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Towards a Subsurface Geothermal Digital Twin: Efficient Construction of Geological Scenarios for Modelling Fluvial Geothermal Reservoirs

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Summary

During the development of subsurface geothermal energy, geological complexity and uncertainty pose challenges when developing and managing a geothermal resource. We are therefore developing a digital twin for subsurface geothermal energy that will be applied to the geothermal project on the TU Delft campus. This digital twin combines geological modelling, property modelling, reservoir simulation, and data assimilation. A core principle of our approach is to consider multiple geological models of the reservoir and use real-time production data to update them to constrain uncertainties and adapt operational strategies.

This paper focuses on the efficient exploration of geological scenarios and design of geological modelling for the digital twin. We use the Rapid Reservoir Modelling (RRM) platform, which is tailored to quickly create 3D models in data-poor situations. We have developed a novel methodology where RRM is used to design templates of individual layers for a given geological scenario. These templates are then extracted and stacked to create different 3D geological scenarios constrained by NTG and well logs. The resulting model ensemble is geologically consistent and captures a diverse range of heterogeneity, providing a robust starting point for exploring the performance of a geothermal reservoir under geological uncertainty in a digital twin.

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Introduction

Geothermal energy offers a clean baseload alternative to fossil fuels for space heating. The direct-use geothermal project on the campus of the Delft University of Technology, known as "Geothermie Delft," has been initiated not only as a unique research platform but also to produce thermal energy and provide heating for the campus and part of the city of Delft (Vardon et al., 2020; Vardon et al., 2024). Geothermal energy production faces uncertainties due to the incomplete knowledge of the reservoir architecture and heterogeneity of the geological formations hosting the geothermal resources. It is widely accepted that it is not sufficient to explore and quantify uncertainty in production behaviours based on a single geological concept or interpretational scenario (Ringrose & Bentley, 2016).

We propose a workflow for an open-source digital twin for geothermal reservoirs that can be used for quantifying and constraining the uncertainty in production temperature and rate (Voskov et al., 2024). This digital twin includes the following elements (Figure 1): a) Well logs and seismic data are utilized to design multiple reservoir models that capture possible geological scenarios using the Rapid Reservoir Modelling (RRM) software. RRM is a sketch-based modelling software that allows users to rapidly generate a wide range of geologically consistent models and scenarios in 3D (Ringrose & Bentley, 2016). b) Different property distributions are assigned to the facies modelled in RRM to capture uncertainty in the petrophysical data. c) The Delft Advanced Research Terra Simulator (DARTS) is combined with machine learning techniques to create proxy models that enable fast simulations (Khait & Voskov, 2018). d) As new production and monitoring data becomes available, data assimilation techniques like Ensemble Smoother with Multiple Data Assimilation (ESMDA) are applied to update property distributions for each scenario. This iterative process of data assimilation will help users constrain geological and production uncertainties, both of which are key to optimizing operational strategies.

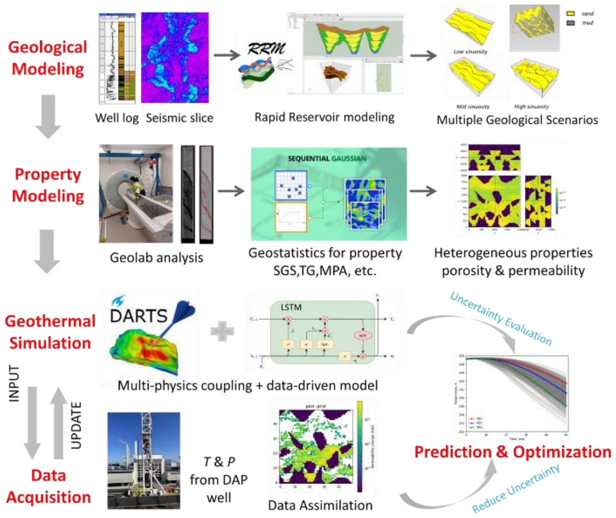

Figure 1 *Conceptual framework of the subsurface geothermal digital twin.*

This paper focuses on the first step of the digital twin, i.e. the efficient exploration of geological scenarios and associated design of geological models. RRM allows users to create complex 3D geological models in a matter of minutes, which is much more efficient than traditional geological modelling tools. To further accelerate RRM, especially when individual geological elements are geometrically very complex in 3D, we have developed a methodology where RRM is used to design templates of individual layers for a given geological scenario. These layers can then be combined in a post-processing step and conditioned to subsurface data (e.g., wireline logs or net-to-gross) to create complex, multi-scale, yet geologically consistent models in 3D representing a broad range of scenarios.

We will demonstrate this approach to efficiently create geological scenarios of fluvial systems that are relevant to the Delft Geothermal Project.

Method

RRM is an open-source, sketch-based modelling tool with an intuitive interface enabling users to swiftly create 3D geologically consistent 3D reservoir models from 2D sketches (Jacquemyn, et al., 2021; Petrovskyy, et al., 2023). RRM uses the concept of surface-based reservoir modelling, meaning that all geological architectures and heterogeneities are represented by surfaces that define enclosed volumes, the geological domains. RRM integrates sketch-based interface and modelling (SBIM) with geological operators and near-real-time flow diagnostics which allows users to build complex 3D geological models in a matter of minutes while flow diagnostics provide approximate information on the dynamic reservoir behaviour within seconds. RRM has been applied successfully to design and screen geological scenarios for CO_2 storage (e.g., Jackson et al., 2022) and geothermal energy production (e.g., Baird et al., 2024). Figure 2 shows the RRM interface where an individual layer of a fluvial geothermal reservoir was created, based on certain constraints such as channel width, net-to-gross, and channel sinuosity.

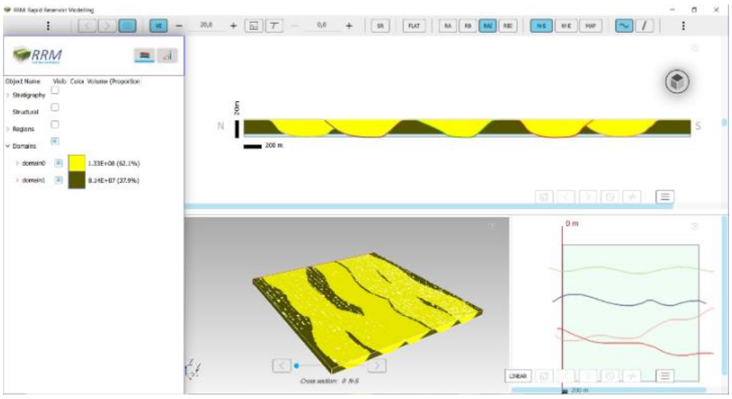

Figure 2 *Screenshot of the RRM interface. The sketched model corresponds to a geological scenario representing a single layer in a fluvial reservoir where the fluvial channels have a width of 500 m, the NTG is 60%, and the channels have low sinuosity.*

Table 1 *Orthogonal design for a number of individual layers in a fluvial geothermal reservoir based on channel sinuosity, NTG, and channel width.*

Layer Case	Sinuosity	NTG	Channel width /m	Layer Case	Sinuosity	NTG	Channel width /m
1	low	40%	200	6	mid	80%	200
2	low	60%	800	7	high	40%	500
3	low	80%	500	8	high	60%	200
4	mid	40%	800	9	high	80%	800
5	mid	60%	500				

Once a template for a fluvial reservoir layer has been generated, a portion of this template can be extracted and stacked with other layer templates created in RRM. Since the target size in the horizontal direction is smaller than the layer template, the random extraction not only adjusts the size but also allows us to include more uncertainty in the ensemble. Table 1 shows an orthogonal design for nine individual layer templates created in RRM, where each layer has a different channel sinuosity, width, and net-to-gross. Each layer is then mirrored along the X-, Y-, and XY-axis, which creates a total of four layer templates (Figure 3). In this particular application, the library is composed of 36 templates, representing different geological heterogeneity inherent to fluvial geothermal reservoirs. To build the full 3D model, a template is randomly selected from the library and a sub-region at the desired size is extracted (Figure 4). This process is repeated until the target height for the 3D model is achieved. Adjacent layers are not simply stacked. Instead, they overlap in a way that mimics the deposition of fluvial sediments, meaning that portions of the sandstone in the upper layer occupy positions in the lower layer and replace the lithology in those positions. Due to this overlap, the vertical connection and associated heterogeneity between the two layers are maintained. To ensure that the final model honours field data, such as net-to-gross or facies constraints from well logs, can be applied to each layer.

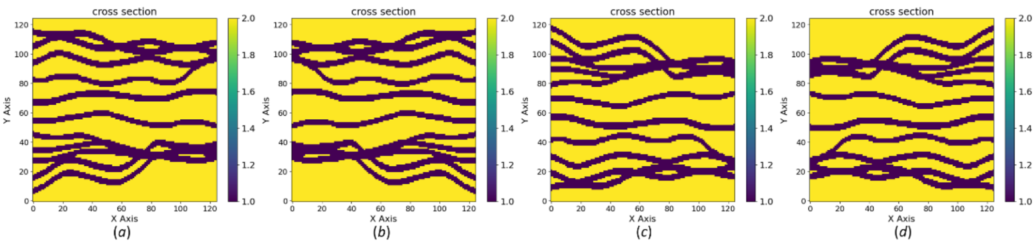

Figure 3 *Creation of a layer template for fluvial channels: (a) Original design of layer case 1, (b to d) mirroring of the original design along the X-, Y-, and XY-axes. Colours indicate the facies distribution where 1 (dark) represents sand and 2 (light) represents mud.*

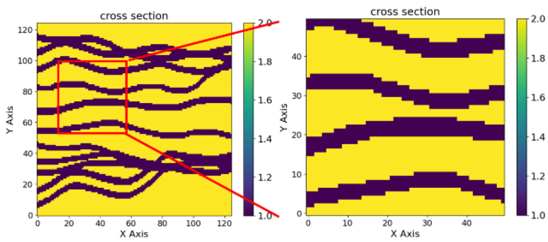

Figure 4 *Extracting an area from a layer template (125 × 125 × 10) to create a smaller layer (50 × 50 × 10) while maintaining the channel sinuosity and channel width of the original large layer.*

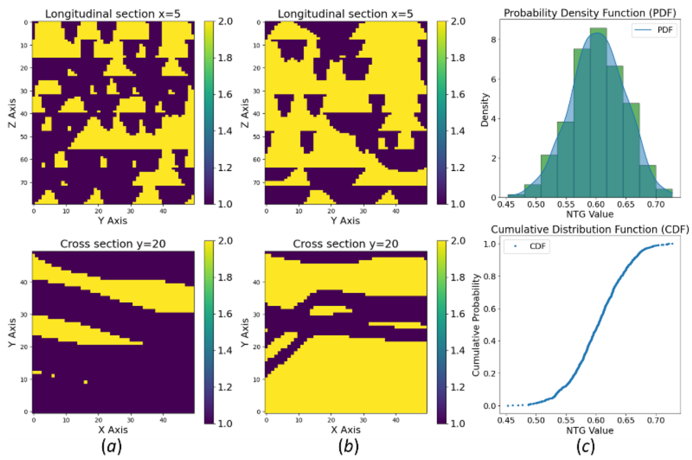

Figure 5 *Two 3D fluvial reservoir scenarios and corresponding* net-to-gross (NTG) *statistics obtained by extraction and stacking the layer templates based on the parameters in Table 1. (a) Realization with NTG of 0.415 with an NTG prior between 0.38 and 0.42. (b) Realization with NTG of 0.604 with an NTG prior between 0.58 and 0.60. (c) Probability Density Function (PDF) and Cumulative Distribution Function (CDF) curves for the NTG for all realizations.*

Figure 5 shows the example application of our method to generate two 3D scenarios for a fluvial geothermal reservoir after partial extraction and stacking of the individual layers created in RRM based on the parameters in Table 1. The size of the initial layer template is 5000m × 5000m × 10m while the target reservoir size is 2000m × 2000m × 80m, requiring a total of 10 layers to be extracted and stacked, with an overlap of 2m for each layer. NTG constraints are prescribed and honoured for each scenario. Additionally, well log facies constraints, such as sand and mud facies along the well, can also be applied when extracting and stacking the individual layers. The resulting scenarios are then part of an ensemble that can be subjected to numerical simulations in DARTS to evaluate the performance of a fluvial geothermal reservoir under significant geological uncertainty.

Conclusions

This paper discusses a new approach for generating a diverse ensemble of geological scenarios that feed into a new digital twin for subsurface geothermal production. The geological modelling is originally based on the Rapid Reservoir Modelling (RRM) platform which allows users to rapidly create and explore geological scenarios, especially in data-poor environments such as geothermal reservoirs. We demonstrate how we can use RRM to design a series of individual geological layers representing diverse features of the fluvial geothermal reservoir. These layer templates are then partially extracted and stacked to design different geological scenarios in 3D, each of which can be constrained to net-to-gross and facies distributions from well logs or cores. The resulting model ensemble is then geologically consistent and allows us to capture a diverse range of geological uncertainties, hence providing a sound starting point for exploring the performance of a geothermal reservoir in a digital twin.

Acknowledgements

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