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DOI
10.3997/2214-4609.2025101348

Publication date
2025

Document Version
Final published version

Citation (APA)
Gesbert, B., Geiger, S., Verschuur, E., Abels, H., & Song, G. (2025). *Insights from Integrated Geological and Seismic Modelling of Fluvial Geothermal Reservoirs*. Paper presented at 86th EAGE Annual Conference & Exhibition 2025 , Toulouse, France. https://doi.org/10.3997/2214-4609.2025101348

Insights from integrated geological and seismic modelling of fluvial geothermal reservoirs

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Summary

Fluvial reservoirs are a major target for geothermal energy production. Interpreting the 3D reservoir architectures from 2D seismic datasets, which usually are acquired for geothermal systems, is difficult. In particular, small-scale geological factors like sandbody connectivity are challenging to resolve. This study addresses these issues through a novel workflow that incorporates 3D geological and 2D seismic modelling methods to assess the seismic responses of stratigraphic attributes in fluvial geothermal reservoirs where data availability is low.

Two synthetic fluvial reservoir scenarios were built, ranging from a single channelised deposit to a geologically more plausible model ensemble of fluvial deposits, which represents the reservoir heterogeneities that could be present at the geothermal doublet at Delft University of Technology. Acoustic finite-difference modelling was combined with seismic imaging to create 2D depth images. Our results reveal how seismic resolution determines our ability to correctly identify sandbody connectivity and capture inner channel details. Whereas channel bodies can be detected, the best frequency spectra for observing certain geological features remain unclear. These findings emphasise that quantitative multi-scale analysis, advanced imaging techniques, and survey design optimisation are central to improving seismic characterisation of fluvial geothermal systems in future research.

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Introduction

Geothermal exploration of fluvial reservoirs is critical to a successful energy transition as they host many geothermal plays. Fluvial deposits are characterised in terms of sandbody connectivity, which is controlled by stratigraphic aspects like channel sinuosity, stacking-patterns and mud-plugs (Larue & Hovadik, 2006; Aghaei et al., 2024). However, seismic interpretation of these channelised attributes is difficult, especially in geothermal projects where budget constraints often restrict data acquisition to 2D seismic surveys (Schulte et al., 2020; Rehling et al., 2023). 2D seismic data typically lack sedimentary information from map view (e.g., on planform geometry) needed to identify geological features from cross-sectional view (Posamentier et al., 2022). Moreover, fluvial channel fills commonly occur below seismic resolution. Nonetheless, the effects of small-scale stratigraphic heterogeneities (e.g., basal lags and mudstone drapes) on heat transfer in fluvial systems are likely modest (Aghaei et al., 2024), suggesting that reservoir performance can still be predicted reliably under significant geological uncertainty.

We propose a new simulation strategy that integrates state-of-the-art geological and geophysical modelling methods for robust 2D seismic characterisation of fluvial systems in data-poor geothermal applications. Based on the Rapid Reservoir Modelling tool (Jacquemyn et al., 2021), we construct different 3D channelised reservoir scenarios with varying degrees of geological complexity. Depth slices from these models are subsequently used in a seismic forward-modelling and imaging workflow to examine the sensitivity of synthetic 2D seismic images to depositional geometries.

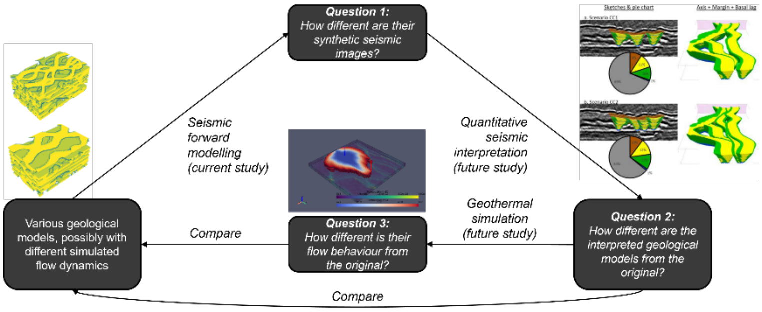


Figure 1. *Workflow and key questions of our seismic reservoir characterisation approach for fluvial geothermal systems, which combines advanced geological, geophysical, and reservoir modelling techniques for exploring how reservoir heterogeneities influence seismic resolution and reservoir dynamics.*

Importantly, simulated fluvial reservoir architectures can be conditioned on real data, such as well-logs and cores from a geothermal well doublet that has recently been drilled by the “Geothermie Delft” consortium at the Delft University of Technology campus, reaching the targeted Delft Sandstone formation at a depth of just over two kilometres (Vardon et al., 2024; Voskov et al., 2024). With direct relevance to the Geothermal Delft well doublet, our study provides the foundation for qualitative and quantitative analyses of multi-scale and hierarchical stratigraphic uncertainties from synthetic seismic images of channelised fluvial reservoir models (Figure 1). This integrated seismic reservoir characterisation framework is a multidisciplinary effort to mitigate risks in geothermal developments more efficiently by better aligning the expertise of geologists, geophysicists, and reservoir engineers.

Rapid Reservoir Modelling

The lack of comprehensive datasets for various geothermal reservoirs implies that a wide range of reservoir scenarios needs to be investigated to evaluate how geological uncertainties may impact reservoir behaviour. For quick and intuitive reservoir modelling, we utilise the open-source Rapid Reservoir Modelling software (RRM; Jacquemyn et al., 2021). RRM is tailored for testing geological concepts in data-deficient environments by creating geologically reasonable 3D models from 2D sketches in a matter of minutes (Figure 2).

Using RRM, models reflecting different stratigraphic heterogeneities for low-enthalpy geothermal systems have been effectively designed and screened (Baird et al., 2024; Song et al., 2024). Song et al. (2024) have streamlined RRM for modelling complex fluvial geothermal reservoir scenarios by creating layer templates of fluvial sediments (Figure 2) that can be combined probabilistically (Figure 3b) while honouring Net-to-Gross or facies constraints from well-logs or cores. We use the models from Song et al. (2024) as they are directly applicable to the Geothermie Delft well doublet.

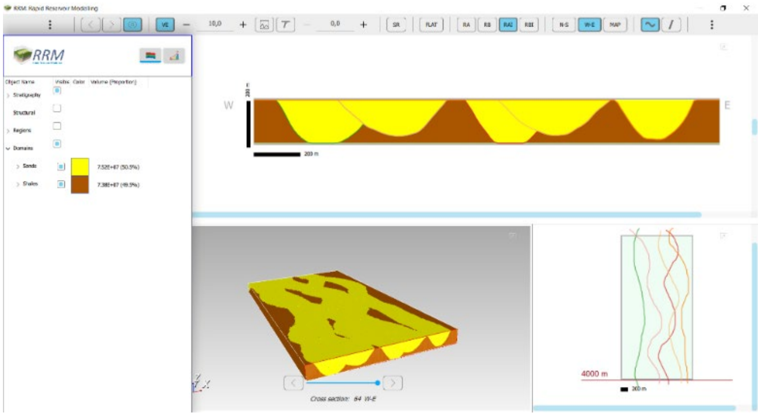
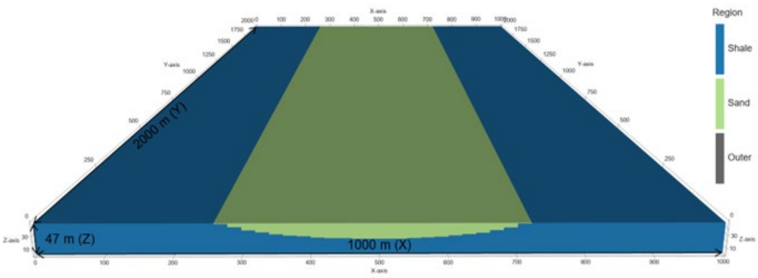


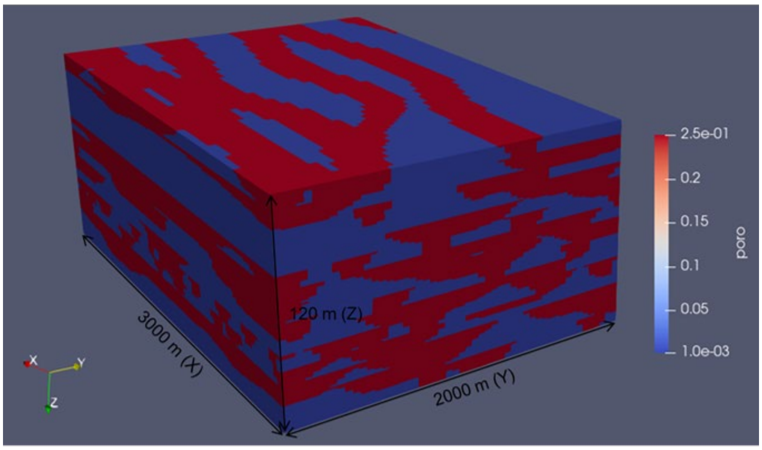
Figure 2. Screenshot of the RRM interface. The sketched model depicts a single layer of a channelised reservoir.

Seismic forward-modelling and imaging

We produce 2D seismic images of fluvial geothermal reservoir models by employing acoustic finite-difference modelling and pre-stack depth migration (Thorbecke et al., 2004; Thorbecke & Draganov, 2011). An RRM model is build (Figure 2) and discretised into a 3D grid (Figure 3a). Facies-specific acoustic parameters are then assigned to extracted 2D depth slices. An overburden and underburden is added to model subsurface and wave-propagation conditions correctly. Active seismic sources and receivers are evenly distributed along the surface to ensure full target illumination. The final seismic image is obtained by summing images from all sources. In this exercise, note that one degree of freedom is the chosen frequency content of the seismic source, and with that the finite-difference grid spacing.



(a)



(b)

***Figure 3.** Two distinct fluvial sand-shale reservoir scenarios: (a) an highly idealised RRM model sampled on a 3D grid in RRM; (b) a geologically more plausible model where channel templates drawn in RRM have been stacked, with red and blue denoting sandstone and shale, respectively.*

Results and discussion

The 2D seismic forward-modelling and imaging procedure is applied to the synthetic sand-shale reservoir scenarios from Figure 3 to explore the effects of opposite extremes of geological complexity on seismic resolution. Figures 4 and 5 show synthetic seismic profiles for a density parameterisation of 2600, 2500, 2000, 1700 and 1000 kg/m^3 as well as a P-wave velocity parameterisation of 3000, 2500, 2300, 2000 and 1500 m/s, which belong to the shale and sandstone in the reservoir and the three overburden layers, respectively. We choose the underburden of the simple reservoir to be a shale layer, and the acoustic parameters of the complex reservoir's underburden as the average of the shale and sandstone values. Source and receiver positions are separated with a 100- and 10-metre spacing, respectively. The finite-difference grid spacing is set to 2.5 metres for an acceptable fit of the two stratigraphic models, having originally been sampled on a 20- (X) by 1000- (Y) by 1.010-metres (Z) grid for the simple model, and a 40 by 40 by 1 metre(s) grid for the complex model.

To investigate if seismic resolution can be enhanced, the finite-difference spacing is refined to 1.0 metre and the source-wavelet's maximum frequency is increased from 100 to 200 Hz such that a broader frequency spectrum can be absorbed on the finer grid. Figure 6 illustrates the resulting variation in illumination for the target reservoir part. For example, one particular channel deposit from the complex model seems to become more visible as a consequence of the denser finite-difference sampling and higher peak frequency. Although it can be argued that the 200-Hz image is sharpest (Figure 6c), it remains uncertain which image adheres most to the underlying geological attributes based on visual inspection alone. Hence, our seismic sensitivity analysis may benefit from a multi-scale approach, with varying frequencies possibly revealing different stratigraphic features.

Nevertheless, the limited seismic resolution is evident. For instance, the inner channel information near the channel edges tends to fall below seismic resolution, as indicated by

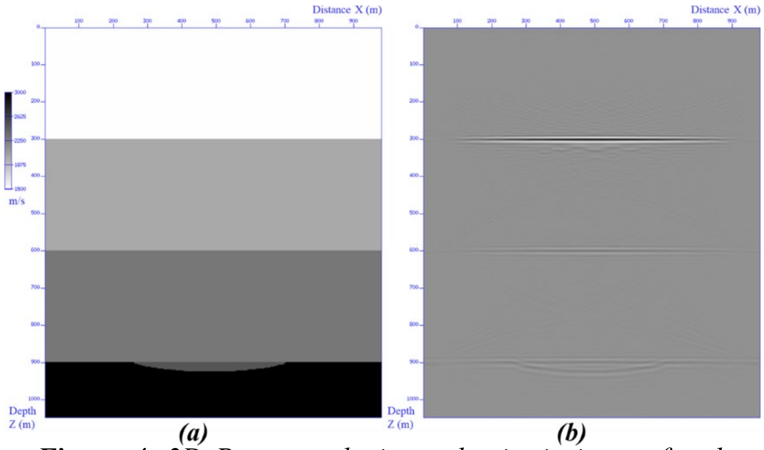


Figure 4. *2D P-wave velocity and seismic image for the simple model embedded between an over- and underburden. The grid resolution and maximum frequency are 1.0 metres and 200 Hz, respectively.*

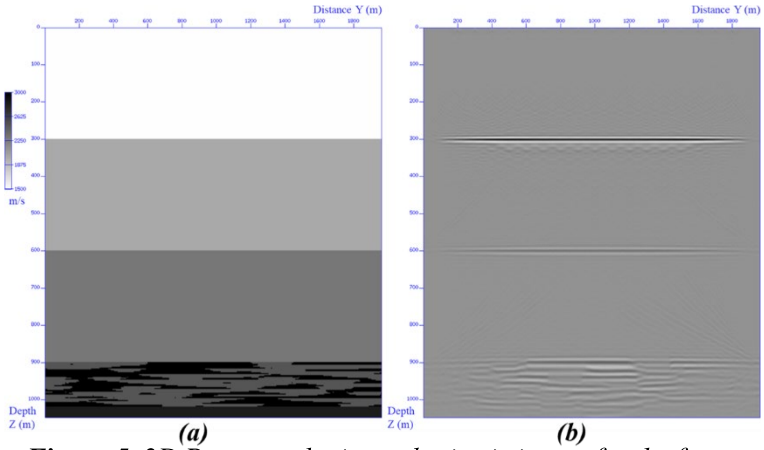


Figure 5. *2D P-wave velocity and seismic image for the front-side slice (X=0) of the complex model embedded between an over- and underburden. The grid resolution and maximum frequency are 1.0 metres and 200 Hz, respectively.*

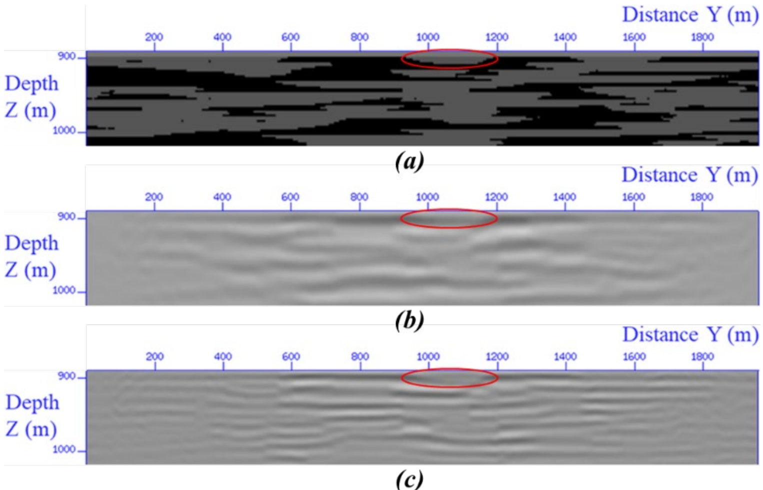


Figure 6. *Experiment demonstrating the impact of the finite-difference grid resolution and frequency range on seismic resolution for a central slice (X=1500) and channel body from the complex model: (a) reference velocity model; (b) 2.5m-grid spacing and 100-Hz peak frequency; (c) 1.0m-grid spacing and 200-Hz peak frequency.*

the simple reservoir's image (Figure 4b). The issue is also visible for the sandbody connectivity in the complex reservoir, where strong continuous reflectors may be misinterpreted as connected sandbodies and the images are locally obscured, especially close to the left and right model edges (Figures 4b, 5b, 6c). In addition, note the artificial wave patterns underneath the 300-metre deep overburden interface (Figures 4b, 5b). Given the variability that is observed even for these two models, further experiments with more realistic overburden scenarios, carefully designed survey geometries, and high-resolution imaging algorithms are crucial to improve seismic resolution and advance our characterisation of the geological structures of the Delft Sandstone, which hosts the Geothermie Delft well doublet below the Delft University of Technology campus and a series of other doublets in the region.

Conclusions

Our paper highlights challenges in characterising fluvial geothermal systems using seismic forward-modelling and imaging. By integrating geological modelling, finite-difference modelling, and depth migration into an innovative workflow, we demonstrated how seismic resolution is affected by channelised deposits and survey parameters. Simulated 2D seismic images, representative of the generally sparse data acquisition in geothermal projects, display significant limitations in resolving stratigraphic details. This problem underscores the necessity of quantifying geological uncertainties in fluvial geothermal reservoirs, being an important next step for developing our seismic reservoir characterisation methodology.

Acknowledgements

We thank the sponsors of the Delphi Consortium, the TU Delft Excellence Foundation, and Energi Simulation for their support.

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