Grid-less Modeling of Reservoir Properties with Maximum Continuity Field Interpolation

Marko Maučec[1], Jeffrey M. Yarus[2], Genbao Shi[3] and Richard L. Chambers[4]

Abstract Traditional Earth modeling practice uses 3D-geocellular grids to represent reservoir volumes. The gridding parameters are required to be estimated upfront, often difficult to infer and commonly hastily set. Often, little thought is given in geocellular parameterization to the appropriateness of the specified cellular dimensions and layering styles, which makes it a time consuming and costly trial-and-error exercise or a compromise. We present a new technology that resolves many common geocellular parameterization and modeling issues by first generating grid-less 3D property models within a sealed structural framework. The geological properties within a volume of subsurface are represented by distributing a plurality of data points in the absence of the grid with the notion of geological continuity and directionality given by a maximum continuity field (MCF). In many depositional systems, changes exist in the local direction of maximum continuity; however, traditional variogram implementation assumes a single maximum direction of continuity. Our method supports defining both a *local* direction of maximum continuity and the associated correlation distance without a standard grid. We validate and benchmark technology by modeling the permeability distribution in a synthetic, complex fluvial system, and combining a set of user-defined MCFs and control well-data points. Finally, we present the method for Assisted Property Modeling that provides the ability to build, create and edit MCF vector maps quickly, insert instantly and interactively guidelines corresponding to dominant geological continuity of any shape and works with a number of different underlying estimation and simulation methods to create reservoir properties.

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[1] Halliburton Energy Services, Landmark Graphics Corporation, 1805 Shea Center Drive, Suite 400, Highlands Ranch, CO 80129, USA.
marko.maucec@halliburton.com

[2] Halliburton Energy Services, Landmark Graphics Corporation, 2107 City West Blvd., Houston, TX 77042, USA.
jeffrey.yarus@halliburton.com

[3] Halliburton Energy Services, Landmark Graphics Corporation, 2107 City West Blvd., Houston, TX 77042, USA.
genbao.shi@halliburton.com

[4] Halliburton Energy Services, Landmark Graphics Corporation, 2107 City West Blvd., Houston, TX 77042, USA.
richardL.chambers@halliburton.com

1 Introduction

Traditional reservoir modeling techniques use simplified *two-point statistics* to describe the pattern of spatial variation in geological properties. Such techniques implement a *variogram* model that quantifies the average of expected variability as a function of *distance* and *direction*. In reservoirs, where the geological characteristics are very continuous and easily correlated from well to well, the range (or scale) of correlation will be large while in reservoirs, where the geological characteristics change quickly over short distances, the correlation scales will be shorter. The later phenomenon is very common in sedimentary environments, where the primary mechanism of transport during deposition is water, resulting in highly *channelized* structures (*e.g.* deltaic channels, fluvial deposits, turbidities). These environments usually demonstrate a large degree of local anisotropy and of correlation variation between directions along the channel axis and perpendicular to the channel axis.

In the attempt to overcome deficiencies of geomodeling based on conventional geostatistics, advances have been made within the last decade in the form of multi-point (geo)statistics (MPS). The approach computes correlations between multiple locations at the same time to reproduce volume-variance relationship and model realizations, conditioned to local sample data [1, 2]. The MPS techniques are rapidly growing in popularity offering the modeler the ability to create geological models with complex geometries, while conditioning to large amounts of well and seismic data. However, as pointed out in [3], MPS is still a relatively new topic, which has had a long academic history and is now just finding its way into commercial software. They also pointed out several deficiencies in current implementations related to 1) performance, 2) training image generation, and 3) non-stationarity.

Recently, technology for 3D volumetric modeling of geological properties, using a Maximum Continuity Field (MCF) has been proposed [4]. The geological properties are represented within a volume of the subsurface by distributing a plurality of data points in the absence of the grid with the notion of geological continuity and directionality represented by MCF, hence entitled and hereafter referred as to Point-Vector (PV) method. It introduces several game-changing components to the area of geomodeling:

- Direct control over local continuity directions is controlled using a predefined azimuth map and the local dip (an angle from the horizontal/azimuth plane) of the horizons. The Fault Displacement Field (FDF), annotated in Fig. 5 with symbol FT (fault throw) can be, for example, calculated from the underlying seismic amplitude data [5].
- Interactive operation with “geologically intuitive” datasets, such as layering intervals, projection maps and hand drawings via the notion of MCF.
- Retention of the maximum fidelity of geological model by postponing the creation of grid/mesh until the final stage of (static) model building,

> immediately before integrating into dynamic model. The reservoir property modeling does not need a standard grid but only the “correct” distance between the points to estimate/simulate the property and data around it.

This paper describes a novel method that has a potential to resolve most of the common geocellular modeling issues by implementing the concept of interpolation or simulation of reservoir properties using Local Continuity Directions [4, 6]. We give the demonstration of performance of PV technology by generating a gridless model of the distribution of permeability in the simplified fluvial system. The validation model is derived from the complex synthetic field-case, combining a set of user-defined MCF and control data points (*i.e.* well location constraints). We further introduce and demonstrate the method to assist interaction with defining vector field and properties from well data that can be used as secondary data during Grid-less continuity field interpolation. The method allows the user to interactively draw guidelines of any shape which instantly (and on-the-fly) creates simple to complex representations (maps) of Maximum Continuity vector fields and by adding/honoring well and pseudo-well constraints provides valuable control in the process of modeling reservoir properties [7].

2 Methods and techniques

The key to implementation of the ideas of Grid-less modeling of geological properties emerges from interpretation of concepts of MCF and their implementation into kriging equations for geostatistical estimation. Among the numerous interpolation methods, the geostatistical kriging algorithm is commonly used in the geosciences. Kriging is an unbiased, linear, spatial least-square regression technique that automatically “de-clusters” data to produce best local or block estimates with minimized error variance. Figure 1 depicts the principles of linear, weighted estimation of the value at location Z_0, based on measured values at locations Z_1 to Z_3:

$$Z_0 = \sum_{i=1}^{n} \lambda_i Z_i \tag{1}$$

where the weights λ_i at locations Z_i are calculated from the variogram model. Unlike the more conventional linear weighting estimators, the kriging weights, $\lambda_{i,}$ account for distance and orientation .The constraint for an unbiased estimator is satisfied by maintaining $\sum \lambda_i = 1$.

Almost all available geostatistical software restricts the user to certain types of variogram model functions (*e.g.* spherical, exponential, Gaussian etc.) to ensure that a unique set of kriging weights can always be found and to ”force” a *single* direction of maximum continuity. However, it is very rare in geology to have a single direction of maximum continuity representative everywhere. The usual approach taken in geostatistical software is to describe the variogram model’s ranges as an ellipse (in 2D) or an ellipsoid (in 3D). The user is required to nominate a single direction of maximum continuity, applicable to a given sub-domain, which is related to the orientation of major axis of the ellipse. In 2D the direction of minimum continuity is in line with the minor axis of the variogram. In 3D ellipsoid the intermediate direction is perpendicular to the principal major-minor plane. Instead of imposing the requirement to nominate the single direction of maximum continuity the geostatistical software should allow the user to specify local directions of maximum continuity. While a few tools offer this flexibility, the proposed PV technology aims to provide such capability also to the industry without the constraint of an underlying grid.

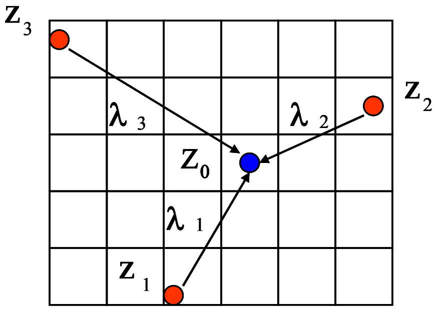


Figure 1 Principles of kriging: the geostatistical interpolation method. The value of the unsampled location Z_0, is estimated based on linear combination of measurements at locations Z_1 to Z_3, where weights λ_i at locations Z_i are calculated from the variogram model.

2.1 Direction of maximum continuity

Geometrically, the spatial continuity is usually associated with the definition of a vector, characterized by its location, magnitude and direction. In the method presented herewith, the vector gets attached to another spatial property, called the correlation length or just length (see Figure 2), along which the magnitude of the geological property remains “substantially the same”, say within 10% of its initial value.

Furthermore, the axes of the variogram model are simply reoriented and follow the local direction of the continuity as specified by the user. As such, the long range of the variogram does not pertain to a particular compass direction but is rather the range of Local Maximum Continuity.

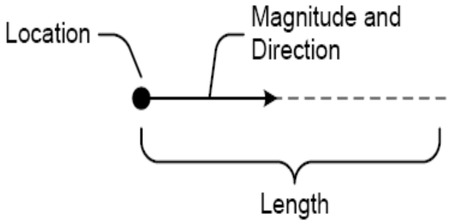


Figure 2 Geometrical definition of the direction of maximum continuity as implemented in the PV method.

2.2 Interpolation of geological properties

For the calculations outlined in this paper, the PV method is implementing the following essential workflow for the interpolation of properties in 3D geological models:

1. Pre-densify a set of points within each stratigraphic interval where MCF is stored and the property values are interpolated along with a structural model. Conversely points can be generated "on the fly" based on the desired level of resolution that may vary within or between intervals.
2. Define the MCF in the entire point-densified area, using some predefined azimuth map (see Figure 6b) and the local dip (an angle from the horizontal/azimuth plane) of the horizons. Alternatively, MCF and local dip can be calculated "on the fly" if points are not pre-densified.
3. Pre-process of all the fault displacements in the 3D grid.
4. Add all the known data points (*i.e.* spatially located known property, such as permeability) to the model, create the covariance neighborhood, and the variogram. The covariance calculations take local continuity into account by aligning the axes of the variogram with the local continuity direction.
5. Run an ordinary kriging estimator, using the created covariance neighborhood. For each point to estimate, the kriging finds the nearest set of known data. The kriging estimation is performed along covariance distances, where expected value operator combines the Euclidean norm δ_{ij}:

   $$\delta_{ij} = \left(\sum_{a=1}^{N} \left(x_{ia} - x_{ja} \right)^2 \right)^{1/2} \quad (2)$$

   with x_i and x_j representing the pair of spatial points (locations) and the index a running over the full set of points.

The interpolation of properties, as implemented in PV method is schematically depicted (2D case) in Figure 3.

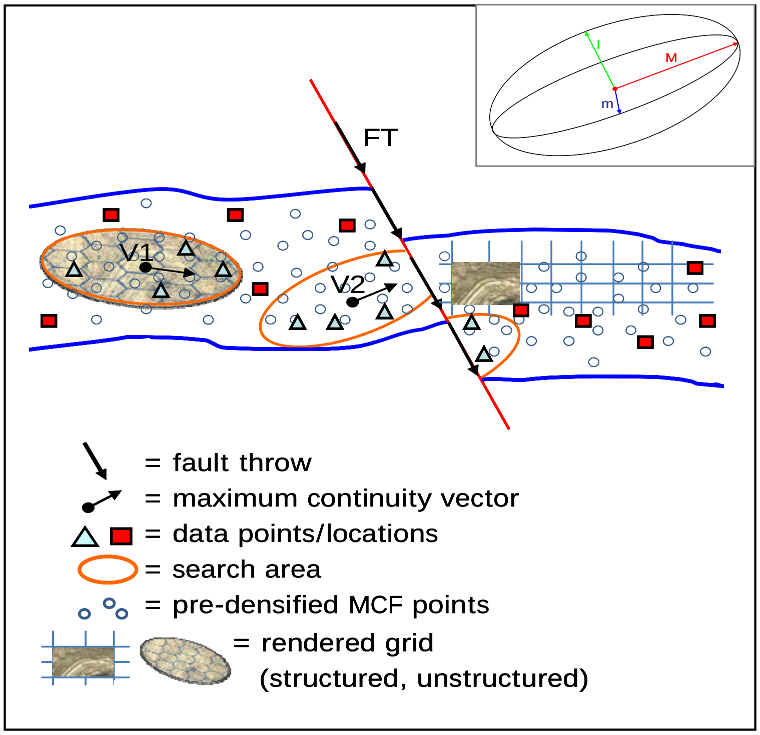


Figure 3 Interpolation of properties in PV method in 2D: the structural framework (see section "Validation") is represented by top and bottom horizons (in blue) and fault line (in red). The maximum continuity vectors and fault throws are depicted by symbols *V* and *FT*, respectively. The data points included in the search neighborhood (ellipse depicted in orange) are represented with triangles in blue, while red squares represent data points excluded from the search. For clarity, 2D cross-sectional case is depicted. Notations M, m and I correspond to maximum, minimum and intermediate axes of the search volume ellipsoid, respectively.

The inserted figure illustrates the definition of the maximum continuity vector MCV. Its main parameters are location, magnitude, direction and length, representing the correlation length (see Figure 3). The MCVs (denoted by V1 and V2), associated with the location of pre-densified set of points are positioned at the centers of search ellipses (or ellipsoids in 3D). The data points, detected inside the search ellipse ("blue" triangles) are considered in the interpolation along the MCV while the data outside the ellipse ("red" squares) are not included. The relative dimensions of the search ellipsoid, *i.e.* the ratios between major, intermediate and minor axis length, representing the "local" anisotropy factor, are subject to optimization by the user (see section "Validation"). In a faulted reservoir the property associated with MCV V2 is interpolated across the fault line, following the fault throw vector FT. In addition, Figure 3 depicts examples of geocellular grids (structured or unstructured) that can be rendered at the end of the geo-modeling process.

3 Validation

The test case used for benchmark exercise of the PV method was built based on a complete synthetic model of the Brugge Field. The original high-resolution model was developed by TNO in the Netherlands as a benchmark project to test the use of flooding optimization and history-matching methods [8]. Essential properties like sedimentary facies, porosity and permeability, net-to-gross and water saturation were created for the purpose of generating wells logs in the 30 wells. The structure of the Brugge Field consists of an elongated half-dome and an internal fault with a modest throw, represented in Figure 4 by fault vector field with displacement of ~50 m.

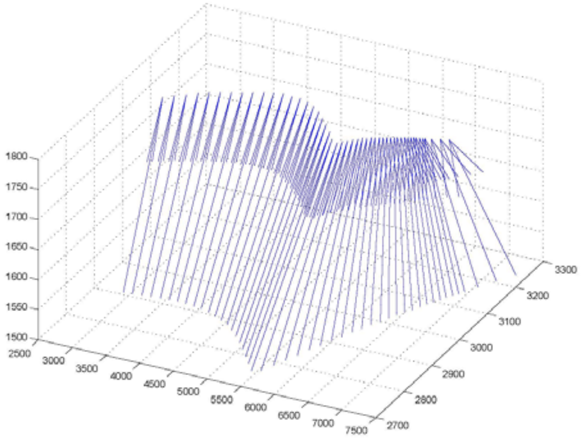


Figure 4 3D visualization of the fault displacement vector field with the constant throw of ~50 m. Dimensions given in meters.

Stratigraphically, the Brugge Field combines four different depositional environments: fluvial (discrete sand bodies in shale), lower and upper shore face (contains loggers, *i.e.* carbonate concretions) and sandy shelf, with irregular carbonate patches. We use the fluvial reservoir zone to build the PV benchmark model (see Figure 5).

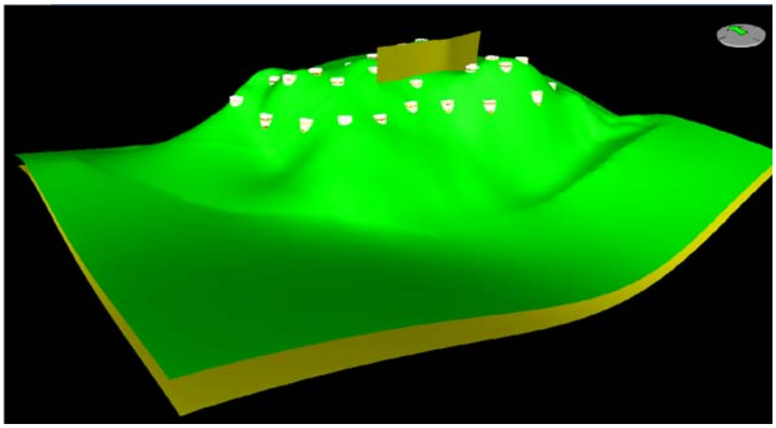
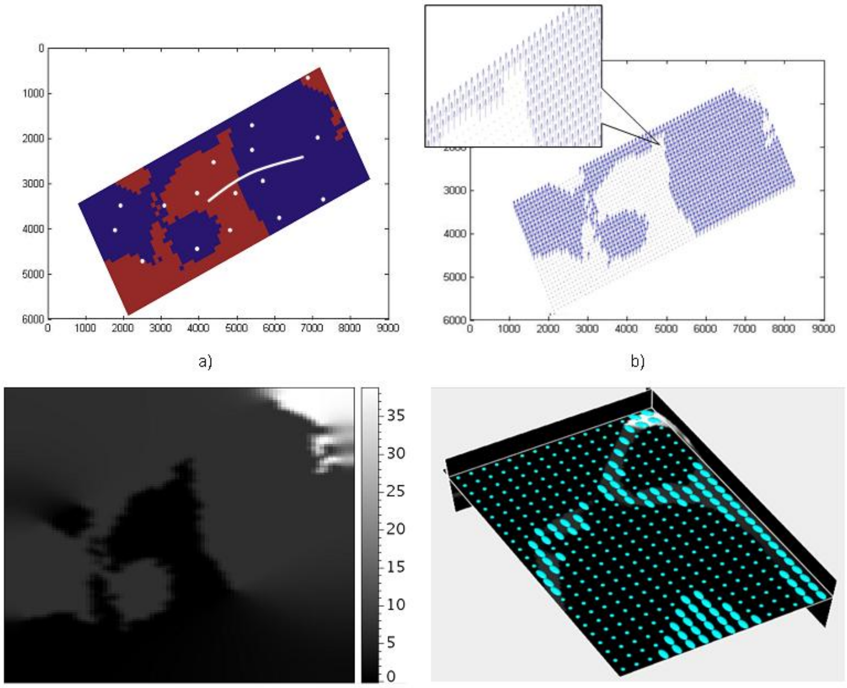


Figure 5 Structural model of Brugge fluvial reservoir depicting the two horizons (top-green, bottom-yellow), faults surface (brown) and a point-set with permeability log data.

In Figure 6a, we give an example of facies realization for the Brugge fluvial reservoir zone. The blue area represents the sand body (pay zone) distributed on shale (non-pay zone in red). Although not required by the PV method, we use the facies distribution as a basis or constraint for the generation of vector field to emulate a certain “pre-knowledge” on the geological structure.

Figure 6b represents MCF defined on virtually regular distribution of points ($\Delta x \approx 42$ m; $\Delta y \approx 91$ m). (Note; a regular distribution is not required!). No particular continuity information (*i.e.* with depicted vectors) was assumed for the shale zone, only for the discrete sand bodies. In Figure 6c the MCF directionality (*i.e.* azimuth angles with respect to true north or y-axis) is visualized by applying a natural neighbor (Sibson) interpolation [9]. The “black” & “white” areas designate two spatially detached shale zones with two distinguished dimensions of data search volume, with no preferential continuity direction, hence represented by spheres with different radii. The “gray” zone corresponds to the main sand body with defined main preferential directions of MCF, resulting in ellipsoidal data search volume and the main axis aligned with the orientation of MCF. Furthermore, the dual mode of the data search volumes as defined in the process of kriging estimation is visualized in 3D in Figure 6d: the shale and sand bodies are represented by the (small) spheres and ellipsoids, respectively, indicating one particular case of local directional anisotropy used for interpolation. We only use the azimuth component from the MCF; the dipping angle is calculated to the normal direction relative to local curvature of the horizon.



a) b)

c) d)

Figure 6 Definition of Brugge fluvial reservoir MCF: a) facies realization used to generate spatially constrained MCF (sand in "blue", shale in "red"), b) the generated MCF, depicted with MCV's, c) MCF interpolated by natural neighbor (Sibson) interpolation and d) 3D visualization of data search volumes as defined in the process of kriging estimation. Dimensions of panels a) and b) given in meters.

3.1 Results

The PV method allows the user to define variable sizes of search ellipsoids throughout the model VOI. By this notion, a single-size search sphere was defined for the shale facies, where no particular continuity information was assumed (see Figure 6b). On the other hand a variable size of the search ellipsoid and different anisotropy factors (*i.e.* ratios between the length of the major direction and minor direction of the search ellipsoid) was considered for the sand zone to validate the effect on the interpolation. The length in intermediate direction was fixed at 50 ft.

Figure 7 depicts permeability fields calculated as a function of variable search ellipsoid size and presented as the flattened 2D maps with marked well locations and the presence of the fault in the model. For better visualization permeability maps were additionally smoothed by a recursive Gaussian filter, using two samples as the filter half-width. Qualitatively, the top row of Figure 7 (major/minor = 100/100; anisotropy ratio of 1:1) can be interpreted for example as the case with entirely uncertain (and less trusted) MCF data, while the bottom row (major/minor = 10000/1000; anisotropy ratio of 10:1) corresponds to the opposite situation. The two middle rows represent cases with "intermediate" uncertainty in MCF, corresponding to major/minor = 300/100 with anisotropy ratio of 3:1 and major/minor = 2500/500 with anisotropy ratio of 5:1.

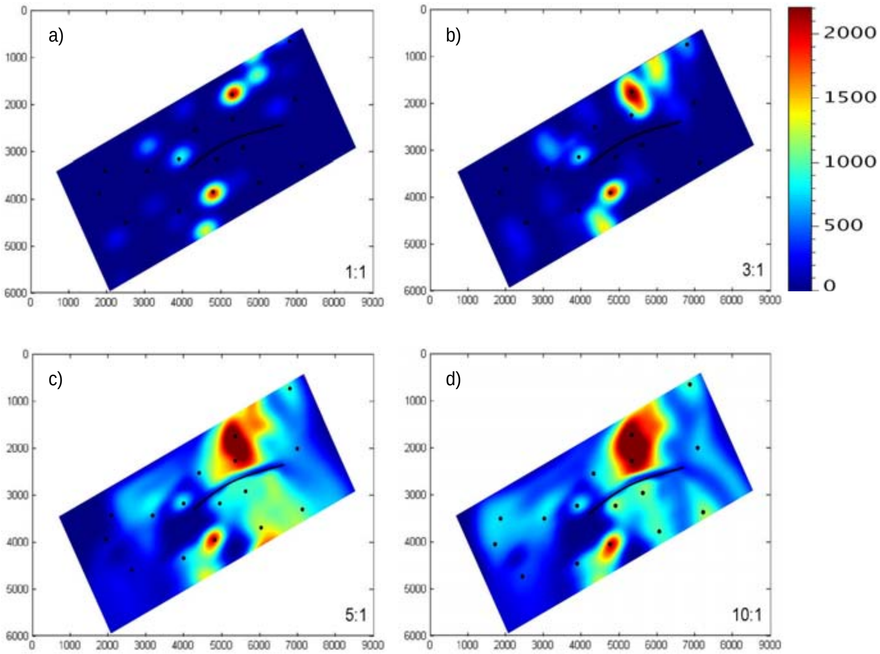


Figure 7 Permeability maps calculated for Brugge fluvial system with the PV method. Anisotropy ratio values of the search ellipsoids (rows): top – 1:1, middle – 3:1 and 5:1 and bottom – 10:1. Dimensions given in meters, color-bar in mD.

It is important to emphasize that the permeability models given in Figure 7 are conceptually different from any property model based on conventional geocellular grid: the permeability calculated here represents a blocked adjusted spatial variable, where the VOI of the structural model is technically represented by a "single cell" and not the discretized grid of cells. Such interpretation allows the user to superimpose any rendition of structured or unstructured computational grid prior to reservoir simulation, without compromising the "original" resolution of the model.

The computational time, required to obtain permeability maps as given in Figure 7 appears strongly dependent on the modeled local anisotropy ratio but mostly on the size (volume) of the search ellipsoids and the number of searched-for data points in the process of interpolation (see Figure 8). While the case with anisotropy ratio 3:1 requires ~30 min to complete on a Linux-based Dual core 2.4 GHz desktop with 8 GB RAM, the cases with anisotropy ratios of 5:1, 7:1 and 10:1 require ~60 min, ~45 min and ~180 min, respectively. We are considering the implementation of multi-threaded kriging interpolation and more efficient data search algorithm to reduce computational times.

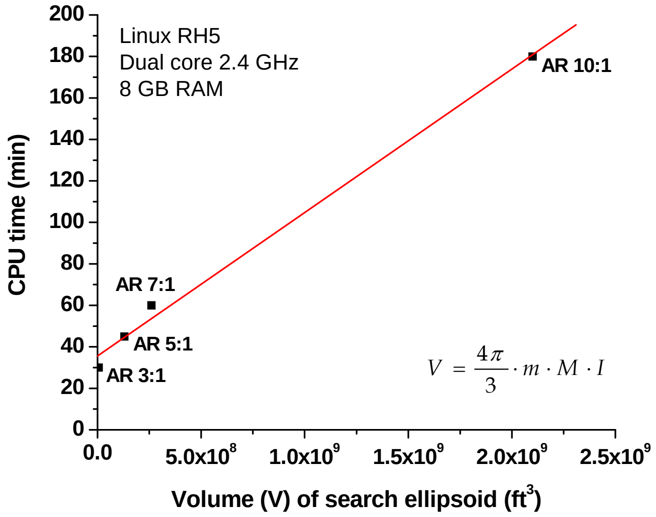


Figure 8 Functional dependence of the computational time of PV grid-less method on the local anisotropy ratio and the size (volume) of the search ellipsoids. Notations M, m and I correspond to maximum, minimum and intermediate axes of the search volume ellipsoid, respectively.

4. Assisted Property Modeling

Various methods exist that offer the ability to integrate varying azimuthal data through the input of a vector field and properties from well data, however, they do not allow the user to apply the vector field information as a post-processing step directly to regionalized petrophysical property maps of volumes while honoring well data (conditional simulation or interpolation), or not (unconditional simulation). They are more commonly used as a secondary input data to control the distribution of properties. While these results can be satisfactory, modifications are tedious and require reinitiating the entire simulation process.

Even the definition of the MCF, as given for example as MCF in Figures 4 and 6b, may quickly become rigid, inflexible, difficult and time-consuming to construct or edit. Changes require redefinition of computational mesh and alternatively, if painting the properties, then patterns do not allow for internal changes in continuity directions local to the object painted. To facilitate seamless user interfacing and interaction the method for Assisted Property Modeling has been developed [7] that provides the ability to honor data (conditional) or not (unconditional) and use pseudo-wells created on the fly via a simple graphical interface which allows the user to build, and create, vector maps quickly. An example of an updated property map with well-log data and azimuth guidelines, defined by the user as secondary information is given in Figure 9.

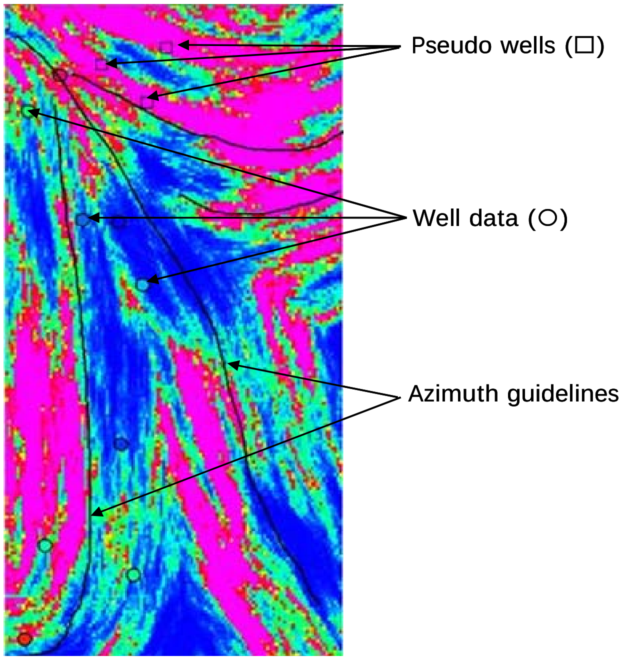


Figure 9 An example of an updated property map, generated with Assisted Property Modeling method with well-log data and azimuth guidelines, defined by the user as secondary information.

The method is unique in its implementation, allows the user to instantly and interactively insert or draw guidelines corresponding to dominant geological continuity of any shape and works with a number of different underlying methods including kriging, conditional simulation, collocated co-kriging and collocated co-simulation in both 2D and 3D. Furthermore, it is applicable across a variety of disciplines including geology, geophysics, earth modeling, and any discipline that uses interpolation and/or simulation.

5. Conclusions

Current geomodeling practice uses grids to represent 3D reservoir volumes. Estimating gridding parameters is a difficult task and commonly results in artifacts due to topological constraints and misrepresentation of important aspects of the structural framework which may introduce substantial difficulties for dynamic reservoir simulator later in the workflow. Moreover, the principles of conventional geostatistical practice still require the nomination of a *single* (average) direction of maximum continuity, which makes its use for modeling complex sedimentary environments highly challenging if not impossible.

In this paper we present the development and validation of the evolving technology for 3D modeling of reservoir properties performed in the absence of a geocellular grid. The new method fundamentally advances the geomodeling process by postponing the creation the parameters of geocellular grid like cell size, number of cells and layering until the very end of the modeling process according to the user definition. The notion of standard “grid resolution” becomes obsolete and the models, generated in such fashion, retain the maximum available resolution and information density, limited only by the resolution of input data themselves and structural continuity. Furthermore, the method allows the user an efficient control over the local continuity directions and enables interactive handling with “geologically intuitive” datasets: layering intervals, projection maps and hand drawings by for example using structural guidelines of any shape which instantly create representations of Maximum Continuity vector field as spatial constraint in the process of modeling reservoir properties

We validate the method by modeling a permeability distribution in a fluvial system where we define both, the maximum continuity and the fault displacement vector fields based on the geological structure of the model. The results demonstrate realistic distributions of permeability and acceptable runtimes.

In the present implementation the variogram is locally aligned with continuity direction and the property interpolation is constrained to ordinary kriging along the Euclidean-based covariance distance. We continue the efforts to further accelerate and enhance the method for Grid-less modeling by:

- Integrating with the method for Assisted Property Modeling to facilitate the construction of vector maps using a graphical interfacing which allows the user to quickly build, create and edit vector maps interactively.
- Optimizing the efficiency of data-search algorithm.
- Incorporating techniques in which distances are calculated by honoring the underlying geological structures with the "curvilinear" point-to-point interpolation [10]. Conceptually, such curvilinear point-to-point interpolation is equivalent to the interpolation along the geo-structurally constrained geodesic distances in the time domain.
- Integrating the method with algorithms for automated estimation of the fault displacement vector fields from underlying images and structural maps [5].
- Implementing intelligent data point densification techniques to optimize the sampling efficiency with underlying spatial geological structure, based on the technology for atomic meshing [11, 12].

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