Response to interactive comment on "Vertical seismic profiling with distributed acoustic sensing images the Rotliegend geothermal reservoir in the North German Basin down to 4.2 km depth" by Ariel Lellouch (Referee).

Dear Ariel,
thank you for your constructive comments and suggestions, which helped us to work out several important aspects of our manuscript more clearly. In the following, we have listed the individual comments, followed by our answers in italic font. After this, the revised manuscript text with the changes highlighted is appended.
Thank you and best regards,
Jan Henninges (on behalf of all authors)

First of all, I think the focus of the paper could be better. What is fundamentally new in your study is not the VSP processing, which is relatively standard, but the deep deployment of a vertical wireline DAS cable that yields excellent data. This example can have significant implications as old wells in which the fiber was not cemented/tubed will become available for different purposes. The fact that the deployment is in a hot area makes DAS even more attractive. Therefore, I'd suggest a change to the title and to possibly further emphasize this aspect in the text.

Response: We agree and have modified the title to "Wireline distributed acoustic sensing allows 4.2 km-deep vertical seismic profiling of the Rotliegend 150°C-geothermal reservoir in the North German Basin", as well as several parts of the abstract accordingly, in order to work out these points more clearly.

Another novel point, which is especially relevant to the DAS community, is the publication of a dataset acquired with the Schlumberger interrogator. One of the main benefits of the hDVS, if I correctly understood the company's claims, is that multiple gauge lengths are acquired during the acquisition step and can later be adjusted during data processing. I suppose there are limitations in what you can show, but it would be nice to see records of different GLs.

Response: It is true that with Schlumberger's hDVS technology, the gauge length can be varied, both during a survey and after recording during data processing. We used this feature and recorded data sets with different gauge lengths during the start-up test. Based on this, we had chosen a gauge length of 20 m for recording in the field, as described in section 2. Then, after derivation of the travel times and interval velocities from the recorded data, we performed the gauge length optimization procedure of Dean et al. (2017) using the average velocity of the target interval, as described in section 3.1. This resulted in an optimum gauge length of 40 m, for which the whole data set was then reprocessed. We will include data recorded or processed with different gauge length in the data publication/supplement to this paper, which is currently under preparation: Henninges J., Martuganova E., Stiller M., Norden B., and Krawczyk C.M.: DAS-VSP data from the Feb. 2017 survey at the Groß Schönebeck site, Germany, GFZ Data Services, doi:10.5880/GFZ.4.8.2021.001, in review. We have added the reference to the data publication under section "Data availability" and the reference list.

In addition, you have pronounced changes in velocity, especially at <1500m. In the spirit of your GL optimization, would it be better to use a shorter GL (maybe the 20 m) for the shallower section if the processing workflow allows for it?

Response: Yes, for processing of the shallower intervals this would be beneficial, as described e.g. in Dean et al. (2017). But as the focus of our current study is predominantly on the deeper Rotliegend reservoir section, such a zoned processing approach was not applied here. We have therefore added the following sentence at the end of section 3.1: "It would also be possible to apply a depth-dependent gauge length optimization, as suggested by Dean et al. (2017), by taking local variations of velocity and frequency content into account. This was nevertheless not performed in the current study, because the focus here is predominantly on the deeper

Rotliegend reservoir section only.

Besides, the useful Dean et al. (2016) derivation is correct for vertically propagating wavefronts to follow up on that point. In your case, especially for the far offsets, it seems like the apparent slowness is significantly faster, thus commanding longer GL. Would it make sense to have a GL that is offset-dependent as well? I think it is important to discuss the variable GL, because using an average velocity to optimize GL is what one expects for more "standard" interrogators.

Response: True, but again, as the focus of our current study is on the deeper Rotliegend reservoir section only, where larger variations of velocity do not occur, as well as on the zero-offset data sets, we feel that it would be somewhat outside the scope of this paper to enter into a deeper discussion on variable gauge lengths. But as noted above, we have included a note on the importance and our approach used here within the text.

There is also a big gap between the acquisition/deployment efforts and the analysis reported here. In the Introduction and Survey design, you set the stage towards 3-D velocity model building/imaging. However, the eventual processing is much more modest – a 1-D velocity analysis with corridor stacks (if I understood correctly). This comment is not a criticism of the work, but I think it would be much better to set reasonable expectations early on in the paper.

Response: To make this clearer we have added the following sentences at the end of section 1 Introduction: "In the following, the survey design and data acquisition, the overall characteristics of the acquired data, as well as the data processing and evaluation for a zero-offset source position are presented. Specific processing and interpretation of a 3D-VSP seismic cube will be the subject of a separate publication."

Also, I found the velocity model building/processing sections very opaque. Did you use all shots, or just the zero-offset ones, for velocity model building? What is the meaning of a corridor stack for non-zero offsets (the re- flection point would be away from the well)?

Response: The building of the velocity model was intentionally only described briefly here, as it was only used for correction of the vertical travel times, as described at the beginning of section 4.3. The velocity model building was part of the 3D-VSP imaging, which will be described in a separate publication, as noted above. The corridor stacks were of course only prepared for the VP10 zero-offset source position. In order to make this clearer we have added "applied to the data from the VP 10 zero-offset position" to the first sentence at the beginning of section 4.4.

Assuming the 3-D analysis isn't ready, can you show gathers (common-receiver in VSP + direct downgoing travel time correction) to illustrate the azimuthal velocity variations and motivate future 3-D work?

Response: In contrast to a common-source gather (one source point recorded by a linear receiver line) it is hardly possible to display a common-receiver gather containing spatially distributed source positions with different offsets and azimuths recorded at one receiver point. We don't believe that an azimuthal velocity analysis can be performed by this.

On a related note, the estimated 1-D velocity model has a much lower resolution than the sonic logs, and I think it merits a discussion. The most obvious example is that the high-velocity zone in the top salt (interesting!) around 2500 m, almost 80 m high, only weakly shows in the estimated velocity model. I can understand why it happens to a certain extent. However, looking at the narrower sweep's signatures, it seems to me that you probably have ∼100 Hz with reasonable SNR down to the bottom of the well for most of the survey. So, you have a more than a wavelength that can fit inside the high-velocity zone that I mentioned. I suspect that the low-resolution in the velocity comes from mixing shots in different azimuths and averaging a 3-D structure into the best possible 1-D approximation, but it is only a guess.

Response: Of course the sonic log has a much higher spatial resolution due to the higher source frequency the tools are using, which usually reaches up to several kHz. But your assumption that the high velocity layer at around 2.500 m depth (a 50 m thick anhydrite layer, with the X2 and X3 reflectors at its top and base, respectively) should be resolvable in the VSP data is nevertheless correct. This layer, as well as the other two high-velocity anhydrite layers at the base of the Zechstein interval, intentionally appear strongly smoothed in the VSP interval velocity profiles, because these were calculated using the method of smooth inversion after Lizarralde & Swift (1999), as described in section 4.3 / line 245 within the text. For further explanation of this method, we have added the following text: "Here a damped least-squares inversion of VSP travel times is applied, which reduces the influence of arrival-time picking errors for closely spaced sampling points, and seeks to result in a smooth velocity/depth profile. In our study, a 1.1 ms residual of the travel times has been allowed for." In the last sentence of this section on the comparison with the sonic log data, we further added: "Taking into account the desired smooting of the profiles resulting from the applied computation method, (...)".

Minor technical comments:
Sorry for referring to my work, but there have been a few recent deployments of downhole DAS in EGS projects. You can see the studies by Junzo Kasahara (mostly abstracts) and myself (Lellouch et al., 2020, SRL, and another one currently on arXiv). These studies have recognized the benefits of DAS in geothermal reservoirs, and I think they can strengthen your introduction and, eventually, conclusions.

Response: Such studies on using DAS for microseismic monitoring are indeed strongly relevant for our study. We have included the following sentence including this and some further references in the introduction: "There is also a growing number of studies applying DAS for microseismic monitoring during hydraulic stimulation (e.g. Molteni et al. 2017, Karrenbach et al. 2017), also including EGS reservoirs (Lellouch et al. 2020)." The following three references were added:
Karrenbach, M., Kahn, D., Cole, S., Ridge, A., Boone, K., Rich, J., Silver, K., and Langton, D.: Hydraulic-fracturing-induced strain and microseismic using in situ distributed fiber-optic sensing, Leading Edge, 36, 837-844, 10.1190/tle36100837.1, 2017.
Lellouch, A., Lindsey, N. J., Ellsworth, W. L., and Biondi, B. L.: Comparison between Distributed Acoustic Sensing and Geophones: Downhole Microseismic Monitoring of the FORGE Geothermal Experiment, Seismol. Res. Lett., 91, 3256-3268, 10.1785/0220200149, 2020.
Molteni, D., Williams, M. J., and Wilson, C.: Detecting microseismicity using distributed vibration, First Break, 35, 51-55, 2017.
It would also be interesting to mention if you picked up any earthquakes during the recording – downhole DAS is much more sensitive than surface arrays.

Response: We did not notice any signs of earthquakes during the processing of the data. The natural seismic activity in the study area is very low.

I think Figures 5 and 6 can be combined into one.

Response: We deliberately plotted this data in two separate graphs, in order to have a clear visualization of the individual traces. We think that the plots would become overloaded when combining the two figures into one, therefore we prefer to keep them separate.

DAS/geophone comparison - the fact that downhole geophones are actually accelerometers is highly confusing (not your fault. . .). It would be better to clearly state this fact and that the DAS comparison is to the vertical axis of the geophone. By the way, if you follow Egorov 2018 for unit conversions, you can scale each point in the F-K domain by ωˆ2/k and do it all in one pass.

Response: The fact that the borehole geophone is an accelerometer is stated within the text in lines 86 and 166, where it is also stated, that the vertical component is displayed, as well in the caption of Fig. 6. We have now also added this information in the caption of Figure 5: "The *borehole geophone is a three-component accelerometer, and the vertical component parallel to the tool/borehole axis is displayed." With respect to the data conversion according to Egorov et al. (2018), yes, you are right, thank you for this notice. We decided to split the conversion process into these two sub-steps for easier comprehension. Technically it is the same procedure.*

Can you show the synthetic (predicted) trace for the logged section? It would be easier to compare with the corridor stacks and see which events are spurious.

Response: We had calculated different synthetics with variation of the input wavelets, spatial sampling, etc., in the course of our analysis. But as the logging data exists only for certain intervals and the results were not fully conclusive, we have not included these here.

For non-expert readers, it would be useful to mention why aren't the sonic logs sufficient for your final interpretation. This is not uniquely related to DAS, but to standard VSP as well.

Response: In the revised abstract and introduction we explain that the DAS-VSP survey was performed in order to gain more detailed information on the structural setting and geometry of the reservoir, and that we derived time-depth relationships, interval velocities, and corridor stacks from the data. Clearly, most of this information is not provided by a sonic log. So this should be clear now, even to non-expert readers.