Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Exploring the impact of different geological scenarios on flow behaviour in sedimentary aquifers in Europe

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Keywords: geothermal exploration, geological uncertainty, hot sedimentary aquifers, direct-use geothermal

INTRODUCTION

Direct heat extraction from deeply-buried sedimentary aquifers offers a sustainable, low-carbon solution for heating across Europe (Bruhn et al., 2022). Despite the considerable geothermal potential, project development faces high economic, technical and geological uncertainty (Daniilidis, 2024), dissuading investment and impeding widespread deployment. The small economic margins of geothermal energy result in relatively limited investments in the critical exploration stage, resulting in the perpetuation of unsuccessful projects (Brémaud et al., 2025).

The EU FindHeat project aims to develop best practice guidelines for geothermal exploration, creating more time- and resource-efficient exploration programmes resulting in more successful projects. Using a range of different geothermal play types within Europe, FindHeat develops a conceptual model-based geothermal exploration workflow, integrating novel exploration tools and new decision matrices (Geiger et al., 2025). By examining which geological parameters have the highest influence on project metrics, it can be determined which geological uncertainties should take precedence when designing exploration programs (Witter et al., 2019).

In this research, we explore different geological scenarios that can impact flow in hot sedimentary aquifers geothermal play type (HSA), informed by the lower Cretaceous Delft Sandstone Member (DSSM), a productive geothermal reservoir in the West Netherlands Basin (WNB), Netherlands. It is well established that geological heterogeneity impacts flow within a reservoir (Jones et al., 1995, Choi et al., 2011, Clark and Pickering, 1996), and that connectivity is one of the fundamental properties which directly affects flow rates and production behaviour (Larue and Hovadik, 2006). Due to the increased adoption of geothermal energy, there is now a renewed focus on investigating the impact of geological heterogeneity specific to geothermal systems (Baird, 2024, Willems et al., 2017a, Willems and Nick, 2019, Aghaei et al., 2024, Chen et al., 2025, Daniilidis et al., 2020).

Rapid Reservoir Modelling (RRM; (Jacquemyn et al., 2021) has been used in this study to rapidly construct a suite of synthetically generated realisations, which have been dynamically-simulated using Open DARTS (Delft Advanced Research Terra Simulator; (Voskov et al., 2024). This allows us to determine which sedimentary and architectural elements have significant impact on the flow behaviour.

By identifying which geological uncertainties are most influential to the geothermal flow response and economic performance in sedimentary aquifers, we can present an appropriate exploration methodology to constrain geological, technological and economic uncertainties. These findings will help inform the best practice exploration guides in the FindHeat project.

1 GEOLOGICAL SETTING / GEOTHERMAL PLAY TYPE

The FindHeat project has eight case studies representing a broad range of geothermal play types found in Europe. Using the DSSM depositional environment to determine the conceptual model, two potential geological scenarios have been identified, and a suite of realisations has been constructed to rapidly screen several geological heterogeneities which can occur related to these fluviodeltaic scenarios. Future research will examine other heterogeneities within sedimentary aquifers using other FindHeat case studies, such as the aeolian Permo-Triassic Sherwood sandstone.

1.1 Delft Sandstone Member (DSSM)

The DSSM is a productive geothermal aquifer located in the WNB (Mijnlieff, 2020, Willems et al., 2020). The DSSM is part of the Nieuwerkerk Formation, which is subdivided into three lithostratigraphic members; the Alblasserdam Member, the Delft Sandstone Member and the Rodenrijs Claystone Member (Den Hartog Jager, 1996, DeVault and Jeremiah, 2002). As a whole, the Nieuwerkerk Formation represents a fluvial to marine transition zone (Willems et al., 2020). The Alblasserdam Member is characterised by alluvial plain deposits with single and stacked channel sands and overbank fines, and is thought to be fluvial in origin (Donselaar et al., 2015). The probably conformably overlying DSSM is characterised as closely-spaced stacked sandstone bodies deposited in a fluviodeltaic setting (Weert et al., 2024, Vondrak et al., 2018). The overlying Rodenrijs Claystone Member consists of grey mudstones with interbedded sandstone and coal-fragments and has been interpreted to be deposited in a lagoonal setting (Den Hartog Jager, 1996, DeVault and Jeremiah, 2002).

By understanding the conceptual model for the DSSM, we can capture scenarios of the unique sedimentological and stratigraphical architectural elements that define this depositional environment, and explore the impact of each of these features on fluid and heat flow within the reservoir through a suite of synthetic realisations.

1.2 Architectural Elements

Two geological scenario end-members represent the DSSM's fluvial deltaic concept. These are the *lower-delta plain (scenario 1)* that is influenced by marine, lacustrine or lagoonal environments and the fluvial-dominated *upper-delta plain (scenario 2)* with less marine influence. Deltaic environments vary in scale, processes, and resulting sedimentary architecture (Nichols, 2009). However, generalised characteristics can be defined for both the upper-delta plain and lower-delta plain. The two geological scenarios are represented by five stratigraphic sedimentological and architectural elements (Table 1).

Table 1. Architectural Elements reflecting the two end-members of a fluvial deltaic environment. We test all parameter combinations using a full factorial experimental design resulting in 48 model realisations

Architectural Element	Setting 1	Setting 2	Setting 3 (if applicable)
A. W/T sand body ratio	W/T 1:20	W/T 1:40	
B. Sinuosity Index	1.5	1.2	
C. Frequency of occurrence	3 per km	1 per km	
D. Aggradation (stacking pattern)	Isolated	Contacted	Embedded
E. Well placement relative to paleoflow	Perpendicular	Parallel	

2 MODELLING METHODOLOGY

A controlled, idealised setting has been constructed to systematically assess how the different realisations of individual architectural elements control heat and fluid flow within a fluvial deltaic reservoir. Each factor has at least two settings chosen to reflect one of the two geological scenarios. A full factorial design of realisations is used to provide a comprehensive analysis, by assessing every combination of factors and their interaction effects. If a specific factor is identified as having significant control, it will be investigated further in subsequent experiments.

The RRM toolbox (Jacquemyn et al., 2021) has been used to construct the different realisations of the geological scenarios. Architectural elements were drawn in combination as surfaces which were defined as geological domains. The surfaces have then been stacked to generate a full-sized reservoir model of 4000 m x 6000 m x 100 m. Dynamic simulations have been carried out using open DARTS (Voskov et al., 2024) following the optimal numerical setup identified in Chen et.al. (2025). Two doublet well placements were used across all models, well position one (WP1) was placed perpendicular to flow direction (E–W) and well position two (WP2) was placed parallel to flow direction (N-S). Wells are perforated through the whole thickness of the reservoir.

A distance-based sensitivity analysis (DGSA) was performed to explore the relationship between realizations and model output . Two outputs from the dynamic simulation were used for sensitivity analysis: system lifetime and temperature at the production well. System lifetime is defined as the time at which the temperature at the production well drops by 1% of the initial reservoir temperature. System lifetime will be used as the key

economic indicator for this study These response metrics allows us to fully understand the impact of the key architectural elements on flow response in the reservoir.

3 RESULTS AND DISCUSSION

Figure 1.A & B shows the variation in temperature and thermal output at the production well as a function of time, with red numbers indicating system lifetime. The present work reports only a subset of the results; a comprehensive DGSA has been undertaken to fully understand the influence of the fluvial architectural elements.

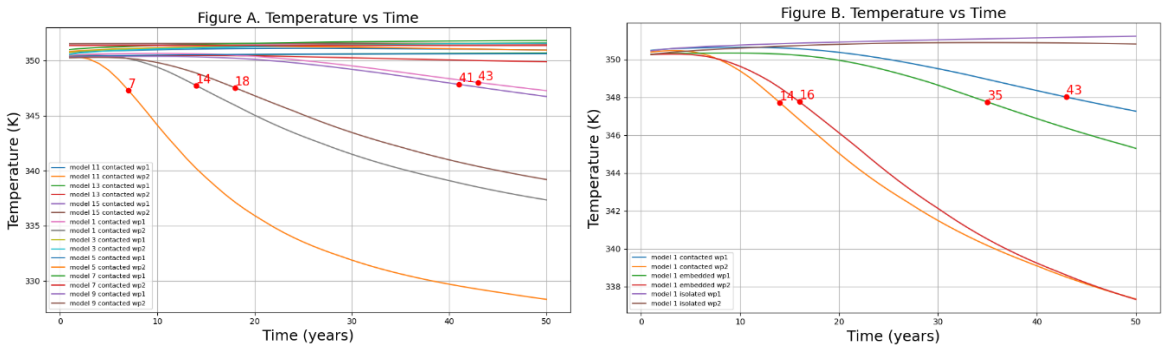


Figure 1.A. Temperature at production well for all models with a consistent aggradation and the two standardised well placements. 1.B Temperature at production well varied by well placement and aggradation effects. Red numbers indicate system lifetime.

An initial screening study occurred to see if a standardised well placement for all models resulted in thermal breakthrough (Figure 1.A). In a number of models, breakthrough does not occur in either the parallel (WP1) or perpendicular (WP2) to paleoflow direction. This occurs when the production or injection well is not placed within a sandbody, resulting in limited connectivity between wells; such connectivity is essential for effective resource management and pressure maintenance (Willems et al., 2017a). This standardised well placement resulted in biasing the migration of the cold plume, with breakthrough occurring where the wells are placed in a sandbody.

For an economically-productive geothermal reservoir, well pairs must enter into a sandbody, and these sandbodies must be connected. Reservoirs with a higher frequency of sandbodies and higher sinuosity (consistent with that of a lower delta plain environment), exhibit a much higher chance of successfully intersecting a sandbody, and thus connected flow paths between wells.

3.1 Aggradation and well placement

The key sedimentological or architectural feature in a lower delta plain which influences flow behaviour in a reservoir is different aggradation styles and the resulting vertical connectivity. The degree to which aggradation influences the system is relative to the well placement. Figure 1.B shows results from a suite of realisations where architectural elements A (W/T = 1:20), B (high sinuosity index) and C (high channel frequency) remain consistent, whilst D and E are varied between settings (Table 1). No aggradation (isolated sandbodies) results in no connectivity between wells, regardless of well orientation, whilst increased levels of aggradation (contacted and embedded) show increased vertical connectivity and a strong influence on flow behaviour. The degree to which aggradation affects system lifetime varies between well placement relative to paleoflow direction. For WP2 the amount of aggradation (contacted or embedded) has a small impact on system lifetime (14 vs. 16 years, Δ2 years), whereas for WP1, the amount of aggradation has a larger impact on system lifetime (35 vs. 43 years; Δ8 years).

Well placement parallel to paleoflow direction (WP2) results in the shortest system lifetime. When wells are aligned parallel to paleoflow (WP2), and sandbodies are either contacted or embedded, they create preferential flow pathways (‘highways’), resulting in rapid migration of the cold plume to the production well. Aggradation has a small influence on system lifetime (14 vs. 16 years, Δ2 years), with contacted models resulting in the shortest system lifetime. This is due to a decrease in reservoir volume, increasing pressure and therefore increasing the migration time of the cold plume. Conversely, paleoflow-perpendicular well placement (WP1) has a more complex fluid pathway and has an increased system lifetime (35 vs. 43 years; Δ8 years) as the cold plume migrates slower.

The degree of influence of aggradation is dictated by the well placement relative to paleoflow. Therefore, during the exploration phase of a project, it is most important to characterise the paleoflow direction and adjust well placement accordingly.

3.2 Future work

This study examined a small range of influential features found in fluvio-deltaic environments with limited response metrics. Next, we will investigate the impact of smaller heterogeneities, as well as the impact of fractures. The response metrics will be expanded to investigate cold plume volume and extent, to further examine the influence on fluvial architectural models on the migration of the cold plume within the reservoir.

The two well placements selected in this study were standardised for all models. This standardised well placement resulted in biasing the migration of the cold plume, with breakthrough occurring in models where the wells were placed in a sandbody. Future studies will consider a third well placement to understand the plume migration when wells are explicitly placed in the sandbody.

4 CONCLUSION

This study investigated the impact of key sedimentological and architectural features inherent to fluvial deltaic sedimentary reservoirs on the performance of low enthalpy geothermal systems. Our results demonstrate that:

1) For economically-productive geothermal heat production from a sedimentary aquifer, a doublet well pair must show connectivity through communicating sandbodies. The chance of a doublet well pair intersecting a sandbody is increased through higher sandbody frequency and higher sinuosity, but the most influential sedimentological or architectural feature controlling well connectivity is vertical connectivity as a result of different aggradation styles.
2) Well placement relative to paleoflow has the greatest impact on system lifetime. Well doublets which are placed parallel to paleoflow have decreased system lifetimes, and therefore decreased economic performance. When wells are placed perpendicular to paleoflow, aggradation controls the system lifetime. The effect of aggradation becomes more pronounced in systems which are perpendicular to paleoflow, with the degree of aggradation controlling the system lifetime.

The full DGSA will show a comprehensive analysis of all relationships, determining which sedimentological or architectural feature has significant control across all realisations. Understanding which sedimentological or architectural feature has the greatest control of fluid flow within a reservoir will enable the prioritisation of features requiring constraint during exploration. Further research will investigate what industry standard exploration techniques and novel exploration tools developed within the FindHeat project can constrain the geological uncertainty.

Acknowledgements

This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement N°101147171. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or Smart Networks and Services Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them. We also acknowledge financial support from the Swiss National Science Foundation, UK Research and Innovation, the TU Delft Excellence Foundation, and Energi Simulation.

ChatGPT (OpenAI) and Claude (Anthropic), were used to support both writing and coding tasks during the development of this abstract. All AI-generated content was reviewed, verified, and modified as needed to ensure accuracy and alignment with the research objectives. We assume full responsibility for the content and conclusions presented.

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