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FAST ASSESSMENT OF THE IMPACT OF MULTI-SCALE GEOLOGICAL HETEROGENEITIES ON FLOW BEHAVIOUR IN COMPLEX CARBONATE RESERVOIRS

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Summary

We discuss the application of the new open-source Rapid Reservoir Modelling software (RRM) to create a suite of 3D reservoir models of a complex carbonate formation where each model is increasingly more refined such that progressively more small-scale geological structures are preserved.

Using flow diagnostics we then calculate key metrics for the dynamic reservoir behaviour to quantify the similarities and dissimilarities of the flow behaviour across the different models. This analysis allows us to identify at which scale geological heterogeneities need to be resolved in the reservoir model to capture the essential flow behaviours.

The workflow presented in this study hence allows us to efficiently and effectively test different geological concepts and analyse how multi-scale geological heterogeneities that may need to be represented in a reservoir model impact the predicted dynamic response, so as to design more reliable and robust reservoir models for a broad range of geoenergy applications.

Fast assessment of the impact of multi-scale geological heterogeneities on flow behaviour in complex carbonate reservoirs

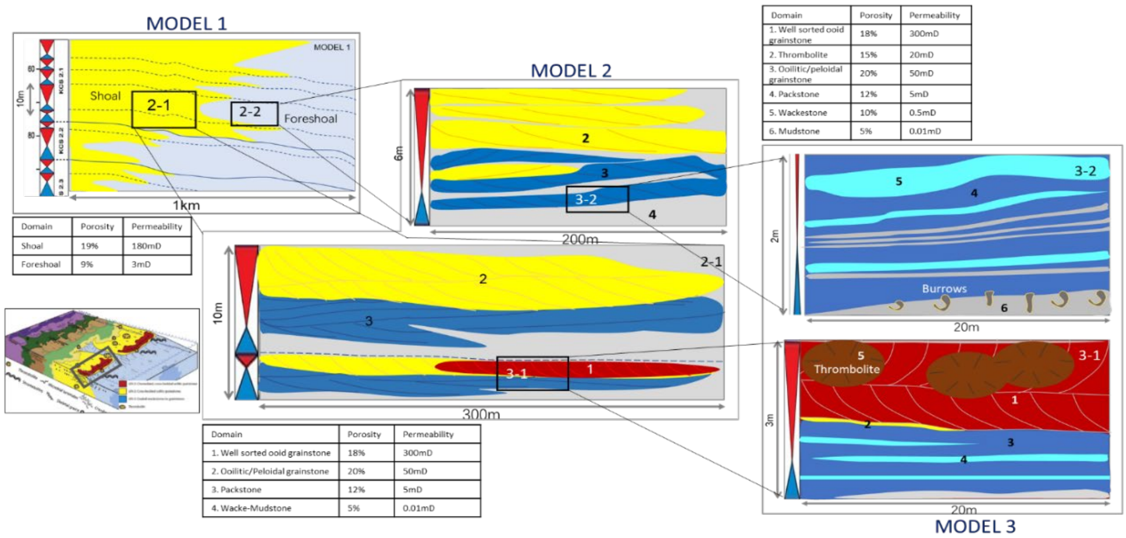
Introduction

Geological heterogeneity needs to be adequately preserved in static reservoir modelling and subsequent dynamic simulation of subsurface geoenergy reservoirs such as hydrocarbon reservoirs, geothermal reservoirs, or CO_2 storages sites. When building a reservoir model, the real geological heterogeneity of the reservoir is inevitably simplified (Ringrose and Bentley, 2015). Which scale of heterogeneity needs to be preserved to design suitable reservoir models remains an open question. Representing the geolocial heterogeneities that are observed in carbonate formations in reservoir models is particularly challenging due the complex multi-scale structures inherent to carbonates.

In this paper, we use the open-source Rapid Reservoir Modelling software (RRM, Jacquemyn et al., 2021) to create a suite of 3D reservoir models of a complex carbonate formation. The models are designed to become progressively more complex as they resolve increasingly more small-scale geological structures that are typical for carbonate formations. We then use the concept of flow diagnostics (Moyner et al., 2015) that are implemented in RRM to calculate key metrics for the dynamic reservoir behaviour to quantify the similarities and dissimilarities of the flow behaviour across the different models. The model that preserves the key scales of geological heterogeneity that capture the essential flow behaviours can then be used for further detailed reservoir modelling and simulation studies in commercial packages.

Geological Data

An outcrop of the well-known Khuff formation in Middle East was selected for the static modelling (e.g., Koehrer, 2014; Eltoma, 2017). The middle Permian to lower Triassic middle and upper members of the Khuff formation on the Arabian Platform are typical examples of carbonate ramp deposits, covering a plate-wide epeiric carbonate shelf composed of subtidal to supratidal dolomites, limestone, and evaporites with prominent carbonate shoal complexes. The shoal-foreshoal facies, being one of the dominant reservoirs in the Khuff formation, was used in this study.



Domain	Porosity	Permeability
Shoal	19%	180mD
Foreshoal	9%	3mD

Domain	Porosity	Permeability
1. Well sorted ooid grainstone	18%	300mD
2. Ooilitic/Peloidal grainstone	20%	50mD
3. Packstone	12%	5mD
4. Wacke-Mudstone	5%	0.01mD

Domain	Porosity	Permeability
1. Well sorted ooid grainstone	18%	300mD
2. Thrombolite	15%	20mD
3. Ooilitic/peloidal grainstone	20%	50mD
4. Packstone	12%	5mD
5. Wackestone	10%	0.5mD
6. Mudstone	5%	0.01mD

Figure 1. *The different scales of geological heterogeneity that are represented in conceptual 3D models of a carbonate ramp (Eltoma et al., 2017). The different facies ("domains") are colour coded, and the petrophysical properties are uniform in each domain.*

Three models of the shoal-foreshoal facies were designed in RRM, each containing an increasing level of geological resolution with Model 1 being being the least resolved model and Model 3 being the most resolved one (Figure 1). Model 1 comprises only two facies ("domains") of shoal and foreshoal, representing the typical heterogeneities observed at lateral scales between 10 and 100 m. Model 2 contains four domains, namely well-sorted grainstone, ooilitic/peloidal grainstone, packstone, and wacke-mudstone that resolve heterogeneities from 1 to 100 m scale. Model 3 contains 6 domains, namely thrombolite, well-sorted grainstone, oolitic/peloidal grainstone, packstone, wackestone, and mudstone that resolves geological heterogeneities as small as 10 cm while also capturing heterogeneities up to 100 m in scale. Each model has a total size of 1000 m x 1000 m x 50 m.

Rapid Reservoir Modelling (RRM)

The key concept of RRM is to employ surface-based reservoir modelling to represent geological heterogeneity as a hierarchy of multi-scale surfaces (Jackson et al., 2013). This approach implies that RRM models do not not contain a grid, which is only generated on the fly for subsequent calculations such as flow diagnostics. RRM uses Sketch-Based Interface Modelling (SBIM) to generate surface-based 3D reservoir models from 2D sketches in cross-sectional and map view. These sketches are drawn easily and intuitively using pens on touch-enabled surface computers and laptops. Geological operators in RRM then ensure that the surfaces which describe the shape of a domain are always interacting with each other in a geologically consistent way (Jacquemyn et al., 2021).

Figure 2 shows an example 2D coss-section of three transgressive-regressive carbonate sediment cycles modelled in RRM; these sedimentary cycles have led to a frequent superposition of mudstone, wackestone, and packstone facies ("domains"). Each domain is separated by a fully enclosed surface. The aerial distribution of geobodies such as grainstone lobes of the shoal facies is sketched in map view in RRM. The interactions of the 2D cross-section and map view controls the 3D shape of each domain. Figure 3 shows Model 1, 2, and 3 as designed by RRM, with their increasingly more detailed geological resolution. A particular advantage of RRM in this case study was that geobodies that have complex 3D shapes, for example thrombolites, could be modelled easily and geologically realistically. Furthermore, additional geological complexity and heterogeneity could readily be added in RRM by sketching additional small-scale features to refine the existing model geometries.

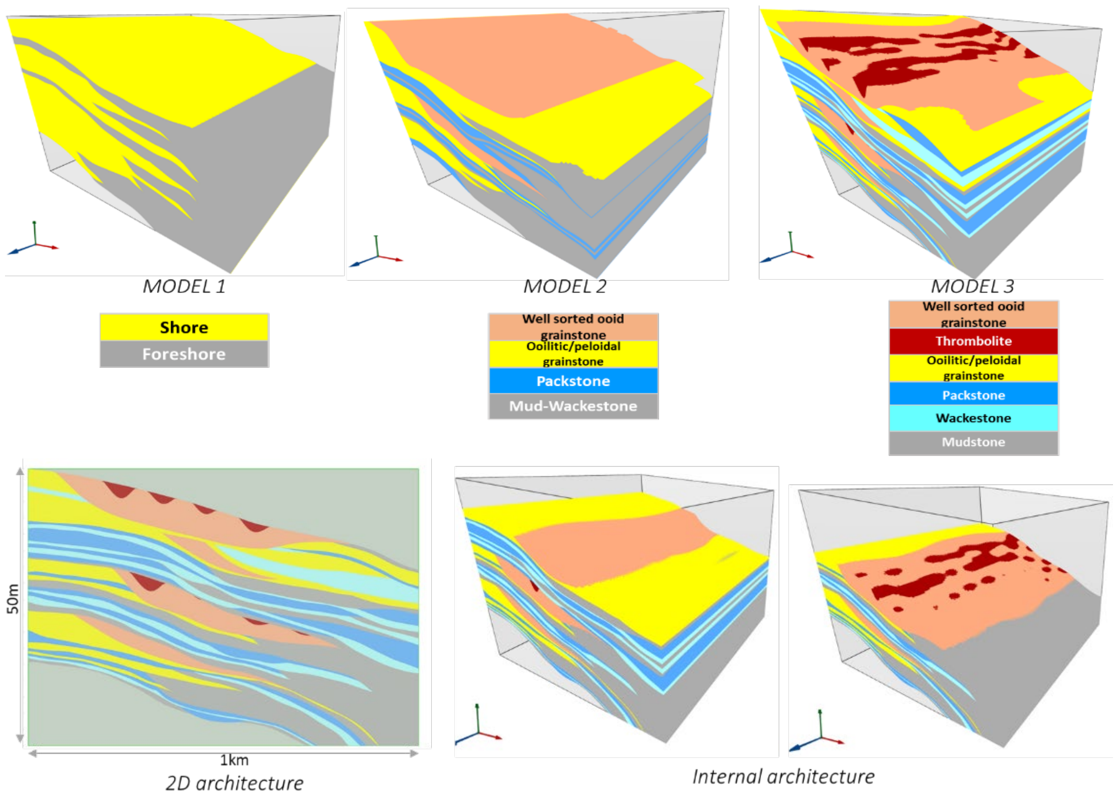


Figure 3. *Three conceptual models for a shoal-foreshoal carbonate ramp setting created in RRM where each model is of equal dimension but has increasing geological complexity (top row) and internal architecture of Model 3, showing the shape of the thrombolite facies (bottom row).*

Flow Diagnostics

Flow diagnostics are computationally highly efficient numerical calculations that probe the dynamic reservoir behaviour by calculating the time-of-flight distribution in the reservoir and defining subsequent metrics that quantify the heterogeneity in the flow behaviour of the reservoir, for example swept and drained reservoir volumes, well-allocation factors, or proxies for the volume of fluids produced (Moyner et al., 2015). Flow diagnostics are hence an efficient tool to compare-and-contrast, rank, and cluster the dynamic behaviour of (many) different reservoir models, such as the ones developed here, and select a small number of representative reservoir models for further, detailed reservoir characterisation, modelling, and simulation studies.

Another advantage of flow diagnostics is that they can be used easily to quantify how different grid resolutions impact fluid flow predoctions. As noted above, because of the surface-based reservoir modelling approach inherent to RRM, grids are only generated on demand. Figure 4 shows the representation of Model 3 (the most resolved model) at four different grid resolutions. Each domain was assigned a uniform porosity and permeability value that is typical for the corresponding facies in the Khuff formation. As the grid is refined, geological structures and their connectivity in space are represented at better detail. An increase in grid resolution, together with the increase in the detail at which geological structures are modelled, are therefore expected to impact reservoir flow predictions. Figure 5 shows a summary of the recovery factor as approximated by flow diagnostics calculations for the geological structures represented by Model 1, 2, and 3; each of these three models was also subjected to 12 different grid resolutions. While different grid resolutions impact the estimated recovery factor by around 5%, there is a marked drop in average recovery factor from over 70% for Model 1 to 63% in Model 2 and 60% in Model 3, suggesting that it is key to represent the geological structures of Model 2 to capture the main flow behaviour of the reservoir.

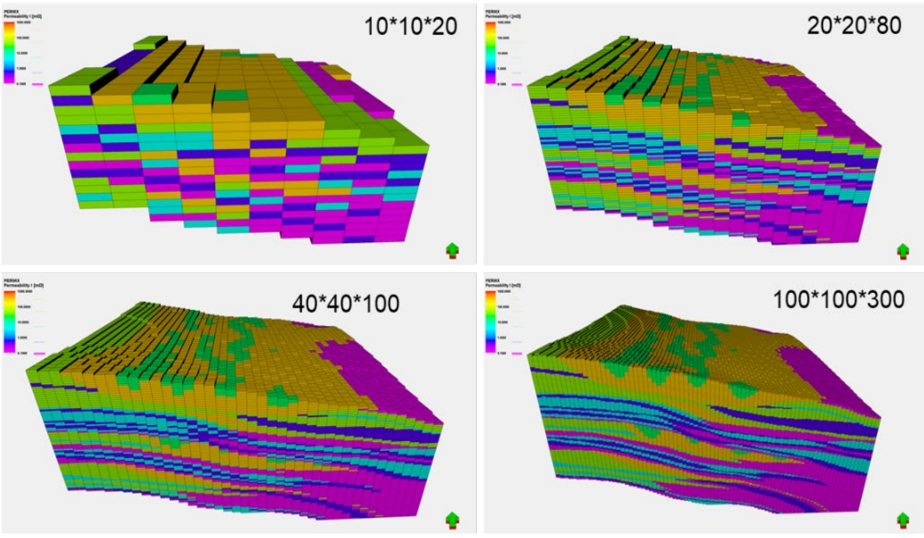


Figure 4. *Discretised representation of the geological structures in Model 3 for four different grid resolutions. Note that the geological structures are represented by surfaces, hence an increasing grid resolution will represent the multi-scale geological heterogeneities more accurately. The colour scale denotes the permeability of the individual facies ("domains") of Model 3.*

Concluding Remarks

This study discusses multi-scale geological modelling of the shoal-foreshoal deposits that are observed in a carbonate ramp of the Khuff formation. We used the open-source Rapid Reservoir Modelling (RRM) software to create different 3D geological models, each model capturing geological details at increasingly more resolution; the most resolved model contains geological features that are 0.1 metres in size within a kilometre sized reservoir model. It is important to highlight that it took about an hour to create the most-resolved and geological consistend reservoir model in RRM by simply sketching the geological features in 2D cross-sections and map view. Using flow diagnostics in RRM, we then analysed how the different scales of geological refinement and grid resolution impact reservoir flow behaviour to identify the key heterogeneities that need to be captured in the reservoir model. Each flow diagnostic calculation took only a few seconds to complete.

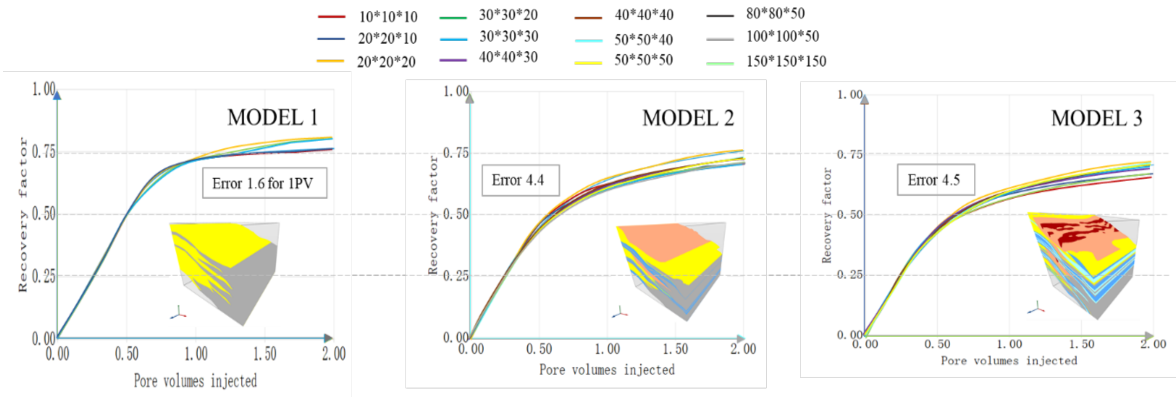


Figure 5. *Recovery factor, as approximated by flow diagnostics, for the three different conceptual models for a shoal-foreshoal carbonate setting created in RRM. Each of these models was represented by 12 differently refined grids which capture the geological heterogeneity inherent to the model increasingly more accurately (see Figure 4 for an example of grid refinement).*

This application demonstrates that RRM is a powerful tool to efficiently and effectively test different geological concepts and analyse how multi-scale geological heterogeneities that may need to be represented in a reservoir model impact the predicted dynamic response. This approach can be integrated seamlessly with existing commercial reservoir modelling methods. Knowledge about which geological detail needs to be captured in a geological model together with the information about the most suitable grid resolution are crucial for designing reliable and robust reservoir models for a broad range of geoenergy applications, from hydrocarbon production to geothermal energy and CO_2 storage.

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References

Eltoma HA, Kubur AK, Abdulraziq, AM Babalola LO, Makkawi MH, Abdullatif OM, Three-dimensional outcrop reservoir analog model: A case study of the Upper Khuff Formation oolitic carbonates, central Saudi Arabia, Journal of Petroleum Science and Engineering, 150, 115–127, 2017.

Jacquemyn C, Pataki MH, Hampson GJ, Jackson MD, Petrovsky D, Geiger S, Marques CC, Machado Silva JD, Judice S, Rahman F, Costa Sousa M, Sketch-based interface and modelling of stratigraphy and structure in three dimensions, Journal of the Geological Society, 178(4), 2021.

Jackson MD, Hampson GJ, Saunders JH, El-Sheikh A, Graham GH, Massarat BYG, Surface-based reservoir modelling for flow simulation. Geological Society of London Special Publications, 387, 271-292, 2013.

Koehrer B, Aigner T, Forke H, and Poppelreiter M, Middle to Upper Khuff (Sequences KS1 to KS4) outcrop-equivalents in the Oman Mountains: Grainstone architecture on a subregional scale. GeoArabia, 17(4), 59-104, 2012.

Moyner O, Krogstad S, Lie KA, The application of flow diagnostics for reservoir management. SPE Journal, 20(2), 306-323, 2015.

Ringrose P, Bentley M, Reservoir Model Design. Springer Verlag, 2015.