Structural Framework and Reservoir Gridding: Current Bottlenecks and Way Forward

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Abstract

After some 20 years of progress, reservoir modeling still raises practical and theoretical challenges. Standard workflows are primarily built in a linear fashion (fault framework modeling, stratigraphic modeling, gridding, petrophysical modeling, upscaling, flow simulation and history matching). Modifying decisions in an early step in this workflow requires performing again all the dependent steps and the associated quality controls. Whereas robustness has significantly improved and makes it now possible to improve automation and running of multiple scenarios, we identify four main limitations in the current workflows and corresponding research axes:

1- Stratigraphic Well correlations are most often deterministic in reservoir models, whereas they are affected by significant uncertainty. We need new ways to effectively sample this uncertainty by using sedimentological concepts and propagate it in existing time-to-depth conversion and gridding workflows.

2- Determination of the fault connectivity is often suboptimal: connectivity is decided from seismic fault sticks before stratigraphic modeling, whereas fault displacement is, with well test data, one of the most important arguments to decide about fault connectivity. We argue that evaluating fault displacement earlier in structural modeling workflows would most probably help choosing more realistic fault connectivity patterns right from the beginning, or stochastically sampling possible fault networks.

3- Gridding is a complex task and should ideally account for geological structures, facies and permeability fields and well geometry. The discretization of flow equations imposes additional gridding constraints to guarantee the performance and accuracy of flow simulation. Stair-step grids are a significant improvement to better handle some of these constraints, but locally flexible unstructured grids are the only way forward to appropriately integrate all available information while honoring discretization constraints.

4- Scale management has been a buzzword in reservoir modeling for years, but the current practice is still to take into account at best for two scales, and this *after* the reservoir gridding stage. We think that multiple scales should be used earlier on, and that connectivity and topological considerations should be used to ensure consistency between scales and between models and first-order dynamic information.

Introduction

Geomodeling has become a standard technology in reservoir management tasks, and is applied by a growing community of users. For increasing productivity, software vendors have all endeavored development of streamlined workflows guiding users through seismic interpretation, structural framework building, gridding, petrophysical modeling, upscaling, flow simulation and history matching. Putting these processes in a common software platform provides clear benefits in terms of model consistency and productivity because it facilitates multidisciplinary integration, for instance by reducing the gap between seismic interpretation and stratigraphic modeling (de Groot et al, 2006; Labrunye et al, 2009).

Workflows provide several other benefits, mainly:

- They make modeling simpler and faster than a completely modular system, by guiding the user through typical modeling tasks and associated quality controls without need for extensive training.
- They allow users to document their choices at several steps of the workflow, making model updating easier.
- In some cases, uncertainty at various modeling steps may also be characterized, leading to sensitivity analyzes and assisted history matching methods.

The downturn of workflows is they may be limited by the underlying modeling technology. Also, as with overhead presentation software, they tend to drive users into sequential tasks; hence, changes in an early workflow step generally induce repetition of all dependent steps to update the model. More importantly, too much guidance can also restrain the creativity of users. The goal of this paper is not to further insist on these intrinsic limitations of workflows, but rather to look at the general philosophy and essential sub-tasks of geomodeling and point out ways for improvement. We will therefore discuss the current way of performing well correlations, which has a significant impact on reservoir layering and connectivity, fault framework construction and gridding. Last, but not least, we will also consider the management of scales, which is a major avenue for improvement in geomodeling.

1. Stratigraphic Well correlation

Since the seminal work of Mac Donald et al (1992) associating stratigraphic sequences and flow units, sequence stratigraphy has been increasingly used as a basis to define layering in reservoir models. From the reservoir grid honoring the geological structures and main layers, geostatistical techniques are then used to sample possible distribution of facies and petrophysical properties. When structural uncertainty is present, it is commonly possible to perturb the reservoir grid geometry away from wells (Abrahamsen et al, 1992; Corre et al, 2000; Goff,2000). However, as pointed out by Borgomano et al (2008), uncertainty in stratigraphic correlation is often present and yet is ignored by this process: the job of most stratigraphers is to find *the right* correlation, albeit logging and core data only provide limited information about the sedimentological and diagenetic processes which govern reservoir layering. As a result, alternative correlation scenarios are seldom made, which may be source of bias in the model.

We suggest that stratigraphic well correlations should be part of the stochastic reservoir modeling workflow, or should at least be used in sensitivity studies to determine the history matching parameters. From a theoretical standpoint, uncertainty about stratigraphic correlation is expected to have the highest impact on dynamic reservoir models when numerous unconformities are present between stratigraphic sequences. Indeed, alternative ways to correlate unconformities across wells directly impact the connectivity of flow units, hence the dynamic reservoir performance. Even in the case of mainly conformable units, uncertainty in the correlation affects the volume of flow units, hence the reservoir volumetrics and dynamics. From a practical standpoint, the impact of this uncertainty has been demonstrated in carbonate reservoirs by Lallier et al (2009; submitted).

Two avenues can be investigated to appropriately sample stratigraphic uncertainty. The ideal one is to combine the stratigraphic correlation directly with the petrophysical modeling; such "process-based geostatistical simulation" is very appealing in principle because it generates at the same time the layer geometry and facies, within a global structural framework (Abrahamsen et al, 2007; Michael et al, 2010). However, it raises a number of challenges for in terms of speed and conditioning to well data. A second, more pragmatic approach is therefore to generate several stratigraphic well correlation models using for instance the dynamic time warping method (Waterman and Raymond, 1987; Lallier et al, submitted). Each of the possible correlation can then be fed to existing reservoir modeling workflows. The major advantages of this strategy are to divide-and-conquer and to easily connect to the existing technology.

2. Structural modeling

Over the last 25 years, the advent of 3D seismic has provided tremendous improvements in one's understanding of overall reservoir geometry. Virtually all geomodeling platforms now provide tools to move from 3D seismic interpretations to reservoir grids which can be used in flow simulators. Classically, structural surfaces are represented as 2D grids or triangulated surfaces, which may be trimmed to account for discontinuities (see review by Caumon et al, 2009), then serve as a framework for various gridding strategies.

In typical structural modeling workflows, the first task is to build a fault network as a set of surfaces and contacts between these surfaces. This step is itself decomposed into surface-fitting, which creates one fault surface from each fault interpretation, and editing in which faults can be extended, filtered and connected one to another based on proximity and modeler's interpretation. Then, horizons are built from seismic picks conformably to the fault network. In our experience, structural modeling is seldom performed smoothly by running these two steps and moving on to grid generation. Instead, significant time is often spent moving back and forth between the fault modeling and horizon modeling steps. Indeed, some inconsistent fault displacement patterns become obvious only once horizons have been built and analyzed. Figure 1 illustrates this observation: without connecting the green fault to the blue fault, a high-curvature ramp appears on the faulted horizon; the fault slip terminates very abruptly on the green fault, which is deemed unrealistic in the tectonic context of the study. Connecting the faults generates a smoother horizon and displacement field, more consistent with geomechanical considerations and the overall tectonic style of the area.

In current geomodeling software, revising the fault connectivity after the horizon modeling step introduces a significant overhead because it affects model topology. Whereas recent progresses in structural modeling methods make such an update easier, the modeling process itself remains suboptimal. For novice users who tend to do little quality controls, there is also a risk to obtain structurally incompatible models by considering that fault and horizon surfaces "look good" instead of thinking in terms of kinematics.

One way to go is to use 3D structural restoration and strain analysis to check for structural consistency (Moretti 2008; Durand-Riard et al, 2010). However, at present, this step also comes after model building, hence does not remove possibly expensive model updates. More simply, we suggest that fault displacement could be computed (albeit approximately) during the fault network construction. The input for computing the fault displacement could come directly from seismic interpretations; boundary conditions set on fault borders may be used to compute the fault slip vector field, for instance as proposed by Røe et al (2010). This would provide a hint for missing contacts before explicitly constructing horizons. Naturally, fast model updating would still be needed to possibly change fault connectivity after full 3D horizon modeling.

Another benefit of considering faults as slip surfaces intrinsically in the model has been highlighted by Holden et al (2003) for structural uncertainty modeling. Indeed, structural interpretations from seismic data are never exhaustive and often leave room for uncertainty in the connectivity and geometry of geological structures. As shown by Cherpeau et al (2010), considering fault displacement and displacement / size laws (Kim and Sanderson, 2005) is very helpful to sample uncertainty about fault network topology. Ultimately, geomodeling workflows should implement such flexible structural uncertainty assessment methods to be used as parameters for model screening and assisted history matching (Cherpeau et al, submitted).

3. Reservoir gridding

Structural surfaces generally serve as a basis for extrusion of pillar-based reservoir grids (Mallet, 2002; Caumon et al, 2004; Fremming et al, 2004) or for volumetric construction of stair-stepped grids (Hoffman et al, 2003; Gringarten et al, 2008). Classically, geostatistical methods to populate these static grids with petrophysical properties are run in the grid's UVW space assumed to represent depositional space. For flow simulation performance, a dynamic grid with a reduced number of cells is built and properties are upscaled from the static grid. Strategies to regroup fine-scale cells into coarse-scale grid blocks vary but are very often limited by corner-point geometry and fixed topology of reservoir grids. Shape constraints on grid blocks are also needed to guarantee flow discretization accuracy. As noted by Durlofsky (2003), adapting the gridding strategy should be part of the upscaling process to combine computational efficiency and geological accuracy in reservoir models.

Most adaptive reservoir gridding focuses on honoring fine-scale background fields of permeability, flow velocity or vorticity (Durlofsky, 2003; Prevost et al, 2005; Mlacknick et al, 2006; Evazi and Mahani, 2010; Merland et al, 2011). Other authors such as Branets et al (2009) conform to discrete structures such as faults, horizons or vector boundaries of sedimentary bodies. Yet, both large scale objects described in structural models and background heterogeneities should ideally be accounted for simultaneously.

This could be achieved in principle by flow-based gridding, which uses a fine-scale pressure solution to determine high velocity / vorticity zones. In practice, however, flow-based gridding also relies on a fine-scale grid, whose resolution is adapted to background petrophysical heterogeneity, but still uses approximations such as transmissibility multipliers to account for flow drains or barriers. The resulting velocity field may therefore have sharp features which raise problems with background-based gridding methods.

Another possible avenue is therefore to improve global gridding techniques such as used by Merland et al (2011) to honor both interfaces and a background metric. A blending factor can be used to balance the weight of both criteria. Better, the background heterogeneity can be used as a local anisotropic metric for the conformable gridding algorithm as done by Branets et al (2009) for adapting the grid density.

Flexible reservoir gridding is definitely a topic for further research; however, we strongly believe that the promising results obtained so far by several research groups should take a fast lane for industrialization and wider use in geomodeling projects. High priority should be given to the application of these methods to generate locally unstructured grids in complex areas.

4. Scale management

One of the biggest challenge in subsurface modeling at large is the management of scales. In computer science literature, many methods have been described to adaptively access terrain models at various levels of resolution (see for instance Losasso and Hoppe, 2004). The problem is notably more complex in geomodeling, not only because of the third dimension, but also because of the unstructured nature of the subsurface and the diversity of uses of geomodels.

In reservoir modeling, the term multi-scale mainly refers to two scales and is closely connected to upscaling with fixed geometry between fine and coarse scales. For example, the method of Jenny et al (2003) decouples the flow and transport equations for optimizing flow simulation. Such a method is extremely interesting for assisted history matching because it helps reducing the number of parameters used in inversion. Nevertheless, multiple scales should also be handled before the flow simulation stage for easier integration of geological principles and well logging, well test, seismic, gravity and electromagnetic data. For instance, among the main results obtained recently, we can quote 3D property mapping and upscaling between a fine-scale model in depositional space and a coarse-scale model in physical space (Gringarten et al, 2008).

Unfortunately, some problems such as creating and maintaining a hierarchy of structural models have received little attention to-date, except in the specific case of fractured reservoirs (Bourbiaux et al, 2002). We think there is a practical interest in generating structural models at various levels of detail, for instance to study the impact of suppression of a fault or the consequence of approximating two parallel faults as a single one. As far as geometry is concerned, Pellerin et al (2011) present a strategy to generate such a hierarchy while maintaining the model connectivity. Conversely, it is also possible to generate several stochastic models honoring connectivity information as obtained from well test data (Bonneau et al, 2011). Interesting avenues for further research are to:

1. define some sort of structural downscaling to simulate several possible structural models having the overall feature as a root coarse-scale model. This would be very helpful in management of structural uncertainties in history matching contexts (Cherpeau et al, submitted).
2. Find a multi-scale parameterization of structural models so that different frequencies can be manipulated independently, as done by Vallet and Levy (2008). This would definitely help solving inverse problems such as history matching. A significant challenge is yet to be addressed in the management of topology.
3. Integrate these multi-scale structural methods with previously mentioned gridding and process-based multi-scale methods.

In all these tasks, a great difficulty is that the sensitivity of model parameters at various scales may be completely different depending on the targeted application (traveltime inversion, potential field modeling, flow simulation, geomechanical modeling, etc.). Therefore, there is a clear need to separate the problem of finding a good hierarchical geological parameterization with the problem of finding which of these parameters is most influential on the physical process at hand.

Conclusions

We have reviewed several recent progresses in reservoir modeling and current avenues for further improvements and research. Overall, we suggest that uncertainty management should not be limited to geostatistics in a corner-point grid, but should be treated in a more systematic manner right from the early stages of interpretation and modeling (namely: well correlation, seismic interpretation and structural modeling). Currently, first-order uncertain reservoir parameters are left frozen in mainstream studies. This is dramatic because ignoring such parameters may lead to significant understatement of uncertainty and increase risk of making wrong decisions in reservoir management. The connexion between the geological parameters and process models requires gridding and discretization. Gridding should be automatic as much as possible, depending on the target application and numerical resolution scheme, and should allow for honoring various types of underground features at once (lines, surfaces and discrete property fields). Last, but not least, an ideal geological model should allow for considering multiple scales of topology, geometry and petrophysics for efficiency in model management.

Another, non technological aspect in geomodeling is to improve education of reservoir modelers. This is a significant problem because the classical university curricula seldom contain geomodeling classes. With significant increase of geomodeling users, teaching is definitely a challenge which should be addressed by further collaboration between oil and gas companies, software vendors and academia. In particular, a strong focus should be made on developing critical sense about how good (or bad) our geomodels are.

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Figures

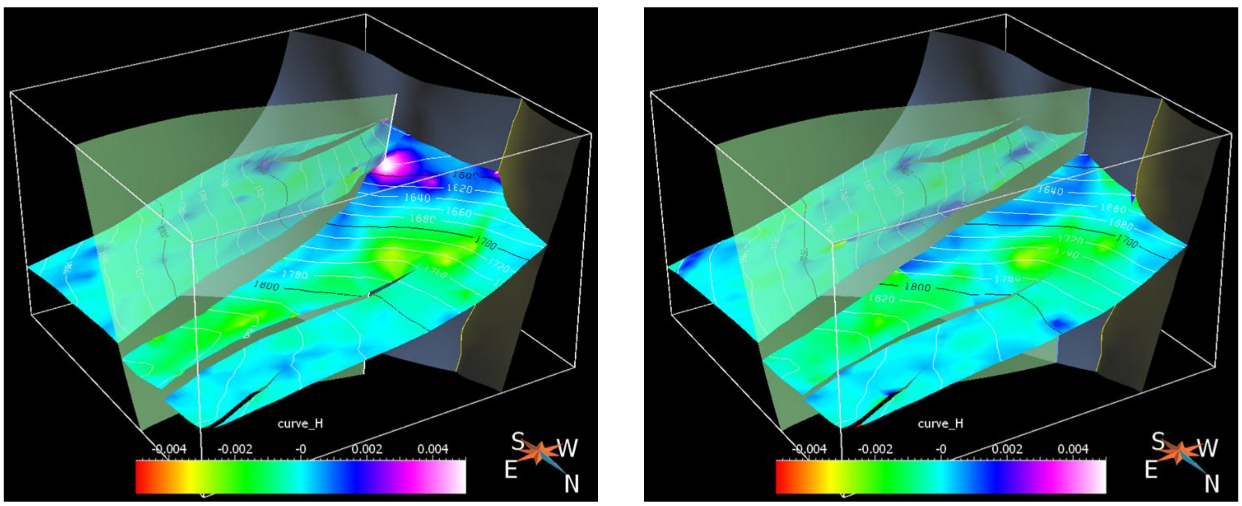

Figure 1: Two interpretations of a structural model. Left: the semi-opaque green fault is not connected to the blue fault, yielding a high-curvature ramp on the horizon and large variation of the displacement field along the fault. Right: connecting the green fault to the blue fault yields a more regular horizon geometry and displacement field. The horizon is colored with average curvature.