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Assessing the impact of hierarchical geological heterogeneities on geothermal energy production.

K. Baird[1], S. Geiger[2], D. Arnold[1], F. Doster[1], G.J. Hampson[3], C. Jacquemyn[3], M.D. Jackson[3], D. Petrovskyy[2], J.D. Machado Silva[4], S. Judice[4], F. Rahman[4], M. Costa Sousa[4]

[1] Herriot-Watt University; [2] Technical University of Delft; [3] Imperial College London; [4] University of Calgary

Summary

Energy derived from geothermal systems is essential to the energy transition. Inherent geological and a lack of data requires the use of computer-driven modelling and simulation to aid decision-making. To make sound decisions, many reservoir models that encapsulate different geological scenarios should be analysed such that the impact of geological uncertainty on geothermal energy production can be evaluated adequately. Current geomodelling workflows, however, are too time consuming to build and explore different contrasting geological scenarios at various scales.

In this study we used the open-source Rapid Reservoir Modelling (RRM) software to design different geological scenarios of a shallow marine succession hosting a potential geothermal reservoir and analyse how multi-scale geological features impact reservoir flow. RRM allows users to quickly create and explore realistic 3D geological models from intuitive 2D sketches. Models arecreated in minutes while flow diagnostics allow us to analyse fluid-flow behavior in real-time. Models are then imported into commercial reservoir simulation packages to investigate the effect of heterogeneity and scale on geothermal energy production. We show how we can quickly evaluate how different scales of heterogeneity impact geothermal production estimates and which heterogeneities must be represented in reservoir models to obtain reliable results about the possible reservoir behaviours.

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Introduction

Geothermal energy is a key component in the energy transition. Many low-enthalpy geothermal systems, which are often targeted for direct heating, are located within sedimentary aquifers at depths around 2.5 km and temperatures ranging from 70 to 90°C (e.g., Crooijmans, et al., 2016; Babaei & Nick, 2019). Given the inherent uncertainty of geological heterogeneity within these geothermal reservoirs, engineering and economic decisions are typically made using computer-driven modelling and reservoir simulation workflows. Due to the lack of data, geological uncertainty is often larger in geothermal reservoirs compared to hydrocarbon reservoirs. Hence, a larger number of reservoir models needs to be considered and explored to evaluate the impact of geological uncertainty on reservoir production. However, existing geomodelling workflows are time consuming and render the creation of suitable reservoir models that explore numerous geological scenarios at various scales difficult.

To quantify the effects of geological uncertainty on geothermal reservoir performance, we use Rapid Reservoir Modelling (RRM) software to build a catalogue of geological scenarios at different scales. RRM is an open-source software that allows users to create 3D geological models from 2D sketches that are guided by geological operators, by integrating sketch-based interface and modelling (SBIM) (Jacquemyn, et al., 2021). The software is unique in that many geological scenarios can be prototyped rapidly through intuitive sketching. The 3D models can then be used to approximate in "real-time" how geological heterogeneity may affect fluid flow, using the flow diagnostics module in RRM (Petrovskyy et al., 2022). Only recently has RRM software been applied to low-carbon energy solutions (Jacquemyn, et al., 2022; Petrovskyy, et al., 2022). In this paper we extend the prototyping of reservoir models in RRM by importing them into a commercial geothermal simulator for further detailed investigation.

Methods

Five different models of shallow-marine parasequences, built by Jacquemyn et al. (2021) with RRM to reflect different interpreted scenarios, are analysed for geothermal energy production using flow diagnostics calculations in RRM and "full-physics" geothermal simulations with an industry-standard commercial simulator (STARS by CMG Ltd.). Geological interpretations and associated uncertainties include variations in the shoreline facies belts, flood tidal delta deposits, and tide-influenced channelised sand bodies. The key reservoir and production parameters are listed in Table 1 while Figure 1 shows some illustrative models. The original models, *SM1-SM5*, were cropped to focus on an injection and production well pair (spaced 1 km apart) with a surrounding area of 2 km in each horizontal direction. Wells target areas of the largest variation in geological heterogeneity between scenarios and perforations target the permeable facies. From the values of cumulative produced energy and the difference in bottom hole pressure between the wells, the overall geothermal capacity for each scenario was calculated.

As initial screening, we calculated the time-of-flight distributions between the injector to producer to approximate breakthrough times of the injected fluid (Jacquemyn, et al., 2022). As the original models do not capture small-scale heterogeneity between the wells, we added more geological complexity step-by-step to analyse how these small-scale heterogeneities, which are often not considered in geothermal reservoir models and simulations, could impact on flow.

As an illustrative example, model *SM1_Clinoforms,* incorporates calcite-cemented nodular layers along clinoform surfaces, which act as barriers to fluid flow, in each parasequence. Studies have shown that the presence of these barriers extending along 70% of the clinoform surfaces has an impact on simulated oil recovery and water breakthrough (Sech, et al., 2009); here, we test the effect of these smaller-scale heterogeneities on geothermal production.

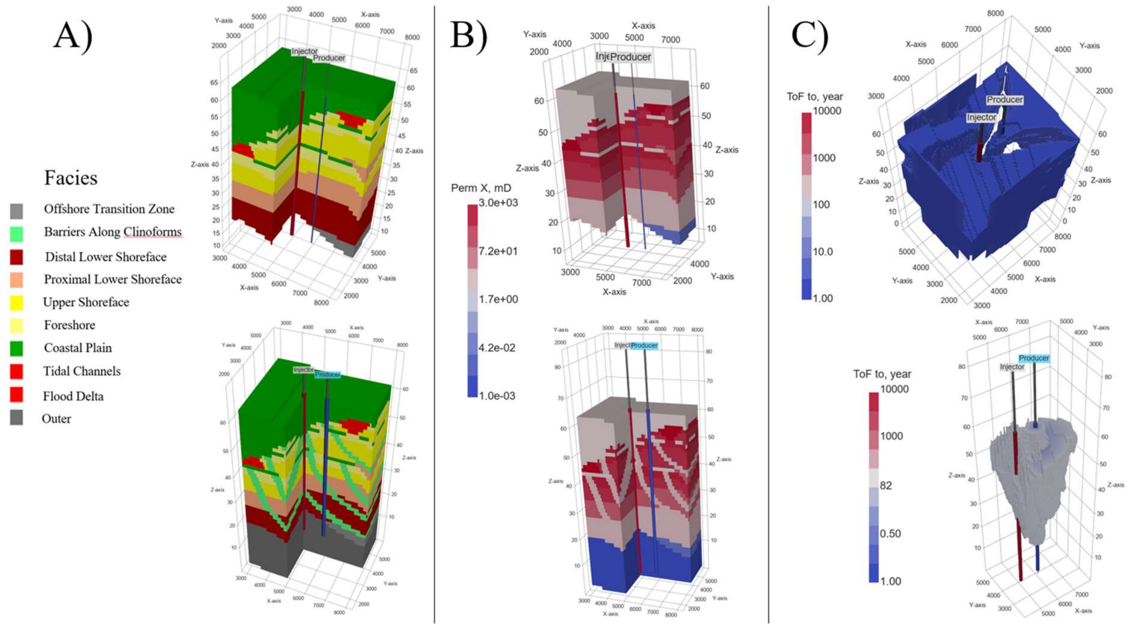


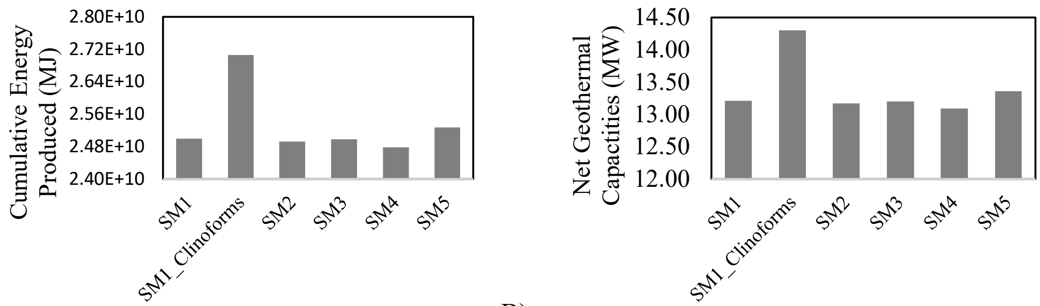
Figure 1 *3D view of two geological scenarios created with RRM: A) Model SM1 (top) and SM1_Clinoforms (bottom) shows the geothermal doublet location and facies, B) Shows the permeability distributions of SM1 (top) and SM1_Clinoforms (bottom), C) Shows the time-of-fight distributions to the producer for SM1 (top) thresholded at 5 years of production and SM1_Clinoforms thresholded at 82 years of production.*

Table 1 *Key geothermal reservoir parameters.*

Initial Reservoir Parameters		Well Constraints
Initial reservoir temperature	90 °C	Injector
Initial reservoir pressure	30000 – 35000 kPa	35000 kPa BHP
Depth of the reservoir top	3 km	70 °C injection temp
		Producer
		4800 m^3/ day
		60 years of production

Results and Discussion

While there are small variations in the production rates, the cumulative produced energy varies only slightly between the original models (Figure 2A). The calculated pump energy in each scenario falls below 1% of the gross production energy, and hence the calculated net geothermal capacities for each scenario are directly related to the cumulative energy produced (Figure 2B). When comparing *SM1* to *SM1_Clinoforms*, differences in reservoir behaviour are apparent, however. The production rate for *SM1_Cliniforms* increases more steadily than in *SM1*, leading to a pronounced increase in cumulative production energy and a larger net geothermal capacity estimate. This is relevant to the difference in fluid-flow behaviours shown by the geothermal fluid contacting different volumetric proportions of each facies, dependent on the reservoir model (Figure 3).



A) B)

Figure 2 *Showing the A) cumulative energy produced over 60 years and, B) the estimated net geothermal capacities for each scenario after 60 years of production.*

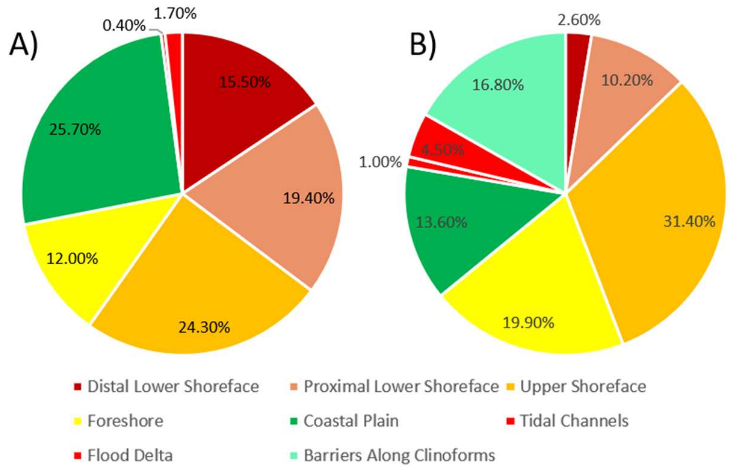


Figure 3 *Percentage of the overall proportion of each facies that has been contacted by the injected cold geothermal fluid for A) SM1 and, B) SM1_Clinoforms.*

The presence of impermeable barriers along the clinoform surfaces increases the time of thermal breakthrough, which results in a higher cumulative production. Figure 4 shows how the injected cold water spreads differently through the reservoir, following the permeable facies and navigating around impermeable boundaries. The increased tortuosity of the flow slows down the advancement of the cold front and allows the production well to draw in hot water from a larger region for a longer time, creating increased energy production rates. This result illustrates how exploring different scales of heterogeneity is imperative to providing robust geothermal energy forecasts.

Conclusions

We show that capturing geological heterogeneity at the right scale is essential to providing more reliable geothermal production forecasts. Given the difficulty in conceptualising quickly models that incorporate heterogeneities at different scales, we opt to use RRM software to assess geological scenarios and thereby identify the conditions under which heterogeneity may affect geothermal production estimates. From these results we can make informed decisions on which scenarios require further numerical simulations using commercial thermal simulators. While future research is necessary to consider a much broader range of hierarchical and multi-scale geological features across different depositional environments, we have provided the first use of RRM within reservoir modelling and simulation workflows for geothermal systems.

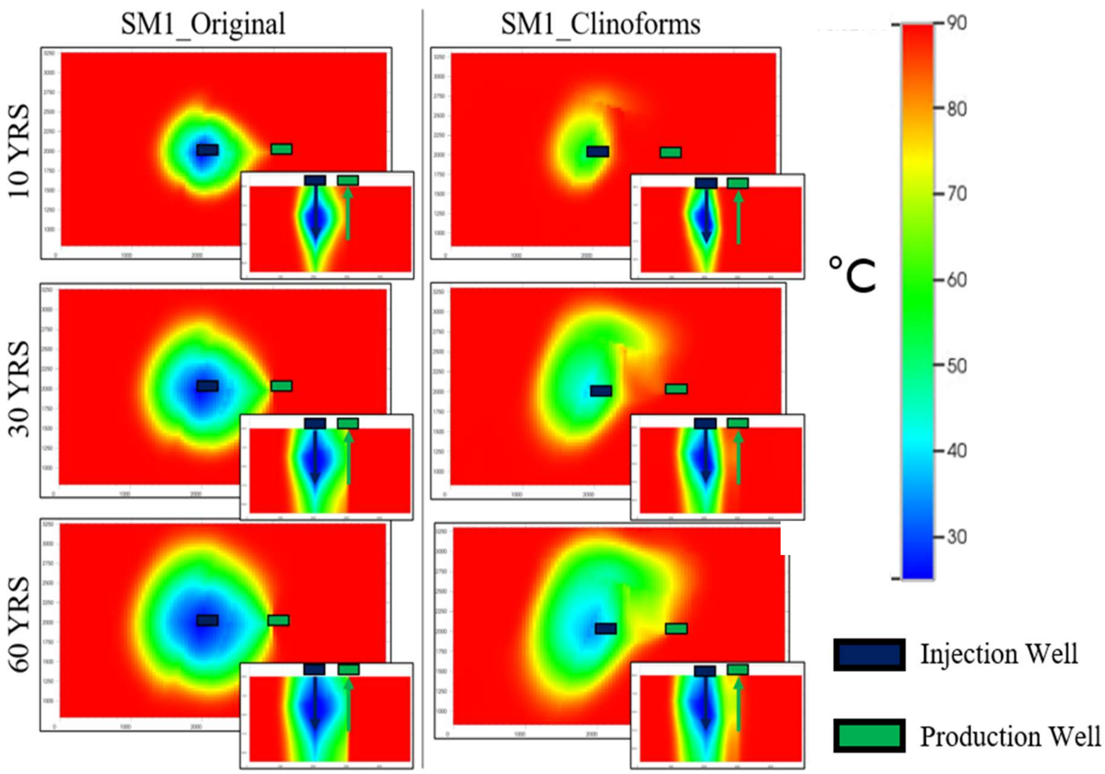


Figure 4 *Temperature distribution for the models SM1 and SM1_Clinoforms at different points in time. The larger images show the temperature distributions at the surface while the smaller images show a cross-section view of the well completions.*

Acknowledgments

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