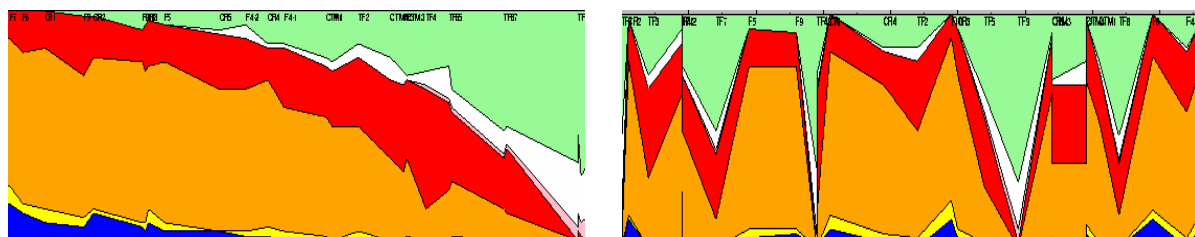

Interpolated facies proportion along two sections: North-South (left) and East-West (right)

Rapport technique du Centre de Géostatistique, N-03/05/G, Ecole des Mines de Paris

In order to take the non-stationarity into account, we define a coarse **proportion grid** (each cell is much larger than the cell of the final simulation grid): a vertical proportion curve must be calculated in each cell of the proportion grid. One technique is to establish first a few representative vertical proportion curves (each one calculated on the subset of the wells contained in a moving domain). Then these vertical proportion curves are interpolated at each cell of the coarse grid using a special algorithm which ensures that the results are proportions which add up to 1. During this interpolation process, a secondary variable, such as the seismic derived information, can also be used. For example, one can consider a seismic attribute:

- In the qualitative way: the attribute is truncated in order to delineate the channels from the non-channel areas for instance, or to detect areas where the same vertical proportion curve can be applied
- In the quantitative way: the attribute is strongly correlated with the percentage of a set of facies cumulated vertically along the unit.

The proportion curves of each cell are finally displayed in a specific way so that the trends can be immediately visualized.
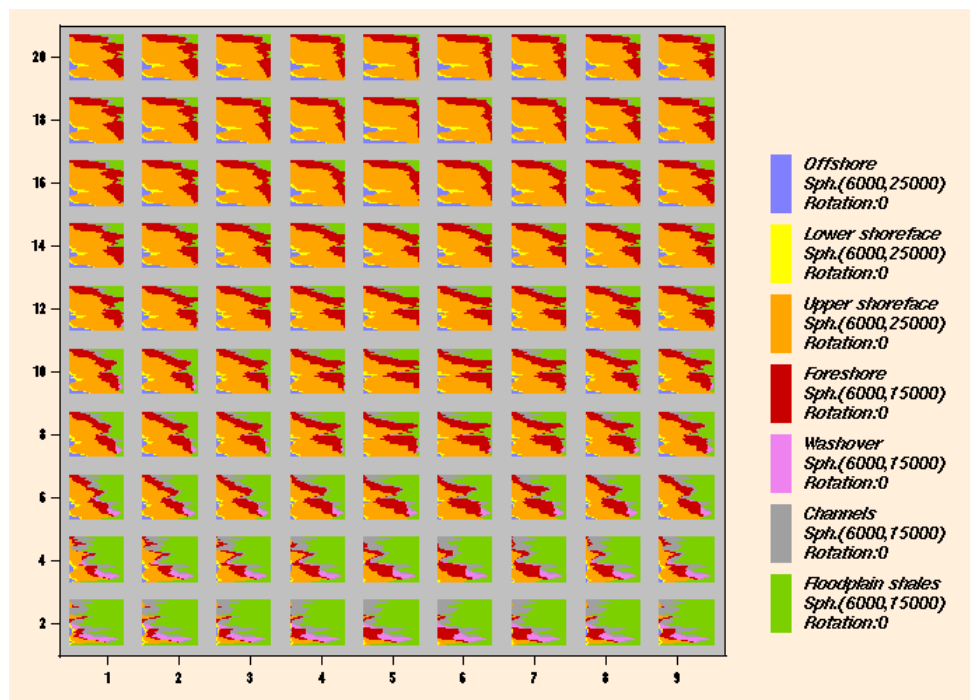
Global view of the vertical proportion curves in each cell of the proportion grid

It is now time to classify the main families of geostatistical simulations that can be used for processing categorical random variables:

- the **gaussian based** algorithms
- the **object based** algorithms

- the **genetic** algorithms

Gaussian based simulation

This technique relies on the simulation of a gaussian underlying variable which can be performed using one of the traditional algorithms (turning bands for example). This variable is characterized by its model. The simulation outcome is then coded into facies using the proportions: hence the name of the **truncated gaussian** simulation technique.
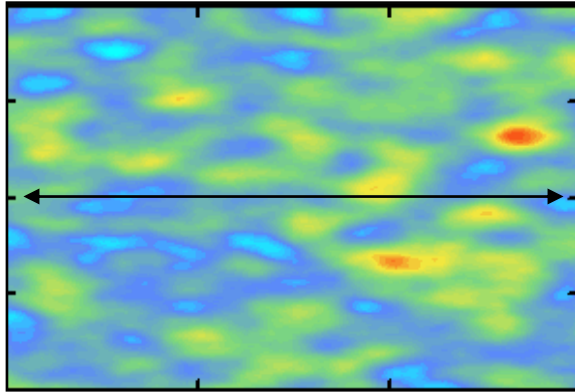

Truncating the same underlying gaussian function:
- *In the stationary case (bottom left)*
- *In the non-stationary case (bottom right)*
The construction scheme in both cases is presented along a section.
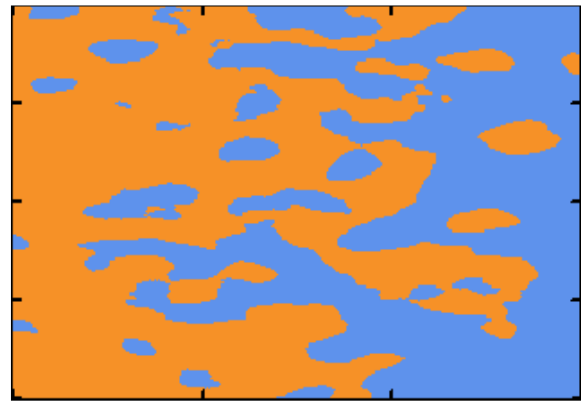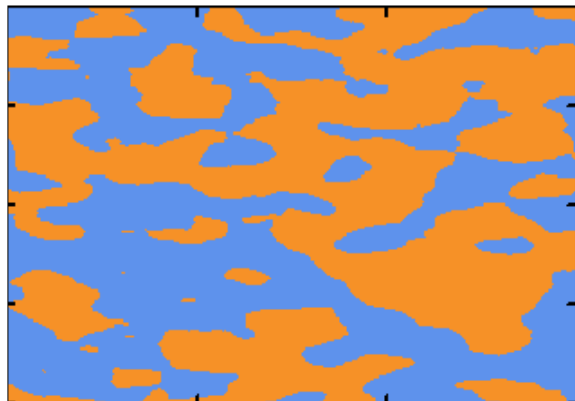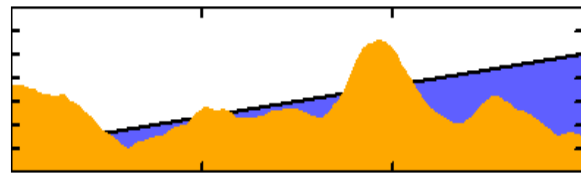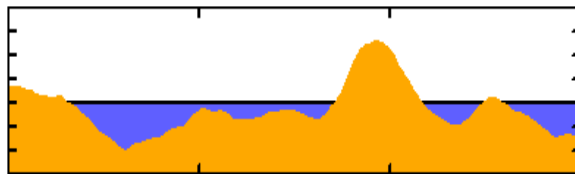
The previous figure demonstrates how one simulation of the underlying gaussian variable is truncated. The simulation is displayed on the upper left corner with the trace of a section of interest. In the stationary case (bottom left) we consider a constant proportion throughout the field (i.e. a constant water level): the immerged part corresponds to the blue facies whereas the emerged islands produces the orange facies. In the non-stationary case (bottom right) the proportion of orange facies increases towards the left edge: it suffices to consider that the water level is not horizontal anymore.
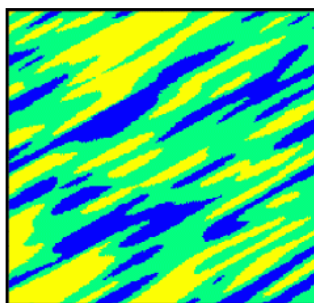
Let us now apply the method with three facies (two levels of truncation) to the simulation of an anisotropic underlying gaussian variable. We see that the facies are subject to an order relationship as we cannot go from the yellow facies to the blue facies without passing through the green one: there is a **border effect**. Moreover, all the facies present the same type of elongated bodies as they all share the same anisotropy characteristics of the underlying gaussian variable.

A more complex construction is needed to reproduce the pictures presented here. The (truncated) **plurigaussian** method requires the definition of several underlying gaussian variables (two in practice). Each of the underlying gaussian simulated variable is truncated using its own proportion curves. The relative organization of the two sets of proportions is provided by the **truncation scheme**.
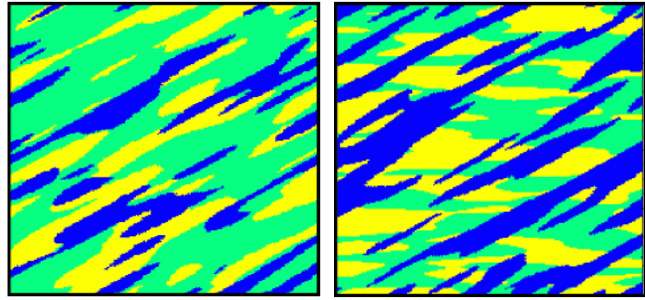
Two plurigaussian simulations with three facies and different truncation schemes

The following figure demonstrates the way the two underlying gaussian variables are combined in order to produce the categorical simulation, according to the truncation scheme (bottom left). When the value of the first underlying gaussian variable (G1) is smaller than the threshold t_{G1}, the resulting facies is blue. When the value of the second underlying gaussian (G2) is larger than the threshold t_{G2}, the facies is yellow, otherwise it is red.
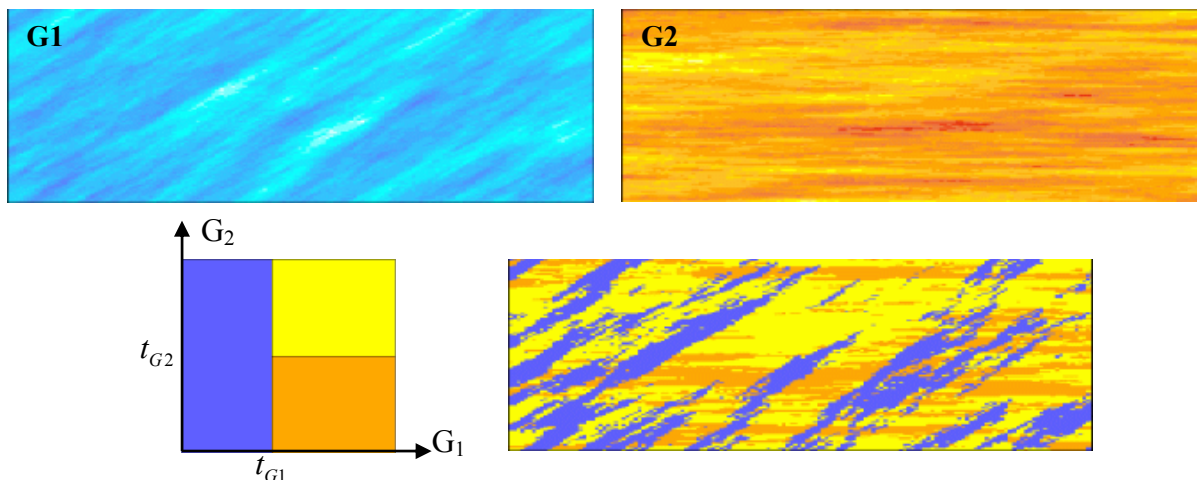
Simulations of the two underlying gaussian functions (top)
Truncation scheme (bottom left) and the corresponding plurigaussian outcome (bottom right)

Moreover the two underlying variables can be correlated (or even mathematically linked) in order to reproduce moderate specific edge effect or to introduce delays between facies.

The major practical problem with these truncated gaussian methods is choosing first the truncation scheme, secondly the proportions for each facies and finally the model for each underlying gaussian variable: this is referred to as the **statistical inference**. One must always keep in mind that the only information used for this inference comes from the facies interpretation performed along the few wells available. In particular, there is no information directly linked to the underlying gaussian random functions as they can only be perceived after they have been coded into facies.

The plurigaussian simulation is an efficient and flexible method which can produce a large variety of sedimentary shapes. However we note that they are not particularly well suited to reproduce the specific geometry of bodies (channels, lenses, ...).

The object based simulation

This type of simulation aims at reproducing the geometry of bodies as described by a geologist. Each individual body is considered as an object with a given geometry and a large quantity of them are dropped at random in order to fill the unit: hence the name of **object based** simulation.

The most popular model is the **boolean** model which considers the union of the objets whose centers are generated at random according to a 3-D Poisson point process. The main parameters of this simulation are the geometry of these objects and the intensity of the Poisson process which is directly linked to the proportion of the facies. The same technique can be generalized to several facies and may take into account interactions rules between the different families of objects (relative positions of the channels and the crevasse splays)
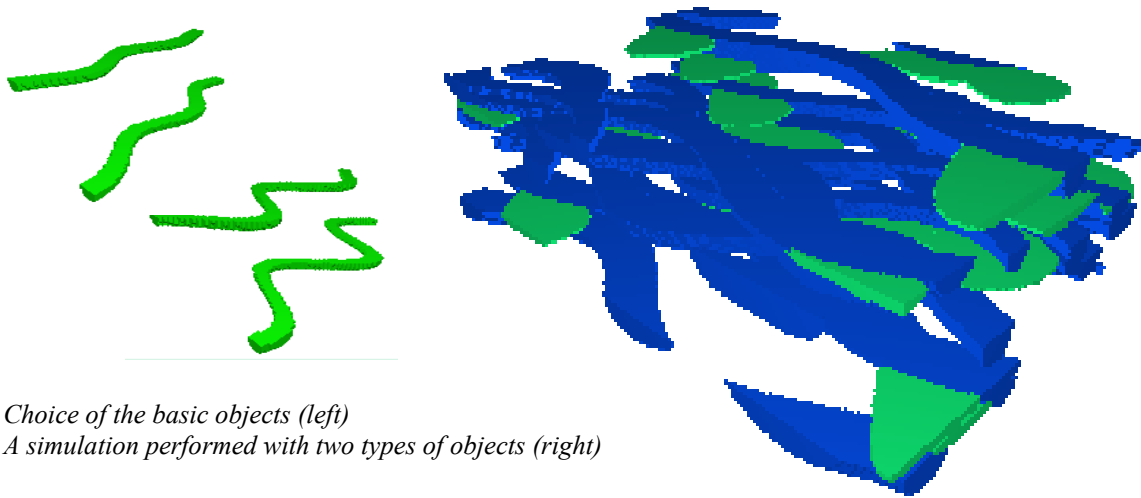
Choice of the basic objects (left)
A simulation performed with two types of objects (right)

The process intensity can finally be extended to the **non-stationary** case (either vertically or horizontally) where the geometry and the count of objects varies throughout the field.
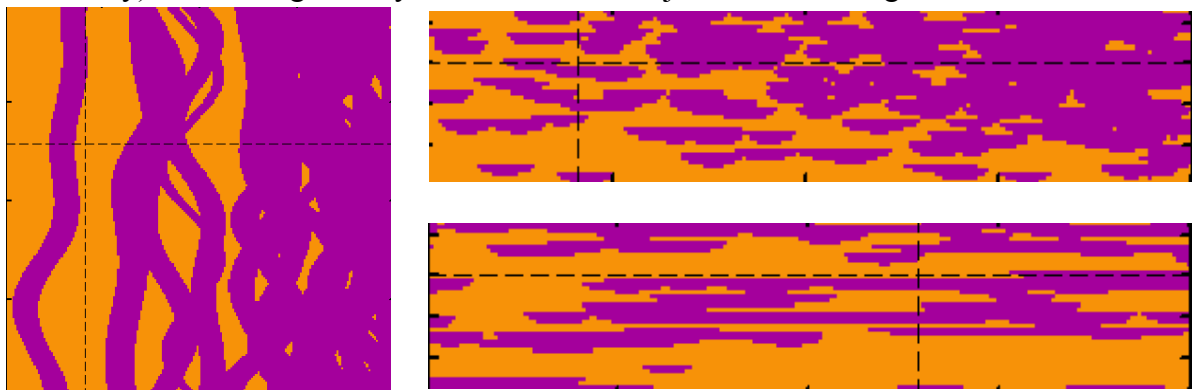
Non stationary boolean simulations of sinusoidal objects (left) with two vertical sections:
- *a West-East section (top right) which demonstrates a trend in the object density*
- *a South-North section (bottom right) where density is fairly stationary*

Once again, the **statistical inference** required by this simulation technique is a difficult step. As a matter of fact, one must keep in mind that even continuous well logs will only provide information on their intercepts with the objects: it will not inform on the geometry of extension of the objects, or the intensity of the 3-D Poisson point process.

The genetic models

The previous simulation methods only focus on reproducing facies heterogeneities statistically but they do not account for the processes that govern the sedimentation. Recent works in hydraulic and geomorphology sciences provide new equations for modeling fluvial processes (Howard 1996) which usually prove unworkable at the reservoir scale. The **genetic** model, developed in the framework of a consortium, combines the realism of these equations to the efficiency and the flexibility of stochastic simulations.

The evolution of a meandering system as well as the morphology of its meander loops are mainly controlled by the flow velocity and the characteristics of the substratum along the channel. We simulate the location of the channel centerline along the time.
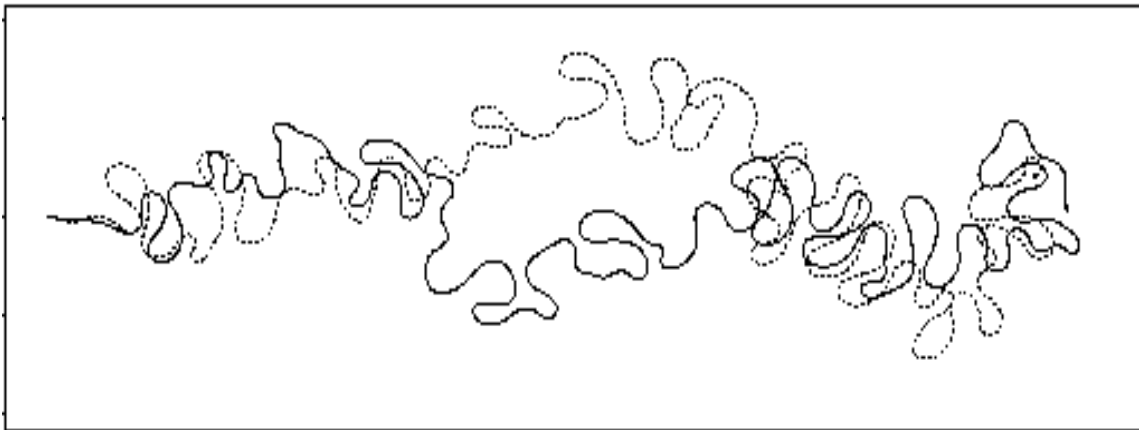
Location of the central line of the channel at two different simulation times (flow from left to right)

This channel migration generates the deposition of point bars and mud-plugs within abandoned meanders. Using a punctual random process along the channel path, some features such as avulsion and crevasse splays are reproduced. Moreover overbank floods are simulated according to a time process.
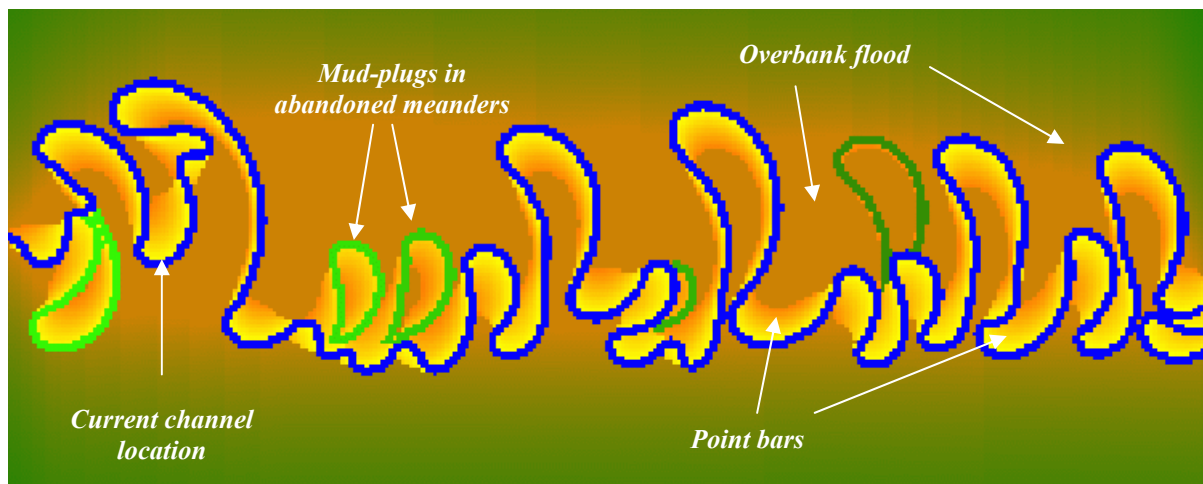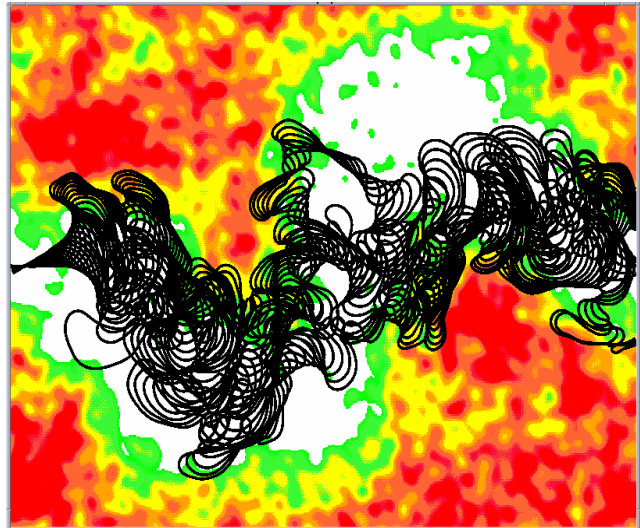

Deposition along the channel

Finally the **accommodation space** is introduced as an additional time process that governs the successive cycles of incision and aggradation**.**

Moreover, we can condition this simulation introducing the **erodibility** coefficient map. This coefficient, which relates the migration of the channel to the structure of the flow, enables us to attract and confine the location of the deposits.

Map of the erodibility coefficient which confines the channel migrations

This simple model leads to a 3-D realistic (genetically consistent) representation of fluvial depositional systems in a reasonable computing time. It identifies the different sand bodies and their sedimentary chronology. Finally, this method also enables us to generate auxiliary information such as grain-size, which can be used to derive petrophysical characteristics.
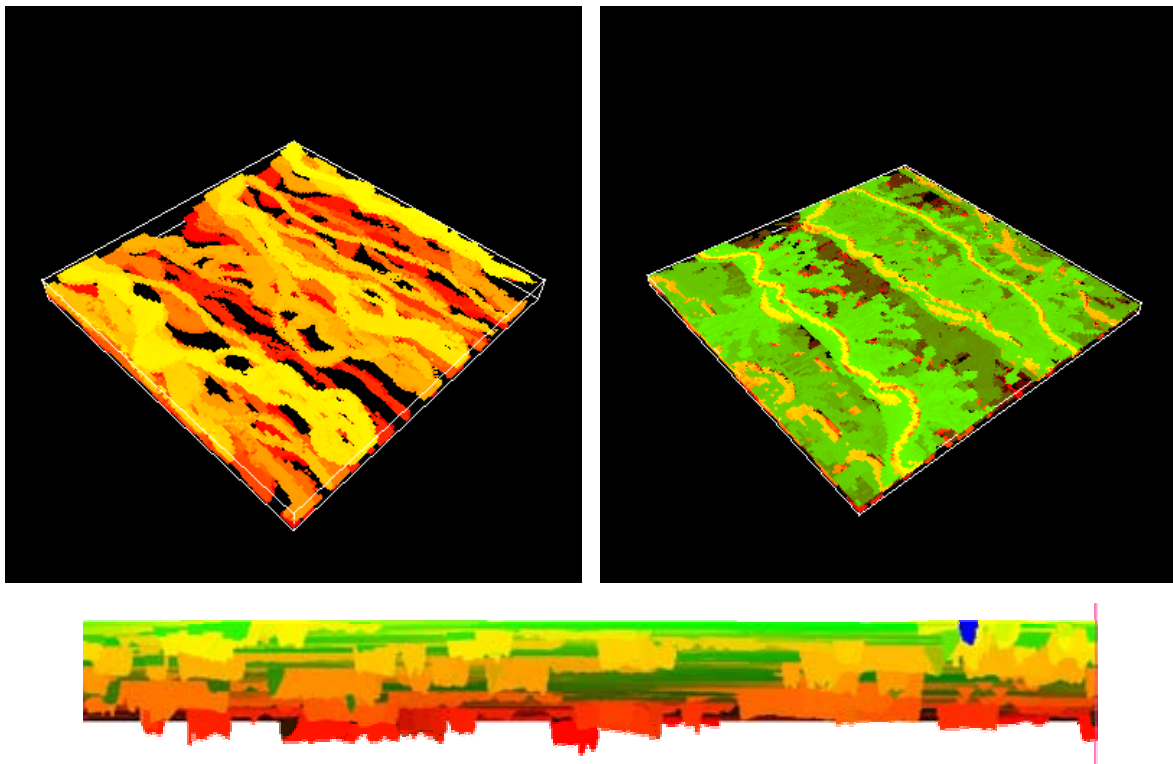
Genetic simulation: channels alone (top left) – channels and sandy to silty overbanks deposits (top right)
A section perpendicular to the slope (bottom)

Channel sands: from red (older) to yellow (younger)
Overbanks deposits and crevasse splays: from brown (older) to green (younger)

The petrophysical model

The last step consists in calculating the petrophysical characteristics of the reservoir, such as porosity or permeability. It is common practice to define each petrophysical variable in relation to the facies as follows:

- either by setting a constant value,
- or by randomizing this value according to a law,
- or by simulating the variable using any traditional technique for continuous variables. In more complex situations, we can take advantage of the correlations existing between different petrophysical variables to simulate them simultaneously on a multivariate basis.
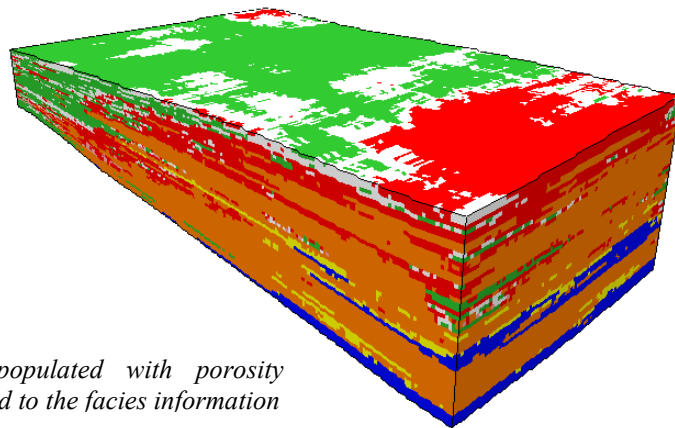
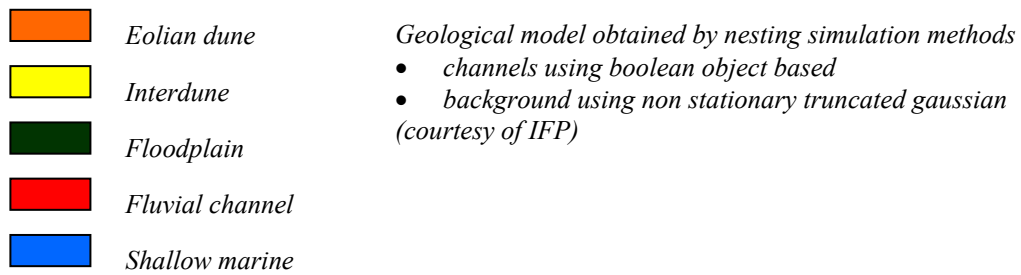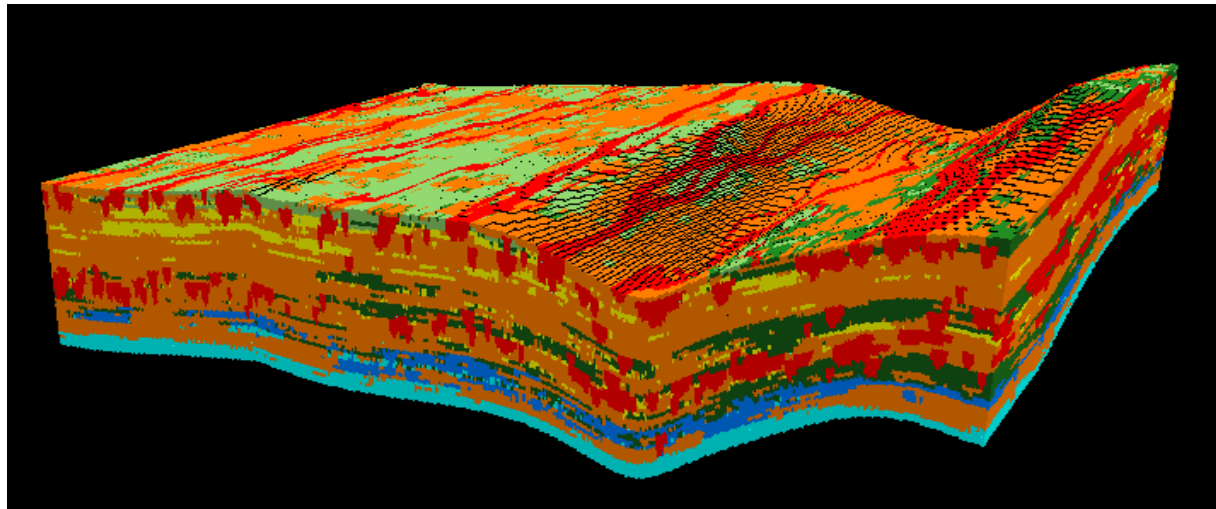*Reservoir unit populated with porosity information related to the facies information*

For technical reasons, the simulated petrophysical fields need to be transformed into larger cells before they can be used in fluid flow simulators. This **upscaling** operation can be trivial in the case of porosity or more complex in the case of permeability.
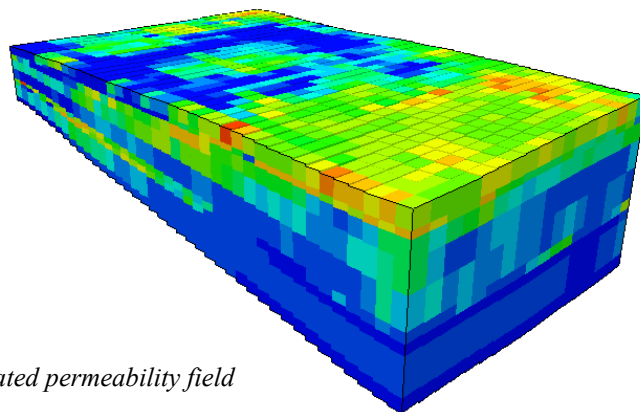

Upscaling of a simulated permeability field

Global reservoir model

For a given unit, according to its depositional environments, several simulation methods can be nested as demonstrated in the next illustration.

🟧	*Eolian dune*
🟨	*Interdune*
🟩	*Floodplain*
🟥	*Fluvial channel*
🟦	*Shallow marine*

Geological model obtained by nesting simulation methods
- *channels using boolean object based*
- *background using non stationary truncated gaussian*
(courtesy of IFP)

When all the units are simulated, they are stacked in the structural position in order to obtain the global reservoir.

Millepore
Sycarham
Cloughton
Ellerbeck
Saltwick

100 m
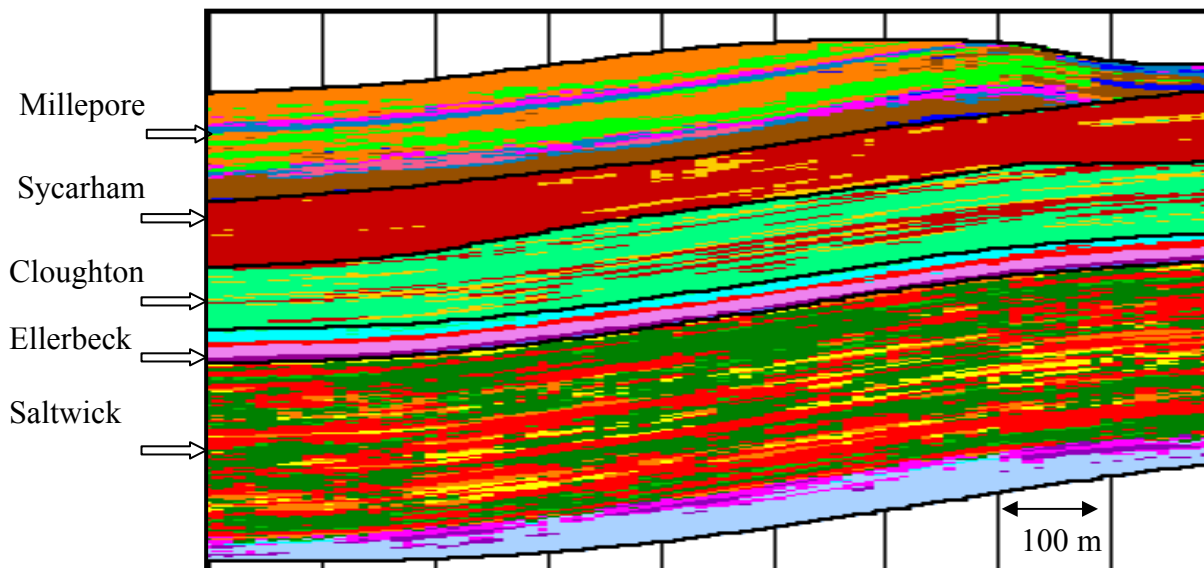
Ravenscar reservoir simulated in five independent units:
- *Millepore: non-stationary truncated gaussian*
- *Sycarham & Ellerbeck: stationary truncated gaussian*
- *Cloughton: boolean object based*
- *Saltwick: nested boolean object based and truncated gaussian*

Results

When the global reservoir characterization is completed, we can perform several checks and derive final calculations. Some of them are illustrated in the next paragraphs.

- Calculation of the volumes (gross rock, hydrocarbon pore volume) above contact for each simulation outcome. The distribution of the resulting volumes can be plotted or viewed as a **risk curve**
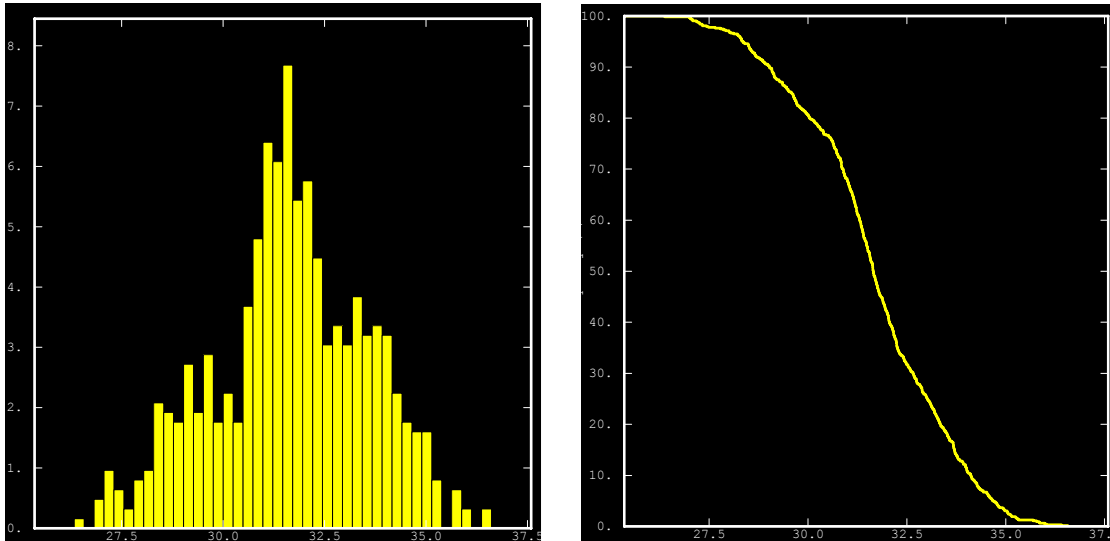
Distribution of the volumes for 100 reservoir simulation outcomes and the corresponding risk

- The lateral extension of the reservoir is bounded by the determination of its spill point. The spill point is calculated for each simulated outcome. Comparing all the outcomes, we can establish the **probability map** which gives the probability for each grid node to belong to the reservoir.
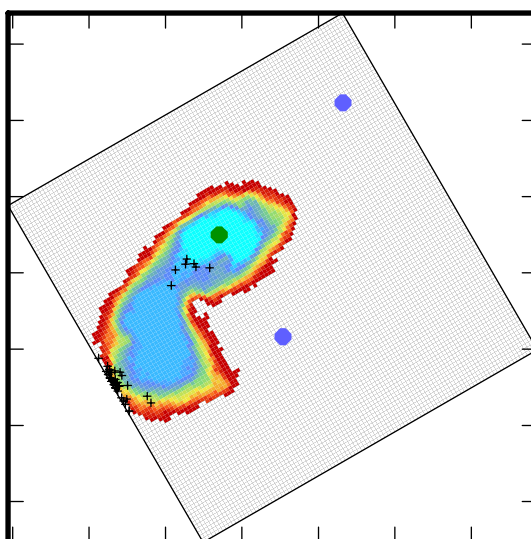

Probability map obtained from 100 reservoir simulation outcomes conditioned by 3 wells calculated above their spill point.

The green well belongs to the reservoir while the blue wells are outside.
The spill points of each simulation are represented by plus marks

- The connectivity check will predict if an injector and a recovery well are connected. This is easily established by computing the connected sand components through the 3-D reservoir.
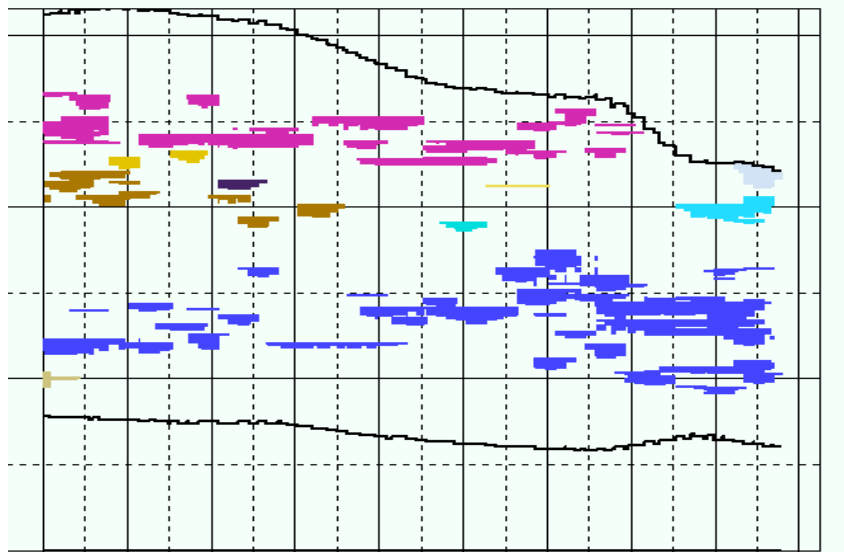
Vertical section where each connected component is represented with a specific color

Implementation

All the methods presented in this paper have been developed at the Centre de Géostatistique of the Ecole des Mines de Paris. They are either implemented:

- within commercial packages:
  - **ISATIS ©**: general geostatistical tool box
  - **ISATOIL ©**: geostatistical construction of a multi-layer reservoir
  - **HERESIM ©**: heterogeneous reservoir simulation workflow
- or simply used for research activity:
  - **SIROCCO**: development of new simulation techniques (non-stationary object based and plurigaussian models)
  - Consortium on **Meandering Channelized Reservoirs**