

Response to Reviewer RC2 comments: se-2020-139-RC2

We thank the anonymous reviewer RC2 for the thoughtful and positive review of our manuscript. The constructive comments helped us to further improve the manuscript. We edited the manuscript carefully and addressed all comments of reviewer RC2. Please find below the detailed reply to the comments.

All reviewer comments are shown and highlighted as bold text, followed by our answers as indented normal text. Line numbers in our response refer to the tracked revised manuscript.

General comments of Reviewer RC2

Seismicity associated with the stimulation of an Enhanced Geothermal System in Finland is presented. A variety of analytical tools are used to extract as much information as possible. While I do not have expert knowledge of the tools, they seem to have been competently used and deliver plausible results.

While I am not personally involved in EGS studies, I found the paper interesting because it relates to work that my group is doing with regard to seismicity induced by mining and the flooding of worked-out mines, as well as shale gas development.

I failed to meet the review deadline, for which I apologise. I downloaded a copy of the Manuscript supplementary material when I reviewed the paper on 14 November. I hope that the supplements are of the same high standard, but I have not checked this.

Authors:

We apologize for the problem of downloading the supplements and hope that the Figures in the supplements also satisfy your expectations.

Generally the paper is well-written. There are some minor grammatical errors that I have indicated on the attached annotated version of the manuscript. The referencing style is also inconsistent - some paper titles are in Sentence case, others in Title Case.

Authors:

Thank you for indicating grammatical errors. We corrected all of them in the revised manuscript.

There are also a few instances where I found the discussion difficult to follow or figures difficult to interpret. I have highlighted these and offered suggestions for improvement.

Authors:

We address the comments and suggestions in detail below where each of them is listed and followed by our response.

Particular comments of Reviewer RC2

1) Ln 225: ‘...Fig S2.’ I was not able to view the supplementary figures.

Authors:

We again apologize for the problem.

2) Ln 233-235: “Two events with $M_w \geq 0.9$ occurred within the first 11 days of the post-stimulation phase. Two further $M_w > 1$ events occurred within 24 hours and 17 days after the stimulation ended, one with moment magnitude of 1.6 (Fig. 2).”

I am confused. Perhaps I do not really understand what you mean by 'after shut-in' and 'end of injection, 'bleed-off of wellhead pressure', 'post-stimulation phase'. After enlarging the graph, I count the seven events, three occurring just after the dashed line (bleed-off). I then see 3 events ≥ 0.9 in days 5-10.

Authors:

Thank you for the hint that there are actually 3 events with $M_w \geq 0.9$ in days 5-10. We apologize for this mistake. Indeed, there are 3 events instead of only 2. We corrected the number in the manuscript.

3) Ln 253-254: “...with two of them located on the NW flank of the injection well OTN-3...”.

Figure 3a only shows one red rectangle to NW of OTN-3. Is the second cluster the events that fall mostly in the cell defined by easting (-600;-400); northing (-200; 0)?

Authors:

Yes, with the second cluster located at the NW flank of the injection well *OTN-3* we meant the clustered post-stimulation events that are located mostly in this cell.

4) Ln 267-268: “The temporal evolution of the CM_0 separated for each hypocenter cluster is shown in Fig. 5.”

Please make it absolutely clear to the reader where these three clusters lie. I suggest that you circle and label them in Figure 3.

Authors:

We marked the three main hypocenter clusters by dashed rectangles in Fig. 3b and labeled them with the same names as we used in Fig. 5 to avoid any misunderstanding.

We further changed the following sentence in the manuscript (lines 281-282):

“The temporal evolution of the CM_0 separated for each hypocenter cluster, marked in Fig. 3b, is shown in Fig. 5.”

5) Ln 325: “...due to appearing ambiguities in...”

I am not sure what you mean by 'appearing ambiguities'. Why not just 'amiguities'?

Authors:

The word “appearing” does not really explain ambiguities any further in this context. We therefore deleted the word “appearing” in the manuscript to not confuse the readers.

6) Ln: 401: "...gravity of the cool water..."

It not clear what you mean here. Perhaps 'gravity-driven movement of the cool water into ...'

Authors:

Yes, the movement of the cool water into warm and less dense pore fluid would be driven by gravity. Thus, any further pressure would not be needed to migrate the water towards deeper parts of the reservoir. However, with obtaining new results (please see also responses to comments #15 and #16 of reviewer RC1), the statement is now more doubtful and thus, we deleted the sentence in the manuscript.

7) Ln 434: "...lightened up..."

Not sure what you mean by 'lightened up'. Perhaps 'activated'.

Authors:

Yes, with "lightened up" we mean "activated".

We changed the sentence in lines 452-453 as followed:

"The 2018 seismicity activated a pre-existing network of small-scale parallel fractures dipping to ENE, in agreement with the dip direction of the inclined part of the injection well."

8) Ln 460: "...the gravitation-driven downwards migration..."

The physics behind the 'gravity-driven migration' is not clear to me. Is this related to the sinking of the cooler water?

Authors:

The observation of the depthward migration of seismicity with time would be comparable e.g. with induced seismicity at The Geysers geothermal field (Kwiatek et al., 2015). For the Geysers, this depthward seismicity migration documents also a migration of cooler injected water into warmer pore fluid toward greater depth without any further pressure needed. The depthward migration of the water is also facilitated by steeply dipping faults which are well-known at The Geysers.

9) Ln 463: "...but weak faults..."

Not sure what you mean by "but weak faults ..". Perhaps. These are thought to be weak faults

Authors:

Yes, these fractures are thought to be weak faults.

We updated the sentence in the manuscript:

"We conclude that seismic slip occurs on sub-parallel network of favorably oriented pre-existing but weak fractures, striking in NNW-SSE direction and dipping 45° ENE."

10)Ln 487-488: "...Seismic Moment Evolution During Hydraulic Stimulations,..". Sentence case, not Title Case.

Authors:

Thank you for the hint. We changed the reference into sentence case.

11) Ln 518-519: "Hardebeck, J. and Shearer, P.: A New Method for Determining First-Motion Focal Mechanisms, Bulletin of the Seismological Society of America, 92, 2264–2276, <https://doi.org/10.1785/0120010200>, 2002."
I would expect the reference to follow Hardebeck and Michael.

Authors:

Thank you for noticing this mistake. We swapped the reference of Hardebeck and Shearer (2002) with the reference of Hardebeck and Michael (2006).

Comments of reviewer RC2 to the Figures

12) Figure 3. I find the display confusing. The colours used to show the seismic events correlate well with the legend; however, the colours on the trace of the well do not.

When I enlarge the Figure 3b I see a bright red tip; above it is an olive green section; and above that a bright green section, then a blue section, and finally a purple section. Are these five sections meant to correlate with P1 - P5?

I also see several red circles plotted on the well trace between -5500 and -5650 (and one at -5500). What do these signify?

Authors:

We apologize for the confusion about the colored bands along the borehole trace in Fig. 3. Unfortunately, the colors along OTN-3 were wrongly plotted. The colors should correlate with the colors of the five stimulation stages. Therefore, we updated the bands, now using the same colors as for P1-P5.

For a better visibility, we also changed the color of the stimulation phase P5 hypocenters to a darker yellow in Fig. 3.

We also apologize for the confusion about the small red circles. This was a mistake in plotting. In the updated version of Fig. 3, we excluded these circles.

13) Figure 4. Figure 2 indicates that seismicity was recorded for 65 days after the end of injection. As I read it, this figure only shows the cumulative moments for 30 days. Am I reading it correctly? If so, please note this in the caption and text.

Authors:

Yes, this is correct, Fig. 4 only presents the time period of 30 days for each stimulation phase and indeed, the post-stimulation time period was 63 days long. However, we decided to not plot the full 65 days due to an insignificant increase in the cumulative seismic moment after 30 days of the end of injection.

We changed the following sentence in the caption of Fig. 4:

"For a time period of 30 days, the temporal evolution of cumulative seismic moment release for the relocated seismicity is shown for each injection phase as well as for the post-stimulation phase."

We also changed the following sentence in the text (lines 274-276):

"Here, we show the temporal evolution of the cumulative seismic moment (CM_0) release for a time period of 30 days during the post-stimulation period and compare it with the evolution before shut-in of injection."

14) Figure 5. Please make it absolutely clear to the reader where these three clusters lie. I suggest that you circle and label them in Figure 3. Ensure that the time axis is marked so that it is clear to the reader that it covers the same duration as Figure 5 i.e. more than 10 days.

Authors:

Thank you for the suggestion. To avoid any misunderstanding or confusion, we marked and labeled the three different clusters in the updated Fig. 3b, as already mentioned in the response of comment 4.

We also changed the x-axes in Fig. 5 to show and label the same time period as the x-axis in Fig. 4.