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Use of Connectivity Criteria

for Checking and Enhancing Geological Models

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Geovariances

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ABSTRACT

To ensure consistency between geological models and dynamic models, it is necessary to constrain geological models to connectivity information coming from dynamic synthesis.

The paper presents a methodology which can be fully implemented using commercial software. It is based on the analysis of connected components calculated on geostatistical simulations in a post-processing phase.

The connectivity analysis in a single lithostratigraphic unit is studied. The use of connected components to QC facies or petrophysical properties simulations is detailed and the impact of simulation parameters (facies proportion, variogram range, etc...) on connectivity is studied.

The generalization to structural geological models is described. In this case, successive lithostratigraphic units can be potentially connected through faults when the fault throw is large enough.

A two-steps workflow for conditioning simulations to connectivity information in difficult cases is presented. The first step is the identification of the realizations matching the connection criteria. The second step consists in choosing additional conditioning data for further simulations ensuring that the wells connection constraints are honored. The efficiency of this workflow is discussed. A method for integrating faults and fractures patterns in connectivity calculations in complex cases is proposed. Calculation optimization issues are discussed.

Once the stochastic realizations of a geostatistical model honor observed connections between selected points, it is interesting to characterize the connection for improving model QC. Some possible ways of using connected components in advanced models QC are suggested.

Some ideas for accounting for connection quality in geostatistical simulations are proposed.

INTRODUCTION

Production History Match optimization and improvement of reservoir models prediction capability require a good consistency between geological static model and dynamic model. This consistency can be obtained by constraining the static model, as much as possible, with information coming from the Basic Reservoir Engineering phase of a reservoir study. Such information is, for example: connectivity between perforations in different wells, average permeability around a well, presence of sealing faults, of permeability barriers or drains, fractures density and impact.

This paper is focused on the study of connectivity, which is a key contributor to flow dynamics in geomodels, but is rarely taken into consideration.

The first section is dedicated to the identification and characterization of connections between wells, in various contexts.

The second section presents several methods for constraining geological models to connections between wells. The impact of the method chosen for populating the geological model with properties is studied. Simple workflows, sometimes specific to some geostatistical algorithms, are discussed. Finally, a general workflow valid for all the geostatistical algorithms but more demanding in terms of computation is detailed.

The third section is focused on the characterization of connections between wells. Assuming that wells are connected, it is useful to characterize and quantify the quality of the connection which impacts the flow between the wells. In effect, the dynamic behavior will be different if wells are connected by a large homogeneous and regular geobody, or by a distorted geobody with a lot of baffles and narrow throats. Some numerical criteria are proposed, to estimate how easy will be the flow between wells and facilitate the ranking between stochastic realizations.

In the end, some possible methods for conditioning static geological models to a given level of connection quality are discussed.

This work is restricted to the high resolution geological model. It is assumed here that the properties upscaling on the reservoir grid will not alter the model characteristics.

IDENTIFYING AND CHARACTERIZING WELLS CONNECTION

Importance of connections between wells

Connectivity analysis is critical for field appraisal and development, but also in production at the EOR (Enhanced Oil Recovery) design phase. Inter-well connectivity affects the recovery factor, therefore the reserve. If hydraulic connections between perforations in different wells are not reproduced in reservoir models, the Production History Match is extremely difficult and may require interactive edition of the model, which affects its prediction capability.

Connections can be identified during the Basic Reservoir Engineering phase of a reservoir study, by analyzing well tests, pressure and fluid production data in neighbor wells and interference tests.

The geological model must be consistent with such information. It can be checked by different methods.

Checking connections between wells

The presence of a hydraulic connection between two perforations, and more generally between two arbitrary points in the 3D space, means that there is a drain joining the two points. In the geological model, such a drain corresponds to a continuous path where all the cells have a permeability value above a given threshold. In geological environments where facies are characterized by contrasted petrophysical properties, with no or very small permeability overlap between facies, drains can be characterized by continuous paths of the most permeable facies. When there is a significant overlap of permeability distributions within facies, it is better to consider a permeability threshold for defining the drains.

The simplest approach to check the connection between wells consists in displaying the model in a 3D view and to switch off non-reservoir facies or low permeability values. This approach is fast, simple, but qualitative. It does not allow any quantification and automation of the model QC.

A more efficient approach consists in calculating connected components, based on facies definition or permeability thresholds. Two cells in the geological model are in the same connected component if they have a common face, a common edge or a common point. In this paper, we will consider only the first case (common face), which is illustrated in Figure 1.

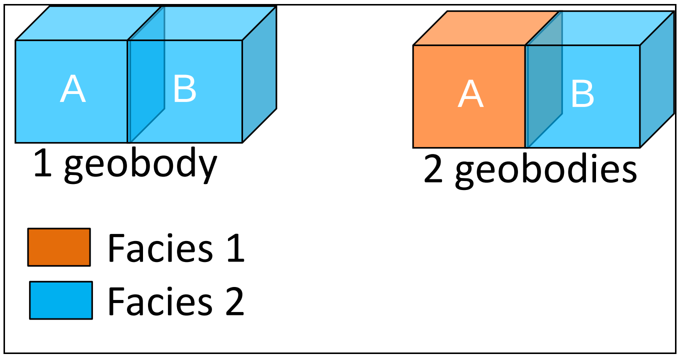

Figure 1. Definition of connected components.

Many geomodeling tools or geostatistical toolboxes offer the capability to calculate connected components and to include the calculations in workflows for automation purpose. An example of connected components is shown in Figure 2, in which it can be noted that they depend on the reference variable (Facies or Permeability) and on the method used for calculating Permeability. Therefore, great care must be taken in the definition of connected components.

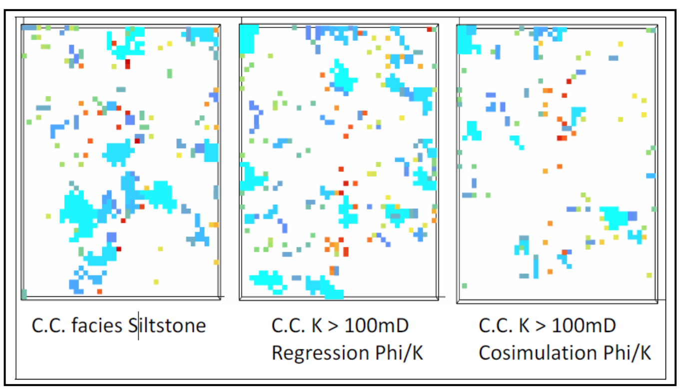

Figure 2. Example of connected components. The color corresponds to the component number (sorted by volume).

Identifying connected wells

Two points of the model are connected if they belong to the same connected component, which is simple to test. Connected components calculations can be optimized by using mathematical morphology tools such as "opening" operator, in order to remove components made of two or three cells only, which are meaningless. Figure 3 shows two connected wells.

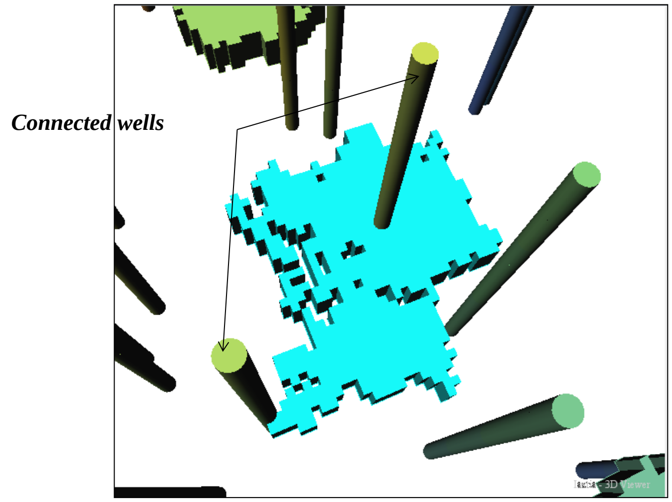

Figure 3. Example of connected wells.

Additional information provided by connected components

In addition, it can be noted that connected components allow calculating the volume of geobodies and the hydrocarbon volume connected to a given point, which must be consistent with production history. It is another way of accounting for dynamic data in the static model.

Morphological tools can also be used to characterize the shape of the geobodies, their dominant orientation, their size distribution, the rugosity of their surface, etc… It provides additional numerical indicators for studying the geological consistency of the static model.

Connected components calculation through fault planes

Connected components calculations are usually made in structured grids, fully characterized by I, J, K indexes, in which it is easy to define the neighbors of a given cell. If the grids are defined in standard geomodeling software, such calculations can be made immediately after geostatistical simulations, in the stratigraphic unit, following sedimentological correlation lines. In presence of strong tectonic effects, when connections occur through non-sealing faults with significant throws and refer to different stratigraphic units, the two sides of the fault must have consecutive in I, J, K indexes. It means that a global structural model merging all the stratigraphic units must be defined.

An example of a structural structured grid superimposed to stacked stratigraphic units is shown in Figure 4. In this figure, drains corresponding to different units (in light and dark green) become neighbors in the structural grid (in red), because of the fault throw. Therefore, standard connected components calculations can be applied and the wells can be connected through the (non-sealing) fault.

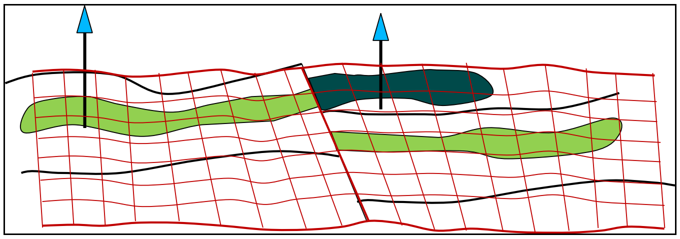

Figure 4. Connection in presence of tectonic structures.

FORCING GEOSTATISTICAL SIMULATIONS TO HONOR CONNECTIONS BETWEEN WELLS

Algorithms for controlling connectivity

In general, geostatistical algorithms available in the existing commercial geomodeling software or geostatistical toolboxes do not account for connection data.

Some tests were made for SIS (Journel and Alabert 1988), and Truncated Gaussian method (Allard 1993), but difficult statistical issues occurred and these approaches have not been developed. An algorithm which can account for connectivity constraints is proposed in Renard et al. 2011. It requires the inclusion of extra conditioning points to honor the connection from MPS training image and this feature is not always implemented in commercial software.

Therefore, forcing geostatistical simulations to honor connection criteria with the algorithms available on the market can be made only with workflows combining geostatistics, connected components calculations and optimization processes. The case of restoring a connection which exists in the reservoir but is not reproduced in the model is considered here. It is a difficult configuration, which requires a thorough analysis of the modelling process to identify the cause of the disconnection.

Cutting inappropriate connections is a symmetric case which can be managed with the same methods.

A Simple case

Sometimes, the problem is due to an inadequate model parameter and is easy to fix. For example, as shown in Figure 5, local Vertical Proportion Curves (VPC) used for defining geological trends may forbid the presence of connecting facies between two wells (Figure 5). Editing a Vertical Proportion Curve may be sufficient for restoring the connection between the wells (Figure 6).

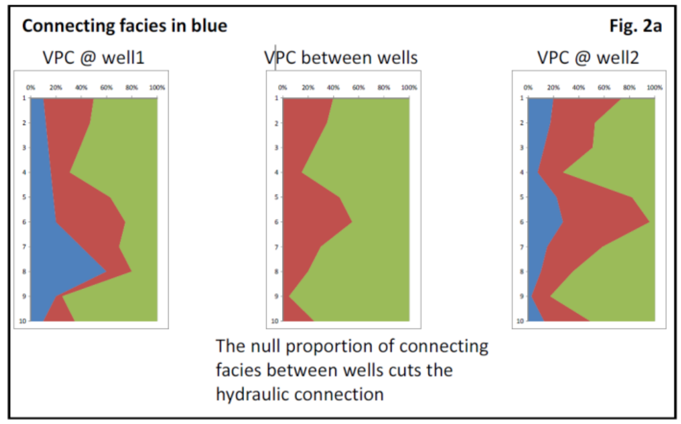

Figure 5. Simple case of disconnection

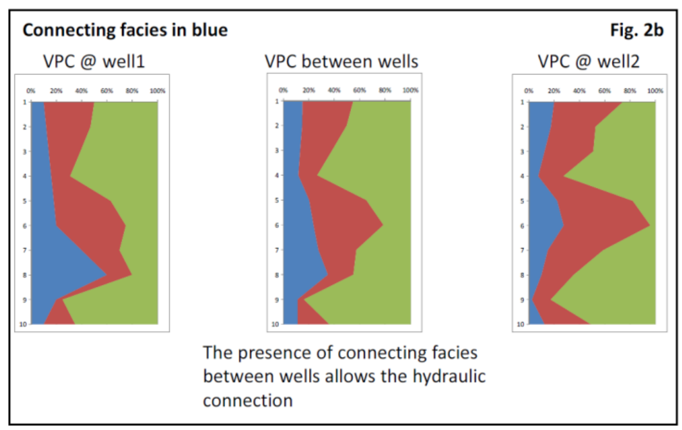

Figure 6. Restoring connection in a simple case

The problem may also come from a too short facies variogram range leading to unrealistic heterogeneity, when pixel based simulation methods are used. It occurs when the spacing between wells is larger than the facies variogram range, which induces an uncertainty on the range. A workflow with a loop testing different range values is usually sufficient for defining the most relevant range value and restoring connectivity between points. The connection is checked at each iteration within the loop by connected components. This method is a way to infer variogram ranges with dynamic information, when hard data are not dense enough. It must be noted that it also allows restoring global continuity observed at reservoir scale, by connecting small geobodies.

Such iterative tests of model parameter values can be adapted to all the simulation methods and applied to specific parameters for which statistical inference is difficult because of lack of data.

Eventually, if varying facies variogram ranges are identified in different sectors of the reservoir, Local Geostatistics tools (LGS) can be used with SIS simulation technique.

Stochastic Connectivity Analysis: determination of the optimal values of model parameters

The reason for not reproducing an observed connection between two points in the model may be due to the combined effect of several factors. It is sometime not easy to identify the main cause.

In such a case, it is worth testing the connection between wells on several stochastic realizations of the same model and calculating the percentage of realizations in which wells are connected. Different configurations can appear which provide useful information on the model consistency:

1. Only few percents of the realizations are valid (wells are connected). In such a case, the geological model cannot be considered as realistic, as it is inconsistent with dynamic data.

2. Forty to sixty percent of the realizations are valid. Then, the geological model is more or less consistent with dynamic data. Input model parameters can be considered as acceptable. It is possible to try to adjust these for enhancing the result, but defining an algorithm for selecting the good realizations may be sufficient.

3. Almost all the realizations are valid. The model is fully consistent with dynamic data and there is nothing to do.

Problems occur in the first two cases and a method must be found to fix the connection issue.

Analyzing the sensitivity of connection between wells to model parameters variations, for a sufficient number of stochastic realizations, provides clues for restoring the lost connection.

An example based on Pluri-Gaussian facies simulation method, with facies characterized by contrasted Petrophysical properties, illustrates this approach.

Two parameters have been considered simultaneously:

- The proportion of the permeable facies which establishes the connection between wells;

- The facies variogram range.

The two extreme Vertical Proportion Curves are shown in Figure 7. It can be observed that the permeable connecting facies proportion varies from about 30% to about 60% at the perforation level (in front of the arrow).

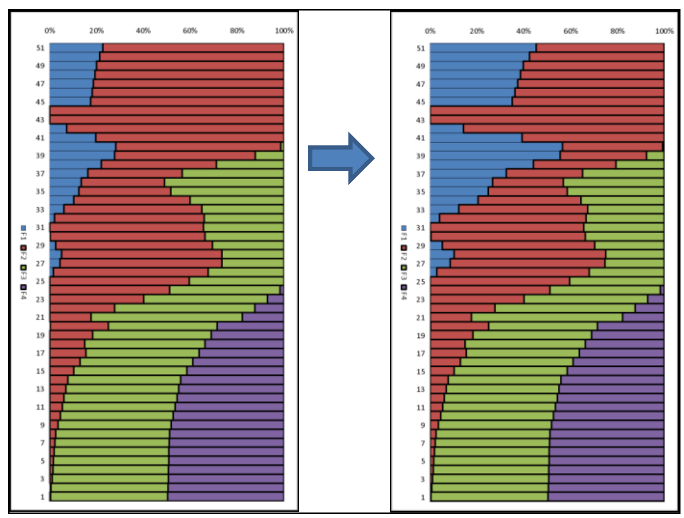

Figure 7. Parameters for sensitivity analysis. The permeable connecting facies is in blue.

The sensitivity analysis results are shown in Figure 8.

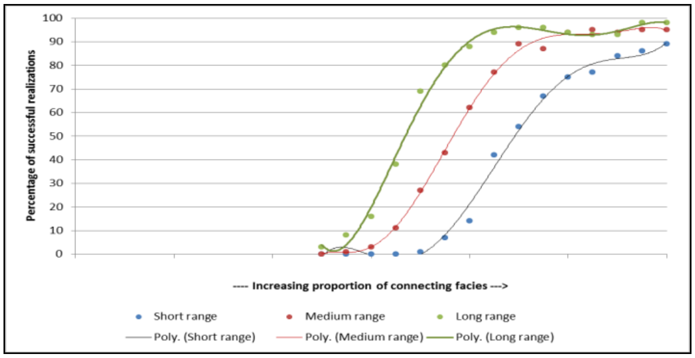

Figure 8. Sensitivity analysis results

This figure represents the evolution of the percentage of stochastic realizations in which the wells are connected, with the increasing proportion or connecting facies. Several curves are provided, each corresponding to a specific variogram range. It can be noted that all the curves have an S shape, which can be divided in three parts:

1. A flat segment corresponding to low proportion of connecting facies. For such low proportion, there are no or very few realizations in which the wells are connected. In this context, the model is not compatible with the constraint of connection between the wells.

2. The flat segment is followed by a fast increase of the number of realizations in which wells are connected.

3. In the end, the curves reach a stabilization level between 95% and 100% of valid realizations.

As expected, the longer the variogram range is, the lower the proportion of connecting facies needed for getting a high percentage of valid realizations is.

Usually, proportion curves and variogram ranges are uncertain parameters. The analysis presented here shows that it is worth playing with the uncertainty on the parameters to determine the most efficient combination of parameters value, which ensures that the wells connection is honored in most of the model realizations.

Stochastic Connectivity Analysis: defining additional conditioning data

In complex cases, taking benefit of the uncertainty on the model parameters may be not sufficient. The issue can be solved by using an iterative workflow to add wisely chosen random conditioning points. The procedure is made of four steps:

1. Calculation of n realizations of the model (n being large enough to ensure statistical robustness);

2. Calculation of the probability of presence of the cell in a geobody connecting the wells for each cell of the grid (Figure 9);

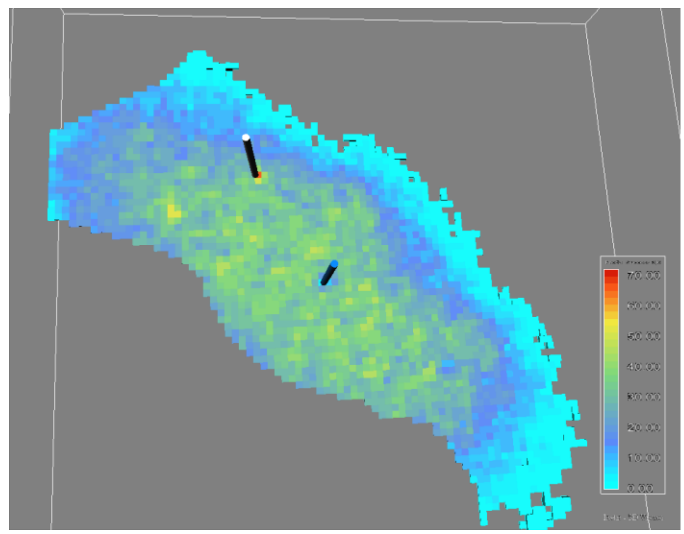

Figure 9. Probability of presence in a connecting geobody.

3. Thresholding of this probability of presence, in order to highlight the cells that are the most often in a connecting geobody (Figure 10).

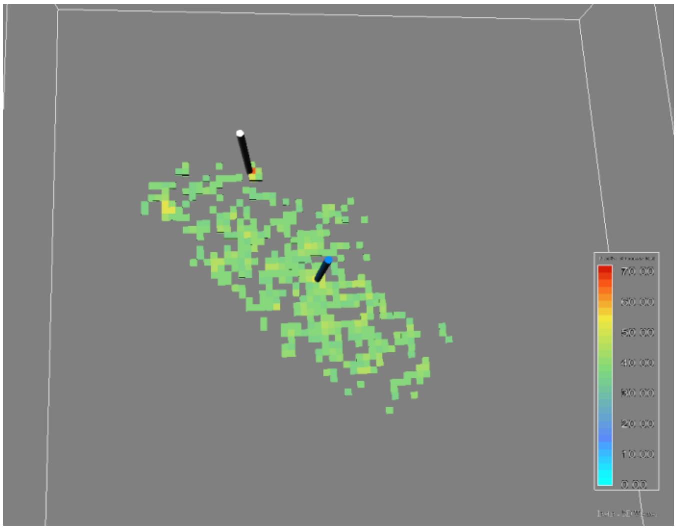

Figure 10. Selection of cells with the highest Probability of Presence.

4. In this sub-set, an automatic random sampling allows defining additional data which will be used as additional conditioning data in furthers stochastic realizations (Figure 11).

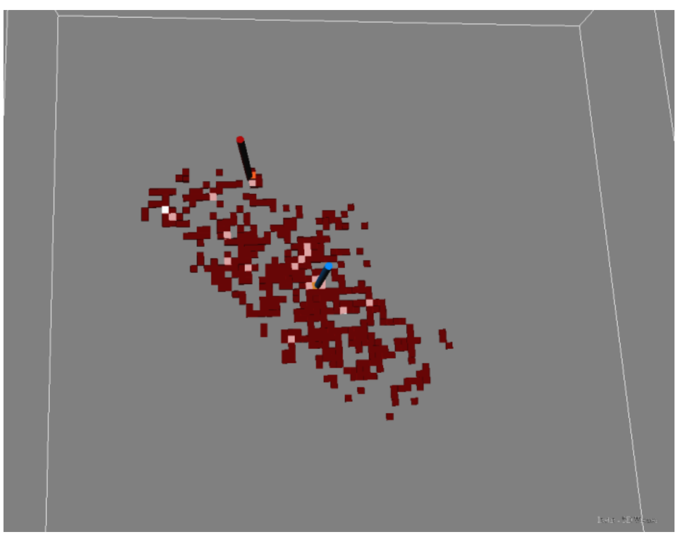

Figure 11. Additional random conditioning data (light color)

This iterative process can be performed in a geostatistical toolbox and ensures that the wells are connected in all the final realizations. This approach also preserves the ability to estimate uncertainty and risks.

Being based on a statistical analysis of several realizations, this workflow requires a significant computation time. Enough realizations have to be calculated to get statistically significant results. It is highly recommended to run this workflow in batch mode, using specific scripts, preferentially on a multi-processors computer to compute several realizations in parallel.

It must be noted that this method cannot be applied if this sub-set becomes too small. Therefore, it works if the starting point is a model for which at least 40% or 50% of the realizations honor the wells connection constraint.

If this method cannot fix connectivity issues, then the whole modeling process must be revisited.

In addition, it can be noted that the same approach allows connecting, at a given location, two successive stratigraphic units simulated independently if applied on the structural grid merging all the units. It allows restoring the continuity of composite bodies made of similar facies, which shape is not concordant with time lines defined from sequence stratigraphy rules.

Accounting for conductive faults and fractures

When model adjustment or determination of additional conditioning data is unable to provide satisfactory results, the model characteristics must be revisited. The problem may be due to the fact that some parameters which are critical for fluid flow are missing. For example, connection between wells may be due to the intersection between sedimentary drains and conductive faults or fractures. If such tectonic features are not taken into account in the model, the wells connection constraints cannot be honored.

It is quite easy to include tectonic features in the connected components calculation. The following workflow can be applied:

- Calculate the distance to faults or fractures, as shown in Figure 12;
- Select cells close to the faults;
- Merge this new selection with the connecting sedimentary “facies”;
- Re-run the connection test

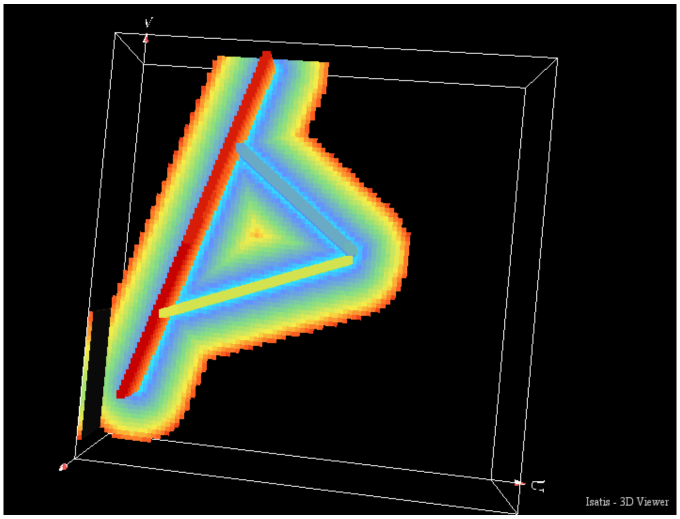

Figure 12. Distance to the closest fault

Then, all the previously presented workflows can be applied.

CHARACTERIZING CONNECTION QUALITY

Why characterizing connection quality?

When a hydraulic connection is observed between two wells, an accurate modeling of the flow between them will require honoring the connection and the characteristics of this connection.

As shown in Figure 13, wells can be connected by a large and quite regular geobody or by a distorted geobody with narrow throats. It can also be noted on the figure that the location of the wells in the geobody may vary. The two examples in Figure 13 are equivalent with regard to the connection criterion. It is obvious that they are not equivalent for flow modeling. The flow behavior and the wells performance will be significantly different in the two cases.

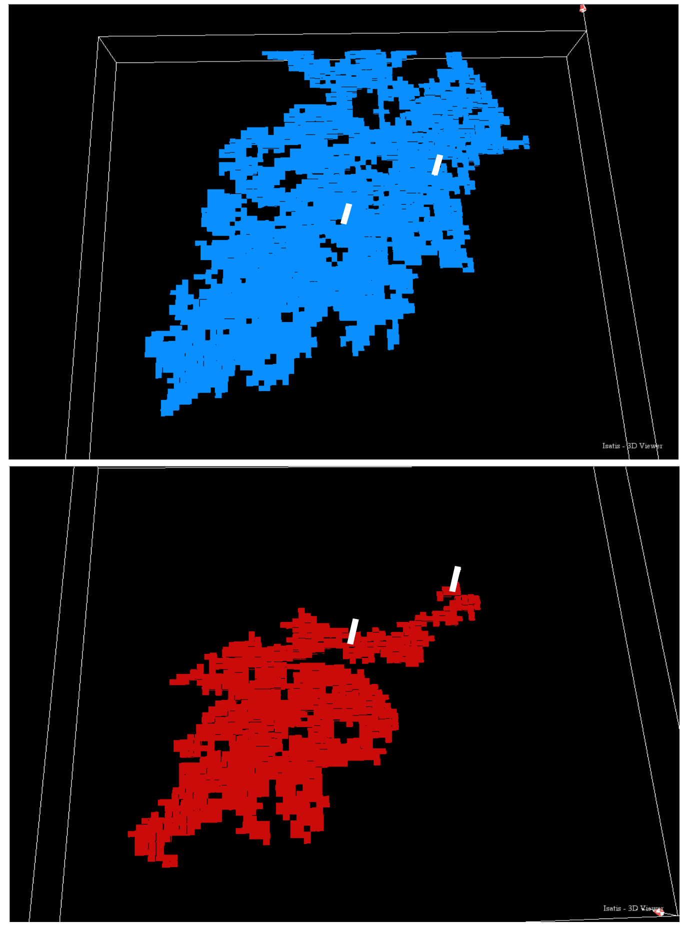

Figure 13. Different types of connection between wells

Therefore, it is important to characterize the shape of the connecting geobodies, which directly impacts the connection quality.

Qualitative characterization of connection quality

A first method for characterizing connection quality consists in a visual check of the connecting geobody. This inspection must be done for all the stochastic realizations in which wells connection is honored.

This qualitative approach allows getting easily and quickly a rough idea of the variability of the connection quality in the model.

It can be enriched by displaying either the distance to the wells (Figure 14) or the distance to the edges (Figure 15).

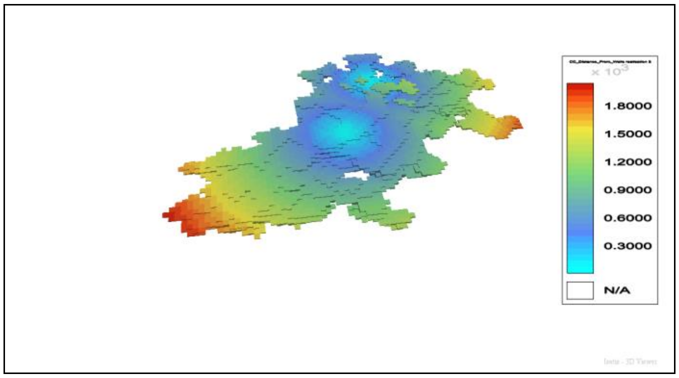

Figure 14. Distance to the wells in a connecting geobody

A large amount of long distance to the wells indicates that the wells are located on geobody's side or that the geobody is big relative to the well distance.

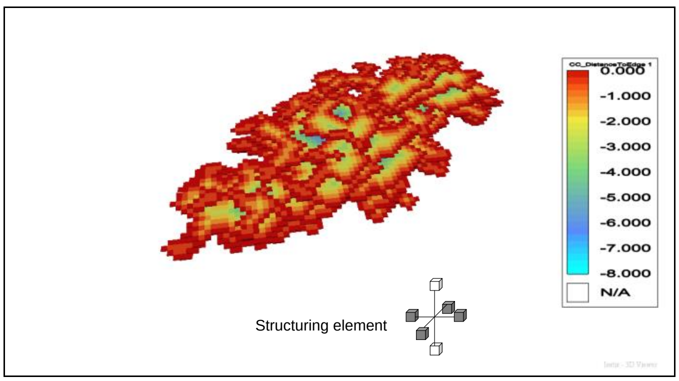

Figure 15. Distance to the edges in a connecting geobody

A large amount of short distance to the edges indicates that the geobody is made of a lot of small blocks connected by narrow throats.

Quantitative characterization of connection quality

A qualitative characterization of connection quality is useful for a preliminary QC of the static model, but it is not sufficient. A quantitative approach is necessary to allow classifying the different stochastic realizations.

Several numerical indexes or functions can be proposed for characterizing the connecting geobodies shape:

- A first simple indicator is the histogram of the distance to the wells (Figure 14). Its dissymmetry and its shape characterize the location of the wells in the geobody, therefore the drainage area.

- The shape of the histogram of the distance to the edges (Figure 15) indicates whether the connecting geobody is made of few large blocks or of a lot of small blocks connected by narrow throats.

- Another useful tool is the curve describing the evolution of the number of connected components when successive erosions (in the sense of mathematical morphology) are applied to the initial connecting geobody. It is very sensitive to the initial geobody's shape regularity and to the number of throats. It allows discriminating the stochastic realizations (Figure 16).

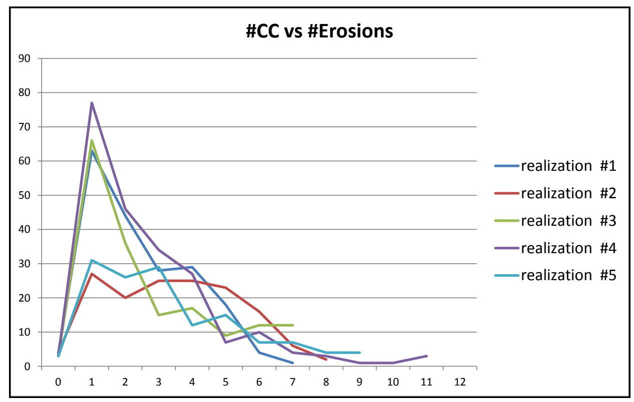

Figure 16. Number of connected components after successive erosions

- Similar information can be obtained with the percolation metric $\Gamma(x)$ defined in Renard and Allard 2013. It is the proportion of cells in the connecting geobody among all the pairs of permeable cells or of connecting facies. This proportion is calculated for each iteration of successive erosions (in the sense of mathematical morphology). This metric depends on connected components geometry and highlights differences between stochastic realizations (Figure 17).

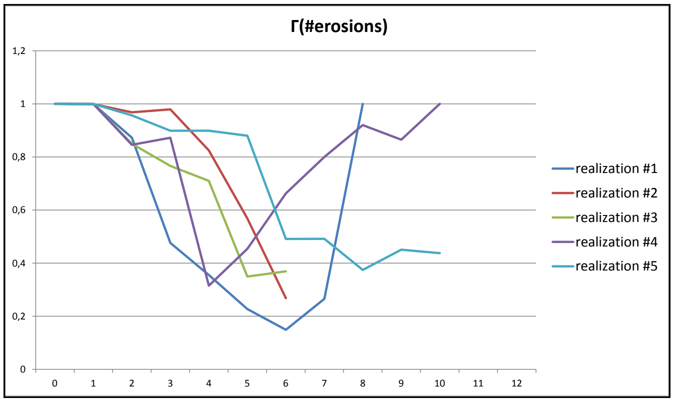

Figure 17. percolation metric Γ(# erosions)

Histogram characteristics like median or kurtosis, or histogram shape itself, or morphological functions can be used in a classification process. It allows discriminating among all the stochastic realizations the ones which have given properties.

HONORING CONNECTION QUALITY IN GEOSTATISTICAL SIMULATIONS?

Honoring connection between wells in static models is nice, but honoring connection quality would be better.

So far, there is no algorithm able to do this and further mathematical developments will be required. Finding a geostatistical simulation method able to deal with such constraints is a mid-term objective.

For the time being, some practical workflows using already available methods and software can be proposed. As mentioned above, stochastic realizations in which wells are connected can be characterized and sorted, with reference to numerical indexes or functions. Therefore, it is possible to select a sub-set of these valid realizations corresponding to specific flow behavior. From this sub-set, two different approaches can be considered:

- A first method consists in determining additional conditioning points for further geostatistical simulations, using the approach described above (Stochastic Connectivity Analysis), from this sub-set only. It requires computing a lot of geostatistical simulations, which is manageable only on massively parallel computers for large datasets, with software able to handle multiple threads. It does not guarantee that all the over-conditioned realizations will have the expected characteristics, but it is an improvement from a brutal force approach which would consist in calculating thousands of realizations and selecting progressively the ones which have the right properties.

- The selected sub-set of realizations can also be used as a starting point for Gradual deformation method (Le Ravalec-Dupin and Hu 2005). This method allows conditioning directly static models to well tests or production data. It includes an optimization loop and flow simulations. Starting from realizations of a static model which are already very compatible with the global flow regime will optimize and speed-up the process.

CONCLUSION

Testing and honoring connections between points in a static model before reservoir simulations is required to ensure consistency with flow. It also has many advantages:

1. It encourages geologists and reservoir engineers to communicate;
2. It allows selecting realizations that fit reservoir engineering criteria, not only statistical properties, among an infinity of possible realizations;
3. It preserves the ability to perform rigorous uncertainty analysis;
4. It avoids interactive edition of the model to fix by hand the connection problems, which alters the prediction capability of the model.

Such model QC induces more work, but it saves a lot of time during the History Match phase and significantly improves the static models. It enhances the robustness of production forecasts based on these models.

It must be noted that the proposed post-processing workflows can be applied with any geostatistical simulation method. Therefore, the geological modeling process chosen by the geologist will always be preserved, if it is consistent with dynamic data. Only the input parameters will be adjusted to better account for constraints defined by the reservoir engineer.

It is obvious that the properties upscaling in the flow simulation grid has to be performed with great care, in order to avoid losing the benefits of the geological model enhancement.

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