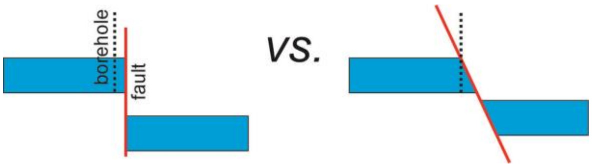
Dear Reviewer,
Thank you very much for your careful review of the manuscript and helpful comments. Authors appreciate your insights and suggestions, which have helped us to improve the quality of the work. All the comments are addressed below and a new version of the manuscript with track changes is uploaded.

The current manuscript is about an automated workflow between structural geological models and physics-based numerical models for evaluating structural uncertainties in HT-ATES. This workflow is tested on 2 examples: an example with variable reservoir thickness and an example of a wedging reservoir with a sealing fault zone. Of course, an automated workflow is of great importance for mesh-based simulations, as re-meshing can be avoided. Nevertheless, the applications should be chosen so that they are not just a proof of concept but can also be used for more sophisticated uncertainty analyses. In the applications presented, a variation in the thickness and position of a sealing vertical fault zone within a thinning geological layer was evaluated. This is a good start but currently seems to be the limit of the method used. Furthermore, only 3 cases were calculated for the first reservoir and only 17 cases for the 2nd reservoir, which is the lower limit for an uncertainty analysis. The content of the manuscript is adequate for GMD, but major corrections are required in order to accept the manuscript.

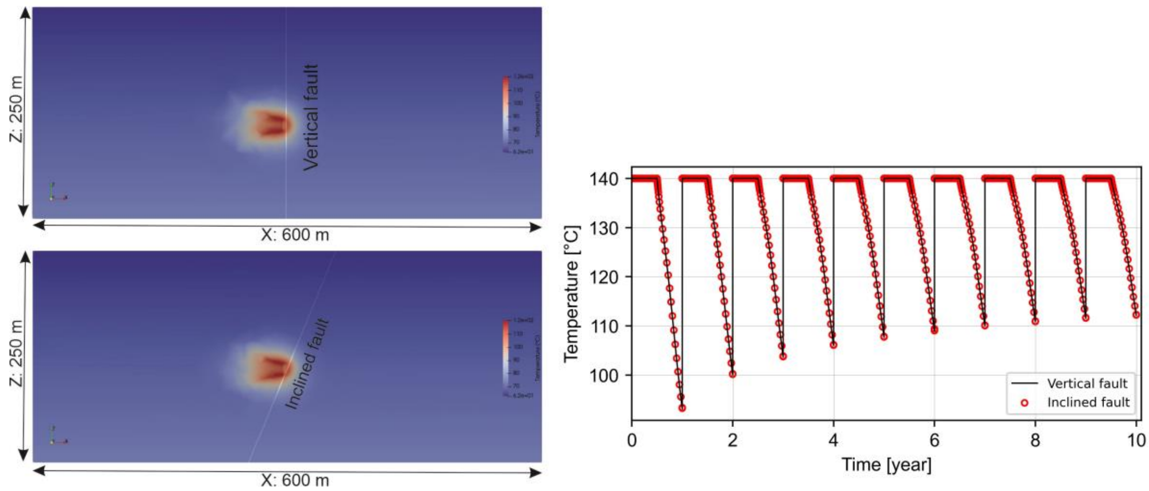
General Reply

The remarks were on two principal aspects:
A) Where are the limitations of the method,
B) There are too few models to perform an uncertainty analysis
The manuscript has now been updated based on the comments of the reviewer. First, we detail these major remarks in a rather general reply:

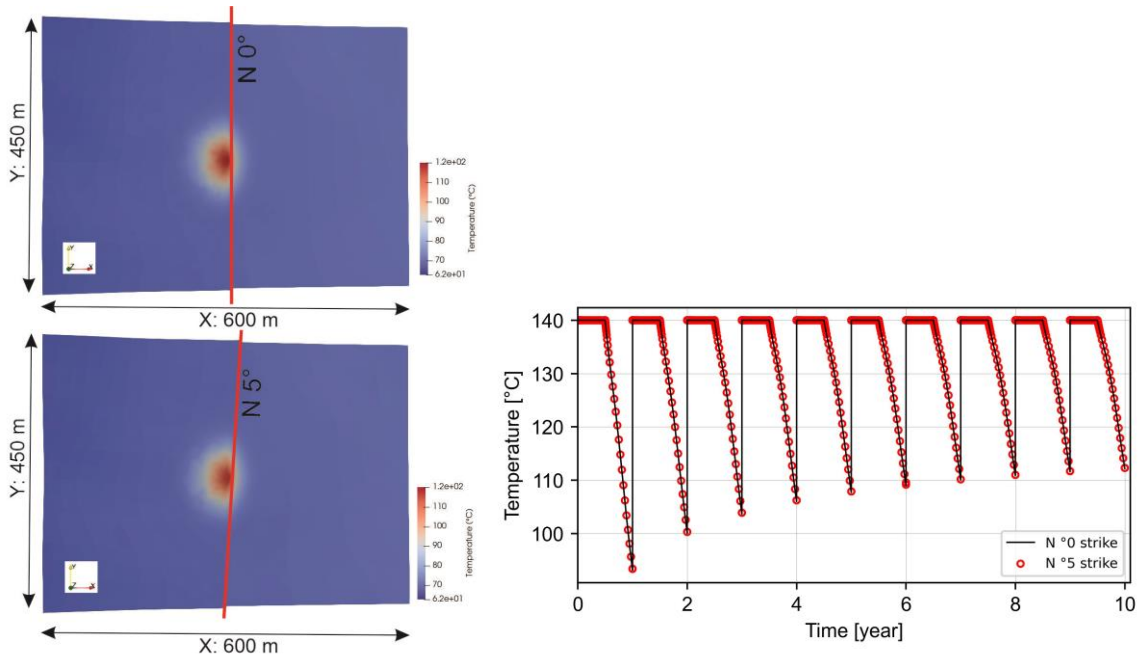
A) The methodology developed has some inherent limitations. As such, a structural variation can only be performed on existing grid points, i.e. vertices (Figure 4) and the fault has to be vertical with a fixed N-S strike (Figure 4). Otherwise, our method offers a high flexibility, on the definition of the surfaces of the aquifer (morphology, dip, and variable thickness) as well as on the location of the (vertical) fault. Applying this method for thermohydraulic calculations offers a high variation of simulations.
It may be noted that the impact of a lower dip angle is rather negligible for layers with defined thickness (e.g. even a 45° dip angle would increase only the apparent near field transmissivity by a factor of 1.4, but the far field transmissivity remains unaffected). The following cartoon illustrates this simplification:



For the sake of comparison, two new special fault models including a fault of 67° dipping angle or ± 5° strike angle have been elaborated and tested against the existing vertical scenario. The comparison was made on the example of the vertical fault in Chapter 3.2 (i.e. fault located 4 m in the east of the well). The following figures show the results in two cases that look almost the same:



Comparison of vertical to 67° inclined fault: figures (left: contour plot of temperature after 10 years i.e. the last production cycle, right: well temperature over time) show a nearly perfect agreement of both cases, i.e. vertical versus inclined fault.

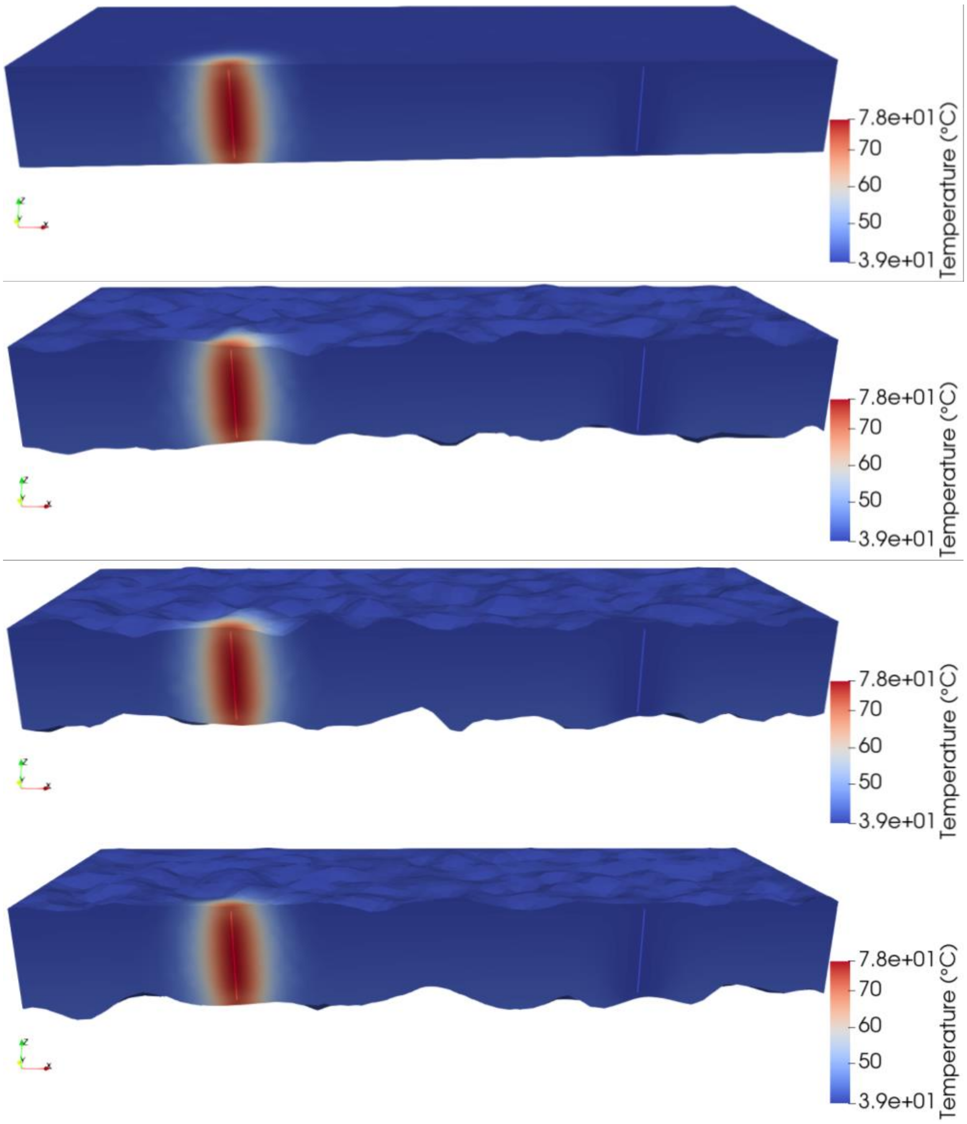


Comparison of vertical to ±5° deviated fault: figures (left: contour plot of temperature after 10 years i.e. the last production cycle, right: well temperature over time) show a nearly perfect agreement of both cases, i.e. N 0° versus N 5° fault.

Corresponding clarifications regarding the limitations of the method are added to Chapter 2.2 of the manuscript.

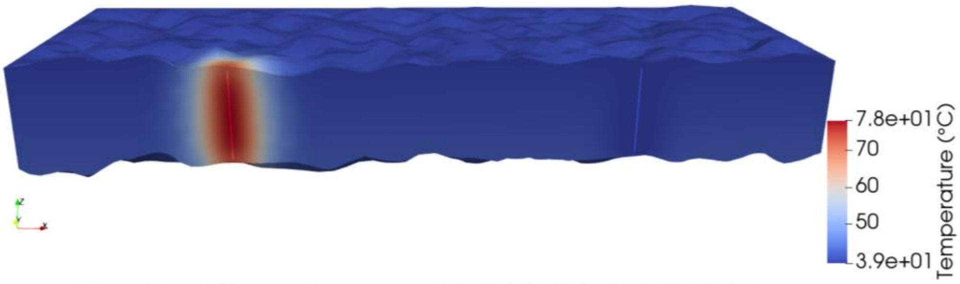
B) The following provides an example of the unlimited application of the code regarding the number of scenarios for the Greater Geneva Basin (GGB). The final resulting storage capacity (temperature production) does not vary and was therefore not presented in the manuscript. For further illustration, we uploaded examples of 101 surfaces ready to be meshed and - due to file storage restrictions - accordingly 14 meshes in Zenodo[1] as well as in Github[2]. Easily, more examples could also be calculated using the uploaded scripts.

In the manuscript, we generated the arbitrary (generic) geometries by adapting the top and bottom surfaces of the reservoir. Out of 11 simulations, three had been presented in the manuscript. As discussed the reservoir performance is independent of the considered uncertainty on that scale. This result is later used in Chapter 4.1 to design an efficient exploration campaign for cases similar to GGB. The following illustrates this statement for 11 scenarios on behalf of the temperature field (after 10 years, i.e. the last production cycle) in the Malm reservoir. The different reservoir geometries are visible by their surface topographies, but they do not have any impact on the temperature field:



[1] https://zenodo.org/records/10256834

[2] https://github.com/Ali1990dashti/GeoMeshPy/tree/main/Examples/Storage_Models/GGB_Case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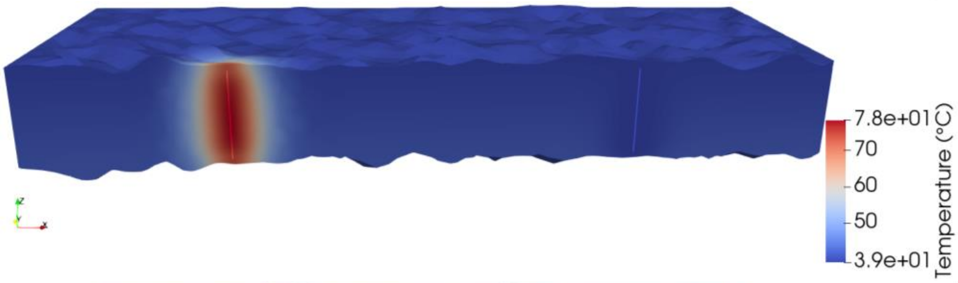
Temperature (°C)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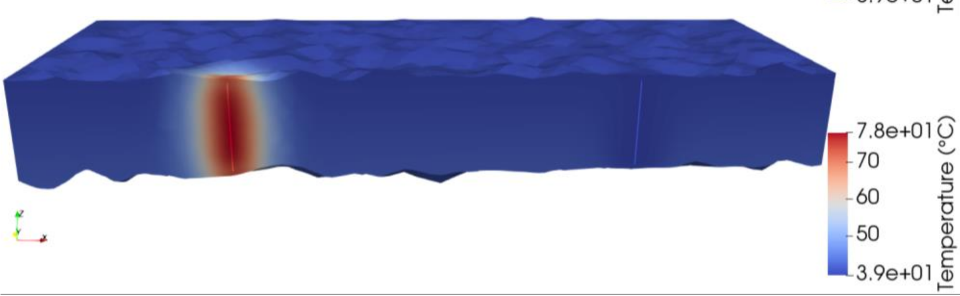
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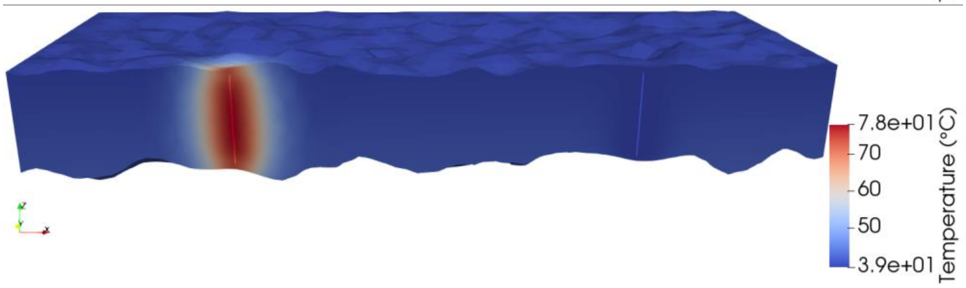
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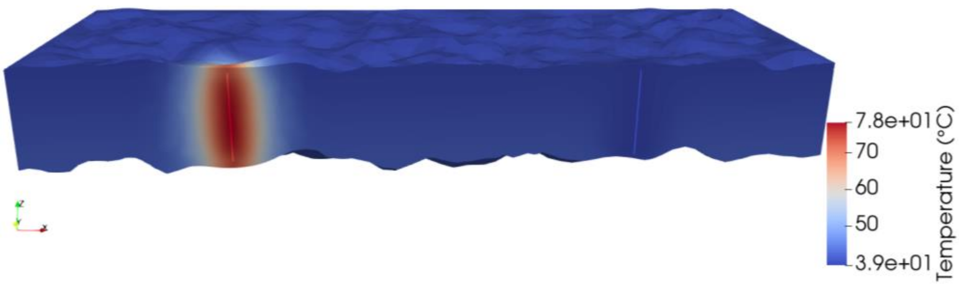
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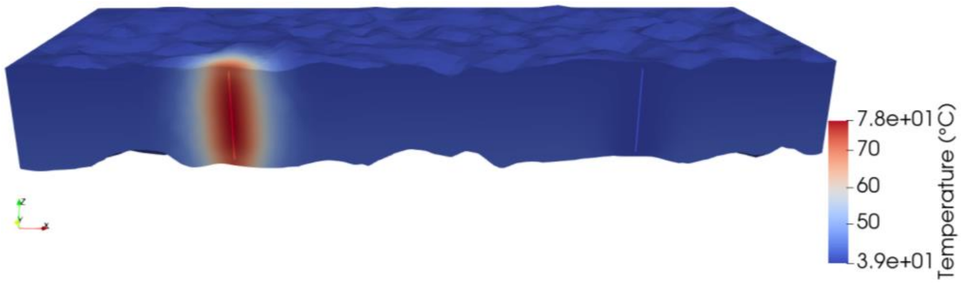


Corresponding clarifications are added to Chapter 3.1 of the manuscript.

Detailed reply to individual questions

P1L19: What does "thick" reservoir mean. There is a noise function on the top and bottom surfaces which alters the reservoir thickness and it should be described that way.

The original term "thick" was ambiguous and has been clarified in the revised manuscript. In the GGB case, the reservoir has a varying thickness, which was initially set to be of uniform 100 m thickness. Our methodology applied a thickness variation of up to 25 %. In the DeepStor case, the reservoir remained uniform with a 10 m thickness.

The text in the abstract is changed to be:

"Developed meshing workflow is applied to two case studies: 1) Greater Geneva Basin with the Upper Jurassic ("Malm") limestone reservoir and 2) the 5° eastward tilted DeepStor sandstone reservoir in the Upper Rhine Graben with a uniform thickness of 10 m. In the Greater Geneva Basin example, the top and bottom surfaces of the reservoir are randomly varied ± 10 m and ± 15 m, generating a total variation of up to 25 % from the initially considered 100 m reservoir thickness."

P1L23: The uncertainty analysis was carried out over a range of 4 m to 118 m for the distance from the fault zone to the well. What is the basis for this range. There is no information whether this comes from the thermal radius of the storage cycles or from geological modeling.

The 4 m to 112 m range is chosen to evaluate the effect of the fault on the heat distribution and also examine the possible relation between the location of the fault and pressure response at the well's location. These points are added to the manuscript. Limitations for the location of the fault are also added to Chapter 2.2 of the manuscript.

Abstract: It is not clear, what is the motivation and the scientific question that is to be answered. It appears that the main consideration is the thickness variation due to some random noise functions and the distance of a sealing fault zone from the wellbore. It seems that the presented approach is limited here for a vertical fault zone with an offset greater than the reservoir thickness. Only in this way the fault zone could be implemented as a hydraulic barrier. What natural scenario is this assumption based on? Does this approach work for inclined faults with less offset and acting as barrier or pre-dominant flow-path, too?

The abstract is re-written. Limitations of the method are also addressed in the new version of the manuscript.

P2L35: ATES characterization using push-pull tests are described in: "Best practices for characterization of High Temperature-Aquifer Thermal Energy Storage (HT-ATES) potential using well tests in Berlin (Germany) as an example, Geothermics, Volume 116, 2024, 102830, ISSN 0375-6505, https://doi.org/10.1016/j.geothermics.2023.102830."

This recently published work is added to the text.

P2L45: (e.g., well configuration, transmissivity, flow rate, conductivity, …) → (e.g., well configuration, transmissivity, flow rate, and conductivity)

The text is updated.

P3L64: "…transfers stochastic structures from geological uncertainty models to a fast and reliable numerical meshing tool…". No geological uncertainty model was described or presented in the present study. How should the scientific community evaluate whether the transformation of a geological model into a numerical model is possible using the presented approach? Here a new mesh is generated and not an existing model is transferred.

The text is updated to be:
"This study expands the application presented in Dashti et al. (2023) by introducing an automated workflow that generates meshes for complex structural models, enabling the quantification of relevant processes in HT-ATES."

P3L85: "…flow rates of <0.5 l/s…". Flowrates should be related the pressure responses. It is not clear if the provided value a design parameter or a limitation by the reservoir performance or submersible pump?

This value comes from the literature, i.e. Guglielmetti et al. (2022), highlighting the low transmissivity of the reservoir in that specific location.
A new sentence is added to the text:
"The flow rate has also been low due to the reservoir's characteristics in that specific location."
Guglielmetti, L., Heidinger, M., Eichinger, F., and Moscariello, A.: Hydrochemical Characterization of Groundwaters' Fluid Flow through the Upper Mesozoic Carbonate Geothermal Reservoirs in the Geneva Basin: An Evolution more than 15,000 Years Long, Energies, 15, 3497, https://doi.org/10.3390/en15103497, 2022.

P4L97: "To perturb the geological model, a randomized noise is superimposed on the top and bottom surfaces of the reservoir layer." But it is not clear which conceptional geological model is responsible for such a noise function. What would be the geological process behind?

The presented work primarily aims to demonstrate that the developed script can generate various complex meshes for the GGB while the source of uncertainty remains generic. Collignon et al. (2020) investigated a storage case for the Malm reservoir with a uniform 100 m thickness represented as a box with flat surfaces. In contrast, our study modifies the top and bottom surfaces of the reservoir in a way to make complex and more realistic geometries for the reservoir. The developed workflow for this instance remains entirely independent of uncertainty. Any type of noise (error) can be superimposed on the initial model with flat top and bottom surfaces. The 2D section in Figure 1-a presents the concept of superposed generic uncertainty. Chapter 2.1 has also been modified accordingly.

Collignon, M., Klemetsdal, Ø. S., Møyner, O., Alcanié, M., Rinaldi, A. P., Nilsen, H., and Lupi, M.: Evaluating thermal losses and storage capacity in high-temperature aquifer thermal energy storage (HT-ATES) systems with well operating limits: insights from a study-case in the Greater Geneva Basin, Switzerland, Geothermics, 85, 101773, https://doi.org/10.1016/j.geothermics.2019.101773, 2020.

P4L100: "For the bottom surface, the range of perturbation is increased to ± 15 m due to the decrease in the quality of seismic data with depth." Again, what is the basis or measurement for assuming that magnitude and distribution of noise? It seems to be a random number.

Publications like Stamm et al. (2019) and Lüschen et al. (2011) have been considered to choose these two ranges. Chapter 2.1 is modified in a way to present the reasoning behind the noise values more clearly.

Stamm, Fabian Antonio, Miguel de la Varga, and Florian Wellmann. "Actors, actions, and uncertainties: optimizing decision-making based on 3-D structural geological models." Solid Earth 10.6 (2019): 2015-2043.

Lüschen, E., Dussel, M., Thomas, R., & Schulz, R. (2011). 3D seismic survey for geothermal exploration at Unterhaching, Munich, Germany. First Break, 29(1).

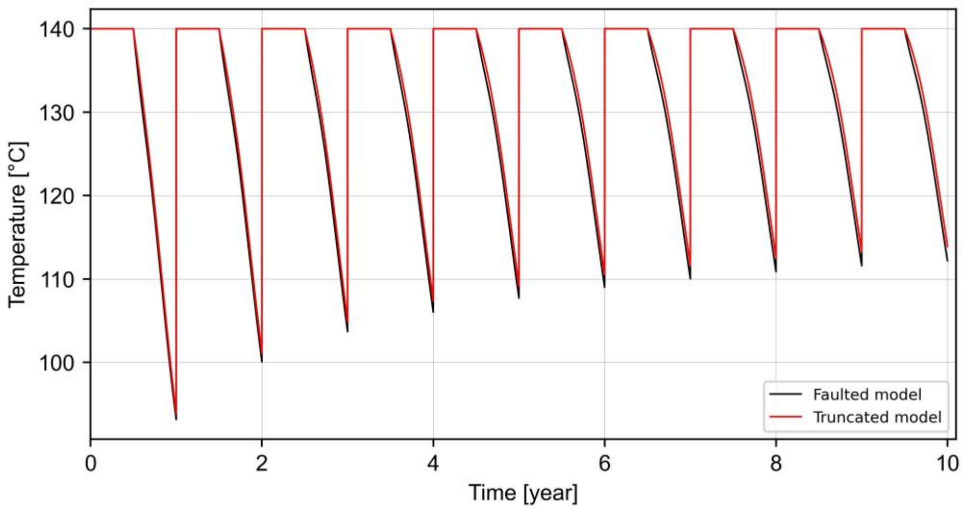
P5L127: A normal fault with a vertical offset of more than the reservoir thickness is presented. Main question is, what is the stress state to generate a normal faulting with such an offset? Generally, normal faults dip with 40 to 70 degree.

(See general comments above)

Another noteworthy point: when altering the dipping angle, a fault could be detected in a nearby well in close proximity to the fault.

P6L145: The sealing fault is represented by an offset exceeding the thickness of the aquifer. To mimic the sealing fault this could even be done by truncating the model at a designated distance. I believe it is worth to check if a truncated model (at the distance of the sealing fault) would provide the same result as the model with fault offset. This could be a discussion point.

Thank you for bringing up this interesting point. Truncating the model can lead to higher temperature values within the model. As shown in Figure 8-b, heat diffusion occurs through the fault plane, potentially influencing the overall temperature distribution. Additionally, truncating the model may introduce boundary effects that could impact the thermal and hydraulic performance of the system during injection/production operations. We investigated this approach for one of the cases and examined the performance difference between a model with a fault located 4 m east of the well and a truncated model. As evident in the following figure, the truncated model exhibits a higher efficiency compared to the faulted model.



Therefore, we did not change the modelling approach on this point.

P6L149: It is still unclear if the fault itself is sealing or the offset greater than the thickness of the reservoir generates the sealing feature. I assume that the second case is the one discussed/represented in the study. Otherwise the question arises, how a sealing fault is implemented in the FEM. Is the permeability of the fault set to zero? Is flow perpendicular to the fault possible (fault is transparent to flow)?

The offset is creating a sealing. The text is updated:
"This pessimistic assumption enables the prediction of the worst case scenarios for the storage in which a sealing fault completely blocks the reservoir by juxtaposing the reservoir against impermeable matrix."

P6L151. Ones more, the normal fault is represented as vertical fault. Is this a limitation of the method? How dip and dip-direction are quantified. If no quantification was made, dip and dip-direction should be analyzed in the uncertainty study.

(See general comments above).
A clarification was added to the manuscript in Chapter 2.2 to explicitly address the limitations of the proposed method:
"The grid resolution in the x direction (14 m in the available DeepStor model) determines the fault location. The workflow is designed to incorporate only N-S striking vertical faults that pass through existing grid points. This is the first limitation of the developed method. For this study, only the barrier effect is relevant and minor changes in the strike direction will not impact the numerical results. Another limitation is the dip angle of the arbitrary fault. For simplicity, the developed script includes a vertical normal fault. For the DeepStor reservoir with a uniform 10 m thickness a change in dip of the sealing fault will have a negligible impact on the simulation results. Even a 45° dip angle would increase only the apparent near field transmissivity by a factor of 1.4, while the far field transmissivity remains unaffected. Additionally, a vertical fault cannot be detected by a planned vertical well, i.e. the well trajectory may intersect the inclined fault."

This point has been added as an outlook to the manuscript:

“Adding new functionalities to the developed Python script can also enable a more comprehensive uncertainty analysis by perturbing the strike and dipping angle of the sub-seismic fault.”

P6L152-155: As mentioned before only few scenarios were considered for this uncertainty analyses. One advantage of the automatized workflow should be the performance. Why not thousands of simulations were performed for varying distances, strike directions and dip angles?

Figure 4 and its accompanying text in Chapter 2.2 provide detailed explanations of how we incorporated the fault into the base case, displaced the reservoir layer, and split the top and bottom surfaces of the reservoir. Regarding the fault location, we were constrained by the grid resolution in the x direction (14 meters in the existing DeepStor model), which determined the locations where the fault could be positioned. The updated text accompanying Figure 4 addresses these limitations. Additionally, the maximum distance was determined based on the thermal and hydraulic radii. Beyond 118 m, the fault has minimal impact on the hydraulic response of the system at the well location.

P11L253: Moose is updated frequently. Therefore, TIGER should be maintained. By my knowledge this is not the case any longer. Therefore, future use of TIGER and the reproducibility of the presented simulations maybe questionable? Maybe the perspective or alternatives like GOLEM (Cacace, M. and Jacquey, A. B.: Flexible parallel implicit modelling of coupled thermal–hydraulic–mechanical processes in fractured rocks, Solid Earth, 8, 921-941, https://doi.org/10.5194/se-8-921-2017, 2017.) should be mentioned as well.

The simulations can be reproduced by GOLEM or available modules of MOOSE like Porous Flow.
The text is updated to make this point clear:
“To reproduce the results, other MOOSE based applications like GOLEM (Cacace and Jacquey, 2017) or available modules of MOOSE, e.g. Porous Flow (Wilkins et al., 2021), can be used.”

P12L282: How do you deactivate the temperature BC for production scenarios? Temperature BC should be assigned for injection mode. For production mode these BC should be deactivated. Was this deactivation considered, if so it should be described shortly.

A control system is implemented to switch the temperature BC. We can define a set of time intervals: from 0 to 6 months the system should be in the injection mode and from 6 to 12 months in production. Then, a temperature BC will be defined for the target nodes. Now, the switch will look into the time interval and in case of being in the first part (injection phase), the temperature BC will activate, otherwise (6 to 12 months) it won’t.
The updated text will have this new information in Chapter 2.4:
“The MOOSE control system dynamically updates the temperature boundary condition (BC) during the simulation. In the injection phase, the temperature BC is applied to the corresponding nodes in the model, either set to 90 °C or 39 °C. During the production phase, the temperature BC is deactivated.”

P13L310: If no boundaries are defined in general a no flow boundary is the default assignment. I wonder if Tiger would deal differently. Therefore, I suggest to check if the lateral borders are open to flow or no-flow boundaries.

Thanks for this hint. Unfortunately, the wrong terminology has been chosen. It is corrected now. No flow BC which acts like Neumann BC with 0 value have been used. The text is updated: "No flow BCs are considered for side faces of the models."

Figure6: What is the reason for an injection temperature of 39C and not of 40C as the reservoir temperature?

For this case the work of Collignon et al. (2020) is followed.

P15L341: "Despite the negligible difference, the case with a fault located 48 m in the west of the well has the best performance…". Yes, but it seems the in a distance of 45 m and more the fault has no influence anymore. It seems that the thermal radius/plume has a radius of approximately 45 m. An explanation is missing why a fault zone having a distance of more than 45 m should influence the simulation results.

The reservoir layer also dips eastward and the heat accumulates in the western part of the tilted layer. Therefore, a barrier in the west can increase the heat-trapping efficiency of the reservoir. Of course, in the long term it is a negative aspect because it reduces the available space.
The new explanation is added to Chapter 3.2:
"For the best recovery, the reason is linked to the total volume of the reservoir and upward movement of the low density hot fluid. The reservoir is tilted and hot fluid moves to the updip direction due to the density effect. Then, a barrier in the updip (west) side of the reservoir can block the movement of the hot fluid and make a more efficient heat storage reservoir."

Figure 7: What is the vertical offset of the fault for these scenarios. It is mentioned to be more than the aquifer thickness. Why we do not see a sub-figure of such a simulation. I suggest to add a figure showing at least one example of the reservoir with fault offset and the related pressure and temperature field. In figure 8 the fault is visible but not the offset. Maybe this figure can be improved be showing all geometric features.

The vertical offset is 15 m. It is mentioned more explicitly in the updated manuscript. It was impossible to visualize the offset in Figure 8. Hence, a new figure (as Figure 10) is added in the Chapter 3.2:

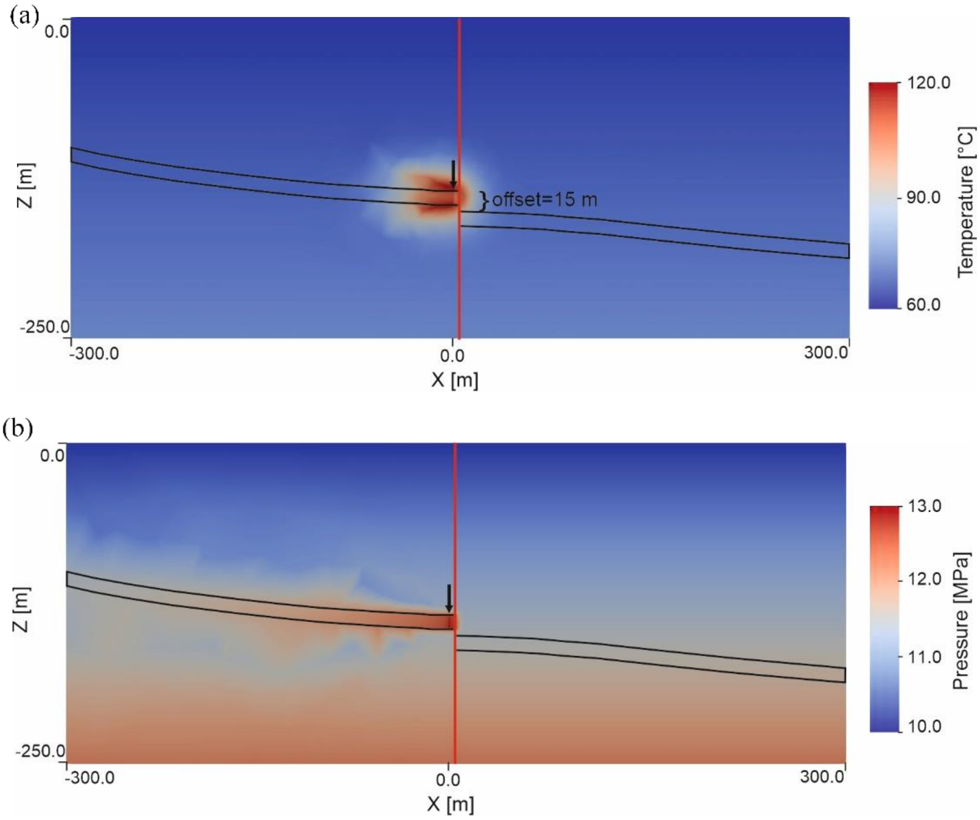


Figure 1: a) Temperature changes in a cross section of the DeepStor model at the end of the last production cycle (10 years). b) Pressure regime in the model after the first injection cycle (6 months). In both subplots location of the well is highlighted by a black arrow in the middle of the model. The fault is represented as a continuous thick red line which locates 4 m in the east of the well and has a fixed 15 m offset. The thick black line also represents the boundaries of the reservoir layer.

P16L355: Ones more, what is the thermal radius of your base case. It can be approximated by using the presented estimation in: Daniel T. Birdsell, Benjamin M. Adams, Martin O. Saar, Minimum transmissivity and optimal well spacing and flow rate for high-temperature aquifer thermal energy storage, Applied Energy, Volume 289, 2021, 116658, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2021.116658.
It seems to be about 50 m. Therefore, a fault in 48 m distance has no influence?

For the DeepStor the thermal radius is about 45 m.

Figure10: As ask before, what would be the effect of truncated model domain at a distance equivalent to the simulated sealing fault. I assume you will obtain similar results without simulating the fault offset.

This issue is fully addressed with a figure in another reply.

P21L411: The chapter "4 Discussion" reads like a summary and not like a discussion. I suggest to rewrite this paragraph to introduce to the subsequent discussion point.

The discussion presents the applications of uncertainty analysis, which are:

1. Designing an exploration campaign,

2. Correlating the geological parameters with reservoir performance

The text is rewritten to make these points more clear.

P21L419: This study was not based on geological models. Therefore, this sentence seems to overestimate the potential of the presented approach which is an automated mesh generation and should be either modified or deleted.

The text is updated to be:

“Geological models and their uncertainty should be transferred into reservoir simulations.”

Figure12: Such diagrams are known from well test analysis and should be compared to other analytical and numerical solutions for the case of “one no-flow boundary” as presented for example in: http://oilproduction.net/files/Fekete_WellTestApplications.pdf

The diagram establishes a relation between fault’s distances with the pressure increase at the well location. Pressure values are calculated numerically with no flow BC.