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Interactive comment on "A numerical sensitivity study of how permeability, geological structure, and hydraulic gradient control the lifetime of a geothermal reservoir" *by* Johanna F. Bauer et al.

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We appreciate the positive evaluation and thank the second reviewer for their comments and suggestions. We will use them to improve our manuscript. Please see our answers to the question raised below:

General comments/ Figures:

Reviewer comment 1.1: Figures in general have a small scale for (small) colored dots and a (uselessly) large scale for the vertical. Furthermore, the colors used are the same. This is misleading the reader. My suggestion is to use different color codes for

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the two parameters (depth and BHG) and change the relative dimensions of the two scales, since the focus of the manuscript is on the BHG (color-coded dots).

Authors reply: We follow the reviewer's suggestions and will adjust the size of the legend for the HDI plots. Further, we'll try to find a different colour scale for the HDI.

Reviewer comment 1.2: Figs.2a-c (as well as other corresponding plots) either have inverted y-axis scale (sic!), or I did not understand the figure and/or the text (cfr. lines 161-165). This produced some initial misunderstanding of the work (the text is not properly describing what is presented in the figure).

Authors reply: The y-scales of each scatter plot show the time to thermal breakthrough, i.e., the time at which the production temperature reaches 100°C. There are no depth scales in the scatter plots. There are no inverted scales in any of the figures of our manuscript. We assume, as the reviewer pointed out in 1.1, that this misunderstanding is caused by the fact that the colours for the scatter plots overlap in parts with the colour code used for the figures showing the HDIs. We will try to find a different colour scale for the figures that present the shape of the HDIs. We are aware that the presentation of the results, owed to the multiple parameters we analysed, is somewhat unconventional. We will follow the suggestion to provide a short introduction/explanation on how to read the figures in the Method section (see also point 1.5, 1.6, and 2.8).

Reviewer comment 1.3: In many experiments the temperature stabilizes at around 100_C (Figs. 2j, 6g, 7g, 8d, 8g, 9g). The reason for this coincidence with the HDI not clear or explained. The author should justify this "convergence" in the various models.

Authors reply: The question why in some of our models the temperature converges to 100°C was also raised by reviewer 1 (RC1s point 7.3). The answer is that in these cases it is a coincidence and the result of a complex interplay between the chosen parameters, i.e. thermal gradient, surface temperature, porosity, permeability.

Reviewer comment 1.4: In Fig.1a the projection of the wells provides the impression that their trajectory is oblique. The Author should either correct the figure or describe the reason for oblique wells as well as quantify it.

Authors reply: The wells are indeed oblique. We will include the parameters in the method section. The reason for the inclined wells is that it allows us to keep the whole well within the damage zone of the fault in Scenario 5, which is also oblique, i.e. it dips. For comparability, we used the inclined wells consequently in all the other models.

Reviewer comment 1.5: In the Figures the Authors should include the number of experiments represented (i.e. the number of dots in the single figure).

Authors reply: The reviewer is correct: The number provided in the figure captions could be misinterpreted. Indeed each of the corresponding plots contains the same results, i.e. the same number of dots. The difference is that in the different plots the same results are presented with different x-axis to explore the impact of the multiple parameters. We will clarify this issue as promised above (point 1.2) using a short introduction in the figure setup in the method section. We will also correct the figure captions, from e.g.: "Plots (a), (b), and (c) contain the results of 225 simulations." to "Plots (a), (b), and (c) each contain the results of the same 225 simulations." We think this is less confusing than presenting in each sub figure the same number of experiments. We hope the reviewer agrees with this option.

Reviewer comment 1.6: The author should discuss the case of a strong variation in the results (e.g. Fig. 1a, red dots for BHG=20 mm/m, at permeability 10-11).

Authors reply: We are convinced that the influence of the BHG is sufficiently discussed in the lines 351 to 368, where we describe that, at high permeabilities, the BHG can outperform the artificially-introduced flow field. We are convinced that the reviewer's question becomes obsolete with the new improved method section that introduces the setup of the scatter plots, i.e. that the scatter plots presented next to each other must be seen in combination and not as stand-alone results. In this particular example cited by the reviewer, the corresponding Figures 2a, b, and c should read as follows. The thermal breakthroughs of less than 20 years, is according Figure 2a, at permeabilities of 10-11 m^2. The same data points in Figure 2b (red dots with lowest thermal breakthrough times) show that this short time to thermal breakthrough is observed for hydraulic gradients that are directed southwards and have a magnitude (colour code red, as shown in the legend) of 20 mm m-1. In Figure 2c, the same data points are plotted according to the porosities used in the models. Here, it shows that, in this case, porosity plays a minor role in determining the expected lifetime of the reservoir. We additionally visualized this connection using horizontal lines that connect results of the same experiments.

Reviewer comment 1.7: Numbers are very small to pretend some statistics (mean, sd), but they could mean unreliable results and should be discussed.

Authors reply: We agree that a further statistical evaluation is futile. We also think that providing parameters like mean and standard deviation might not be the way to further investigate our results, because the present results are from different experiments with varied model parameters. This means, our experiments do not allow such statistics.

Reviewer comment 1.8: The “line connecting the same experiment” is not clear. In Fig. 2 the yellow line connect one yellow dot per figure, and it is easily understood. On the other hand, in other figures (e.g. Fig. 4a-b, green lines) the do connect multiple dots in the same figure. This is confusing: how many numerical experiments were responsible for each dot in each figure (I assumed one)? Maybe they partially overlap.

Authors reply: The reviewer is correct. Each dot in each panel is the result of one numerical experiment, and each of the according panels contains the same model results. Due to the large number of experiments, we unfortunately cannot avoid that, in some cases, the line connecting the dots, which belong to same experiment, also cross other points. In this case (Figure 4a, b), it shows that the varied parameters (direction and magnitude of the BHG) does not influence the time to thermal breakthrough in the modelled time span. Consequently, the dominating parameter that determines the reservoir's lifetime in the low permeability series is the permeability contrast. Please see also lines 370f and 204f of the discussion paper. Please see also our answer to point 1.6.and 2.8.

Specific comments

Reviewer comment 2.1: In lines 34-39 the Authors discuss the poor improvement in porosity due to the presence of fractures. This is true, but the author are not considering the main role provided by fractures in improving the effective porosity by connecting isolated pores, as is normally achieved in tight-gas reservoirs (gas-shale). In general, the manuscript is not discussing on the difference between total porosity and effective porosity. I guess that the porosity they consider in the numerical experiment is merely the effective one, and this should be clearly mentioned. On the other hand, a brief note on the role of influence of fractures on effective porosity is required to complete the introduction and the discussion paragraphs.

Authors reply: We will now mention the effect of fractures on matrix porosity. The second part of this question address how permeability is implemented in the models. The same issue was raised by reviewer 1 (e.g. point 6.8), it will be answered in the method section and we will clarify that the permeability in the models is not linked to matrix porosity. Instead the continuum approach (Berkowitz et al., 1988; Lege et al., 1996; Kolditz, 1997), which uses replacement media for the fractures and provides mean hydraulic properties of a given fracture system, was utilized.

Reviewer comment 2.2: Equations in Line 72,81,82 seem correct, yet references for the general audience (as Solid Earth also has) are required.

Authors reply: We will follow the reviewer's request and will provide additional literature.

Reviewer comment 2.3: Line 91-92. The limit to 20m is not easy to be understood (e.g. where these 20m were located along the well). Maybe a better way to express this correction would be to express it as a percentage of the well hole surface (the

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cylinder), or by presenting the equivalent reduction in permeability between the well cell and the surrounding ones in the mesh.

Authors reply: We thank the reviewer. A similar question was raised by reviewer 1 (point 6.3). We will follow the suggestion of the reviewers and rewrite this part accordingly. Standard well diameters are a few decimetres. This in turn would need a very fine mesh. To avoid this issue we use a larger diameter for the wells. To account for the unrealistic high diameter and thus the area of the "perforated production and injection zone" we choose to adjust the size of the area via its length to a size that is in a realistic range.

Reviewer comment 2.4: Line 96: I guess that the geothermal gradient is in reality expressed by m and not by km. . .

Authors reply: We thank the reviewer and correct the typo.

Reviewer comment 2.5: Line 105 and 113. I guess that "computational costs" really intends the more appropriate expression "computational time". It would be of interest to the readers to quantitatively justify this sentence: add in lines 69 71 information on the used computer platform and the approximated run-time for a single numerical experiment. Line 126 and through all the experiments.

Authors reply: We will now provide information on the computer platform and the differences in the runtime for the fully- and unidirectional coupled experiments.

Reviewer comment 2.6: My opinion is that a permeability of 10exponential-11 m2 is unfair to be reached in a reservoir at the used resolution of the model, with the exception of karst cavities. The Author might include here a descriptive correspondence to the reservoir permeability (e.g. tight reservoir for 10 exponential -15 m2, medium-high permeable reservoir 10 exponential -13 m2, karst structures 10exponential-15 m2).

Authors reply: Both of the here addressed issues are also made by reviewer 1. The first point regarding the high permeabilities is answered by how permeability and porosity are implemented in the models. We are now aware that we were not clear enough about this and will now address this issue in the method section to avoid potential misunderstanding. Please see our answer to your point 2.1 and to e.g. point 6.8 by reviewer 1. This second question, which also ties directly in with a request of reviewer 1, is to provide some real world examples. We will improve the Introduction and try to find the best compromise between both suggestions.

Reviewer comment 2.7: Lines 143-147 more references on measure of permeability in fault core are important here (e.g. works by R.J Knipe and/or Q.J Fisher).

Authors reply: We will provide more literature on fault permeability, as also requested by reviewer 1 (point 6.9). We, however, prefer to present them in the introduction instead of placing them in the results. We hope the reviewer finds this compromise acceptable.

Reviewer comment 2.8: Line 161-165. As mentioned, the only way I found to correlate text and Fig2a-c is to invert the Y-axis scale. Anyhow the description, even with this correction, does not correlate for 10exponential-11 permeability experiments, that scatter results all along the entire span 0->200 a apparently without any rule (e.g. red dots). Did I understand properly the figure? If not, a more careful introduction to the figure and description might be necessary.

Authors reply: Please see our answer to your points 1.2 and 1.6. We will provide an introduction on how the plots are to read. In detail, on the example of figure 2a-c. Each of the plots a), b), and c) contains the same model results for all combinations of the three porosities, the three permeabilities, the eight directions of the hydraulic gradient and of the 4 different magnitudes of the BHGs. As the reviewer agrees, these are a lot of parameters to visualize. Whereas this is a typical approach to plot results in multi parameter studies, it is not very common in the geosciences. We decided to keep the y-axis constant, which shows the time to thermal breakthrough. The x-axis was used to plot the same data points in different ways, to produce the patterns that show the different effects of the different values (permeability, direction of the hydraulic background gradient, porosity). In consequence, it is important to see these plots as a whole, i.e. the value they provide only becomes apparent by looking at them in combination. The connecting line is used to show the above issue and connects the same result of one experiment and allows to identify the parameter values for each individual model run.

Reviewer comment 2.9: In the Figs. the meaning of the represented surface is not completely described. The Authors refer to "HDI shape". I am not sure but I guess that, considering the experiments, these surfaces represent the envelope of the volume where the temperatures become lower than the HDI due to the successful heath extraction. An explanation on the meaning of the HDI shape is required in the text (and maybe in the caption for the fast readers. . .).

Authors reply: We accept this point and will improve the description of what the HDI actually is. The reviewer is correct with the description. The HDI encloses the volume with temperatures lower than 100°C.

Reviewer comment 2.10: Line 173-174 the probability concept should be better introduced.

Authors reply: We accept the suggestion and will describe in more detail that elongated ellipsoidal HDIs, where their direction is controlled by the HBG, may result in a reduced probability/chance that the injected cold fluid reaches the production well.

Reviewer comment 2.11: Line 178: I guess the Authors intend Fig.2g and not 2e.

Authors reply: We thank the reviewer to point out this mistake. We will also rephrase the according lines for better readability: . . ..."The two contrasting BHGs in Fig. 2g show, either fast (e), or almost no decrease (f) in production temperature". . ...

Reviewer comment 2.12: Line 198 "three series". This is not clear: I see in the figure3 different permeability (these are the three series), 4 permeability contrasts and 8 different orientation for BHG with 4 possible gradients, for total of 3x4x8x4=384 combinations. Then just three BHG shapes, but for the same permeability (same series). This might be confusing. A more complete description of the model procedure might help to understand the results.

Authors reply: We will improve the text. In detail in line 203 (discussion paper) we will directly refer to the according figures and model series when introducing the permeabilities. We will also mark in the figures the series to which they belong. With regard to figures 4c, f, and i, we selected exemplarily three HDI shapes from the medium permeability models. Given the 300 individual model runs presented in this scenario, we decided to show these because they constitute a good compromise, i.e. they (1) are in a realistic permeability range and (2) clearly show the effect of the permeability contrasts.

Reviewer comment 2.13: Fig4b is not clear, and in general figs 2, 4, 5 are not easy figures. Same color dots appear both on high and very low times to breakthrough. This could mean the excessive scattering of results, or that results are from experiments with different, not specified, parameters.

Authors reply: Regarding the Figures in general, please see our answer to your points 1.6, and 2.8. Regarding Figure 4b in particular please see our comment on your point 1.8. Figure 4b shows, in combination with Figure 4a, that the only controlling factor in this low permeability case is the permeability contrast in the reservoir, i.e. the orientation and magnitude of the BHG is of no importance. This correlation however is altered (Figure 4d, e and Figure 4 g, h), if the permeability of the reservoir layers increases, i.e. the BHG can, in these cases, compensate the limitations introduced by the permeability contrast. Please see lines 376f and results 3.2 Models of layered reservoirs in the discussion paper. We assure the reviewer that all parameters are specified and can be picked in the figures as described in e.g. point 2.8.

Reviewer comment 2.14: I think to have properly understood the relations between the dots in Fig. 4a, b and the reason for the limited connection presented in Figs. At the present stage, the figure is very difficult to be understood (also due to the high number of combinations in the experiments – i.e- the number of parameters used - and the limiting 2D of the journal pages. . .). The Author could try to improve the correlations by either using different symbols for each experiment (good luck, it would be a big effort with questionable results) or by adding a reference number to each dot. The diagrams have a relative small number of dots and al lot of empty space. A simpler alternative might be to add in the text the clear description of a correlation among dots as an example. There are also some evident overlap of dots (just comparing among figures) and this should be described (or slightly move one of the dots within the resolution of the results).

Authors reply: We assure the reviewer that we have discussed and tested many options to present the data, including the ones made by the reviewer, i.e., using different symbols and/or adding references. It, however, did not improve the figures, as expected by the reviewer. We found that the way we finally chose, as is common in multi-parameter studies, is probably the best. However, we will provide an additional section in the methods that helps to understand the concept of the figures. See also our answer to your points 1.6, 1.8, 2.8, 2.13 above.

Reviewer comment 2.15: Line 215-220 again: the cited 70 years seems to correspond to 130 years in Fig.4d, second column. Is there again reversed the Y-axis scale?

Authors reply: Here we are writing about the range of observed lifetimes. The range of observed lifetimes, in this case, is indeed about 70 years, i.e. between 130 and 200 years.

Reviewer comment 2.16: Line 235. As previously mentioned. Why at 100_C? This should be justified by the Authors.

Authors reply: Please see our answer to your point 1.3.

Reviewer comment 2.17: Fig.5 the origin of dots on top of the plots a-c (i.e. at >200a) is not clear.

Authors reply: In this, as in many other model runs, the production temperature did not fall below the 100°C threshold. In consequence, we decided to assign the results of expected lifetimes to be at least 200 years, i.e. the time modelled. On the example of Figure 5. This the only model configuration that allowed a hydraulic connection between the wells because the fracture anisotropy is parallel to the well alignment. In the other cases, the fracture anisotropy, even the lowest, hinders the reinjected cold fluid reaching the production well, and consequently, under the applied model setup, the temperature stays above the threshold.

Reviewer comment 2.18: Line 264-265 Fig. 5g shows that temperatures stabilize at 100_C. How this happens at exactly the critical temperature chosen for the HDI? Is this input in the model? Some explanation is needed.

Authors reply: Please see our answer to your point 1.3.

Reviewer comment 2.19: Lines 340-349 Here is perhaps the proper space to discuss the total porosity and the effective one I discussed above. As I understand, the chosen porosity is intended to be 100% effective. A sentence explaining this should be anyhow added to the article.

Authors reply: Please see also our answer to point 6.8 from reviewer 1 and your point 2.1.

Reviewer comment 2.20: Line 371. This assumption may be too forced, and I am sorry for the referenced articles. Secondary fractures and faulting allow permeability to take over thinner clay layers that lose their sealing property. This is more difficult in thicker clay layers. I understand that in the useful proposed model are necessary simplifications, but it is not the case for the complexity of real geothermal reservoirs.

Authors reply: We acknowledge that the reviewer agrees that this is an unfortunate but necessary restriction of the models. This is however, the concept of our study, i.e. to use simplified models and to show that, even with these simplifications, predictability of the modelled systems is extremely complex. This agrees also with the reviewer's point 2.27 that our manuscript presents a first step in pointing out these difficulties. We agree, of course, with the reviewer that fractures also propagate through "sealing" layers. Even though such softer layers hinder fracture propagation. For this reason we wrote,"restrict fluid flow across them" to avoid a too strong statement. We will additionally rephrase the sentence in line 371 (discussion paper) to: "(Sub)horizontal permeability contrasts can be caused by layering in sedimentary rocks and can span several orders of magnitude (Zhang, 2013), even though these sealing properties are altered or reduced by barren fractures." We hope this is an acceptable compromise.

Reviewer comment 2.21: Line 399. I do not see evidence in Fig. 5b to justify this sentence. At my sight, the resulting timings are fully independent from the BHG values (colored dots). May be the Authors are referring here on the BHG orientation of Fig.5c.
.

Authors reply: The reviewer is correct. Indeed, we refer here to Figure 5a, b, and c. With this correction, the statement in line 399 is justified. The sentence in Line 399-400 will be rephrased to: "Second, fracture anisotropy in the range of 1 order of magnitude, with respect to the bulk permeability, leads to either very short- or long-lived geothermal reservoirs, depending on the BHG properties and the orientation of fracture anisotropy (Fig. 5a, b, c)."

Reviewer comment 2.22: Line 423-414 Fractures and secondary faulting associated to faults have generally various angles to the faults and only a minority lies parallel to it (cfr. Riedel). This results in: fracture intersections, fracture opening by the stress induced from the kinematics along the fault (friction). These factors guarantee the higher permeability of fault damage zone to a certain extent, as described in the literature. To be explicit: "often-observed" of "fault-parallel fracture anisotropy" does not correspond to either field outcrops and cores across fault zones, apart from S-C structures, where in any case C planes are generally subordered in number to S ones, My suggestion is simply to eliminate the “often-observed” attribute.

Authors reply: We accept the reviewer’s comment that our statement is eventually too strong. However, following the suggestion to delete “often-observed” makes the statement much stronger. We will modify the sentence to: “This typical characteristic of fault zones thus increases the chance of good hydraulic connection between injection- and production wells and is potentially further improved by fracture anisotropy in the damage zone, which is often (sub)parallel to the fault.”

Reviewer comment 2.23: Line 429 The previous concept is repeated here: useless redundancy and same comment.

Authors reply: We do not fully agree with the reviewer. In the lines 411 to 425, we discuss why faults have become recently prime targets in geothermics and the difficulties that have been reported. In lines 425 to 440, we discuss the results of our models and how they agree or disagree with common knowledge. We will slightly modify the sentence in line 425-426 to: “Our simplified models support these findings and show that faults, with damage zones that constitute positive permeability contrasts of just 2 orders of magnitude, exhibit these channelling effects (Fig. 6).” to make the structure of this section clearer.

Reviewer comment 2.24: Line434-435 the use of the terms “opposed/opposite” to indicate opposite (!) dipping is misleading. A rephrase would solve it.

Authors reply: We accept the reviewer’s suggestion and will rephrase the sentence accordingly to: “We observed that, when the BHG is oriented against the dip direction of a fault, the fault can be considered a more sustainable target for geothermal exploitation than a fault with a BHG oriented in dip direction (Figs. 7e, f, 8e, f)."

Reviewer comment 2.25: Lines 62, 442: they were 1027 (from line 150). This is an interesting and serious number of runs and it would be effective to remark this number both in the introduction (say, “over one thousand numerical experiments”) as well in the Conclusions “(1027)”. My impression is that “large series” or “a series of” would be –alas – interpreted as much smaller number in present-day publish-or-perish scientific environment.

Authors reply: We very much appreciate that the reviewer values our work and we will stronger pronounce the number of experiments carried out by us.

Reviewer comment 2.26: Line 457: This is not so simple. This sentence does not take in consideration the improvement of the effective porosity that is induced by fracturing that in turn may be enhanced by the oriented stress that develops in presence of strong BHG. Since the point about effective porosity changes is not taken into consideration in the presented models, my suggestion is to specify this in the sentence (referring to “in many cases” might be not sufficient).

Authors reply: The reviewer is correct that effective porosity is, in many cases, improved by fracturing. However, the reviewer accepts also that an investigation of this effect is not part of our experiments. We, here, refer to our model results that show that the positive effect of porosity has on heat capacity and thus on the reservoir lifetime is minor, compared to that of permeability and BHG. We will rephrase the sentence accordingly to “, in many cases, the positive effect of porosity has on heat capacity and thus on the reservoir lifetime, is minor, compared to that of permeability and BHG....”. We hope that the reviewer can accept this solution. Please see also our answer to point 2.1, in which we explain how porosity and permeability are implemented in the models.

Reviewer comment 2.27: Line 459-462. On the contrary, results from this work well represent the first step to model real, complex geothermal reservoirs with their Stochastic modelling by adding in the mesh the proper random values! And I am sure that the “computational costs” at that stage will be an insignificant obstacle. This might be a further point and a better conclusion to your article (follow the Hollywood-movie style:

end always your articles with a true, positive sentence on your results. . .).

Authors reply: We thank the reviewer for the positive evaluation and welcome the suggestion to extend the conclusions and end the manuscript as proposed with a positive outlook, i.e., how our findings help to improve geothermal exploration in the future. We will include at the end of our manuscript: “Our results show that realistic site-specific models are difficult to achieve, because parameters, such as permeability structure and BHG, are often poorly constrained but can have unforeseeable large effects on the lifetime of geothermal systems. Thus our findings provide an important step forward to judge which parameters must be known to which degree to make site specific models as reliable and accurate as possible in the future, by implementing the controlling parameters in advanced stochastic models.”

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