Use of connection constraints for checking and enhancing geological models

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Abstract

To ensure consistency between geological models and dynamic models, it is necessary to constrain geological models to information coming from dynamic synthesis about permeable pathways between some points in the reservoir. 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 analysis of physical connections 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 the presence of permeable pathways in the static model 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 information about connections between points 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 model's statistical properties being preserved. The efficiency of this workflow is discussed. A method for integrating faults and fractures patterns in calculations in complex cases is proposed. 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. In the end, some ideas for accounting for connection characteristics in geostatistical simulations are proposed.

Résumé

Pour assurer la cohérence entre les modèles géologiques et les modèles dynamiques de réservoir, il est nécessaire de prendre en compte dans les modèles géologiques les informations venant de la synthèse dynamique relatives à l'existence de passages perméables entre divers points du réservoir. Cet article présente une méthode permettant cette prise en compte, qui peut être mise en œuvre à l'aide de logiciels commerciaux. Cette méthode est basée sur l'analyse de composantes connexes calculées sur des simulations géostatistiques au cours d'une phase de post-traitement. L'analyse des connexions physiques est faite à l'intérieur d'une même unité lithostratigraphique. L'utilisation de composantes connexes pour contrôler la qualité de simulations de facies ou de propriétés pétrophysiques est expliquée en détail et l'impact des paramètres des simulations (proportion de faciès, portée des variogrammes, etc..) sur la présence de passages perméables dans le modèle statique est étudié. La méthode est ensuite généralisée aux modèles statiques en position structurale, dans lesquels des unités lithostratigraphiques successives peuvent être connectées par des failles, lorsque le rejet des failles est assez grand. Une méthodologie en deux étapes est présentée, qui permet de conditionner les simulations aux informations de connexions entre points dans ce type de contexte difficile. La première étape consiste à identifier les réalisations qui respectent les critères de connexion entre points. La deuxième étape consiste à choisir des données conditionnantes supplémentaires pour le calcul des réalisations suivantes, de telle façon que les informations de connexion entre puits soient respectées et que les propriétés statistiques du modèle soient préservées. L'efficacité de cette

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méthodologie est analysée. Une technique permettant d'inclure les failles et fractures dans les calculs est proposée, pour les cas complexes. Lorsque les réalisations stochastiques d'un modèle respectent les observations relatives aux connexions entre des points choisis, il est intéressant de caractériser les connexions afin d'améliorer le contrôle de la qualité du modèle. Des façons possibles d'utiliser les composantes connexes pour du contrôle qualité avancé sont proposées. Enfin, quelques idées pour tenir compte des caractéristiques des connexions dans les simulations géostatistiques sont proposées.

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: 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 aim of this work is to provide immediately usable tools for accounting for connection information in geological models. This paper is focused on the study of the conditions in which geostatistical simulation algorithms allow generating permeable pathways related to geological facies between selected points in a static model. It is also dedicated to the description of methods for ensuring that static models honor observations about the presence of hydraulic connections between wells. Such connections are key contributors to flow dynamics, but are not always taken into consideration in geological modeling.

It must be noted that the QC approaches and geostatistical simulations conditioning methods presented in this paper are intentionally designed to be applied using any geostatistical simulation method implemented in currently available commercial software. This restriction is important as it forbids the use of interesting and powerful research algorithms and limits the complexity and sophistication of the proposed methodologies. It forces to define post-processing approaches applicable with common simulation algorithms. On the other hand, it allows defining approaches that can be immediately applied by geomodelers in their daily work in an industrial context, which should help them to deliver geological model consistent with connections information.

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 based on the properties of variogram based geostatistical algorithms are discussed first. Then, a general workflow which can be used with all the geostatistical simulations algorithms is detailed. The third section is focused on the characterization of connections between wells. Assuming that wells are connected, it is useful to characterize the geometry of the connecting geobody, 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 characterize the shape of permeable pathways between wells and facilitate the ranking of stochastic realizations.

In the end, some possible methods for conditioning static geological models to some connection characteristics 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 Well Connections

Importance of Connections Between Wells

The analysis of physical connections between selected points, such as well perforations, is critical not only for field appraisal and development, but also in production at the EOR (Enhanced Oil Recovery) design phase. 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.

There are several ways for defining connectivity measures in a 3D model, which have been studied and detailed by several authors. It is outside of this paper's scope to describe connectivity measures, but interested readers will find deep analyses and very detailed syntheses in Hovadik and Larue (2007) or in Renard and Allard (2013).

Connections between wells are considered here as permeable pathways related to geological facies characteristics and it is assumed that connected wells have been already identified, which is not always easy to do. Connections can be identified during the Basic Reservoir Engineering phase of a reservoir study, for example by analyzing well tests, pressure and fluid production data in neighbor wells and interference tests. Many authors have worked on this issue and there is actually a great variety of methods for detecting the presence hydraulic connections between wells, which are based on various kinds of measurements such as flow rate fluctuations, pressure perturbations or multiwell productivity (Albertoni and Lake, 2003; Yousef et al., 2006; Tiab and Dinh, 2008; Kaviani et al., 2010; and Soroush et al., 2014). These methods will not be detailed here and the uncertainty on interwell connectivity inference will not be addressed.

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 permeable pathway joining the two points. In the geological model, it 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, connections can be established 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 connection paths.

Eventually, a more sophisticated parameter than permeability might be considered, like the "resistivity index" defined in Hird and Dubrule (1995) and expanded to 3D grids by Ballin et al. (2002), as long as it is a parameter that can be populated in the 3D geological grid, and which is related to the facies (or rock class) used in geostatistical simulations. It must also be noticed that the definition of the "connecting facies" or of the parameter threshold to be applied depends on the type of fluid and on the production method. These issues are out of this paper scope and will not be discussed here. It is assumed that the geologist and the reservoir engineer have already worked together to define the most relevant facies to be considered, or the most relevant rock class defined from a petrophysical parameter threshold.

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 binary sets corresponding to facies indicators or calculated by thresholding a petrophysical parameter. 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.

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, as mentioned before, great care must be taken in the definition of the binary set on which connected components are calculated, which implies a preliminary work involving geologists and reservoir engineers.

Identifying Connected Wells in the Model

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.

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, or the rugosity of their surface, as examples. 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 the 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 I, J, K indexes. It means that a global structural model merging all the stratigraphic units must be defined.

An example of a structural grid superimposed to stacked stratigraphic units is shown in Figure 4. The facies and petrophysical properties simulated in each stratigraphic unit must be sampled or upscaled in this grid. Then, permeable pathways in 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.

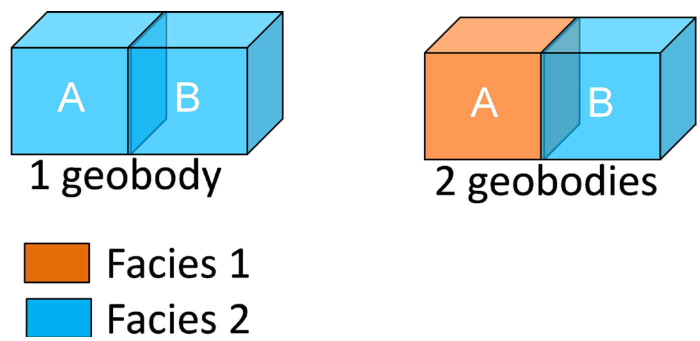

Figure 1. Definition of connected components. Two cells assigned to the same facies, being in contact by one face, are in the same connected component.

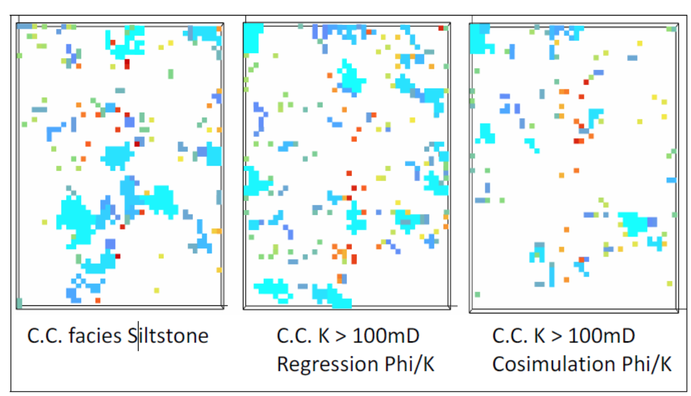

Figure 2. Example of connected components. The application of the connected components definition to a geomodel leads to several independent geobodies of various shapes.

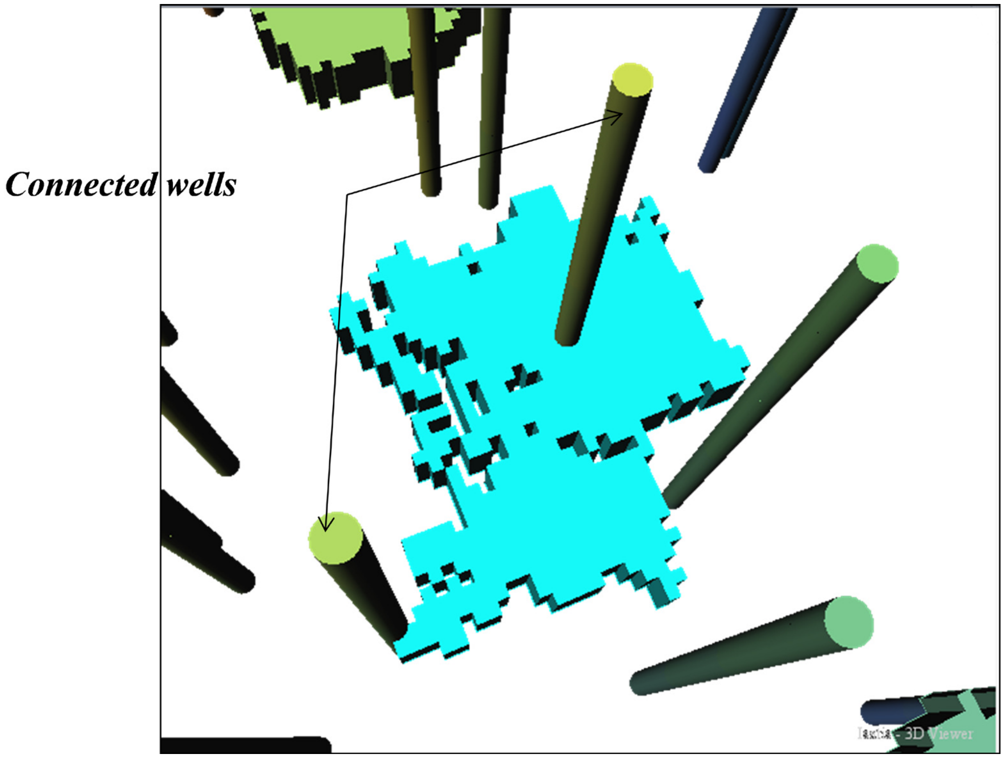

Figure 3. Example of connected wells which are intersecting the same connected component.

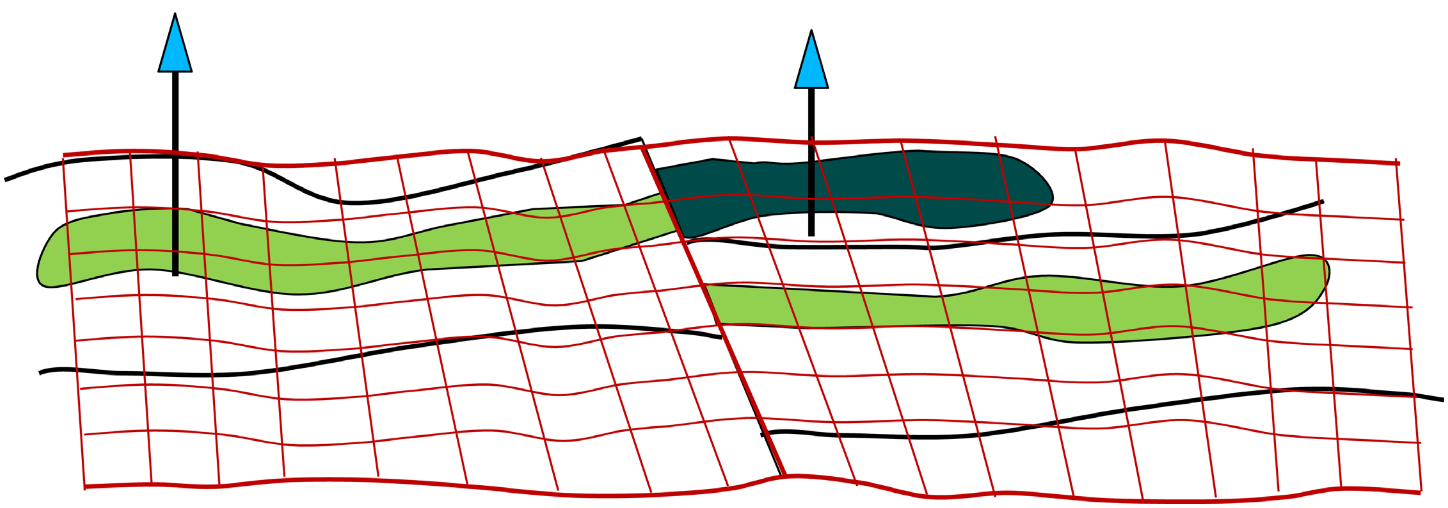

Figure 4. Connection in presence of tectonic structures. Geobodies of similar properties can be put in contact by a shift along a fault. The two geobodies on each side of the fault must be in the same grid and must be neighbors in terms of grid indexes to be merged in the same connected component.

Constraining Geostatistical Simulations to Honor Connections between Wells

Algorithms for Controlling Connections

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 the proposed approaches have not been developed. An algorithm which can account for physical connection constraints is proposed in Renard et al. (2011). It requires the inclusion of extra conditioning points to honor the connection using MPS method and a training image. This feature is not always implemented in commercial software.

Therefore, constraining geostatistical simulations to honor criteria of physical connection between points, 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 (Fig. 5). Editing a Vertical Proportion Curve may be sufficient for restoring the connection between the wells (Fig. 6).

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 connection 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. It is obvious that the efficiency of this approach will depend on the number of input parameters of a simulation method. These iterative tests are general but are easier to manage when the facies distribution depends on few synthetic parameters only. In that sense, using pixel based methods like PluriGaussian Simulations is advantageous. PGS is very versatile, able to reproduce many geological environments and is fully characterized by few parameters: variogram, local Vertical Proportion Curves and rock type rules (Armstrong et al., 2011).

Eventually, for pixel-based methods, if varying facies variogram ranges are identified in different sectors of the reservoir, Local Geostatistics tools (LGS) can be used with SIS simulation technique. This method is presented in Magneron and Petit (2008).

Stochastic Connection 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:

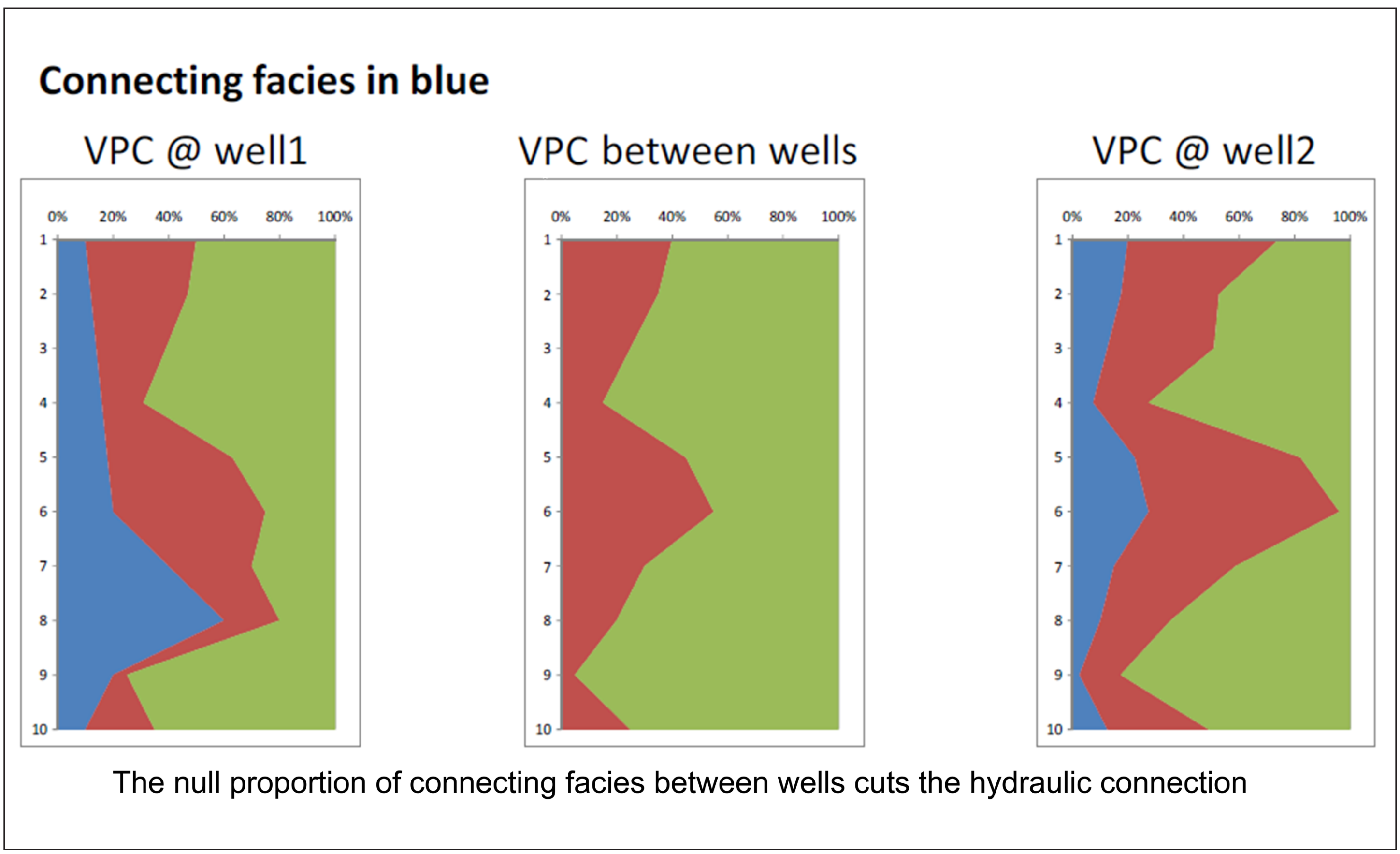

Figure 5. A configuration leading to disconnection: it is impossible to join the two wells by a connected component because of the absence of the permeable facies (in blue in the figure) between the wells (null proportion of this facies in the intermediate local VPC).

1. Only few percents of the realizations are valid (wells are connected by a permeable pathway). In such a case, the geological model cannot be considered as realistic, as it is inconsistent with the reservoir engineer interpretations.
2. Forty to eighty percent of the realizations are valid. Then, the geological model is consistent with dynamic data analysis. 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 analysis 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).

The sensitivity analysis results are shown in Figure 8. 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.

The curves shape evoques percolation effects. It is out of this paper's scope to develop the relationship with percolation theory. Interested readers can refer to Larue and Hovadik (2006), to Hovadik and Larue (2007) and to Renard and Allard (2013).

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 well connection is honored in most of the model realizations.

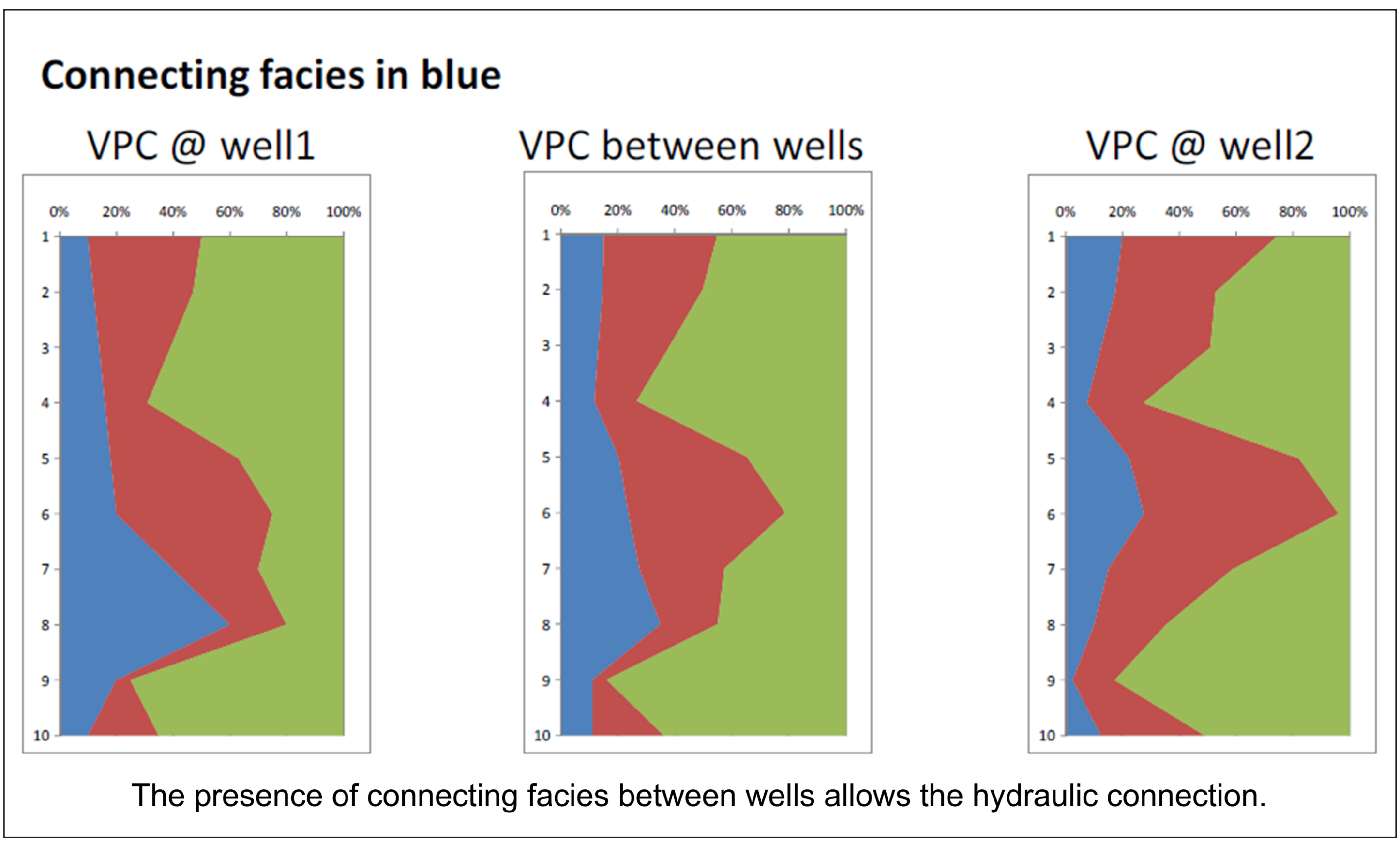

Figure 6. Restoring connection in a simple case: the presence of the permeable facies in all the local VPCs (at well locations and between wells) allows the creation of a connected component joining the wells.

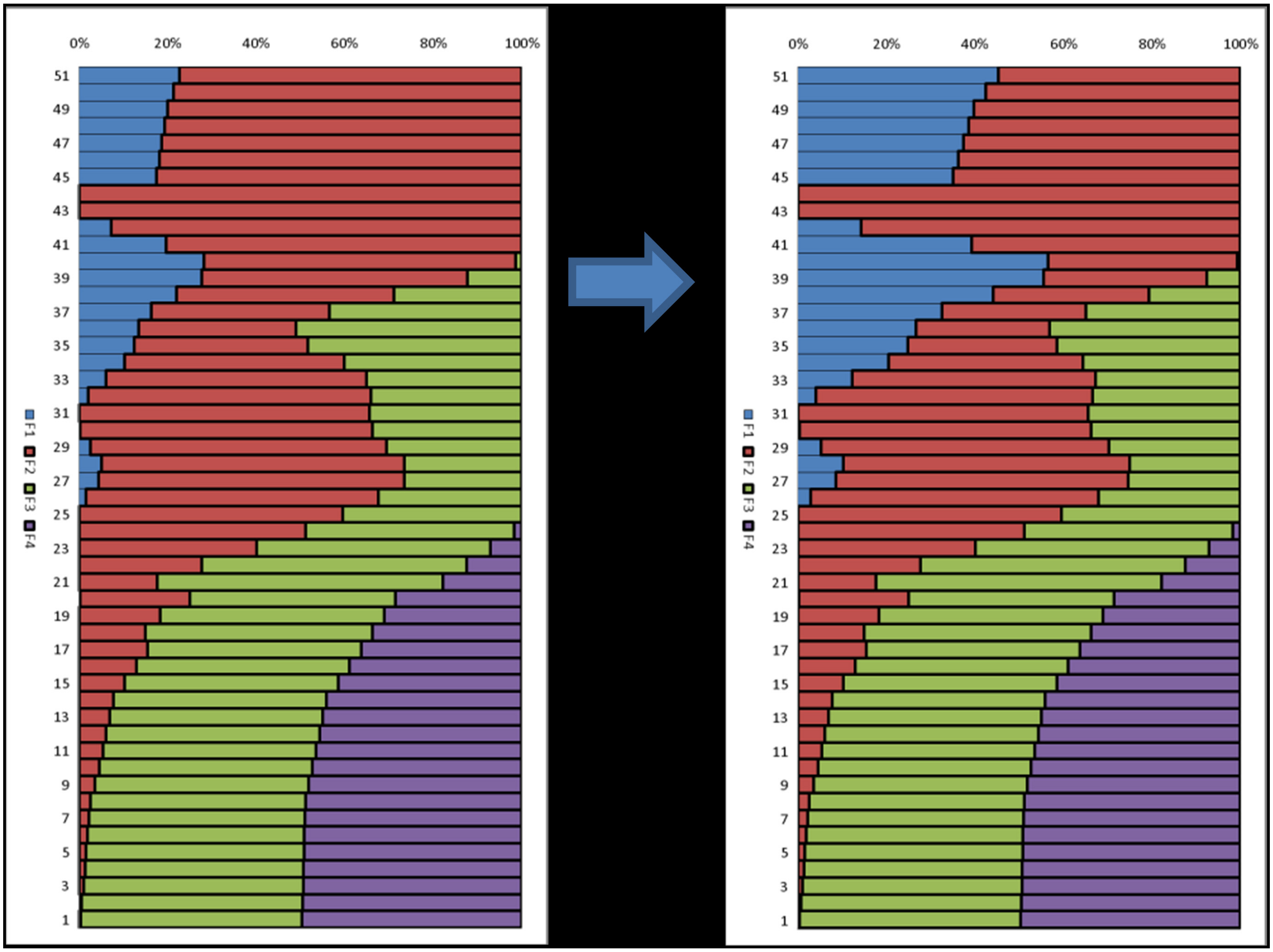

Figure 7. Analyzing the sensitivity to permeable facies proportion: the permeable connecting facies is in blue, and varies from 30% to 60% in the vicinity of the perforations (at the arrow location). Several stochastic realizations are calculated, using VPCs with varying blue facies proportion, and connected components are calculated in each case.

Stochastic Connection Analysis: Defining Additional Conditioning Data

In complex cases, taking benefit of the uncertainty on the model parameters may be insufficient. Points in the model that are expected to be connected may remain disconnected in most of the realizations.

Making statistics on many realizations of a stochastic model and testing the sensitivity to model input parameters provides much more information about the model robustness and accuracy than checking a single realization. Therefore, if the expected physical connection is established in less than 40% of the realizations, then either the geological interpretation or the physical connection hypothesis has to be revisited. Such an amount of realizations in contradiction with the observations means that something is wrong in the model characteristics, in the geological modeling process or in the reservoir engineering analysis:

- In general, mistakes in the geological interpretation come from lack of data, which may occur at a very early stage of a reservoir life.
- The way the connection between points is defined in the model may also be wrong. The connection definition is based on a geological facies or on a threshold on permeability or on any other adequate petrophysical parameter. If the facies definition is not appropriate or if the permeability threshold has been poorly defined, then strong contradictions may occur.
- There is also an uncertainty in the reservoir engineering analyses, and hydraulic connections between wells are not always easy to prove. Sometimes, we may work with a simple suspicion of connection, not with a proven connection, and the connection hypothesis may be discussed in case of strong contradiction with the other sources of information.

Whatever the cause of the issue, the solution will come from an integrated work of the different specialists involved in reservoir studies. The proposed stochastic connection analysis does not provide a solution, but it allows detecting the problem and provides useful information for the specialists' discussions.

If 40% to 80% of the realizations are correct, meaning that the expected physical connection is honored, it is possible to force the connection in 100% of the realizations 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. Estimation of the probability of presence of the cell in a geobody connecting the wells for each cell of the grid (Fig. 9). The probability of presence is estimated here from the percentage of realizations in which a given cell belongs to a geobody connecting the wells.
3. Thresholding of this probability of presence, in order to highlight the cells that are the most often in a connecting geobody (Fig. 10). Therefore, most of the times, the connecting facies (or range of permeability) is assigned to these cells.
4. In this sub-set, an automatic random sampling allows defining additional data which will be used as additional conditioning data in further stochastic realizations (Fig. 11).

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.

Before using this approach, it must be kept in mind that introducing new conditioning data in the simulations may alter the statistics and introduce some bias. In particular, if the same samples are added to all the realizations, these points will play the same role as real data, without being real data. It will lead to a local bias of the model, which significantly alter the calculation of local uncertainty. In order to minimize this effect, it is of primary importance to restrict the use of this approach to the cases where only few additional samples are required, these samples being extracted from a set large enough to allow modifying the new data from one realization to another. Therefore, this method works if the starting point is a model for which at least 40% or 50% of the realizations honor the wells connection constraint. The number of additional samples required to ensure the physical connection between two selected points in the model depends on its spatial variability. The idea is to force sedimentary bodies to merge to generate a continuous path between two points. With a variogram based simulation method (SIS, PGS), such a result will be obtained with few additional samples if the variogram range is long in the direction defined by the two points that have to be connected. In very heterogeneous environments,

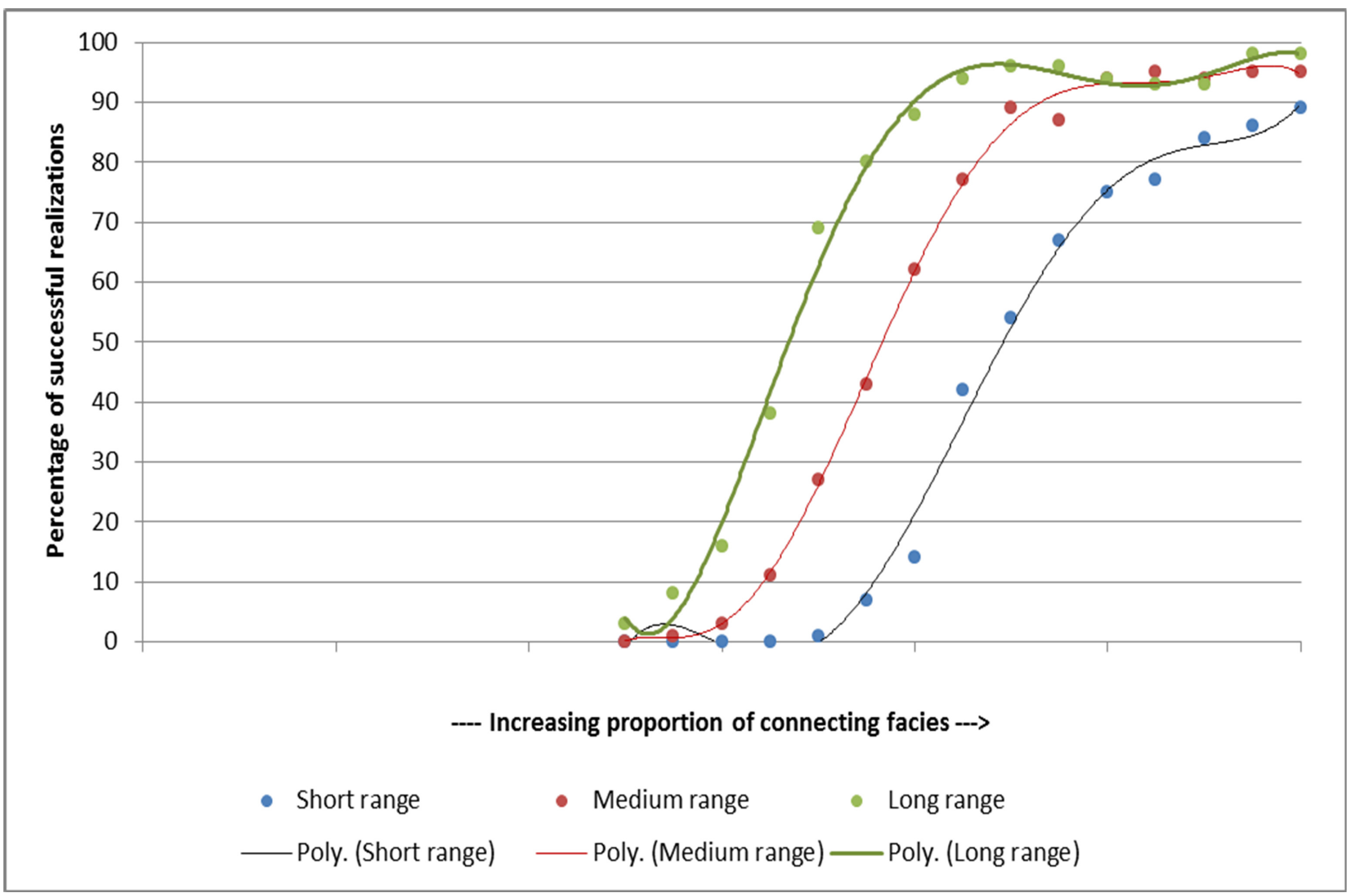

Figure 8. Sensitivity analysis results: when the permeable proportion increases, the percentage of stochastic realizations in which the wells cross the same connected component increases. Each S-curve corresponds to a given facies variogram range.

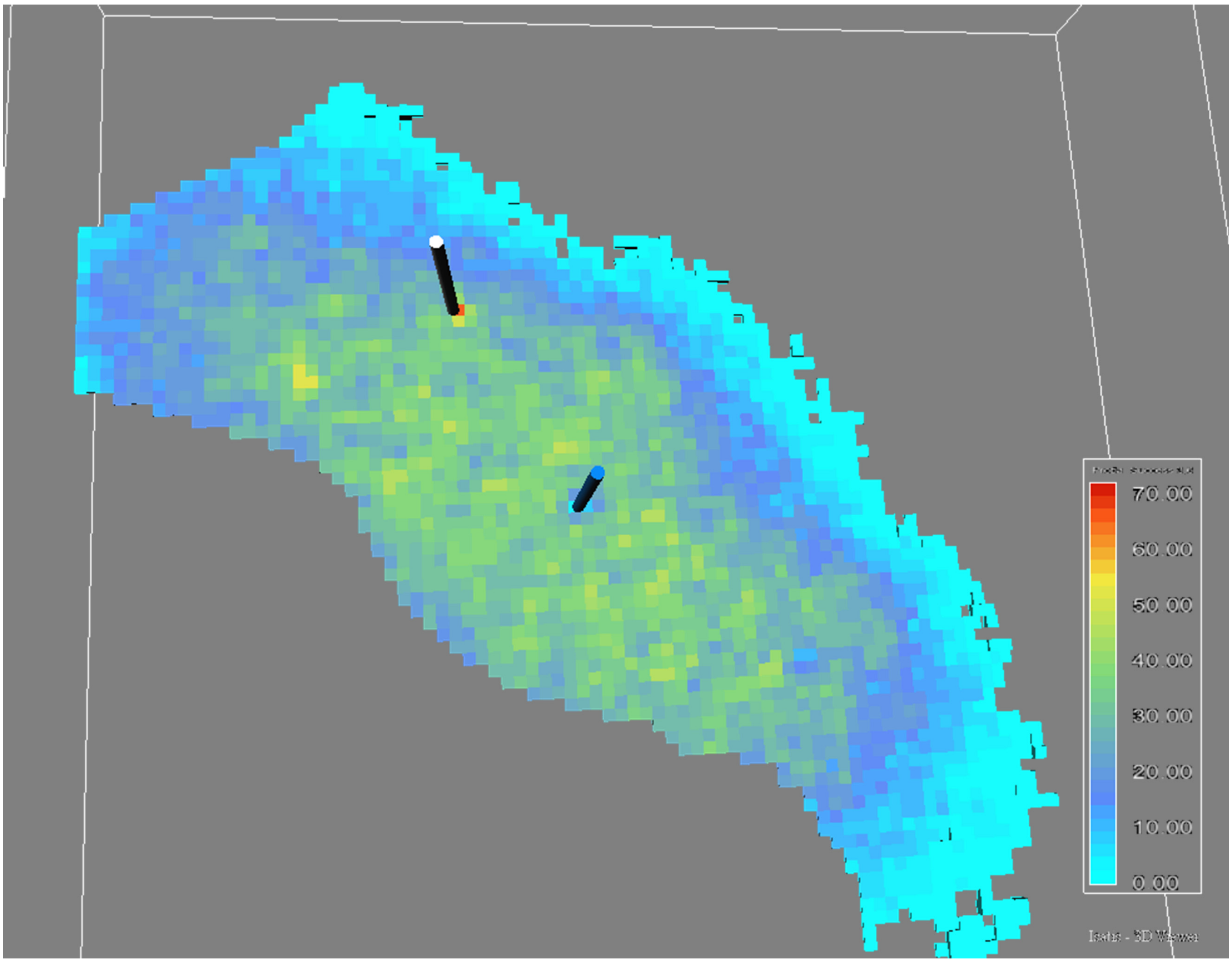

Figure 9. Probability of presence in a connecting geobody, estimated by the percentage of stochastic realizations in which a cell belongs to a connected component joining the wells.

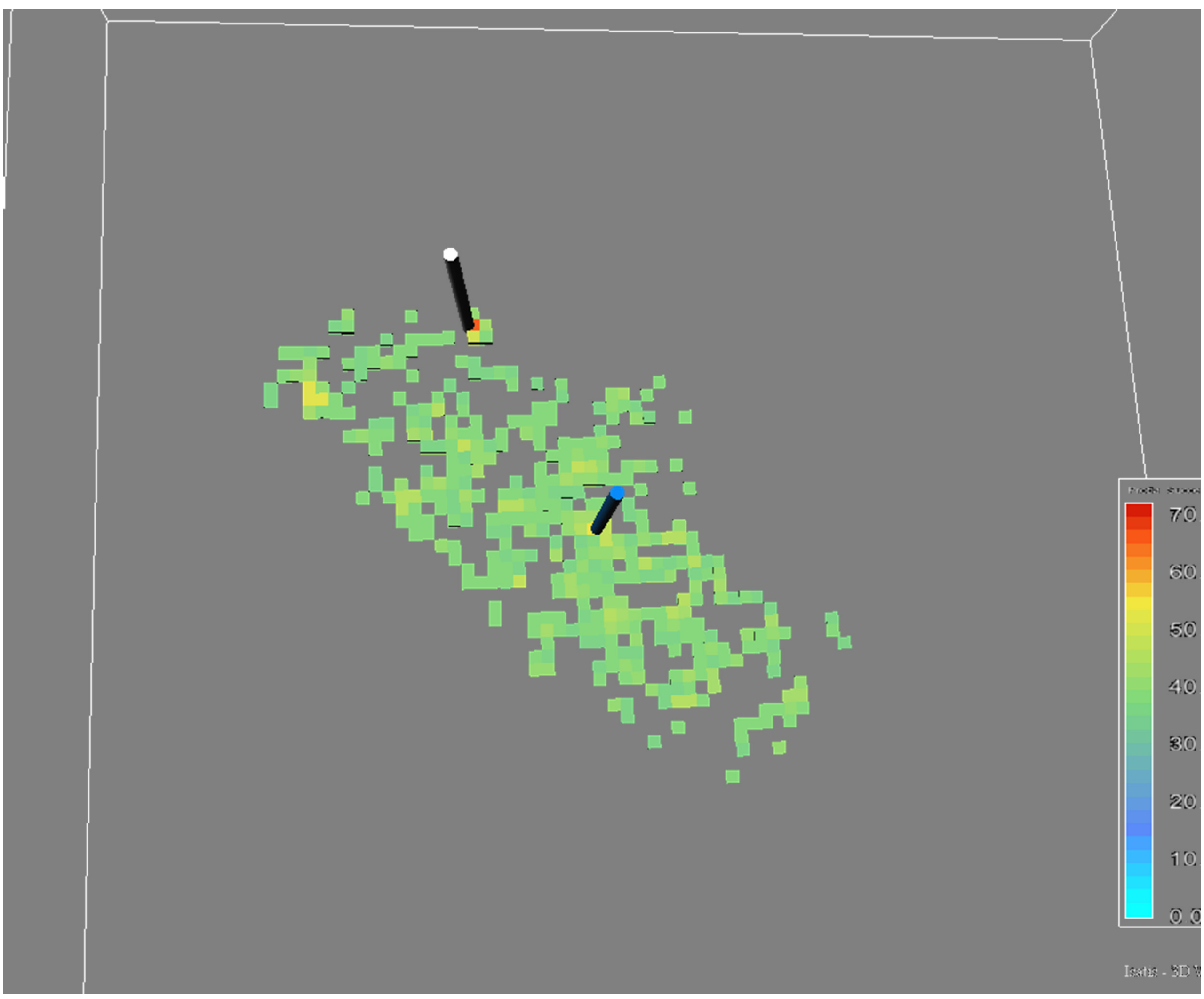

Figure 10. Selection of cells with the highest Probability of Presence: it corresponds to a thresholding of the variable shown in Figure 9.

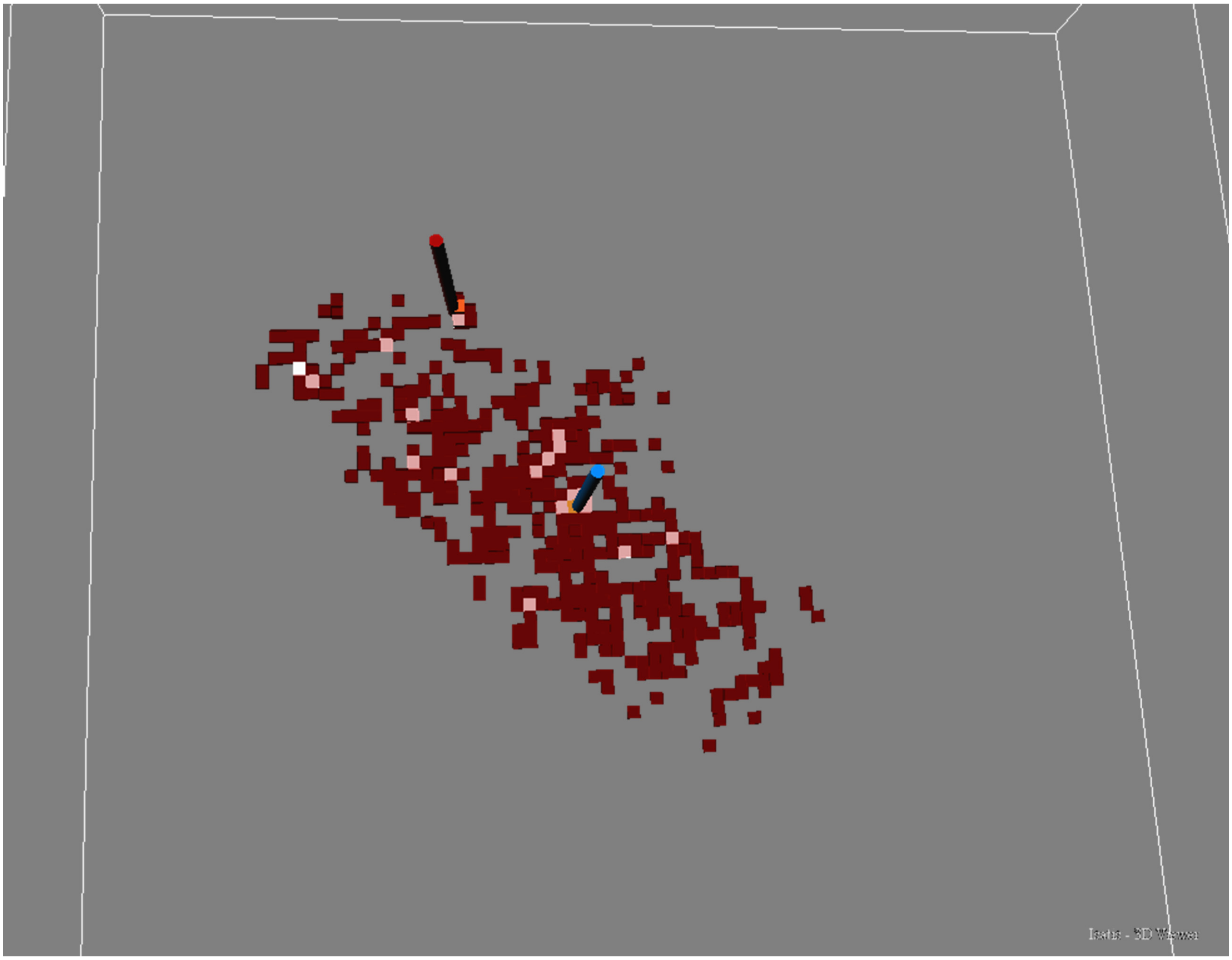

Figure 11. Additional random conditioning data (light color): it corresponds to a random sampling of the selection shown in Figure 10 (displayed with dark color).

many additional samples may be required. There is no formula defining the optimal sampling pattern and rate accounting for the great variety of geological contexts and simulation methods. Therefore, it is recommended to make an empirical calibration analysis at step 4, by testing various sampling patterns and rates on one new realization of the model to determine which ones are the most accurate.

The local vertical proportion curve may also be affected by the addition of new data. In practice, if the number of new samples is low, the practical impact on local VPC will be very limited and will depend on the scale of the VPC, therefore on the size of the area to which the VPC is assigned. The local VPC around the additional data will actually correspond to the local VPC, at the same location, in the initial realizations which were connecting the wells before the introduction of new data. Therefore, if applied on an initial model for which at least 40% or 50% of the realizations honor the wells connection constraint, the method will lead to acceptable VPC modifications.

In any case, the robustness of the main parameters characterizing the geological model must be checked. In addition, it can be noted that the same random sampling approach allows connecting, at a given location, of two successive stratigraphic units simulated independently if applied on the structural grid merging all the units. The method consists of sampling cells corresponding to the right facies at the border of the unit. The samples are then copied at the same XY location in the next lithostratigraphic unit and used as additional constraints in this last unit. 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 permeability streaks 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.

Then, all the previously presented workflows can be applied.

Characterizing Connections

Why Characterizing Connections?

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. Therefore, it is important to characterize the shape of the connecting geobodies.

Qualitative Characterization of Connections

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

This qualitative approach allows getting easily and quickly a rough idea of the variability of the connections geometrical characteristics in the model. It can be enriched by displaying either the distance to the wells (Fig. 14) or the distance to the edges (Fig. 15).

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. 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.

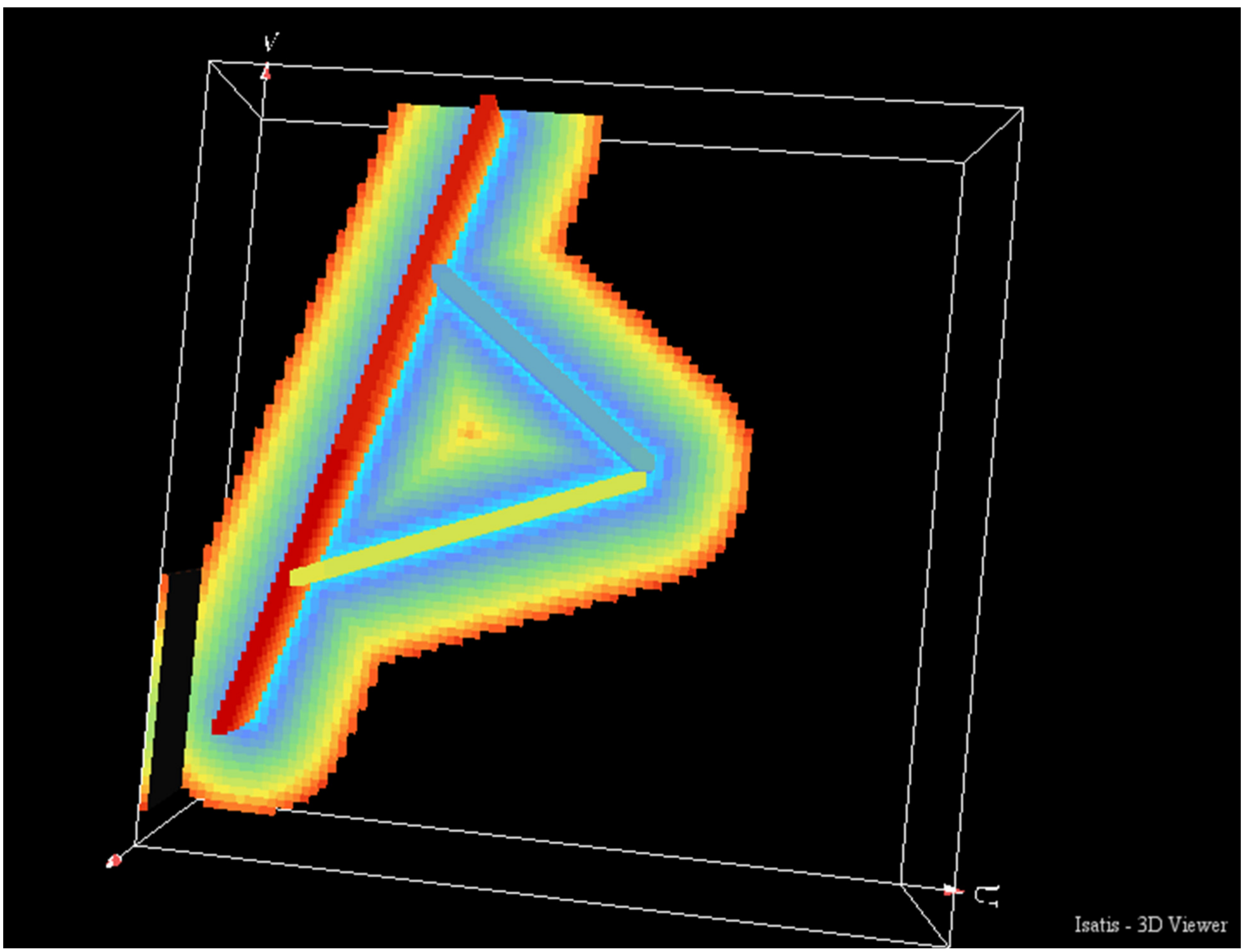

Figure 12. Distance to the closest fault, calculated in the geological model. A simple thresholding of this variable allows identifying the cells close to conductive faults, which have to be included in connected components calculations.

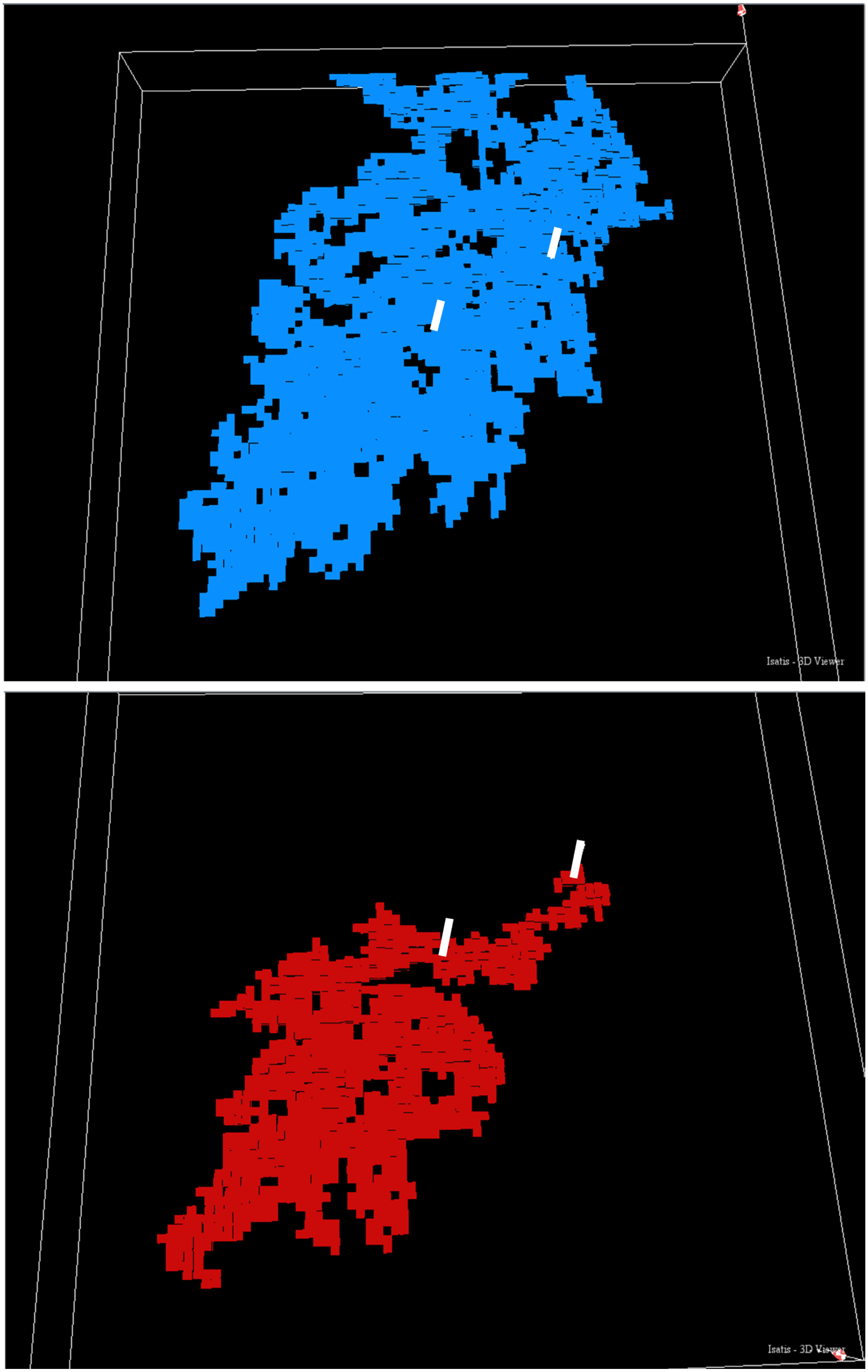

Figure 13. Different types of connection between wells. Due to their shapes and to the location of the wells in the connected components, the two cases will correspond to very different flow behaviors.

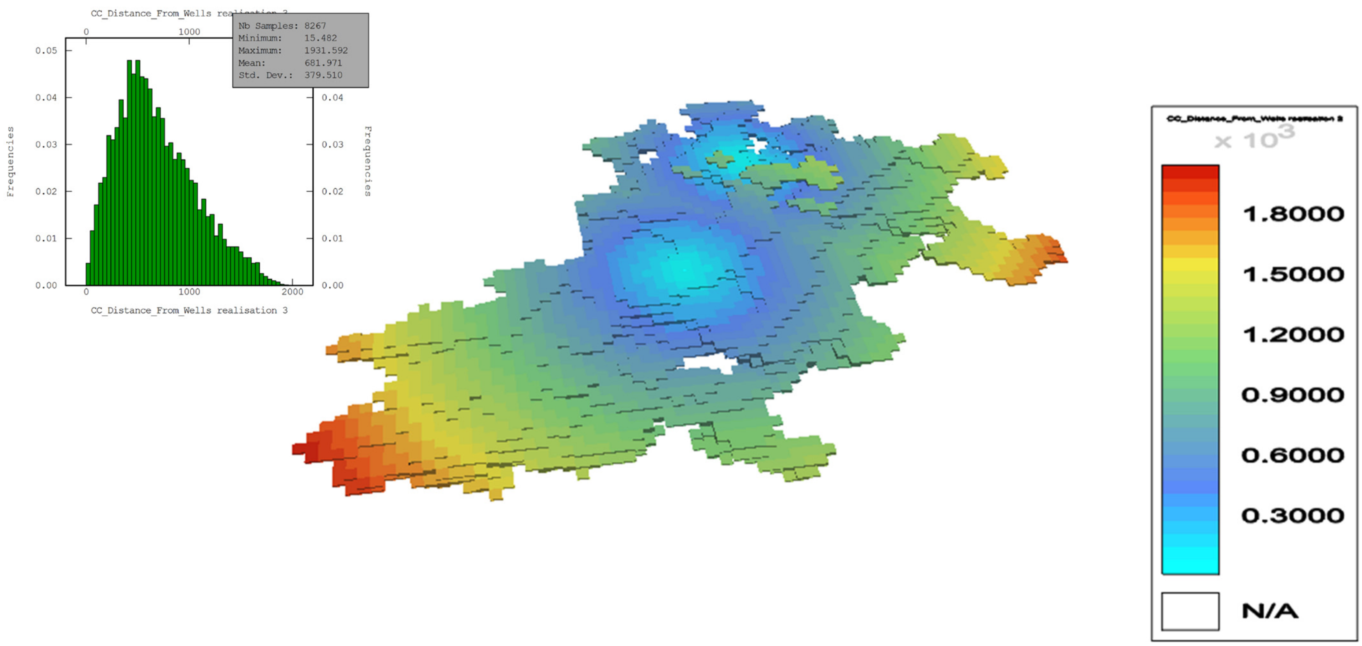

Figure 14. Distance to the wells in a connecting geobody, which can be used to characterize geobodies.

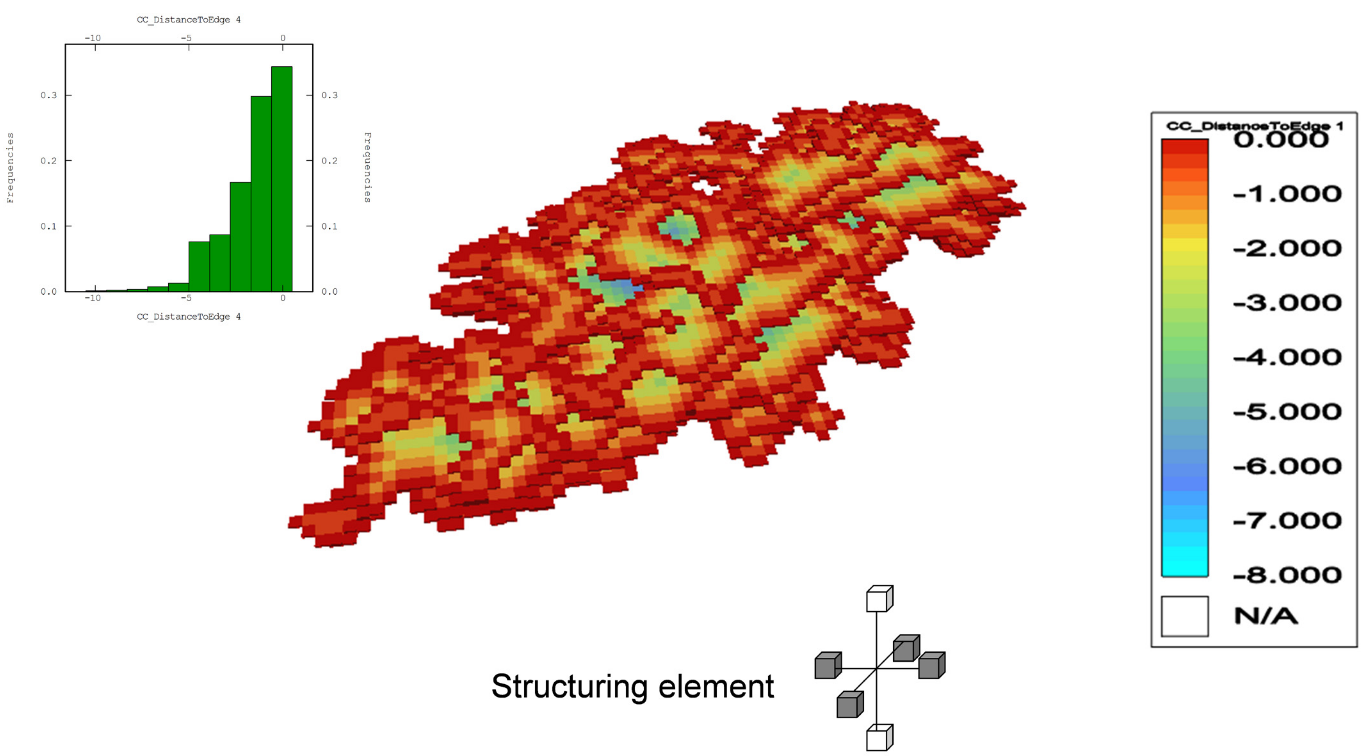

Figure 15. Distance to the edges in a connecting geobody, which can be used to characterize geobodies.

Quantitative Characterization of Connections

A qualitative characterization of connections 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, as for example:

- A first simple indicator is the histogram of the distance to the wells (Fig. 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 (Fig. 15) indicates whether the connecting geobody is made of few large blocks or 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 (Fig. 16).
- 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 (Fig. 17). 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 Characteristics in Geostatistical Simulations?

Honoring connection between wells in static models is useful, but honoring connection characteristics would be much better. As far as we know, there is no commercial algorithm able to do this and further developments will be required. Finding a geostatistical simulation method able to include such constraints in its input parameters is a mid-term objective. Nevertheless, useful methods for characterizing connecting pathways between wells are detailed in Hovadik and Larue (2007) or in Renard and Allard (2013).

Some practical workflows using already available methods and software can also 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:

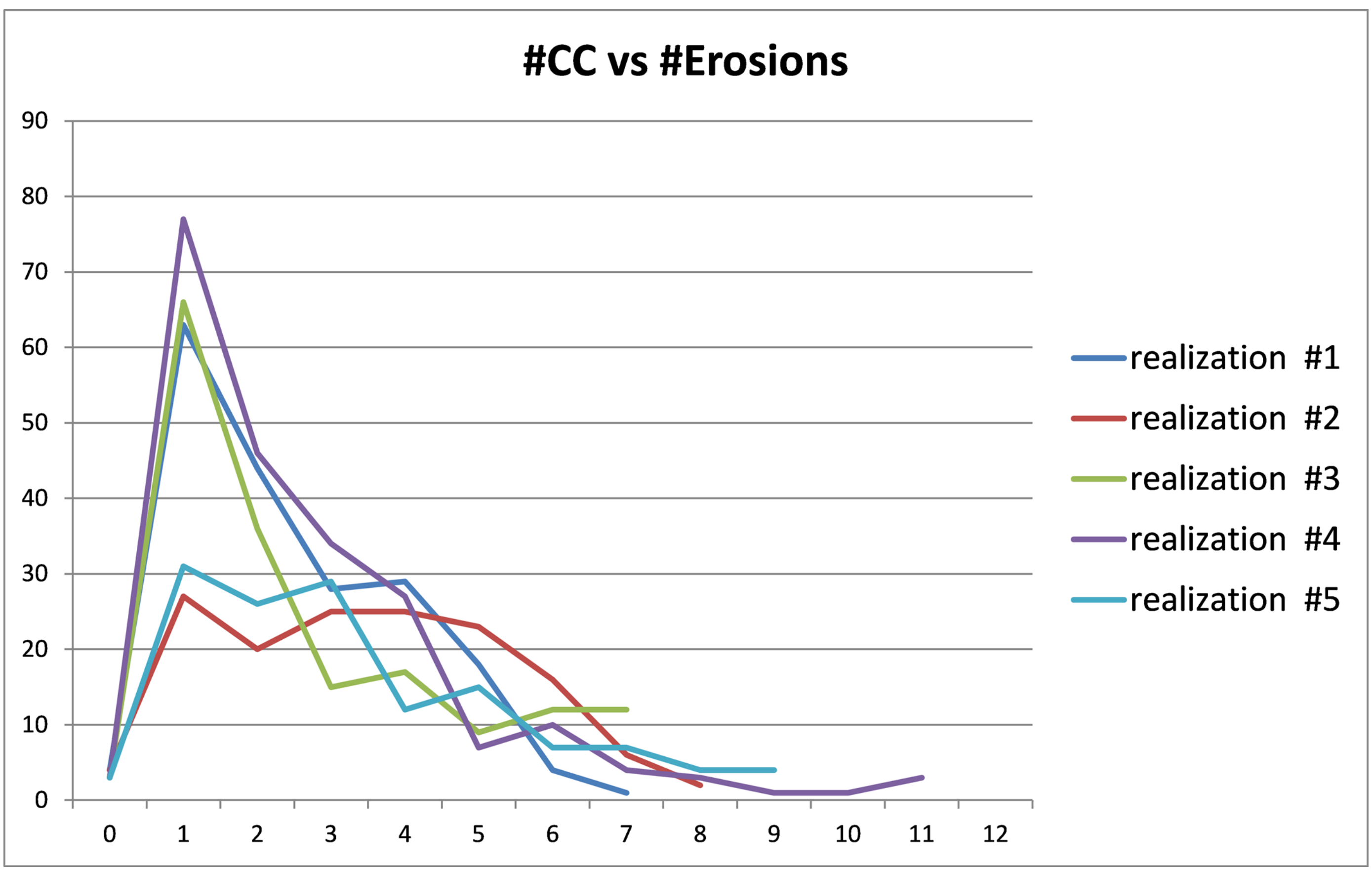

Figure 16. Number of connected components after successive erosions, which can be used to characterize geobodies.

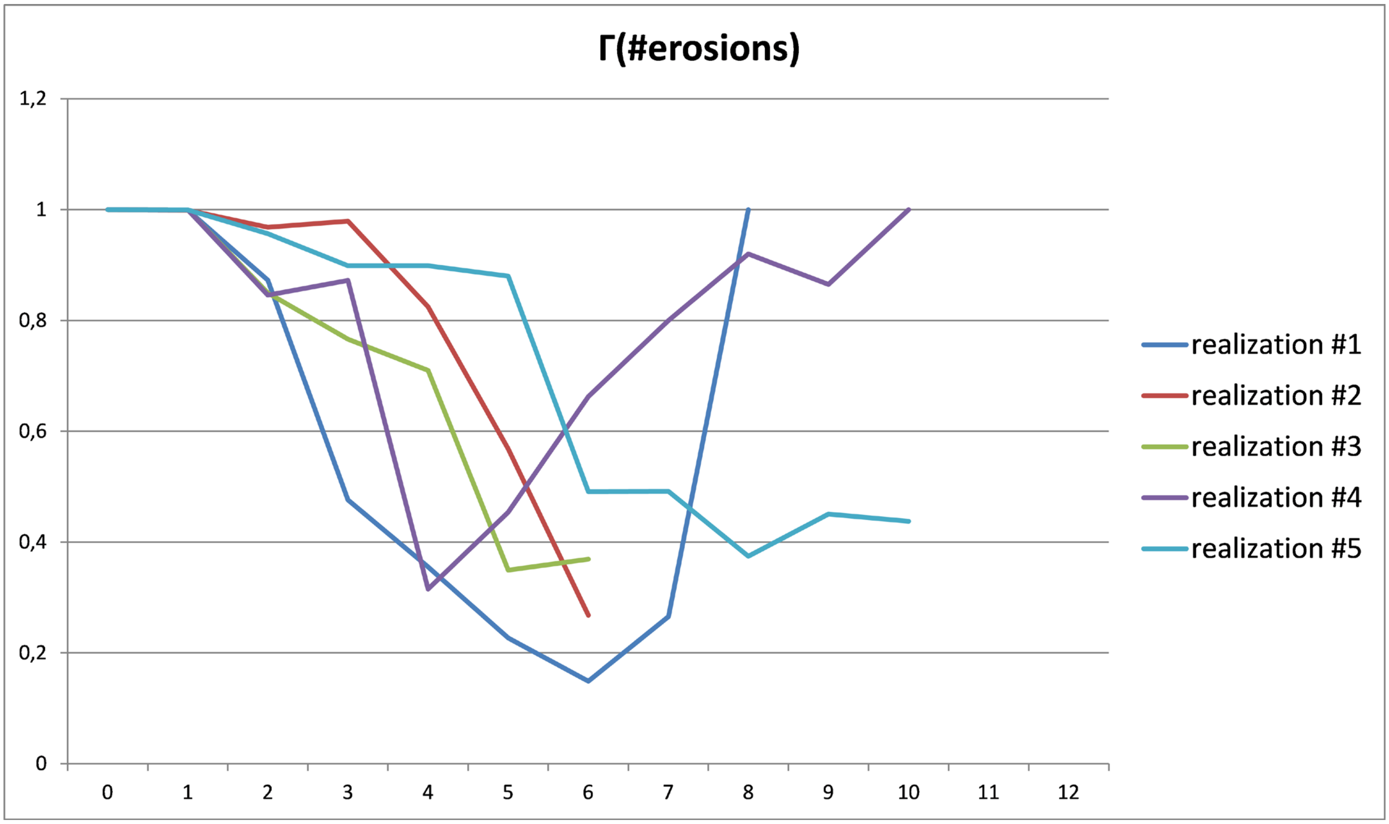

Figure 17. percolation metric Γ(# erosions) , which can be used to characterize geobodies.

- A first method consists in determining additional conditioning points for further geostatistical simulations, using the approach described above (Stochastic Connection 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 improvement from a brutal force approach which would consist of 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 the Gradual deformation method detailed in 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.

It has been shown that it is valuable to perform the model QC by analyzing several stochastic realizations of the model. Making statistics on the realizations provides a lot of information on the model accuracy and realism, which may enrich the discussions between geologists and reservoir engineers. Such model QC induces more work at the geological modeling phase, 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.

The methodology presented in this paper was designed for being used in already developed fields for enhancing static models. It may also be used at an early stage of a field life or in undeveloped areas for anticipating the model response by checking which future wells might be connected, in which conditions.

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