Forward Stratigraphic Modelling at reservoir scale, statistical comparison with common geostatistical methods and fractal behaviour

Introduction

Constructing a geological model that accurately represents and predicts the reservoir behaviour depends on having a static geomodel that captures lithofacies heterogeneities and their associated petrophysical properties. The several geostatistical methods commonly used for this task apply a combination of hard and soft constraints provided from cores, well logs and seismic interpretation. A major challenge remains in (1) bridging the resolution gap between these multi-disciplinary datasets and thus (2) reproducing the geological complexity of depositional environments where no or few data is available.

In this communication, we propose an innovative approach that combines Forward Stratigraphic Modelling (FSM) with geostatistics in order to construct geomodels that accurately capture the reservoir heterogeneities while accounting for geological processes and uncertainties. Fractals and metrics of geobodies connectivity are used in order to quantify the benefits of such FSM method compared to Truncated Gaussian Simulation (TGS) and Sequential Indicator Simulation (SIS).

Context and method

This case study is based on a giant carbonate field from the Middle East. The reservoir of interest consists of a 40-60 feet-thick succession of carbonates, dominated by shallow marine limestones. A 3D forward stratigraphic model was constructed to reproduce the reservoir heterogeneity as a function of geological processes such as subsidence, sea level, palaeo-bathymetry, wave impact, carbonate production, and transport (Hawie et al. 2015). The model has been calibrated to facies data from 14 wells and to an existing sequence stratigraphic framework. However, vertical discrepancies (mainly caused by the scaling issue) are always identified between the simulated facies and the equivalent well data. Therefore, in order to overcome this issue, an innovative workflow is applied to reach a better match between FSM simulation and well data. This post-processing correction is made by running a TGS with a very strong constraint (99%) from the FSM results with texture ranking from mudstone to grainstone.

Two facies/texture simulations have been run, respectively with TGS and SIS and geobodies connectivity is computed on four different types of simulation: FSM, FSM matched to wells with TGS, TGS only and SIS. Visual comparison of the various simulations shows that FSM produces more geologically-sound results compared to both TGS and SIS even with the integration of secondary data like vertical proportion curves (figure 1). The well-matching post-processing approach creates only minor variations in the FSM results compared with the fully calibrated statistical models.

Connected geobodies volumes have been computed for the four different types of simulations in order to statistically compare the various methods. Several statistical tests have been produced using log-log plots:

- **log-log plots of normalized connected geobodies volumes versus frequency** (fig. 2) enable the assessment of noise proportion (Carlson & Grotzinger 2001) and degree of inner organization of the geostatistical results (Wilkinson and Drummond 2004, Purkis et al. 2007)

- **log-log plots of exceedance probability versus raw connected geobodies volumes** enable the measurement of the size distribution within each geostatistical result as well as quantification of scale invariance and self-similarity behaviours (Purkis et al. 2005). Exceedance probability is defined as $P = m/(n + 1)$, where $m$ is the ranking from smallest to largest and $n$ is the number of samples, and represents the cumulative probability $P[X \geq x]$ of a given geobody of volume $X$ having an volume larger than $x$ (Rankey 2002).

This type of plots allows fitting power laws to the distribution each modelling method (geostatistical vs. FSM) that describes their statistical and fractal behaviour. Power laws are under the form of $f = aV^{-\beta}$, where $a$ is a constant, $V$ the volume of connected geobodies and $\beta$ the slope of the power law. The value
of $\beta$ can be linked to the fractal dimension $D$ as $D = \text{euclidian dimension of geobodies (here 3 as they are in 3D)} - \beta$ (Schroeder 1991).

**Figure 1** Visual comparison of FSM with geostatistical methods (including integration of secondary data like vertical proportion curves -VPC-)

**Results**

Visually FSMs results are much closer to a geological image compared with common geostatistical method. From a statistical point of view, FSM results, both raw and matched to wells, exhibit a lower dispersion of values in log-log plots of normalized connected geobodies volumes versus frequency (fig. 2) as shown by the $R^2$ values. This indicates a lower noise in FSM compared to SIS and TGS (Purkis et al. 2007).
Figure 2 Log-log plots of connected geobodies volumes (normalized) against their occurrence frequency for the four different type of simulation

The figure 2 shows also the decreasing of the slope parameter $\beta$ from FSM, to TGS and SIS. This indicates a decreasing degree of organization from FSM compared to common geostatistical methods. Besides, raw and matched to wells FSM exhibit the same statistical distribution showing little modification of the geobodies distribution during the matching process.

These plots (fig. 2) means that FSM produces more organized and stratigraphically connected bodies while preserving a high degree of heterogeneity indicated by the high frequency of smaller geobodies.

The computation of exceedance probability of connected geobodies volumes has been conducted on the raw volumes in order to compare the absolute size of geobodies. It appears (fig. 3) that FSM produces much larger volume at a given probability of occurrence. A factor ten separates SIS method from TGS and TGS from FSM and a factor hundred separates SIS from FSM.

Figure 3 Log-log plots of connected geobodies volumes against exceedance probability with power law fit of each curve portion

The curves of exceedance probability versus raw connected geobodies volumes have the same shape for the three compared facies distributions. They can be organized in three segments each. The first one encompasses the first 80% of the data (smaller geobodies) and the third one encompasses the last 5% of the data (bigger geobodies). In between those two parts, there is a transition segment representing around 15% of the geobodies. This organization is due to varying statistical behaviours depending on the size of the geobodies.

The first segments have a very $R^2$ and have a fractal exponent around 2 indicating a scale invariant Brownian distribution of the geobodies for all compared methods. However, FSM have lower slope indicating a better inner organization compared to TGS and SIS. The second segments have a fractal exponent ranging form -1 for the SIS up to 2 for the FSM. It indicates still fractal behaviour for the FSM and TGS, but SIS exhibits a non-stochastic distribution of larger geobodies. It means that in SIS 20% of the larger geobodies does not follow any statistical law, even implicit, and appears randomly. The third and last segment shows very high fractal exponent (over 12) indicating a non-fractal behaviour for
the three compared method. Therefore, the 5% bigger geobodies follows a non-stochastic distribution for all the facies distribution. Their occurrence is due to exceptional stratigraphic events interrupting the processes allowing the distribution of smaller geobodies.

Exceedance probability distribution shows that all facie distribution may be scale invariant up to a certain geobody volume. The bigger is this volume the more organized is the facies distribution. FSM methods produces then more connected geobodies distribution compared to common geostatistical methods. Gaussian methods (TGS) offers intermediate distribution compared with sequential one (SIS à and FSM.

Conclusions

Forward stratigraphic modelling produces more realistic results compared to TGS and SIS. Both visual aspect and statistical parameters show that the obtained distribution of facies is more geologically sound. It enables both preserving the observed heterogeneity at wells and gaining in geobodies connectivity. This last parameter is a key advantage when passing from static to dynamic models. Therefore, FSM can contribute significantly to reservoir characterization workflows either directly or as a tool for generating soft constraints that can render traditional geostatistical methodologies a more geological validity.

References


