Data Integration and Scale Changes in Shared Earth Models

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Abstract

This paper proposes to develop a new reservoir modeling workflow extending the parallel approach (Tureyen and Caers, 2005) to the GeoChron framework (Mallet, 2004). Integrating both frameworks has several advantages and opens new perspectives for reservoir characterization, uncertainty assessment and history matching. On one hand, a GeoChron model is a flexible representation of reservoirs in which the geometry, the layering and the properties are modeled and can be altered almost independently one from each other. On the other hand, the parallel approach is a closed-loop history matching method aiming at building both a static high resolution model and a coarse dynamic model consistently with each other in order to achieve a better and easier integration of all the relevant sources of information into the model. Hence, contrary to the current reservoir modeling practice, this workflow should allow to extend the type and number of perturbed parameters during history matching while producing consistent models with all the relevant information at multiple scales. However developing and implementing the proposed framework introduces new research challenges in the flow simulation, history matching and reservoir characterization domains that need to be tackled and are presented here.

Keywords: Data integration, history matching, parallel modeling workflow, GeoChron model.

Introduction

Modeling reservoirs consists of integrating in a consistent manner various sources of information either static (i.e. well logs and cores, seismic, analog outcrops, etc.) or dynamic (i.e. production data, time-lapse seismic, etc.) into a common 3D numerical representation. Such a representation is an essential tool for petroleum and reservoir engineers to describe and understand the subsurface heterogeneity, assess the corresponding uncertainty and manage risk. In practice, reservoir models are used for testing and validating hypothesis on the reservoir internal geology and architecture, estimating the location, volume and spread of oil accumulations, predicting and optimizing future production, designing surface facilities, etc. However, not only reservoir modeling is carried out by different specialists with various, and eventually divergent, objectives but also faces a large disparity in the available relevant data in terms of scale, quantity and quality. Hence, multiple models representing the same phenomenon at different scales are built, but these are, in most cases, inconsistent with each other which is not satisfactory.

The GeoChron model introduced by Mallet (2004), and of which an implementation can be found in Moyen (2005), is a first step to overcome this problem. In this framework, reservoirs are modeled by two separate grids embedded in different spaces and linked through a parametric
function: a geological space where an unstructured grid represents the actual reservoir geometry and a geochronological space where the reservoir is mapped into its depositional coordinates and where petrophysical properties are represented by a simple Cartesian grid. In theory (Mallet, 2004), as properties are modeled independently from the grid covering the geological space, any application grid can be built and populated from the geochronological space using specific upgridding/upscaling algorithms. However, both the high resolution model and the unstructured mesh are build from static data only and there is little chance that either matches the historical production. Multiple algorithms can be considered for this purpose, among them we propose an extension of the parallel reservoir modeling approach developed in Tureyen and Caers (2005) to the history matching of GeoChron models. After a broad overview of the proposed reservoir modeling workflow this paper outlines some of the research needs to bridge the gap between both frameworks.

1. The GeoChron Framework

Currently most reservoir models are represented using corner-point or stratigraphic grids which account for (1) the reservoir geometry (i.e. position of the main horizons and faults), (2) the reservoir internal stratigraphic layering and (3) the reservoir petrophysical properties (i.e. porosity, permeability, fluid saturation, etc.). In addition, they are often dedicated to a particular application, for instance flow simulation, which may requires specific grid features like orthogonality between cell faces. Hence, the design of such grids calls, in most cases, for a trade-off between the accurate representation of the reservoir geometry, its properties and the application problem (Caumon et al., 2004). As a consequence, inconsistencies with the actual geology are often introduced into the model (especially in structurally complex areas) and modifying consistently its geometry during history matching is tedious (Suzuki et al., 2006; Caumon et al., 2007).

Alternatively, the GeoChron framework aims at modeling these three concepts separately.
For this, reservoirs are represented simultaneously in two different spaces (see Fig. 1): the geological space containing a grid representing the actual reservoir geometry and the geochronological space where the reservoir is mapped into its depositional coordinates. Then, both spaces are linked through a parametric function associating any point \((x, y, z)\) in the geological space to its corresponding point in the geochronological space \((u, v, t)\) where:

- \(t\) represents the geological time at which the sediment located at \((x, y, z)\) was deposited;
- \(u\) and \(v\) are the 2D paleo-geographical coordinates of the point \((x, y, z)\) at the deposition time, before any deformation.

In the current implementation (Moyen, 2005) a reservoir is modeled in the geological space by a tetrahedral mesh conforming to (and discontinuous across) the reservoir faults and main boundaries (essentially the top and bottom horizons). The parametric function is modeled by three properties \((u, v, t)\), whose values are stored at every node of the tetrahedral mesh and are linearly interpolated within each tetrahedron. This function is computed such that it accounts for the main stratigraphic horizons, the fault throws and the reservoir deformation style (either flexural slip, pure bending or a mix). Finally, reservoir properties are modeled in the geochronological space. In this space the reservoir grid is assumed to be mapped into depositional coordinates, where a Cartesian grid is created and can be populated directly using existing geostatistical algorithms.

For reservoir modeling, this decoupling of the reservoir geometry, layering and properties has several advantages over the current practice (Mallet, 2004):

- It is a far more flexible and accurate model when it comes to represent structurally complex areas. Indeed, the use of an unstructured grid focusing only of the reservoir geometry allows to represent intricate faults and horizons networks;
- Modeling the reservoir properties can be carried out independently from the grid covering the geological space. As a consequence, once the parametric function and its support in the geological space are defined, it is possible to build a unified property model whatever its future use and whatever the ultimate application grid. Then only an upscaling/upgridding algorithm adapted to the problem at hand (CO\(_2\), compositional flow, etc.) is required;
- Finally, from a history matching point of view, decoupling reservoir geometry, layering and properties allows generating independent perturbations using optimization codes adapted to each component.

2. Closed-Loop or Parallel Reservoir Modeling Workflow

The idea of a parallel reservoir modeling approach has first been investigated in Mezghani and Roggero (2001) and Tuyeren and Caers (2002). Contrary to the current reservoir practice consisting of a series of hierarchical stages often carried out independently, first static at a high resolution and then dynamic at a coarse scale, this modeling approach aims at building both high resolution and coarse flow models consistently with each other. The workflow combines in the same iterative closed-loop a history matching and an upscaling algorithm: reservoir properties are modeled and altered on the high resolution grid while flow simulations are performed on the corresponding coarsened model and guide the history matching procedure. The outcome is then a high resolution model build consistently with the geological data and whose corresponding
coarse model matches the production data. In addition Tureyen and Caers (2005) suggest to optimize the upscaling/upgriding steps to ensure that the coarse model reflects effectively the impact of the fine scale heterogeneities on the flow problem at hand (CO₂, compositional, etc.).

In this way, (1) every source of information is integrated into the reservoir model at its own scale and consistency between data sources and both models is maintained through the entire characterization process; (2) since history matching is directly carried out on the high resolution model, it focuses effectively on altering actual geological parameters and is no longer limited to the perturbation of global parameters only such as fluid properties or some type of transmissibility multiplier; and, (3) integration of new data requires restarting the loop from the last history matched model instead of completely rebuilding the reservoir model at the fine scale. This workflow has been successfully applied on actual producing hydrocarbon reservoirs in which rock permeability or the position of calcite bodies have been altered (Tureyen, 2002). However, reservoir modeling consists of much more than just modeling one or more petrophysical properties. One of the main sources of uncertainty is the structural model itself (Thore et al., 2002). This calls for an extension of the closed-loop or parallel modeling method to a more general and flexible reservoir representation such as the GeoChron framework in which, as seen above, the reservoir geometry as well as the internal layering can also be altered to achieve a history match.

3. Proposed Workflow & Research Needs

Extending Tureyen’s approach to the GeoChron framework in a new reservoir modeling workflow, such as presented in Fig.(2), has several advantages and opens new perspectives for reservoir characterization, uncertainty assessment and history matching: On the one hand, the use of the GeoChron model would allow the perturbation of every component of the reservoir model, i.e. the reservoir geometry, layering and properties. On the other hand, using the closed loop reservoir modeling approach would allow producing GeoChron models consistent with all the relevant data (both static and dynamic). However several challenges exist to implement this framework, among which the followings can already be identified.

1. How to run flow simulation on a GeoChron model?

In any history matching, particularly in the proposed modeling workflow, it is the mismatch between historical production data and flow simulation results that guides the entire procedure. However, running flow simulation on a GeoChron model is far from trivial, in practice neither the tetrahedral mesh in the geological space (Moyen, 2005) nor the Cartesian grid in the geochronological space are built with flow simulation in mind: the “geological” mesh aims only at representing accurately the reservoir geometry, i.e. its main faults and horizons, while the Cartesian grid is too large (in practice several millions of cells) for conventional finite-difference flow simulators and does not take into account the actual deformed geometry of the reservoir¹. This calls for building in the geological space an entire new grid dedicated to flow simulation

¹Another objection could be that the Geochronological space is not a physical space since the vertical coordinate is the time, and not a volume. This is only partly true, because the sedimentation rate is available at all locations of the geological space (Mallet, 2004), making it possible to compute volumes directly in Geochronological space. This is not fully true, because eroded domains and hiatuses are represented in Geochron space, although flow obviously should ignore these volumes of sediments
and to populate this grid based on properties in the geochronological space using some upscaling technique. This might be tedious, but building the grid after property modeling, as outlined in Mallet (2004), would allow the proper integration of reservoir geometry, local heterogeneities that impact flow and wells in a consistent manner while at the same time considering the physics of the flow problem at hand.

Addressing this problem calls for the development of a methodology to generate a coarsened model, either structured or not, based on the high resolution model at a scale adapted to the flow problem at hand. This methodology should includes a gridding algorithm, an upscaling technique and above all an estimation of the high resolution model flow response, using for instance streamline simulation. This last element is mandatory to guarantee that the actual coarse model represents effectively the high resolution one and to ensure that the history matching corrects effectively geological parameters and not some upscaling error as shown in Tureyen and Caers (2005).

In this respect, the work of Prevost (2003) appears to be an excellent starting point. This methodology consists of an iterative process during which an initial unstructured coarse grid is refined/updated until a satisfactory flow response is achieved. In practice each iteration consists of four main stages:

1. Generation or adaptation of the coarse unstructured mesh;
2. Estimation of effective (upscaled) reservoir properties at the coarse scale from a high

Figure 2: Proposed workflow extending the parallel reservoir modeling approach described in Tureyen and Caers (2005) to the GeoChron framework (Mallet, 2004).
resolution model (in Prevost (2003) a Cartesian grid);
3. Flow simulation on the coarse model;
4. Evaluation of the coarse mesh quality by using the mismatch between the previous flow simulation results and those obtained from a reference simulation at the fine scale. Finally, if needed, the coarse scale model is refined locally based on various diagnostic attributes (for instance the average velocity within a cell or a breakthrough time obtained by streamline simulation).

This iterative gridding/upscaling loop has been successfully applied to build efficiently unstructured coarse scaled models but only from Cartesian high resolution models. In case one would start from a GeoChron model two questions arise: First, how to carry out the local upscaling used to estimate the effective properties of each coarse cell? In the present version (Prevost, 2003) high resolution properties are defined on a Cartesian grid while in the GeoChron model, followings the upscaling tool presented in (Mallet, 2004) they would be still defined on a structured regular grid but which is no longer orthogonal. Second, how can we obtain a reference flow simulation to diagnose the quality of the coarse model?

2. How to populate consistently the reservoir properties within the geochronological space?

Following GeoChron’s framework, it appears logical to model reservoir properties (i.e. facies, porosity, permeability, etc.) in the geochronological space which, in theory, represents the original sediment deposition space. However mapping between this space and the actual geological one introduces some volume distortion which may bias geostatistical modeling. For instance, two elementary cells in the geochronological space have identical size but represent different volumes in the geological space. Rigorously, both cells having different volumes should be modeled with different dispersion variance (Journel and Huijbergs, 1978). It would be interesting on one hand to develop algorithms able to account for such volume distortion, hence to investigate the magnitude of error the equally volume assumption introduces for the particular flow problem at hand.

3. How to perturb a GeoChron model (i.e. not only the properties but also the structure) to achieve a match?

As outlined previously, within the GeoChron framework each of the reservoir components (i.e. its geometry, layering and properties) can be modeled and thus altered in theory almost independently from the other. In this respect, several specific techniques can be considered and developed, for instance, properties can be perturbed directly in the geochronological space using history matching algorithms such as the probability perturbation method (Caers, 2003) or the gradual deformation (Hu and Le Ravalec-Dupin, 2004). Uncertainty in the main reservoir boundaries and faults (Thore et al., 2002) would be accounted for by perturbing the tetrahedral mesh itself using editing tools such as those presented in Tertois et al. (2005); Caumon et al. (2007). And finally, since internal reservoir horizons are isovales in time of the parametrization function, their position can be randomized by adding some scalar spatially correlated field to the function values (Caumon et al., 2007).

However this raises further questions that need to be tackled:
• First, what is the impact of modifying the reservoir structure, either globally or internally on the modeling of properties? Indeed, if modifying the reservoir properties in the geochronological space does not affect the reservoir geometry the inverse is not true. Any modification of the reservoir geometry or the parametrization function would affect the way data (i.e. wells, seismic but also variograms and histograms) are transformed into the geochronological space. Hence, after modifying the reservoir geometry what is the reliability of a previously computed property model?

• Secondly, perturbation of the reservoir geometry can be carried out only up to a certain extent. Indeed, a too large modification may affect the grid such that topological inconsistencies appears requiring a complete model reconstruction. Hence how to carry out such reconstruction? How to recompute the parametric function? And, again, how should we consider a previously computed property model?

• Finally, history matching being a particularly ill-posed problem, it is likely that by modifying only one of the reservoir components and ignoring the other one can still achieve a match which might not be satisfactory. Hence this raises the question on which and how many components should be modified? In which order (may be structure first and then properties)? And to what extent?

Conclusions

In this paper we have proposed to extend the closed-loop or parallel modeling approach described in Tureyen and Caers (2005) to the GeoChron framework (Mallet, 2004). Integrating both frameworks should allow during history matching to add several first-order geological modeling parameters to the commonly used set of perturbed variables. while still producing consistent and flexible numerical models at various scales. However the proposed framework generates new research challenges, among them : How to generate a coarsened model, either structured or not, based on the high resolution model at a scale adapted to a particular application problem for instance a flow simulation? How to run flow simulation on a GeoChron Model ? How to populate consistently properties within the geochronological space while accounting for the distortion in volume introduced by the parametrization ? And how to perturb a GeoChron model (i.e. its property but also its structure) to achieve a history matching ?

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References


