Abstract

One of the key points in reservoir modeling is the building of a complex 3D-mesh, which must integrate various constraints: respecting the geometry of the fault network, taking into account stratigraphic knowledge, computing petrophysical properties by geostatistical methods, allowing upscaling and/or flow simulation… The building of this mesh relies on the use of a parametric coordinate system \((u,v,t)\) such that \((u,v)\) corresponds to “horizontal” curvilinear coordinates tangent to the horizons while \((t)\) corresponds to the “vertical” curvilinear axis approximately orthogonal to the horizons. So far, common practice consists in covering the geological domain with a “regular structured stratigraphic grid” with hexahedral cells and then to use the \((i,j,k)\) indexes of the nodes of these cells as a sampling of the \((u,v,t)\) coordinates. This kind of structured mesh is necessary to geostatistics, and to a lesser point flow simulation, which rely heavily on the implicit structure of the mesh to define neighborhoods and relationships between cells. However, such a regular grid may lead to errors or approximation, for example when trying to model complex faults networks or heavily folded horizons in such a way that edges' cells never cross these structural surfaces. In this article, we propose a completely new approach based on the recently introduced “GeoChron” model where the \((u,v,t)\) parameterization of the geological space is computed independently of any stratigraphic grid. This approach allows a consistent 3D-parameterization to be built whatever the complexity of the fault network, using only a tetrahedral mesh respecting the faults. Stratigraphic data, such as unconformity or sedimentation styles, can be taken into account in the construction of such a parameterization.

The main benefit of such a parameterization of the 3D geological space is to allow past, present and future geostatistical methods to be implemented in the \((u,v,t)\) parametric space without using any stratigraphic grid. As a consequence, it is then possible to populate polyhedral grids with the petrophysical properties computed in the parametric space.

Introduction

Modeling physical properties such as permeability and porosity in a reservoir is a problem of paramount importance for the oil and gas industry. For that purpose, common practice consists in proceeding in two steps. First, one cover the reservoir with a “Structured Stratigraphic Grid” consisting of a set of hexahedral (cubic) cells regularly aligned along the layers and whose edges never cross the faults. Next, the implicit curvilinear coordinates \((u,v,t)\) along the \((i,j,k)\) axes of such a grid are used by geostatistical methods to compute property values for each cell of the stratigraphic grid. There are, however, several important drawbacks with such an approach:
- in the case of complex fault networks, it is not always possible to build a structured stratigraphic grid;
- to honor the shape of the faults, one generally introduce bending in the edges of the hexahedral cells which, in turn, induce distortions of the \((u,v,t)\) coordinate system and result in geometric bias in the geostatistical computations.

To address the problem of complex fault networks for the purpose of flow simulation, a new generation of stratigraphic grids with polyhedral cells has recently been introduced. From a geometrical point of view, these grids offer much more degrees of freedom than traditional stratigraphic grids which use cubic cells only. However, the polyhedral cells of these unstructured grids are no longer associated with \((i,j,k)\) indexes and it is thus impossible to use the geostatistical methods to populate them.

The aim of this article is to show that it is possible to compute high resolution geostatistics without using any stratigraphic grids. The main advantages of this new approach are the following:

- It makes it possible to compute the geostatistics before building any flow-grid used by the flow simulator. As a consequence, such a flow-grid can be built independently after the computation of the properties. This opens the door to local optimizations of the shape and size of the cells of the flow-grids in regard to the properties.
- It is possible to populate any type of flow-grid. In particular, it is easy to populate polyhedral cells with upscaled properties.
- The properties are computed independently of any flow-grid. As a consequence, several flow-grids can be “painted” with the same properties.

It is also shown that this method may be used in seismic interpretation.

The GeoChron model

Only a quick summary of the theory behind the GeoChron model is presented here, the complete mathematical description may be found in [3]. The main idea is to consider each stratigraphic horizon as an iso-value surface for the \((t)\) component of the 3D-parameterization.

Let us consider a bounded region of interest \(G\), in the currently observable geological space. We call \(G\)-space, for “Geological-space”, the space which embeds the region of interest \(G\). Some geological assumptions are made on the formation and behavior of the geological terrains contained in this space:

1) at geological time \(t\), sediments are deposited on an horizontal plane \(\overline{H}_t\);
2) any sedimentary particle deposited before geological time \(t\) and re-deposited later at time \(t\), is considered as a new particle;
3) during its geological history, the flat horizon \(\overline{H}_t\) is transformed into a potentially folded and faulted horizon \(H_t\), which can be observed at present time;
4) the petrophysical properties of the different particles of sediment observable today strongly depends on their location and properties at deposition time \(t\).

On each initial horizon \(\overline{H}_t\), it is possible to define an orthonormal basis \((\overline{u}, \overline{v})\). It is also possible to define a common vector \(\overline{t}\) orthogonal to each horizon. The \((\overline{u}, \overline{v}, \overline{t})\) basis defines a
parametric space containing all the horizons $H_i$, which we call “Geo-Chronological space”, or $\mathcal{G}$-space (see figure 1). The $\mathcal{G}$-space is similar to the concept of time stratigraphic sections introduced by Wheeler [5].

Figure 1: Notion of Geological space (noted $G$-space) and Geo-Chronological space (noted $\mathcal{G}$-space). From [3].

Building a GeoChron model amounts to computing a “$\mathcal{G}$-parameterization” function $u(x,y,z)$ so that:

$$
\forall \ p = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \in G \quad u(p) = \begin{bmatrix} u(p) \\ v(p) \\ t(p) \end{bmatrix} \in \mathcal{G}
$$

At this point, it is important to note that any point $p$ of the $G$-space has exactly one image $u(p)$ in the $\mathcal{G}$-space, but erosion can cause some points of the $\mathcal{G}$-space to have no counterparts in the $G$-space. A parametric domain $D$ can be defined as the subset of the $\mathcal{G}$-space whose points are image of points of the $G$-space:

$$
\forall \ u^* \in D, \ \exists \ p^* \in G : u(p^*) = u^* \in \mathcal{G}
$$

This domain corresponds to the notion of “holostrome” as defined by Wheeler. On this domain (and only on this domain), a function $x(u)$ can be mathematically defined, so that:

$$
\forall \ u \in D \Rightarrow x(u) \in G : u(x(u)) = u
$$

The function $x(u) = x(u,v,t)$ is the parametric representation of the $G$-space associated with the $\mathcal{G}$-parameterization. It has the following interesting properties:

- if $t$ is fixed while $(u,v)$ vary, the image $x(u,v,t)$ moves on an horizon $H_i$;

- if $(u,v)$ are fixed while $t$ vary, the image moves on a curve whose image in the $\mathcal{G}$-space is a vertical. Such a “$t$-line” is called an “Iso-Paleo-Geographic line”, or IPG-line.
The *IPG*-lines provide a powerful way of building a $\vec{G}$-parameterization. However, it is very important to note that, in practice, there is no need to compute the $x(u,v,t)$ function. Indeed, following the standard modeling process, it is never necessary to know the $G$-coordinates of a given point in the $\vec{G}$-space:

1) transferring initial geological data, such as well or seismic data, from the geological to the GeoChron space is done using the $u(x,y,z)$ function;

2) once geostatistical computations are done in the $\vec{G}$-space, what is needed is the property value $\phi(x, y, z)$ of given points $(x,y,z)$ in the $G$-space, which can be read through $u(x,y,z)$ as $\phi(u(x,y,z))$.

There are potentially several methods allowing $u(x)$ to be built. We propose to use the Discrete Smooth Interpolation method (DSI) to interpolate three piecewise continuous functions $u(x,y,z)$, $v(x,y,z)$ and $t(x,y,z)$ at the vertices of the tetrahedral mesh (see [2]) such that:

1) the functions $u(x,y,z)$, $v(x,y,z)$ and $t(x,y,z)$ are continuous excepted across the faults (see figure 2);

2) $t(x,y,z)$ is constant on the horizons $H_i$;

3) the functions $u(x,y,z)$ and $v(x,y,z)$ are known on at least one horizon;

This building process may be improved with the use of the *IPG*-lines, which are always orthogonal to the flatten horizons $H_i$. Although this is not always true, for example in the neighborhood of listric faults, an *IPG*-line can usually be approximated by a line orthogonal to the horizons $H_i$. An *IPG*-line extractor module based on a Runge-Kutta method [4] was implemented in the gOcad geomodeling software [1].

**Stratigraphic grids and GeoChron model**

It is common practice in reservoir modeling to cover the domain of study with a regular structured grid (a stratigraphic grid). This is mainly due to their strong implicit topology, which is very useful for geostatistics and, to a lesser point, to flow simulation. Indeed, geostatistics relies heavily on the notion of neighborhood of a point, from which data used in the interpolation or simulation algorithms are taken. This neighborhood is generally defined using a variogram which is used as a basis for a search ellipsoid. The variogram is computed from the geological knowledge and well data, and is independent of the type of mesh used to discretize the 3D-space. However, the practical computation and scanning of the search ellipsoid is much more easy and fast on a structured mesh, where neighborhoods of a given node are implicit. Currently, almost all geostatistical algorithms are applicable only on structured grids, regular or irregular (like the so-called stratigraphic grids).

However, any stratigraphic grid construction workflow must make some approximations, especially in complex fault networks. For example, if more than two faults are converging to a common point, it is mandatory to remove some faults around the convergence node. This problem is caused by the need to keep a strong alignment along the three curvilinear axis $(i,j,k)$ of the grid.

It is now possible to build unstructured stratigraphic grids, with polyhedral cells, the simplest kind of cells being tetrahedrons (see figure 2). On such grids, the exact geometry of the fault network is more easily honored, and the errors introduced by the stratigraphic grids vanish. However, it is then difficult to compute geostatistics on such grids, since there is no implicit
parameterization attached to it. This is an open problem, on which different approaches are possible. As shown below, in the frame of the GeoChron model, it is now possible to populate these grids, since a $G$-parameterization function can be computed, at any point $(x,y,z)$.

![Figure 2: Structural model of a simple fault network with two horizons, and unstructured tetrahedral mesh covering the domain of study. Only a few blocks are shown here. The tetrahedral mesh fits to the faults, but not necessarily to the horizons.](image)

**Application to geostatistics**

Once a $G$-parameterization (i.e., three functions $u(x,y,z)$, $v(x,y,z)$ and $t(x,y,z)$) is computed on any kind of mesh (usually a tetrahedral grid), one can easily compute the $G$-image of all the data relevant for property modeling, like wells and well curves, proportion maps, and so on. Then, as figure 3 shows, the $G$-space can be covered with a regular grid of the needed resolution, and geostatistics can be computed in this grid, using all the available sources of data.

![Figure 3: Example of sequential gaussian simulation computed on a regular grid covering the $G$-space. A sequential gaussian simulation algorithm was used to define facies (channels, levee and flood plain) populated with porosity values. Each channel was defined in a horizontal plane.](image)
An important remark here is to note that in the $\overline{G}$-space, since horizons are unfaulted and horizontal, the correlation between horizons corresponds to the vertical correlation. Therefore, the grid to use in this case may be a regular structured grid, which is numerically easy to manage, and the variogram computed in the $\overline{G}$-space is much more simple to model, since it is no longer modified by the present geometry of the layers, the $\overline{G}$-parameterization removing this effect. However, since the $\overline{G}$-space can be seen as an image of the sediments at time of deposition, integrating late diagenesis or syn-sedimentary process in this kind of modeling is possible but not trivial.

Once the petrophysical properties are modeled in the $\overline{G}$-space, many different tools may be used to visualize and use the result. It is possible to paint the initial tetrahedral grid with the computed geostatistics, either directly with 3D texture mapping (see figure 4), or indirectly, with any upscaling method: for a given tetrahedron, one can compute which cells of the $\overline{G}$-image are corresponding, and even, if needed by the upscaling algorithm, which cells are around in any direction of space.

Figure 4: Tetrahedral grid painted with a 3D texture map computed on the porosity simulation of previous figure. Some internal fault blocks were removed for a better view. Note that channels are no more horizontal and are affected by faults.

Application to seismic data processing

Many type of information can be extracted from a seismic cube, but the interpretation of horizons and faults is of particular importance in the geometrical model building. This interpretation may be done either manually or automatically, but in both cases, it is a complex work because of the noise inherent to the seismic signal, and the uncertainty on the geological setting.

It is however possible to ease this task with a GeoChron model. Indeed, if we suppose that a GeoChron parameterization of a volume covered by a seismic cube is already built, then it is possible to look at the GeoChron image of this cube (see figure 5). Since they were used to build the $\overline{G}$-space, the horizons are unfaulted and horizontal, but the resolution of the seismic cube is unaffected. Therefore, it is likely that the seismic data will be easier to process, because the geometrical effects of faults or structural dip are removed.
The major drawback here is that we suppose that a $\overline{G}$-parameterization is already built, however building such a parameterization requires a knowledge of the fault network, and of some horizons (to define the $(t)$ function). As a consequence, such a parameterization cannot be computed before a first interpretation of the seismic data has been done. The application of the GeoChron framework to seismic data can thus only be used as a kind of post-processing to a seismic interpretation, and not a per se interpretation tool. However, in this clearly defined frame, it still has its advantages.

Figure 5: Application of the GeoChron framework to seismic data. Top: synthetic seismic amplitude cube in the geological space (same data set as previously). Bottom: image of the cube in the $\overline{G}$-space. The seismic reflectors are now horizontal and unaffected by faults.

For example, such a “flattening” of the seismic cube can be used to check the validity of the first interpretation:

1) Since no fault trace should be visible in the $\overline{G}$-space, if the image of the cube in the $\overline{G}$-space still displays strong discontinuities, then it is very probable that one or more fault was not seen.
2) It is then possible to look at the original position of the discontinuity zone in the geological space to try and locate another fault.

3) An approximation of this fault may be built from the $\overline{G}$-image of the cube, and moved back to the geological space, where it may be used as an indication of the real fault.

In this way, faults in complex zones may be more easily located and modeled.

Major intermediate horizons (between the ones chosen to build the $(t)$ function) are also easier to extract, since they should be perfectly horizontal. Internal sedimentary boundaries are not always horizontal, even in the $\overline{G}$-space (for example, facies boundaries may not be iso-time surfaces), but their image is more simple than the real surface in the $G$-space, especially in complex structural settings.

There are however some limitations to this approach. For example, it is not possible theoretically to use any attribute which is related to the geometry of the seismic signal, or to correlations in special directions of space (like dip analysis), because this kind of data is not preserved by the $\overline{G}$-parameterization.

Conclusions

In this article, using the GeoChron model, we have shown that it is possible to compute a high resolution geostatistics honouring the stratigraphy without using any Stratigraphic Grid. This may result in very important consequences such as:

- allowing a unique property model to be built and used to paint several flow-grids with these properties, including unstructured flow-grids;
- optimizing locally the size and the shape of the cells of the flow-grid in order to capture local variations of the properties.

Last but not least, the authors hope that such an approach may contribute to stop a common practice consisting in building a Stratigraphic Grid without building the “real” Structural Model and then “forgetting” the oversimplifications which were needed to build such a grid.

Bibliography


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