

We would like to thank the anonymous reviewer who examined the resubmitted version of the manuscript for his/her additional comments and suggestions. We include the original comments followed by our reply.

In addition to changes based on reviewer's 1 and 2 comments, we performed an extensive work on discussion section and refined geological findings after discussion with colleagues who also worked on Rissdom-A project. Therefore, three additional co-authors who helped with data interpretation were included as co-authors Manfred Stiller, Ben Norden and Jan Henniges. The list of this additional changes can be found after the reply to the reviewer's comments.

## Remarks

The references to pages and document lines are made using the document "clean" manuscript version

## Anonymous Referee #2

1. **Thank you for your submission. The manuscript shows an important application of seismic imaging at a geothermal site using distributed acoustic sensing (DAS). The manuscript shows a migrated 3D volume using DAS vertical seismic profiling and provides structural and stratigraphic interpretation of the main reflectors. This is one of the few applications using 3D VSP with DAS for characterization of geothermal sites.**

**Overall, the manuscripts shows the necessary figures for its claims. However, I would suggest also adding a synthetic seismogram using well logs if possible. Additionally, I believe the paper needs careful proof reading to improve the readability and clarity. More specifically, the introduction should contain clear objectives, the claim and main manuscript outcomes. More work is needed in the literature overview to describe the previous research using DAS in geothermal sites and their achievements. Furthermore, I have added specific comments in the attached pdf.**

Thank you for your comment. An additional figure with synthetic seismogram, well logs and seismic cross section through the boreholes was added to the manuscript. Following the recommendation, readability and clarity of the paper was improved. Introduction section was rewritten following the structure suggested in the supplementary comments document.

## Supplementary comments

2. **I suggest re-working the Introduction as follows:**

**(1) review - what is the problem? what has been done before to solve the problem? List the citations you have. This part needs more information regarding the use of DAS in geothermal fields.**

**(2) claim - how is your work different from the previous work? How is it better and what are the challenges? Mention the limited use of DAS VSP with wireline fiber and how it can benefit characterization of geothermal fields. Describe your goals.**

**(3) agenda - summarize what you will show in the paper and how it relates to your claim. Summarize your findings.**

Introduction was rewritten following suggested structure (Pages 1-3).

3. **The authors provide a series of citations and applications, but more information on the applications of DAS in geothermal projects is needed. In particular, it's missing what has been done and what was found in the literature when it comes to DAS applications in geothermal fields. In addition to that, the authors should present why your application of DAS is different compared to what is seen in other geothermal fields and how it is helpful.**

Literature overview is added to the introduction section (Page 2, lines 38-52). Information on novelty of the presented work can be found on page 2; lines 53-58.

**4. what type of additional challenges?**

More explanation added on page 2 lines 38-41.

**5. acronym should be inside parenthesis**

Corrected (Page 4, line 90).

**6. Increasing the gauge length will have an effect similar to a spatial filtering, smoothing the signal. Can you add more discussing around how choosing 40 m gauge length might influence the resolution?**

More discussion on the influence of the 40 m gauge length to the resolution is added on page 4, lines 94-98.

**7. Was the 3D VSP from both wells merged to create one volume?**

Yes, correct. Data from both wells were processed uniformly and used as an input for the migration. For additional clarity name of the table changed to: 3D DAS VSP data processing flow for wells E GrSk 3/90 and Gt GrSk 4/05 (Page 5).

**8. It's not very clear to me what this step is? is this something like spectral whitening?**

No, we used a moderate wavefield sharpening by a tau-p method (slant stacking). For clarity, in table 1 (Page 5) step "Data enhancement" was renamed to "Coherency enhancement", description was changed from "Moderate wavefield enhancement" to "Moderate wavefield sharpening by tau-p method".

**9. Too many paragraphs, which ended making for a difficult read. It could be condensed into one.**

Formatting of the text was improved: paragraphs were merged into one (Page 6; lines 118-124).

**10. the fold map seems to be quite uneven, were there issues in acquisition or accessibility issues during the survey?**

The original acquisition campaign was planned in 2 boreholes. Unfortunately, due to the cable failure event described (section 2.1, page 5 lines 106-109) the resulting coverage was significantly restricted. In addition, sentence on budget limitations shifted from the discussion section (Page 4; lines 101-102).

**11. The result after MPD reduces the relative amplitude quite significantly of what looks like is signal in comparison with the strong 3.7km reflection. This makes me think there could be some signal leaking after MPD? Or is there another explanation? For example, the strong reflection at 4.1km, present on both volumes, has much lower amplitude on the MPD result.**

Substantial tests were performed to guarantee little to no amplitude leaking after the MPD. In Martuganova et al. 2021 it was demonstrated that suggested denoising successfully identifies resonances in the data and significantly improves the S/N without considerable influence on the signal.

The observed differences in amplitudes were present on a first version of Figure 5 due to a few amplitude normalisation processes. 1) Due to uneven distribution of the bin density, data is normalised (divided by) bin density for migration to ensure more even amplitudes. 2) Amplitudes are normalised using RMS amplitude calculated in a window from 3400 to 4400 m.

In the updated version of Figure 5 (Page 10) we tried to improve amplitude balancing for the noisy cube such that the signals amplitudes are more equivalent and remaining differences are most of all MPD-caused.

**12. It would be helpful to point where the noise is.**

Horizon discontinuities pointed out by arrows; Noisy region highlighted by blue ellipse (Figure 5; page 10). Corresponding references to these pointers are added to the text (Page 11; lines 200-201).

**13. where is this shown?**

Size estimations added to Figure 4. In addition, text was modified accordingly (Page 10, Figure 4). In addition, the corresponding text modification was introduced on page 11, lines 203-205.

**14. It's difficult to follow this just from Figure 6.**

Additional ticks are added to the Figure 6 (Page 12), so the maximum depth of 4500 m is easier visible.

**15. are the vibration points for the surface seismic the same? or denser?**

Vibrator points locations are not the same. 3D surface seismic survey used a regular grid with source positions. The corresponding acquisition scheme can be found in Krawczyk et al. 2019 or Stiller et al. 2018.

**16. The fact that the binning of the surface seismic is 2x less dense seems to have been a choice in the processing, correct? The surface seismic doesn't have the same issues with illumination, I assume due to having denser shot points.**

The binning of the surface seismics is based on its acquisition geometry, i.e. source and receiver spacing. For the borehole data different bin size was chosen to achieve a compromise between sufficient bin fold and dense spatial sampling.

**17. please spell out your calculation.**

Description of the performed calculation was added to the text (Page 11, lines 211-217).

**18. are you able to produce a synthetic seismogram using sonic and density logs? how do these reflections compare with a synthetic seismogram?**

Additional figure (Figure 7, page 13) with synthetics, logs and 2D cross-sections intersecting wells was added to the paper.

**19. Please add 2D cross-sections intersection the wells, including the well tops. It is difficult to see from the 3D view where the top and base on the seismic.**

Additional figure (Figure 7, page 13) with synthetics, logs and 2D cross-sections intersecting wells was added to the paper.

**20. On the 3D VSP, it looks like the reflection is at the top rather. Could you comment on this difference?**

This is the artifact of the 3D visualisation. Since the 3D cube is tilted and the inline is located on some distance from the borehole trajectory it creates such visual effect.

**21. I'm not sure if I fully understand this. When I look at Fig.4a, the blue rectangle includes areas of what seems to be zero coverage. Was any extrapolation used?**

After discussions with co-authors originally suggested blue rectangle was changed to a complex polygon which follows the shape of the data better (See Figure 4a; page 10). This allowed to clip out excessive areas of extrapolation. For gridding convergent interpolation method (Petrel software) was used with a grid cell size 12.5 to 12.5 m.

**22. please make sure you check the journal's rules for citing manuscripts in preparation.**

Reference (Norden et al., in preparation) was changed to pers.comm. and removed from the reference list.

**23. for this project or overall?**

For the project. "within this project" was added to the sentence for clarification purposes (Page 18, line 303).

**24. This statement is a bit unclear. Based on what?**

"with permanently installed fibre optic cable" added to the sentence for clarification (Page 18, line 315).

**25. I don't fully agree with the low cost because the wireline cables can be quite expensive and you still count on rig time. It could be possibly lower the cost when compared to geophone VSP.**

"in comparison with VSP acquired using geophones" added to the text (Page 18, line 318).

**26. could you comment on the coupling mechanisms of the wireline fiber?**

Details on survey, including cable installation can be found in the section 2.1 In addition, "and hanging freely with 1 m slack applied" added to the text for additional clarity (Page 3, line 87-88).

**27. I agree the authors present a unique dataset in the field of geothermal, specially when it comes to 3D VSP acquired on wireline data, which is a very unique niche itself. However, there have been other examples of seismic data acquired with DAS at geothermal fields. One example is the FORGE site, in Utah, USA, to detect microseismic events and to record guided waves. I suggest the authors add a more comprehensive literature overview in particular to geothermal applications.**

Literature overview was added in the introduction section (Pages 1-2).

**28. specify what are good results.**

Good results change to "A detailed imaging of the target reservoir interval (with vertical resolution up to 16 m)" (Page 18-19, lines 332-333).

**29. I suggest adding this information to Section 2.1 for clarification on the data acquisition.**

Sentence related to budget limitations was moved to section 2.1 (Page 4, lines 101-102).

**30. This belongs to the literature overview.**

This section was modified to shift more into the direction of the comparison of our survey with other known DAS VSP campaigns (Page 19, lines 338-347).

**31. This is new information in the discussion - some evidence or citation to previous work must be added.**

This is a conclusion for our dataset specially. "for our dataset" was added to the text. I hope that this clarifies the issue (Page 19, lines 357).

**32. move to the beginning of section**

The paragraph was rewritten according to latest discussions on geological data (Page 20, lines 377-382).

**33. can you comment on possible sub-seismic faults?**

Thank you for a good question. Sub-seismic faults are important for the geothermal energy reservoirs, since they are often considered as a pathways for fluid flow. One of the scientific objections for this detailed imaging using vertical seismic profiling was to study local discontinuities elements in the reservoir section. As a result, neither borehole seismic cube nor surface seismic cube detected apparent faults or fractures. Nevertheless, although the DAS seismic cube had a higher resolution than same cube from 3D surface seismic, it is still limited at these large depths.

First, the created fracture by the hydrofracturing cannot be imaged unless there is a distinct acoustic contrast or offset detectable by seismic methods. For 3D DAS VSP imaging, gauge lengths of 20 and 40 m were used. These values might be too high to detect small scale features, such as fractures. Theoretically, a smaller gauge length is necessary for small scale details imaging, such as fractures, but it comes at the expense of having a lower signal-to-noise ratio, which is important at these large depths.

To achieve a sharper and more detailed image at the Groß Schönebeck, it is necessary to further improve the velocity model used for migration. Sophisticated anisotropy study and inclusion of the heterogeneities into the existing layered velocity model will allow to further improve the reservoir image. This might be especially important for the potential fracture mapping in the case of data acquisition with active seismic methods.

To better understand the expected response from the fractures, it is essential to perform modelling to predict the wave propagation in the fractured reservoir. It could help to estimate the size, contrast required to image a fracture, characterise, and interpret the individual response with such modelling. Further modelling studies are needed to evaluate necessary acquisition parameters.

**34. I suggest removing this or adding an explanation why you consider still a new method.**

"is still a relatively new method" was removed from the text (Page 21, line 407).

**List of the additional changes to the manuscript:**

1. Figure 3 (page 9). Bundsandstein was corrected to Buntsandstein
2. Figure 3 (page 9). Zeichstein was corrected to Zechstein.
3. Figure 4 (page 10). The position of the inline 104010 in Fig (a) was corrected slightly moved to SE
4. Figure 8 (page 14). Position of the horizon R3 for XL 23825 was corrected.
5. Throughout the text the name Elbe basis sandstone was changed to Elbe reservoir sandstone (ERS).
6. Former bottom Elbe basis horizon interpreted from the DAS VSP data renamed into intra-bottom Elbe reservoir sandstone horizon (intra-bottom EBS).
7. Throughout the text the name of the horizon R1 changed from top of Hannover Fm. to within Mellin-Schlichten R1.

8. Throughout the text the name of the horizon R3 changed from top Dethlingen Fm of to within Dethlingen Fm R3.
9. Definitions of the interpreted horizons introduced to the text.  
R1 (Page 14, lines 245-248).  
R3 (Page 14, lines 249-251).  
Top Elbe sandstone reservoir (Page 15, lines 280-281).  
Intra-bottom Elbe sandstone reservoir (Page 15, lines 269-274).
10. Acronym Slb changed to Schlumberger (Page 3, lines 85-86).
11. fine-to-coarse grained sandstone added on page 15, line 257 for the characterisation of Dethlingen Fm.
12. "This layer was deposited in aeolian setting and then reworked by aquatic processes." – was added for the characterisation of Dethlingen Fm. (Page 15, lines 258-259).
13. Contributions of additional co-authors has been added in author contributions section
14. Acknowledgement section was corrected, excluding co-authors of the current version of the manuscript.
15. Spelling of "signal-to-noise" ratio was made consistent throughout the text
16. Spelling of "upgoing" ratio was made consistent throughout the text
17. Spelling of "ray tracing" ratio was made consistent throughout the text
18. Small text corrections, such as changing from seismic to seicmics, articles corrections, typos corrections, language improvements (changes marked by red in case of deletion, blue in case of added words in revised version of the manuscript)

# 3D deep geothermal reservoir imaging with wireline distributed acoustic sensing in two boreholes.

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**Abstract.** Geothermal exploration will help moving towards a low-carbon economy and provide a basis for green and sustainable growth. The development of new practical, reliable methods for geophysical characterisation of a reservoir has the potential to facilitate a broader application of deep geothermal energy. At the Groß Schönebeck in-situ laboratory, a unique vertical seismic profiling (VSP) dataset was recorded in two 4.3 km deep geothermal boreholes using fibre optic cables in early 2017. The experiment set-up consisted of 61 vibrator points organised in a spiral pattern around the well site to ensure a proper offset and azimuth distribution in the target reservoir section. Data were processed using a standard workflow for VSP. As a result, a detailed 3-dimensional 0.75 x 1 x 4.5 km size image around the existing boreholes was created using the Kirchhoff migration algorithm with restricted aperture. The imaging resolved small-scale features in the reservoir essential for the future exploration of the geothermal research site. Borehole data with vertical resolution up to 16 m revealed the existing depth variations of the Elbe basis-reservoir sandstone horizon at 4.08 - 4.10 km depth and indications of an unconformity in the area where we expect volcanic rocks. In addition, in the borehole data a complex interlaying with numerous pinch outs in the Upper Rotliegend reservoir section (3.8 to 4 km depth) was discovered. Thereby, we demonstrate that wireline fibre optic data can significantly contribute to exploration by providing an efficient and reliable method for deep geothermal reservoir imaging.

## 15 1 Introduction

The EU aims to expand geothermal energy use and reach 2570 TWh by 2050 (The European Commission, 2021). Nevertheless, in Europe, the amount of easily accessible hydrothermal resources are limited. Consequently, the primary growth in geothermal power production is expected to come from projects associated with developing enhanced geothermal systems (EGS) (Carrara et al., 2020). The development of geothermal plants which exploit EGS reservoirs is associated with increased developing costs, high risks associated with the drilling of deep wells, and the possible requirement of well stimulation (Carrara et al., 2020). Due to these reasons, EGS plants are quite rare within the EU (IEA Geothermal, 2020). To overcome the high upfront investment costs barrier and to support the growing demand for the exploration of deep geothermal reservoirs (3.5-4 km), it is essential to develop modern, reliable technological solutions to reduce costs and risks related to the deep geothermal wells drilling

and EGS plants installations. According to the geothermal energy technology development report 2020 (Carrara et al., 2020) 25 , geothermal exploration could be optimised by utilising new methods, i.e., applying fibre optics cables to measure particle displacement.

Measurements with a fibre-optic cable installed in diverse environments are widely applied for seismic data acquisition for versatile research topics such as ~~urban seismology (Dou et al., 2017; ?; Yuan et al., 2020)~~, glacial studies (Booth et al., 2020; Brisbourne et al., 2021; Hudson et al., 2021), ~~geothermal exploration (Li and Zhan, 2018; LeHouch et al., 2021)~~, ~~volcanology (Nishimura et al., 2021)~~ and ~~underwater seismology (?Lior et al., 2021)~~ ~~volcanology (Nishimura et al., 2021)~~, ~~underwater seismology (Spica et al., 2020a; Lior et al., 2021)~~ and ~~urban seismology (Dou et al., 2017; Spica et al., 2020b; Yuan et al., 2020)~~. Perhaps, one of the most well-studied distributed acoustic sensing (DAS) applications is cable deployment for data acquisition in boreholes. Measurements with a fibre-optic cable installed along the casing or behind the tubing are widely and successfully applied for borehole seismic data acquisition. 3D vertical seismic profiling (VSP) imaging results with permanent cable installation 35 include applications for oil and gas exploration (Jiang et al., 2016; Shultz and Simmons, 2019; Zhan and Nahm, 2020), the monitoring of CO<sub>2</sub> reservoirs (Humphries et al., 2015; Götz et al., 2018; Correa et al., 2019; Wilson et al., 2021), and for mineral exploration and mining (Bellefleur et al., 2020). Nevertheless, in a vast number of already drilled ~~and cased~~ boreholes, only measurements with a wireline logging cable are feasible. Surveys with ~~wireline installation~~ ~~retrievable fibre optic cable~~, such as the dataset collected for petroleum exploration in China, near Tangshan, Hebei (Yu et al., 2016), are still quite unique and 40 rarely found in the ~~literature. For geothermal exploration, a very limited number of wireline DAS with active seismic source was applied (Miller et al., 2018; Henniges et al., 2021). Data acquisition in a harsh environment, such as elevated temperatures, poses peer-reviewed literature.~~

~~Geothermal exploration sites pose~~ additional challenges in terms of the requirements for the instrumentation. ~~Fibre optic cables have increased durability and are less subjected to corrosion compared to conventional sensors (Reinsch et al., 2015).~~ 45 ~~Therefore seismic data acquisition using DAS becomes feasible for harsh conditions (elevated pressure, salinity, temperature, high acidity) for extended time periods. One of the essential aspects of the EGS project development is microseismic monitoring during hydraulic fracturing. Lellouch et al. (2021) demonstrated that a vertical downhole DAS array could be successfully used to detect low-magnitude earthquakes at a range of up to 10 km from the borehole location in the Frontier Observatory for Research in Geothermal Energy (FORGE) site in Utah. Fibre optic cable buried at a depth of 0.5 m at Brady geothermal field allowed to record a substantial amount of earthquakes and provided information on the evolution of the seismicity during geothermal plant operation (Li and Zhan, 2018). Using optical cables, a allows surveys with dense spacing, which are very expensive and often cost prohibited for geothermal applications in case of data acquisition with conventional methods. A detailed image of the subsurface can be created, using, for instance, using various seismic imaging techniques (Krawczyk, 2022). In addition, the deployment is more efficient in terms of time and costs. Nevertheless, DAS VSP surveys for geothermal are still~~ 50 ~~rarely acquired (Miller et al., 2018; Trainor-Guitton et al., 2018). Miller et al. (2018) demonstrate limited results in the form of unmigrated seismograms with a maximum depth of 297 m. In the case of the 3D imaging results presented from the Brady geothermal field, the major difference is in comparison with a standard installation of conventional borehole instruments. Therefore, data collection with an application of fibre optics technology can provide a reliable and efficient method for~~



~~exploring and monitoring geothermal reservoirs~~-depth, which is limited to 600 m in this case study (Trainor-Guitton et al., 2018)

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Although there are a few examples of geothermal exploration applications, only one shallow geothermal VSP has thus far been reported in the literature with 3D imaging results. Constantinou et al. (2016) showed a test wireline DAS-VSP dataset with a maximum surveyed depth of 2580 m MD acquired at Rittershoffen geothermal site, however, there has not been any 3D imaging results reported from a deep geothermal well using wireline DAS VSP to the best of the author's knowledge. Moreover, only a very limited number of publications on wireline DAS applications with active seismic sources can be found in the literature. Therefore, further thorough research on the evaluation of the wireline DAS data in geothermal applications is needed.

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This paper presents results from one of the first applications of DAS VSP for deep geothermal exploration at the Groß Schönebeck geothermal research site down to 4 km depth. First, we evaluate the acquired data and demonstrate cable installation's influence on the data quality. Then, after a brief explanation of the processing flow, the 3D DAS VSP imaging results at Gross Schoenebeck will be presented, followed by geological interpretation. In conclusion, we will focus on the deliverables of the 3D DAS VSP and how this can contribute to the characterisation of the reservoir and geothermal exploration.

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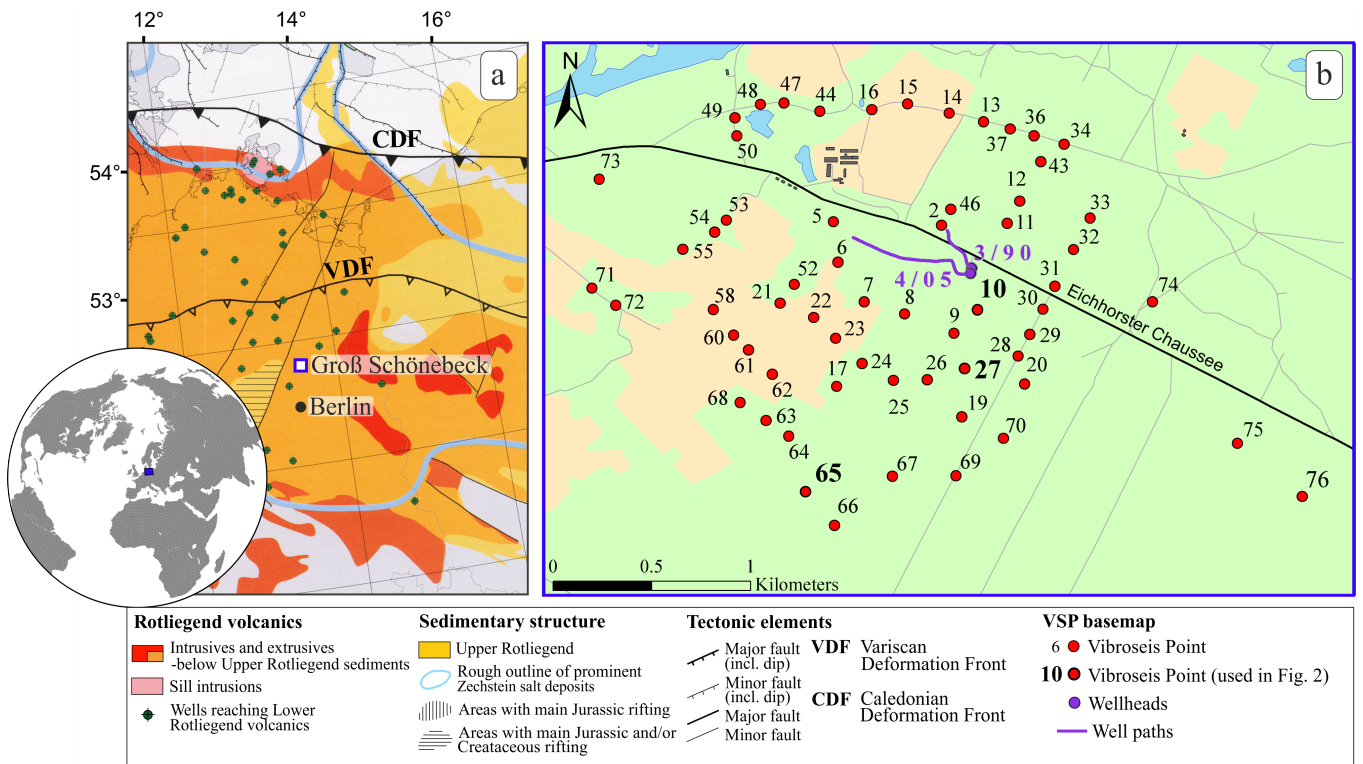
## 2 The Groß Schönebeck site

The in-situ laboratory Groß Schönebeck is located in the Northern German Basin, one of Germany's main regions with deep hydrothermal resources. The joint research project RissDom-A (RissDominierte Erschließung in German: fracture-dominated exploitation) aims to gain expertise in sustainable energy production from low permeability geothermal reservoirs by developing Enhanced Geothermal Systems (EGS). The Buntsandstein sandstone formation and volcanic rocks of Lower Permian (Rotliegend) (Figure 1a) age are of interest for the direct use for the geothermal energy production (Blöcher et al., 2016). A successful geothermal exploration case study can lead to broader geothermal energy usage in the regions without hydrothermal potential. Moreover, the geological setting at the experiment site is typical for a broad part of Northern Europe. Therefore, the acquired knowledge from this case study can be applied to geothermal exploration programs in other areas with similar geological conditions.

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To deepen the understanding of the geological structures interpreted on sparse vintage 2D seismic lines and locate possible faults within the area of interest, a high-resolution 3D reflection seismics acquisition campaign was carried out in February/March 2017 (Stiller et al., 2018; Krawczyk et al., 2019). The 3D surface seismic survey was designed to cover an area of 8 km by 8 km, focusing on target reservoir depth from 4 to 4.3 km. Since the studied geothermal reservoir zone is located at a depth greater than 4 km and overlaid by Zechstein salt, it is a challenging target for exploration with conventional seismic methods.

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**Figure 1.** Location of the Groß Schönebeck geothermal site. (a) Rotliegend volcanics and sedimentary distribution in the Southern Permian Basin (compilation from Krawczyk et al. (2019)). (b) Base map of the Groß Schönebeck geothermal site with two boreholes (violet circles) in the centre and 61 VSP source points (red dots) arranged in a spiral pattern around.

## 2.1 The distributed acoustic sensing vertical seismic profiling survey

90 In contrast to surface seismics, VSP has the advantage of shorter reflection travel paths. Therefore, the amplitudes are theoretically less subjected to attenuation. As a result, this provides a better [signal-to-noise ratio](#) and broader frequency content. Thus, to improve the resolution of seismic data, which is limited due to the thick salt layer (more than 1 km), and to provide detailed imaging around the existing boreholes, an extensive VSP experiment using wireline DAS technology was conducted prior the main surface seismic experiment in February 2017. Two wireline hybrid cables (electrical and optical;

95 from [SLB-Schlumberger](#) (NOVA-F) and GFZ (Rochester)) (Henninges et al., 2011) were temporarily deployed [and hanging freely with 1 m slack applied](#) inside the casing of two deep water-filled boreholes. Nearly vertical well E GrSk 3/90 (maximum inclination  $7.2^{\circ}$ ), which was formerly used for oil and gas exploration, and Gt GrSk 4/05 (maximum inclination  $49^{\circ}$ ) form a geothermal doublet (Figure 1b). Two [hDVS](#) (heterodyne distributed vibration sensing ([hDVS](#))) interrogator units from Schlumberger were connected to single-mode fibres and used to record the strain along the boreholes with 5 m spatial sampling.

100 A 20-m gauge length was used for data recordings in the field. Later, this value was adjusted to 40 m for E GrSk 3/90 according to the velocity profile in the reservoir section to get an optimal [S/N ratio](#) and preserve data resolution

(Dean et al., 2017). Data recorded in Gt GrSk 4/05 were used with only 20-m gauge length due to the loss of the raw fibre optical data. Although the approach suggested by Dean et al. (2017) should help to optimise the data quality, a 40-m gauge length might be too high to detect small scale features, such as fractures. Theoretically, a smaller gauge length is necessary for small scale details imaging, such as fractures, but it comes at the expense of having a lower signal-to-noise ratio. More details on gauge length optimisation for the dataset acquired at Groß Schönebeck can be found in Henniges et al. (2021).

The measuring campaign consisted of 1 start-up testing and 3 data acquisition days in total. The 61 vibrator source points (VPs) had a spiral layout around the target area with varying offsets from 188 to 2036 m around the boreholes to ensure a good azimuth distribution (Figure 1b). Due to budget limitations, the number of vibrator points had to be restricted and often positioned in such a way that they do not have overlapping ray penetrating areas. As seismic source, four heavy Mertz M12 Hemi 48 vibroseis trucks were used with a peak force of 200 kN (45100 ~~Hbf~~Lbf) each. All source units vibrated simultaneously at each VP location and guaranteed an average vertical stacking fold of 16 per source location. A linear sweep of 10 – 112 Hz and 36 s length was used for data acquisition. Several VPs with larger offsets, were recorded using a sweep from 10 to 96 Hz.

Due to the cable failure in Gt GrSk 4/05, the recording of the last 500 m in the reservoir section was lost, and the maximum surveyed depth is limited to 3716 m measured depth (MD). Moreover, we were only able to record 18 VPs from the originally planned 61 because the cable was retrieved from the borehole after only 1 day of acquisition. This event led to significantly reduced subsurface coverage of the survey design between the two wells. In E GrSk 3/90, we recorded the planned 61 VPs and the maximum surveyed depth is at 4251 m MD. Nevertheless, recorded datasets from this borehole have inconsistent amplitudes caused by unknown reasons, which requires further investigations (Henniges et al., 2021). Overall, all mentioned details make this dataset acquired at the Groß Schönebeck geothermal research site very challenging for data processing. We will focus on the processing flow in the next section of the paper, which we used to successfully identify reservoir details.

### 3 Data processing

For the 3D DAS VSP dataset a processing flow containing typical elements was adapted to the Groß Schönebeck survey specifics and then applied to the data (see Table 1). The major steps and parameters details are discussed in the following sub chapters.

#### 3.1 Data ~~preconditioning~~conditioning

As first step the proper geometry was assigned to the raw uncorrelated data, which included source and receiver coordinates, elevations and true vertical depths calculated using boreholes trajectories. Each VP recording set contained a various number of recorded sweeps, ranging from 12 to 37. Data within each VP were sorted on increasing MD and vertically stacked using a trimmed mean stack, which helped to exclude amplitude outliers. Wireline records are frequently suspected to ringing noise, which ~~occurs~~represent a standing wave phenomenon, occurring in those depth intervals of the boreholes where the cable can move freely ~~and~~(Martuganova et al., 2021). This type of the noise creates resonances with a fundamental frequency and higher overtones in the amplitude spectrum.

**Table 1.** 3D DAS VSP data processing flow [for wells E GrSk 3/90 and Gt GrSk 4/05.](#)

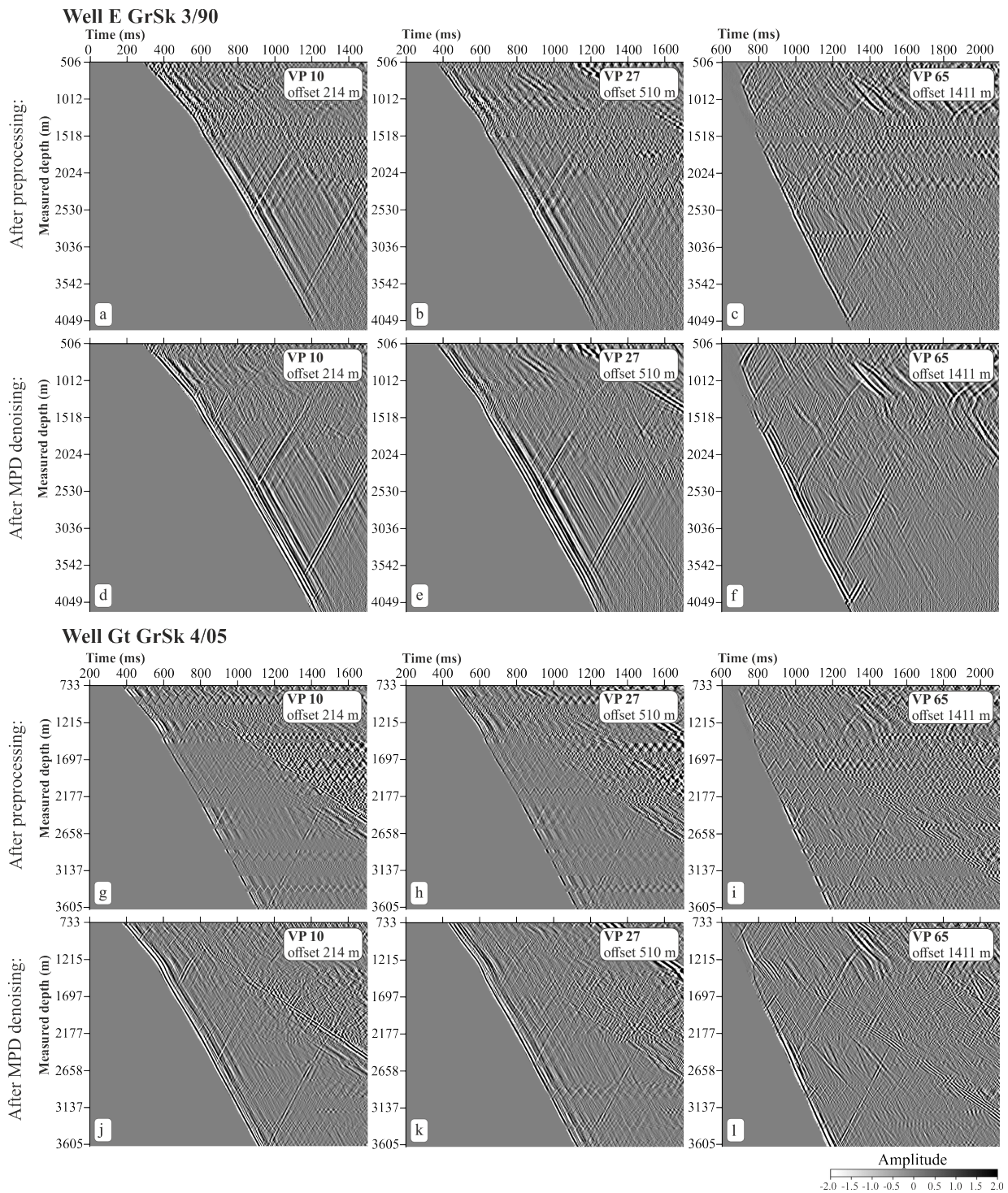
Processing step	Description and parameters
Geometry input	Source and receiver coordinates, depths
Trimmed mean stack	Suppression of impulsive noise
Ring noise suppression	Matching pursuit decomposition (MPD) with Gabor atoms
Correlation with pilot sweep	10 - 112 Hz, 10 - 96 Hz, 36 s, 360 ms taper
Conversion to strain rate	Time derivative
First arrival time picking	The peak of the direct downgoing P-wave
Amplitude corrections	Spherical divergence compensation ( $t^{1.5}$ ) and lateral equalisation
<a href="#">Data Coherency</a> enhancement	Moderate wavefield <a href="#">enhancement</a> <a href="#">sharpening by tau-p method</a>
Velocity model building	Migration velocities from 3D surface seismics and sonic log from E GrSk 3/90 as initial velocity model, checked and optimised by <a href="#">ray-tracing ray tracing</a>
Ray tracing	Mapping of the reflectivity for all source receiver pairs
Wavefield separation	Subtraction of downgoing P-wave field (median filter) by a 9 trace median operator
Deterministic deconvolution	Waveshaping zero-phasing of the upgoing wavefield, removal of multiples
Polarity reversal	180° phase shift, to match polarity convention of conventional geophone data
3D imaging	3D Kirchhoff migration with restricted aperture of 12 degrees

Figure 2 shows selected VPs with variable offsets such as 214 m, 510 m and 1411 m for the borehole E GrSK 3/90 after pre-  
135 processing (vertical stacking, correlation with the pilot sweep and subsequent differentiation) and denoising. All seismograms have a distinct P wave arrival; however, they are heavily dominated by a coherent characteristic striped or zig-zag noise. For instance, depth intervals 890 - 966, 1588 - 1816 m for VPs recorded in E GrSK 3/90 are contaminated by this type of noise (Figure 2 panels a, b, c). It appears that the noise distribution does not change significantly from one VP to another and affects shallower depth regions more than the deeper ones. Also, it can be noted that borehole Gt GrSk 4/05 has more noisy intervals,  
140 in comparison with E GrSK 3/90, and with higher amplitudes, for example, for depth regions at 873 - 980, 2177 - 2177, 3330 - 3409 m (Figure 2 panels g, h, i).

Ring noise clearly represents a challenging problem and should be tackled by means of data processing. We did a few denoising test using different denoising approaches, including Burg adaptive deconvolution ([Burg, 1972, 1975](#)) and Time-Frequency domain attenuation ([Elboth et al., 2008](#)). The optimal denoising result was achieved using a novel approach based  
145 on matching pursuit decomposition (MPD) using Gabor atoms, described in Martuganova et al. (2021). According to this method we formed an overcomplete Gabor dictionary to decompose the original signal. Then using atomic parameters such as amplitude, frequency and position in time we determined parts of the signal representing slapping of the cable and subtracted them from the data to perform the denoising. To improve the [S/N-signal-to-noise](#) ratio of the data we applied the MPD denoising

method after stacking, but before correlation to avoid smearing the noise by the correlation process. The results of denoising  
150 for two boreholes [are](#) given in Figure 2 on panels d, e, f and j, k, l for E GrSK 3/90 and Gt GrSk 4/05 respectively. MPD  
denoising eliminated almost all noise on the seismograms and significantly improved traceability of the reflections, which are  
no longer obscured by the ringing noise.

After denoising, the correlation with the pilot sweep and time-differentiation to convert data to the strain-rate were applied  
to the data. This was followed by amplitude corrections (spherical divergence correction and lateral equalisation) and moderate  
155 wavefield enhancement. Also, measured depths were converted to true vertical depth below seismic datum elevation (TVDSD),  
and later in the text, we refer to it as depth.



**Figure 2.** Common-source gathers displays for different source positions with offsets 214 m, 510 m and 1411 m after preprocessing (a), (b), (c) for well E GrSk3/90 and (g), (h), (i) for well Gt GrSk4/05; after noise subtraction using MPD denoising method and a moderate coherency enhancement (d), (e),(f) for well E GrSk3/90 and (j), (k), (l) for well Gt GrSk4/05.

### 3.2 Velocity model building and ray tracing

Several independent data sources were used to determine the velocity function for main stratigraphic layers of the region and assign appropriate P-wave velocities (Figure 3). First, velocity profiles recorded at zero offset source position were calculated with the Lizarralde smooth inversion method (Lizarralde and Swift, 1999) to get the main trend (Figure 3a black curve). Then, velocity values were updated according to calibrated sonic log data (Figure 3a thin grey curve) and the surface seismic velocity cube (Figure 3a, dark blue curve). The model was checked using the ~~ray-tracing results~~ ray tracing results calculated in commercial software VSProwess X (VSProwess Ltd.), and iteratively optimised to minimize the drift between the recorded and modelled arrival times for the rig shot at source position 10.

To improve the fit for far offset VPs a small anisotropic drift was included into the model. Thomsen's P-wave anisotropy parameters (Thomsen, 1986), namely  $\epsilon$  and  $\delta$ , for transversely isotropic (TI) media, 4 %  $\delta$  and 16 %  $\epsilon$  were selected for all layers down to the top salt. These parameters were tested and optimised, which allowed to reduce the standard deviation of drift for the longer offset VPs. Finally, all VPs were ray-traced through the constructed model, and reflection points (loci) for each source-receiver pair were extracted. The ~~comparison of the picked arrival and ray-traced~~ picked arrival times were compared with the ray traced times to check whether the smallest misfit for all available data was achieved. The average of the mean model drift for all VPs is 2.43 ms for the borehole E GrSk3/90 and 7.7 ms for Gt GrSk 4/05, respectively.

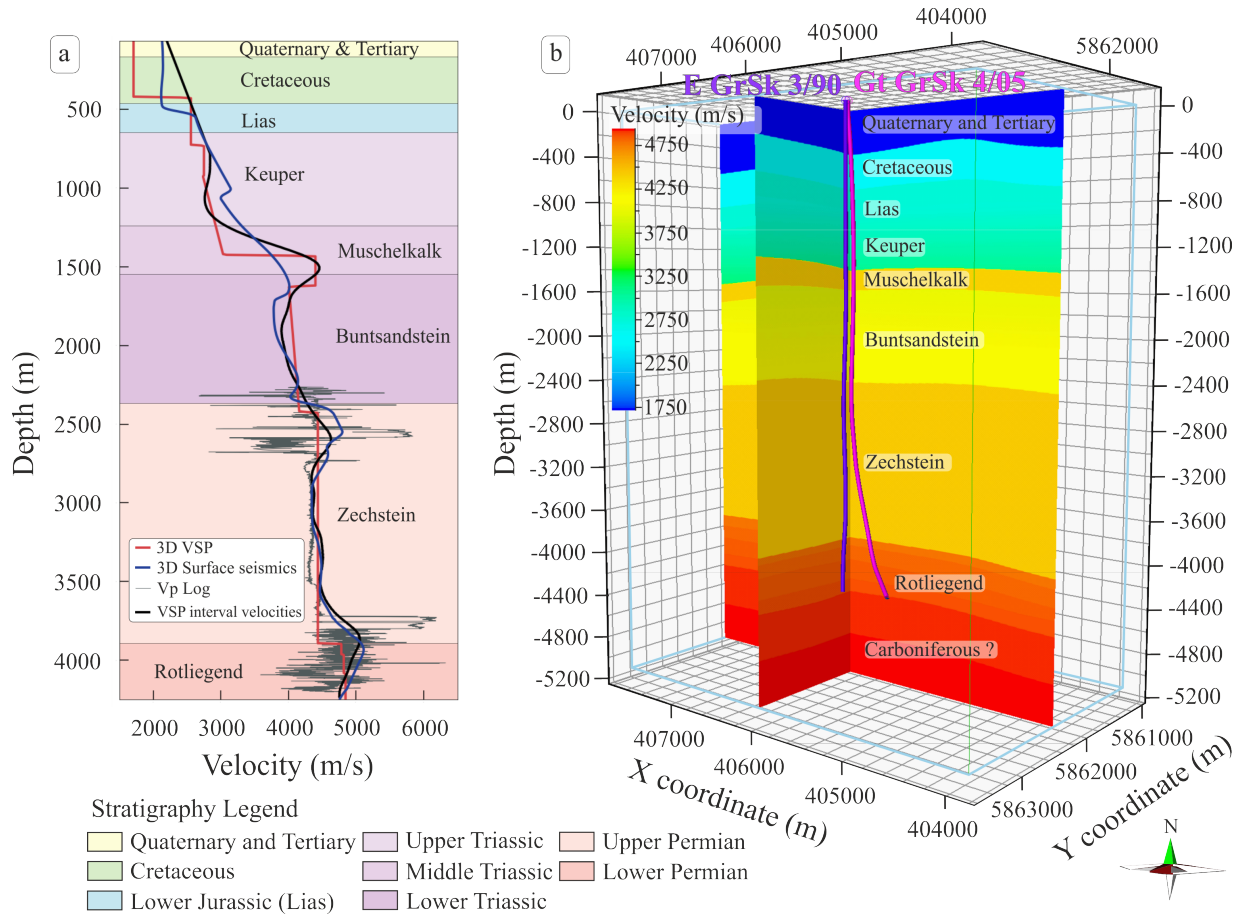
The layered 3D DAS VSP velocity model follows the geological model (Moeck et al., 2009) and has constant ~~or-vertical~~ layer velocities or vertical velocity gradients indicated by the sonic log data (Figure 3a red curve; Figure 3b). Potential lateral variations are not accounted for. The values vary from 1750 m/s in the upper Quaternary and tertiary layers to 5000 m/s in the Rotliegend (Permian) reservoir section.

### 3.3 Data preparation for migration

The next processing step includes wavefield separation and deconvolution. To separate the ~~up-going-upgoing~~ wavefield the downgoing P-wave field was subtracted using a median filter. We tested a few different wavefield separation techniques (~~F-K~~ FK transform, FP transform), and the cleanest result was obtained by applying the median filter. This filter delivered a cleaner residual ~~up-going-upgoing~~ response with less smearing of the amplitude artefacts, and also preserves the resolution of data. Prior to deconvolution, the ~~up-going-upgoing~~ wavefields were scaled by -1 changing the polarity of DAS data to match the required European convention (increase AI = negative number on a trace.) The separated wavefield was deterministically deconvolved, using individual downgoing responses as trace-by-trace operators, followed by a bandpass filter 8, 12 – 70, 80 Hz and a front mute.

To further prepare the data for imaging, source ~~staties~~ static corrections were applied. Additionally, data were moved to pre-migration depth using a model-based stretch to map points according to reflection-point loci. Due to significant data quality variations between shots caused by unknown changes in the response of the fibre, the amplitudes across all data points were normalised using RMS amplitude values calculated in a depth window selected on the most prominent salt sequence reflection

event. Each trace then was scaled by the inversed RMS trace value. The resulting pre-migrated seismograms were used as input for 3D imaging.



**Figure 3.** Velocity information at the Groß Schönebeck research site. (a) Velocity functions at the borehole E GrSk3/90 location. Red line - the curve extracted from the 3D DAS VSP velocity model shown in (b); dark blue line - the curve extracted from the 3D velocity model used for the 3D surface seismics prestack depth migration; thin grey line - sonic log measurement; thick black line - VSP interval velocities derived from the first break peaks using the method of smooth inversion after Lizarralde and Swift (1999). (b) 3D DAS VSP velocity model created using top formation surfaces to build an initial velocity model, which was then checked and optimised according to ray tracing results.

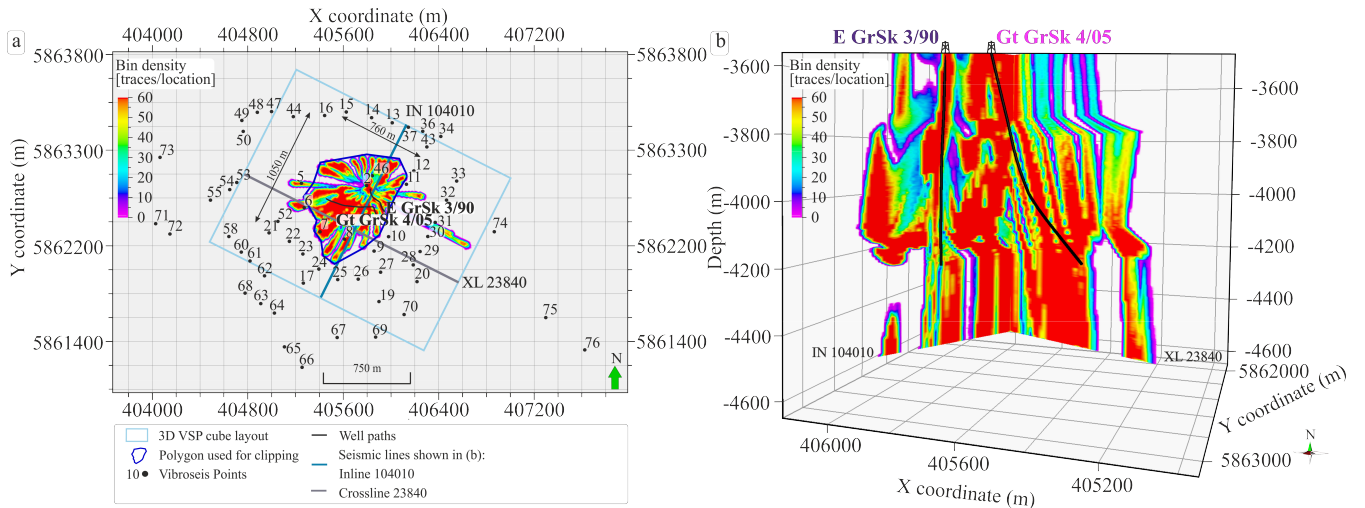
### 3.4 3D imaging

For imaging, a commercial 3D Kirchhoff migration algorithm (VSProwess Ltd.) was used. Calculated via [ray-tracingray tracing](#), the reflection-point loci for each source-receiver pair [is-are](#) interpolated and used to map each processed sample to its modelled image point coordinate. This is routinely known as VSP common depth point (CDP) mapping ([Dillon and Thomson, 1984](#))

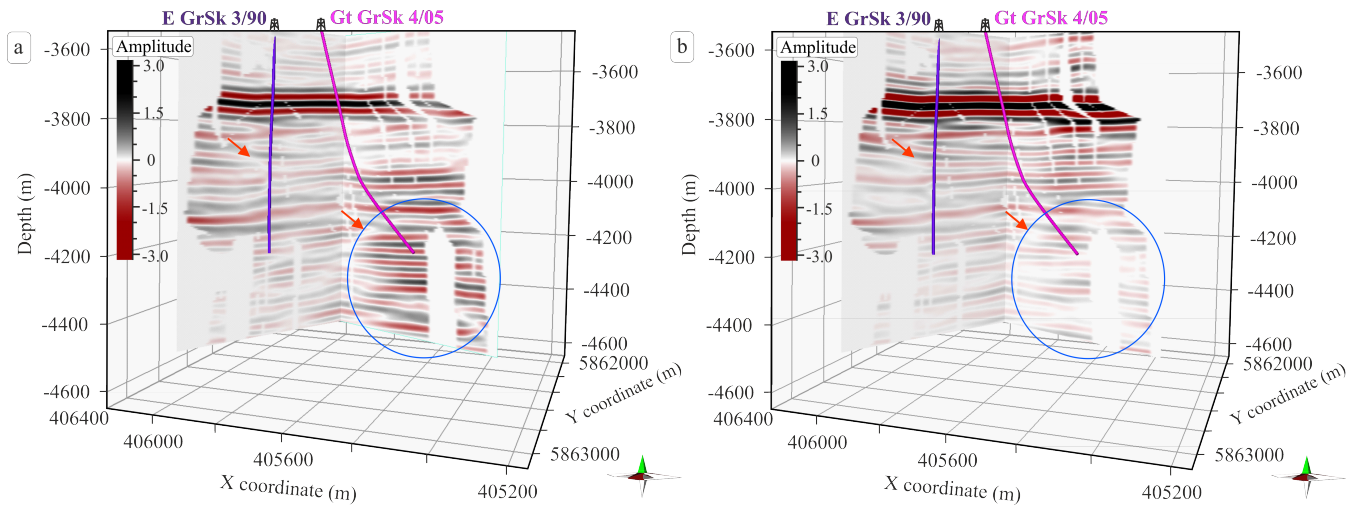


195 . Once the reflectivity is mapped approximately to the correct location it can be binned. An efficient surface tracking algorithm is used to find all those bins within the specified aperture angle intersected by the reflection ellipsoid.

For migration, we used a 12.5 m x 12.5 m horizontal and a 5 m depth bin size. After extensive testing, we chose a 12-degree aperture which allowed to sum the main reflections best and to preserve image details. In addition, the migration operator



**Figure 4.** Examples of the ray coverage for the study area. Depth slice of a 3D bin density volume at 4100 m depth (a). 3D visualisation of two seismic lines in the 3D bin density cube (b) (for location see a).



**Figure 5.** A comparison of 3D DAS VSP cubes generated with a model-based Kirchhoff migration algorithm (a) without and (b) with MPD denoising.

removed some of the imaging artefacts. A scaled version of each mapped sample is summed into each of these bins (normally  
200 cos-squared window). A by-product of migration is a bin count cube. A 3D bin density image along two lines and the depth  
slice at 4100 m are shown in Figure 4. This 3D visualisation discloses holes in the seismic coverage at 4100 m depth. Gaps  
in coverage are particularly noticeable east of the observation well. To avoid imaging artefacts, bin density information was  
used first to normalise amplitudes in the 3D DAS VSP volume. Afterwards, the bin density information is utilized to identify  
high uncertainty areas where the image fold is sparse and to clip the resulting cube in accordance to it. Furthermore, the  
205 density cube was employed to determine an area with a reasonable coverage (Figure 4a, dark blue rectanglepolygon) for further  
clipping of horizon maps. ~~Examples of the ray coverage for the study area. Depth slice of a 3D bin density volume at 4100 m  
depth (a). 3D visualisation of two seismic lines in the 3D bin density cube (b) (for location see a). A comparison of 3D DAS  
VSP cubes generated with a model-based Kirchhoff migration algorithm (a) without and (b) with MPD denoising.~~

The suppression of the ringing noise by means of MPD denoising and amplitude normalisation techniques, significantly  
210 improved the imaging results. Figure 5a shows the result of the migration which excludes denoising from the processing flow.  
The first problem that can be noticed are inconsistent significant ~~amplitudes~~ amplitude anomalies, especially clearly visible  
around borehole Gt GrSk 4/05 (Figure 5a, blue ellipse) in the reservoir section from 4000 m till 4500 m depth. Apart from that,  
the "noisy" cube has decreased resolution and horizon continuity in comparison with ~~a~~ the "clean" cube (Figure 5b, orange  
arrows).

## 215 4 Reservoir imaging

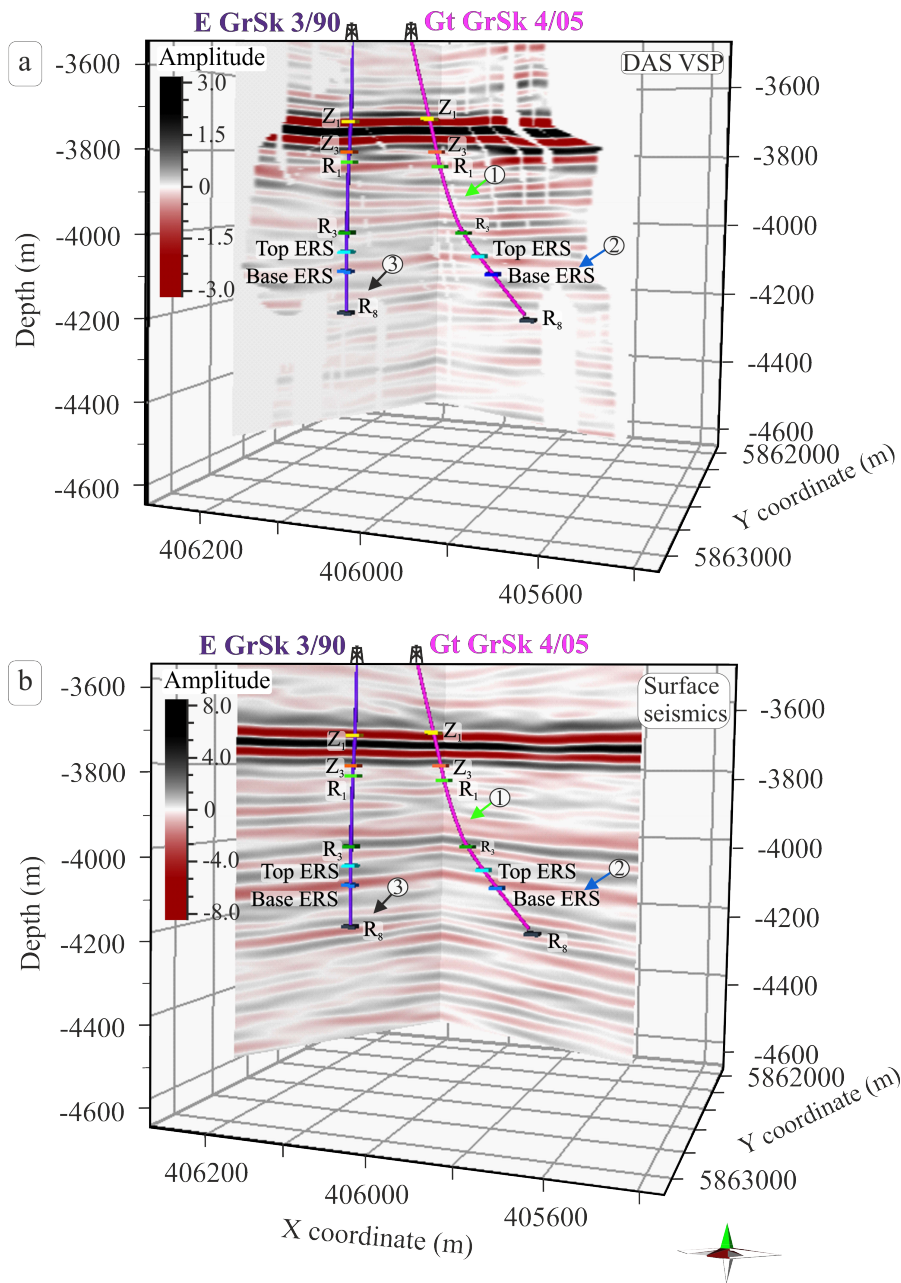
The resulting 3D DAS VSP cube image is 1600 m x 2000 m, which has a relatively limited illumination range with a maximum  
~~inline/crossline extent of less than 900 m~~ extent of 760 and 1050 m along inline and crossline direction respectively (extension  
estimated based on polygon for clipping; Figure 4). The image of the subsurface is the most complete and best around the  
boreholes. Reflections in the vicinity of the wells reach up to 4500 m depth (Figure 6). To interpret the 3D DAS VSP imaging  
220 results (Figure 6a), we compare it with the 3D surface seismic cube (~~Krawczyk et al., 2019; Norden et al., in preparation~~)  
(Krawczyk et al., 2019; B. Norden, personal communication, April 28, 2022) after prestack depth migration (Figure 6b). The  
polarity of the DAS data was changed to match the polarity of the geophones. The 3D surface seismics was ~~clipped~~ restricted  
according to the 3D DAS VSP cube layout. Bin size for borehole volume is 12.5 m x 12.5 m and for surface seismic volume is  
25 m x 25 m. This means that inlines / crosslines of the 3D DAS VSP cube are 2 times denser.

225 The reservoir section is situated at a depth interval between 4 - 4.5 km and has an average velocity ~~of~~ around 4700 m/s; the  
dominant frequencies in 3D surface seismics are between ~~20 and 50~~ 25 and 47 Hz. With wireline 3D DAS VSP the frequencies  
are from ~~30 to 70 Hz.~~ 34 to 73 Hz. Vertical seismic resolution can be estimated as quarter of the wavelength ( $\lambda$ ), which depends  
on velocity ( $V$ ) and frequency ( $F$ ) as follows:

$$\lambda = \frac{V}{F}. \quad (1)$$

230 This gives a vertical resolution estimation of ~~24-25~~ - 47 m for the conventional surface seismic cube and a more favourable 16  
- 34 m for the borehole seismic dataset.

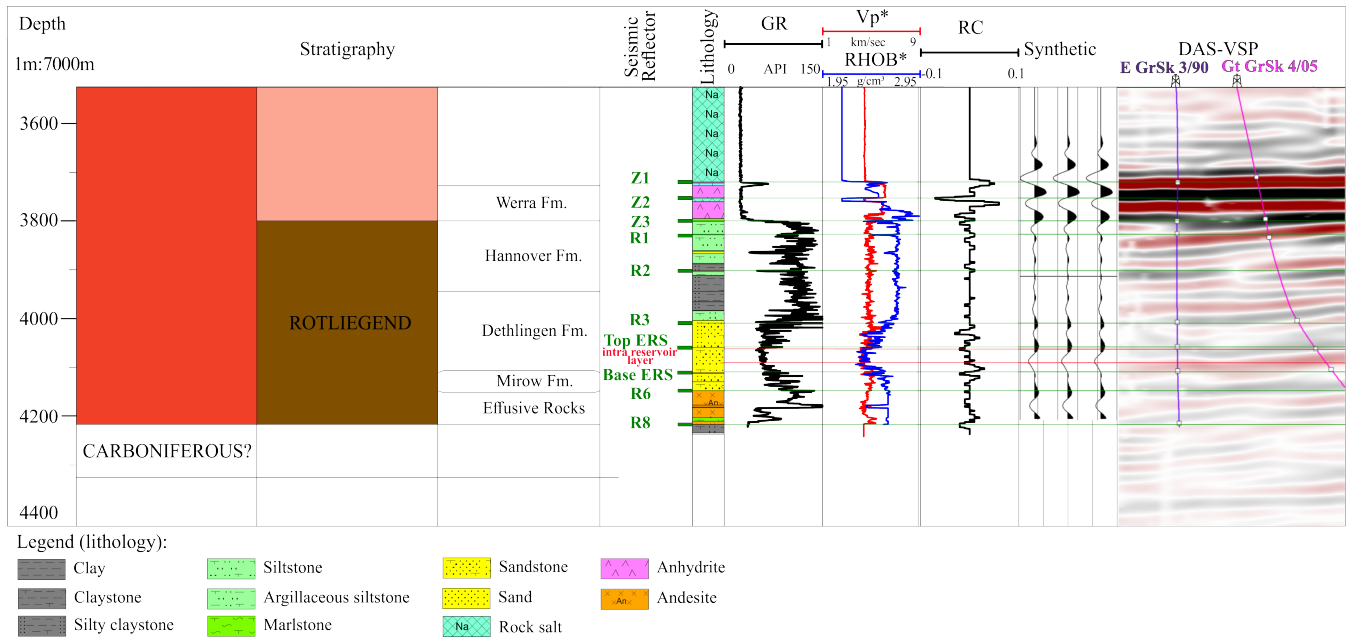
Several reflectors can be mapped with high confidence across both volumes. Especially the main marker horizons of the  
typical stratigraphy in the North German Basin were successfully imaged (Figure 6): top Staßfurt-Basalanhydrit Fm ( $Z_1$ ), top  
Rotliegend ( $Z_3$ ), ~~top of Hannover Fm.~~ within Mellin-Schichten ( $R_1$ ), ~~top of~~ within Dethlingen Fm ( $R_3$ ), the top and the bottom  
235 ~~Elbe-basis-sandstone (EBS) layers~~ of Elbe sandstone reservoir (top ESR, base ESR), and possibly top of the Carboniferous  
( $R_8$ ). Although both cubes have similarities, there are distinct differences related to the higher vertical resolution of the VSP  
measurements. In the following chapters we will focus on each structural feature separately.



**Figure 6.** A comparison of 3D DAS VSP cube (a) and prestack depth migrated 3D surface seismic cube (b). Arrows with numbers highlight major interpretation features in the 3D DAS VSP and 3D surface seismic cubes. Light green arrows (1) point out the difference in seismic resolution in the upper Rotliegend; dark blue arrows (2) show the position of the Elbe reservoir sandstone horizon. Dark grey arrows (3) mark the location of unconformity in lower Rotliegend formation. Main seismic reflectors labelled on the figures: top Staßfurt-Basalanhydrit Fm (Z<sub>1</sub>), top Rotliegend (Z<sub>3</sub>), within Mellin-Schichten (R<sub>1</sub>), within Dethlingen Fm (R<sub>3</sub>), top ESR - top of Elbe sandstone reservoir, base ESR - base of Elbe sandstone reservoir, R<sub>8</sub> - Base Effusive Rotliegend.

#### 4.1 Upper Rotliegend horizons

The most prominent reflections in both seismic cubes are closely situated reflection bands from the transition from salt to anhydrite (Staufurt-Basalanhydrit Fm (Z<sub>1</sub>)), followed by the reflection Z<sub>3</sub> from the base of Zechstein. Together these closely situated seismic responses create a complex wavelet superimposition consisting out of 5 phases – (Figure 6). Most clearly a characteristic Zechstein reflections are visible on the Figure 7, which shows a seismic cross-section extracted between two boreholes with well logs (gamma ray (GR), bulk density (RHOB) and sonic velocity (Vp)), lithology data and stratigraphy. Salt layers are underlayed by upper Rotliegend sediments.

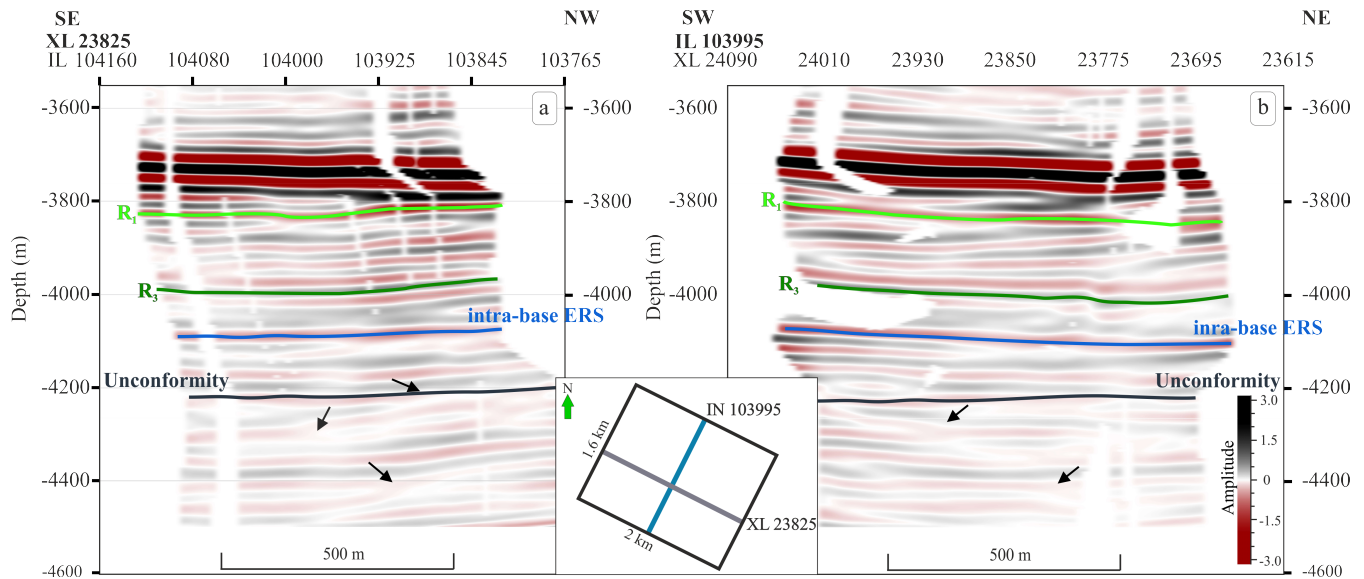


**Figure 7.** DAS-VSP seismic cross-section through the boreholes plotted together with well logs (GR: gamma ray, Vp: sonic velocity, RHOB: bulk density), lithology, stratigraphy, reflector coefficient (RC) and synthetics.

Göthel (2016) refer to seismic horizons in Rotliegend as "Phantom horizons", since they are highly variable in depending on regional geological settings and do not have a reliable definition. For the first time in the area of the research platform Groß Schönebeck, borehole seismics allows the separation of thin interlaying of siltstone and silty mudstone structures in the upper Rotliegend sediments in the depth range from 3800 m to 4000 m (Figure 6a, light green arrow (1)). On the 3D surface seismics (Krawczyk et al., 2019; Norden et al., in preparation) (Krawczyk et al., 2019; B. Norden, personal communication, April 28, 2022) a thick unresolved high amplitude continuous layer with visible thickness variations can be observed at approximately 3900 m (Figure 6b, light green arrow (1)). In contrast to the 3D surface seismic cube, on the 3D DAS VSP cube, two closely situated thin layers can be traced with a relatively constant thicknesses (Figure 6a, light green arrow (1)).

By comparing the depth sections between 3800 m and 4000 m on both cubes, it can be noted that thin interlayered horizons in the 3D DAS VSP cube have various dipping characteristics, whereas the 3D surface seismic cube shows only thicker horizontal lines, sometimes even not continuous and with amplitudes variations along them. This might be related to the broader frequency content between difference in the frequency content of surface and borehole seismic surveys, and as a result with the latter case having a higher resolution. The results of 3D DAS VSP imaging allows to trace a few thin horizons in the upper Rotliegend interval.

Figure 8 demonstrates the inline and a crossline extracted from the central part of the seismic cube with interpreted horizons corresponding to top Hannover reflections within Mellin-Schlichten ( $R_1$ ) and top Dethlingen Fm within Dethlingen Fm ( $R_3$ ). A negative amplitude event associated with a sandstone interlayer inside siltstone sediments of Hannover Fm around the depth of 3800 m could be followed throughout the DAS-VSP volume and is interpreted as reflector  $R_1$  (Göthel, 2016; Moeck et al., 2009). There is a decrease in gamma-ray, neutron porosity and  $V_p$  logs at this interval, resulting in decreased acoustic impedance values (Figure 7). A positive amplitude event at a depth of 4010 m is mapped as the reflector  $R_3$  (Henninges et al., 2021; B. Norden, personal communication, April 28, 2022). It marks the transition from the Dethlingen sandstones to a succession of siltstones, followed by mudstones. A change in lithology can be identified by increased gamma ray, density, and sonic velocity values, which leads to the increase of acoustic impedance (Figure 7). Depth variations of these horizons are visible already in a small volume around the boreholes. The indication of these variations in lithological sequences is also present in the corridor stacks within this interval (Henninges et al., 2021).



**Figure 8.** Seismic lines extracted from the 3D DAS VSP cube with horizons interpretation. (a) Seismic cross-line and (b) seismic inline, showing thin interlayered horizons in the upper Rotliegend (light green and dark green lines), base of Elbe sandstone reservoir (dark blue line) and the Lower Rotliegend unconformity (dark grey line). Black small arrows point out the locations of the numerous pinch outs.

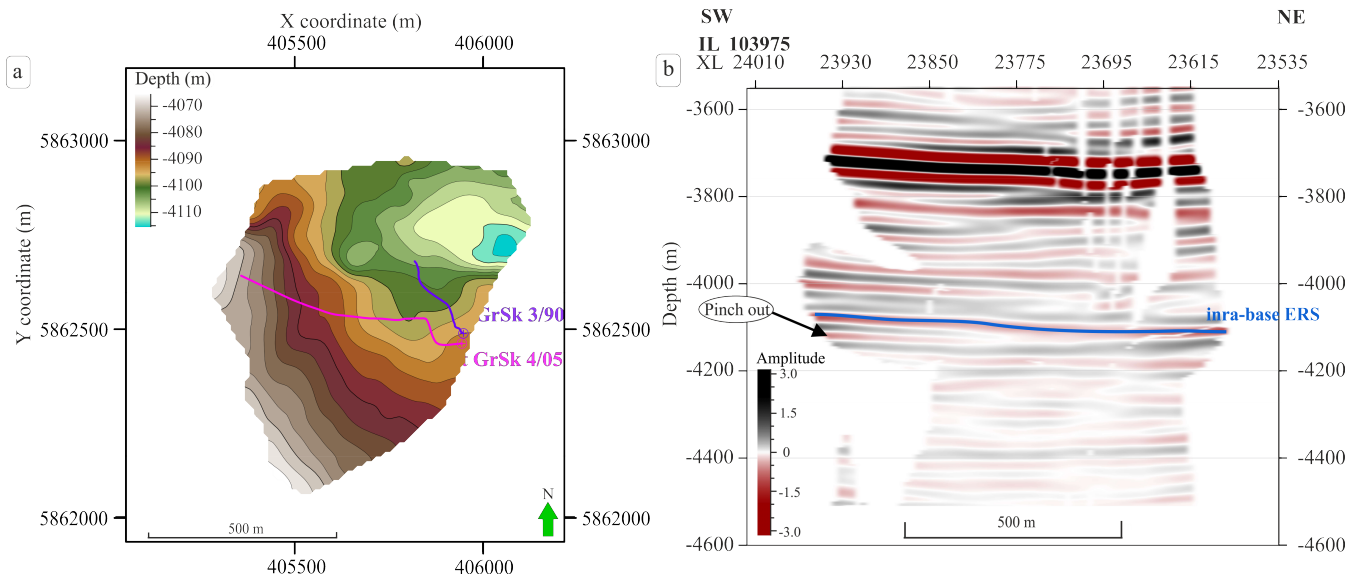
## 270 4.2 Elbe ~~basis-reservoir~~ sandstone layer

One of the possible targets for geothermal exploration are sandstones of the Dethlingen formation / Lower Elbe subgroup. In the Brandenburg area the lower part of the Dethlingen formation comprises fine-to-coarse grained sandstone with high quality reservoir properties (porosity 8-10 % and permeability of 10 - 100 mD ), ~~which has been deposited in a fluvial setting.~~ ~~This geological unit, also known as the Elbe basis sandstone layer,~~ (Trautwein and Huenges, 2005). This layer was deposited in aeolian setting and then reworked by aquatic processes. The Elbe reservoir sandstone (ERS) layer is located between 4060 to 4100 m depth within the sandy section of the Dethlingen Formation in the E GrSk 3/90 well (Bauer et al., 2020) (Figure 7). On well logs this interval is characterised by decreased P-wave velocity, caused by an increased porosity of this section (Trautwein and Huenges, 2005). This geological unit was successfully imaged on both 3D images (Figure 6, dark blue arrows (2)).

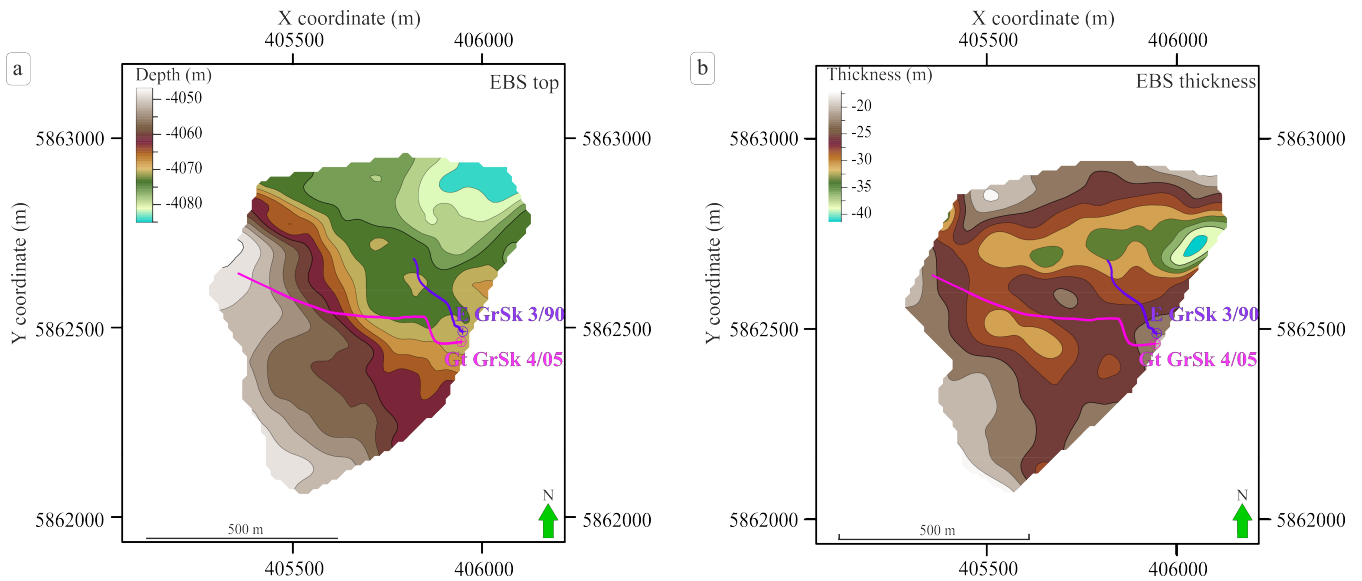
280 In the conventional surface seismic image (Krawczyk et al., 2019; Norden et al., in preparation), the base EBS (Krawczyk et al., 2019, B. Norden, personal communication, April 28, 2022), the base of ERS horizon can be traced as a continuous negative phase at around 4080 m depth, with increasing thickness toward the southwest direction. Even the theoretical resolution should be between 24 - 47 m. Bauer et al. (2020) showed via finite-difference forward modelling that this complex layer in the reservoir section still won't be adequately resolved since the theoretical resolution cannot be achieved due to challenging geological settings above and below the ~~EBSERS~~.

285 Within the depth range from 4060 to 4100 m the depth section from 4070 to 4090 m shows a low variability in logs values, indicating an even "cleaner" part of the ESR sandstone layer (Figure 7). The high resolution of the 3D DAS VSP cube allows ~~to trace seeing an internal structure inside this interval and tracing~~ depth variations of the ~~Elbe basis sandstone horizon-base of the intra-reservoir horizon within Elbe sandstone reservoir.~~ It may represent porous parts of a stacked fluvial sandstone body within the sandy Dethlingen Fm. succession. Below in the text we will refer to this horizon as intra-base of Elbe reservoir sandstone layer (intra-base ERS). This interval's base is characterised by negative phases (decreased acoustic impedance) on the seismic 3D DAS VSP cube. We picked this horizon through the entire volume and created a depth contour map (Figure 9a). The map was clipped using ~~a the~~ dark blue polygon shown on Figure 4a, to avoid interpolation artefacts in the regions with low coverage. The ~~base EBS-intra-base ERS~~ horizon lies at 4080 m on the southwest and at approximately 4100 m depth on the northeast. On the seismic section (Figure 9b), it is clearly visible that there is a pinch out on the southwest part of the profile, which was not distinguishable on the 3D surface seismic cube and visible as a thickness variation.

295 The top of the ~~EBS horizon (Figure 10a) in general~~ ERS horizon corresponds to positive phase (increased acoustic impedance) on 3D DAS VSP cube. In general it follows similar paleo relief of the ~~base EBS-intra-base ERS~~ with the deepest values around 4050 m in the southwest and 4080 m in the northeast (Figure 10a). However, local depth variations are present, and therefore the thickness of the Elbe ~~basis-reservoir~~ sandstone layer is highly variable in close proximity to the boreholes (Figure 10b). It ranges from 20 to 35 m.



**Figure 9.** (a) Spatial extent of the Elbe basis-reservoir sandstone layer. Depth contour map of the Elbe basis-sandstone bottom-reservoir intra-base horizon. The dark blue line marks the location of the inline shown in (b): seismic section from the 3D DAS VSP volume with the interpretation of the internal structure of the Elbe basis-reservoir sandstone (EBSERS) horizon.



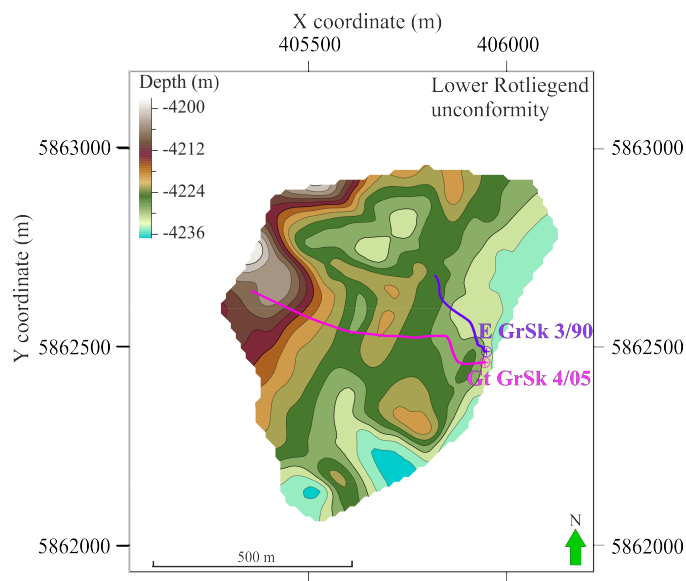
**Figure 10.** Mapping results within the study area: depth contour map of the top Elbe basis-reservoir sandstone layer (a) and the EBSERS thickness (b).



### 4.3 The lower Rotliegend unconformity

Another essential feature of the seismic interpretation on the 3D DAS VSP and the 3D surface seismics (Krawczyk et al., 2019; Norden et al. (Krawczyk et al., 2019; B. Norden, personal communication, April 28, 2022) cubes is the change in seismic reflection pattern (Figure 6) at a depth around 4200 m. On the 3D surface seismics, this is visible as a change from horizontal continuous reflectors to layers with inconsistent amplitudes and a lower reflectivity in the lower Rotliegend formation (Figure 6b, the dark grey arrow (3)). On the 3D DAS VSP cube, a change from nearly horizontal to inclined reflectors can be detected (Figure 6a, the dark grey arrow (3)). This change of the seismic facies evidences the existence of an unconformity in the area where we expect volcanic rocks. We will refer to it as lower Rotliegend unconformity.

On the seismic cross-line and inline shown in Figure 8 a and b, the possible unconformity boundary is marked by a thick dark grey line. This reflection has weak, uncertain characteristics. Small black arrows indicate numerous exciting pinch outs below this horizon, which were used as indicators of the type change of the layering. Due to reduced reflectivity and gaps in the cubes, tracing this horizon accurately is a pretty challenging task. Therefore the resulting depth contour map might have errors, especially at the edges of the dataset. Nevertheless, in the area between the two boreholes where we have the best coverage, we can see that the depth variation of the lower Rotliegend unconformity is relatively limited to the depth range between 4200 - 4230 m (Figure 11).



**Figure 11.** Spatial distribution of the unconformity boundary. Depth of the Lower Rotliegend unconformity.

## 5 Discussion & Outlook

### 5.1 The Groß Schönebeck experiment

With this study, we investigated the applicability of the DAS wireline acquisition method for detailed deep geothermal reservoir imaging and the capability to bridge the gap between well logs and 3D surface seismics. 3D DAS VSP provides, on average, [a two times better-resolved image than 3D surface seismic-seismics within this project](#) and has a significant potential in the geothermal sector. Data acquisition using constellation fibres or new interrogators with higher signal-to-noise ratio can help notably improve the quality of the wireline DAS data recording and compensate for signal losses in the deep reservoir section. Nevertheless, more research on fibre coupling improvement and location control in the borehole is strongly advised, which could allow wireline DAS acquisition to become a routine for numerous applications.

VSP surveys conducted with distributed sensors permanently installed behind casing or along the tubing provide the advantage of good coupling conditions and the possibility to perform time-lapse studies. Successfully reported case studies include applications for unconventional exploration in Texas (Shultz and Simmons, 2019) to create a detailed image of the formation around the well. Application of DAS for CO<sub>2</sub> monitoring (Götz et al., 2018; Correa et al., 2019) is a well-known routine to provide a reliable method for targeted, detailed imaging and 4D monitoring of the site. 3D DAS VSP surveys in oil and gas exploration reduce exploration risks in regions with a challenging environment, for instance, in the presence of strong production noise (Jiang et al., 2016), in areas with complex salt tectonics (Bartels et al., 2015) etc. In general, all the surveys [mentioned above with permanently installed fibre optic cable](#) have a better signal-to-noise ratio than data typically recorded with wireline DAS acquisition.

Wireline DAS, however, has a great advantage. It allows to acquire seismic data in already drilled and [cemented-cased](#) boreholes. This can be done at a low cost and in a small amount of time [in comparison with VSP acquired using geophones](#). Even though wireline 3D DAS VSP at the Groß Schönebeck site has worse coupling conditions than conventional DAS cemented behind the casing, the resolution of the imaged seismic volume is still in the same range of 20 m [\(Götz et al., 2018; Correa et al., 2019\)](#)

To the best of the authors knowledge, there are only limited examples of wireline DAS applications with active seismic sources for geothermal exploration. One known example was recorded in 2016 at the geothermal field at Brady Hot Springs, Nevada (Miller et al., 2018). A fibre optical cable was deployed into the accessible 363 m portion of the vertical well 56-1. This dataset has a limited depth range (up to 297 m only), and only two shot points were used for data acquisition. [No Trainor-Guitton et al. \(2018\) presented 3D image-was-created-imaging results from the same geothermal field, which are limited to the depth up to 600 m. Although some reflectors were imaged, they have a Hyperbola-shaped reflections often dominate these imaging results, making the interpretation challenging.](#) Therefore, the experiments conducted at the Groß Schönebeck in-situ laboratory and Brady Hot Springs are quite different and it is [problematic-challenging](#) to compare these two datasets. Thus, recorded data at the Groß Schönebeck is unique among the experiments conducted for geothermal exploration, with reflection information recorded down to 4.2 km deep.

350 A spiral survey design at the Groß Schönebeck site led to a ray focusing on the target reservoir area yielding an equably distributed offset and azimuth coverage. ~~Good results were~~ A detailed imaging of the target reservoir interval (with vertical resolution up to 16 m) was achieved with only 61 VPs. Nevertheless, low to zero ray coverage in some regions of the 3D VSP survey resulted in a lack of data required for a successful migration process without excessive artefacts. ~~Due to budget limitations, the Limited~~ number of vibrator points ~~had to be restricted and quite often positioned in such a way that they don't~~ have overlapping ray penetrating areas. Therefore, resulted in a petal-shaped footprints, with the highest coverage in the centre, are prominent in bin density slices (Figure 4a) revealing a partial illumination problem. Consequently, the resulting migrated depth slices have gaps and are not well suitable for classical attribute analysis. These limitations led to the usage of the 3D DAS VSP cube for structural interpretation only. ~~A~~

A more similar experiment to the Groß Schönebeck survey was conducted for hydrocarbons exploration in China's Hebei 360 region (Yu et al., 2016). DAS walkaway and walkaround VSP with wireline survey consisted of 386 successful shot points, 6 times more than at the Groß Schönebeck experiment. The data acquisition for the in-situ laboratory in the Brandenburg area was ~~probably likely~~ less time-consuming, ~~effortful and costly and cheaper~~ than this experiment in China. However, densely regularly placed source positions allowed to get a detailed resolved 3D image for the area of interest in Hebei region without gaps and prominent migration artefacts. Most recently Lim et al. (2020) showed a remarkable dataset from methane hydrate research test well in North Slope, Alaska, USA. A survey consisted from 1701 VP arranged around the borehole and a permanently installed fibre optic cable. Phenomenal dataset quality of the 3D DAS VSP data revealed indications of the sub-fault system that are not presented in the surface seismic data. The experiment in China and Alaska showed that with a larger amount of source points a better coverage can be achieved, however, one should always look for a trade off between a reasonable coverage and acquisition cost ~~during the planning phase.~~

370 ~

## 5.2 Data processing

The experiment at the Groß Schönebeck allowed gaining valuable knowledge on survey planning and data processing. One of the biggest challenges for this dataset was a ringing noise problem. At the early stages of the data processing, an intermediate solution for denoising included ~~the~~ Burg adaptive deconvolution combined with careful exclusion of depth intervals with a poor 375 signal-to-noise ratio from the data processing. To further improve imaging results and limit migration artefacts due to sparse coverage, it was necessary to improve the signal-to-noise ratio of the data and include more data into migration calculations. Therefore, an essential part in successful data imaging results played careful denoising using the MPD approach.

Besides the quantity of the data, another important parameter, which will significantly influence the imaging results, is the migration aperture (~~Schleicher et al., 1997; Sun, 2000~~) (Schleicher et al., 1997; Sun, 2000). After extensive testing we came to 380 the conclusion that a strict restriction of  $5^\circ$  can lead to an ambiguous and inconsistent summation of the main horizons for our dataset. On the other hand, a too broad aperture can reduce the resolution of the horizons. Thus, a compromise between these parameters should be found. Additionally, due to its stacking nature, the migration operator will also attenuate to some extent the residual noise in the data.

### 5.3 Future geothermal exploration plans

385 The results of our 3D DAS VSP experiments prove that ~~this type of measurement~~ wireline DAS VSP measurements can significantly contribute to exploration campaigns. The wireline DAS VSP allows reducing risks and cost, and can have a higher resolution compared to the conventional 3D surface seismic interpretation which does not provide enough information due to the limited resolution of the data. ~~The Elbe basis~~ This case study can be of special interest for geothermal wells with complex structures, or with thin reservoirs which are hard to image. Especially deep thin geothermal reservoirs, or reservoirs  
390 that require stimulation with a low economical value may benefit from wireline DAS, for which a conventional VSP would otherwise have been cost prohibited. These deep reservoirs may require a high frequency content for high resolution imaging which is only preserved with a VSP due to the one way travel path.

The Elbe reservoir sandstone layer currently ~~represent~~ represents one of potential targets for the future geothermal exploration. The 3D VSP imaging results clarified the sandstone layer's effective thickness with good reservoir properties. According to our estimations, it varies between 25 to 40 m (Figure 10b) near the boreholes locations. The fluvial nature of these deposits is perhaps responsible for this high variability. Previously the ~~thickness of this layer was overestimated to be effective thickness of the Elbe reservoir layer was estimated at~~ around 80 m (Zimmermann et al., 2010). ~~Our results are also supported by~~ The updated thicknesses from the 3D surface seismic experiment, calculated using wavelet transform-based seismic facies classification (Bauer et al., 2020; Norden et al., in preparation). ~~An assessment of the geothermal resources depends on the geothermal reservoir's geological formation and thermal and hydraulic properties. One of many parameters required to estimate the geothermal reservoir heat capacity include reservoir volume, which is determined as a product of reservoir area and reservoir thickness. The heat stored in the geothermal reservoir is linearly dependent on the volume reservoir, which directly depends on the thickness of the reservoir. In other words, the thinner the reservoir, showed the predominate thickness of 40 m (Bauer et al., 2020; B. Norden, personal communication, April 28, 2022). Our imaging results from the 3D DAS VSP~~  
400 further refine the reservoir geometry and reveal thickness estimations of the lower the extracted heat. Therefore, according to the new information, the planned economical operation analysis for the heat extraction from Elbe basis sandstone should be reevaluated. ~~intra-reservoir layer.~~

The observed lower thicknesses may explain why a matrix-dominated exploration approach did not succeed at the Groß Schönebeck as the reservoir volume which is able to contribute to the fluid flow is considerably lower than expected beforehand.  
410 However, the mapped variations of the more porous reservoir thickness, representing most likely the variability of facies-related petrophysical properties, should be considered for the design of the fracture-dominated geothermal systems. Further investigations on fluid flow estimations should be conducted using independent temperature data, well logs and hydraulic tests data.

At the depth level around 4200 m, we mapped ~~lower the~~ the lower Rotliegend unconformity. There is a hypothesis that deposits of permo-carboniferous volcanic rocks lay below this border, which represent another possible target for future  
415 exploration (~~Norden et al., in preparation~~). (B. Norden, personal communication, April 28, 2022). According to literature sources (Guterch et al., 2010), lower Rotliegend volcanics have a significant time-gap in sedimentation and therefore mapped unconformity horizon could indicate a difference in layering caused by erosion. The 3D DAS VSP imaging successfully con-

tributed to the determination of this critical boundary since it was not well characterised on the 3D surface seismic cube. The bottom of permo-carboniferous volcanic rocks is not detectable neither on the 3D DAS VSP nor on the 3D surface seismic cubes. This implies that the thickness of this deposit's sections can be greater than 300 m. Considering this information, the economic profitability is significantly higher for treated volcanic rocks than for the Elbe ~~basis-reservoir~~ sandstone layer. Nevertheless, we believe it is crucial to determine the exact depth by drilling, perform core analysis, and use well logging methods to determine the precise composition of sediments below this border and essential parameters such as porosity and permeability before developing concepts for possible reservoir treatments in volcanites.

The exact development plans of the site are still under discussion. Possible scenarios include implementing a new stimulation concept and possibly drilling a new well (GrSk 5) or deepening the existing borehole E GrSk 3/90.

## 6 Conclusions

We analysed the 3D DAS VSP imaging results acquired with wireline DAS installation at the Groß Schönebeck geothermal research site. Despite the numerous difficulties during the data acquisition campaign, the borehole seismics was able to image the target interval and substantially contribute to the detailed interpretation of the geothermal reservoir.

The 3-dimensional image created using borehole yields:

- Resolution of thin complex upper Rotliegend geological structure;
- Mapping of the ~~target base Elbe basis sandstone~~ horizon Elbe reservoir sandstone;
- Detection of the lower Rotliegend unconformity in the region with possible volcanic rocks.

The interpretation of the 3D DAS VSP cube evidenced the unexpected absence of faults with larger vertical offsets and fractures. Furthermore, no indications for free gas were found in the data. These findings are important for the further development of the Groß Schönebeck in-situ geothermal laboratory. ~~Wireline DAS is still a relatively new method. It~~ Wireline DAS allows for a significantly increase in the number of sensors and a larger recording aperture, which results in imaging over a larger depth interval. Thus, it is cheaper and faster than the application of conventional borehole sensors. Nevertheless, careful survey planning and sophisticated data processing are vital for successful imaging results. ~~A~~ This successful case study at the Groß Schönebeck site can play a crucial role in developing and applying modern, efficient geothermal exploration methods in the Northern German Basin and other regions with comparable lithology.

*Data availability.* Data will be available after the embargo period at the end of the year via the GFZ repository ([dataservices.gfz-potsdam.de/portal](https://dataservices.gfz-potsdam.de/portal)).

445 *Author contributions.* JH, MS and CMK planned the experiment. JH and MS supervised the fieldwork and data acquisition. EM performed the seismic data processing and analysis under supervision of MS and CMK. EM interpreted the data under discussion with with all co-authors. EM, MS, BN, JH and CMK discussed the results and contributed to the final manuscript. JH and CMK supervised the project.

*Competing interests.* The authors declare that they have no conflict of interest. Charlotte M. Krawczyk is chief executive editor of SE.

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## References

- Bartels, T., Gelhaus, M., and Humphries, M.: VSP Measurements Used as a Tool for Sub Salt Near Field Development, in: 77th EAGE Annual Meeting, Expanded Abstracts, p. We N104 15, <https://doi.org/https://doi.org/10.3997/2214-4609.201412918>, 2015.
- 460 Bauer, K., Norden, B., Ivanova, A., Stiller, M., and Krawczyk, C. M.: Wavelet transform-based seismic facies classification and modelling: application to a geothermal target horizon in the NE German Basin, *Geophysical Prospecting*, 68, 466–482, <https://doi.org/https://doi.org/10.1111/1365-2478.12853>, 2020.
- Bellefleur, G., Schetselaar, E., Wade, D., White, D., Enkin, R., and Schmitt, D. R.: Vertical seismic profiling using distributed acoustic sensing with scatter-enhanced fibre-optic cable at the Cu–Au New Afton porphyry deposit, British Columbia, Canada, *Geophysical Prospecting*, 68, 313–333, <https://doi.org/https://doi.org/10.1111/1365-2478.12828>, 2020.
- 465 Blöcher, G., Reinsch, T., Hennings, J., Milsch, H., Regenspurg, S., Kummerow, J., Francke, H., Kranz, S., Saadat, A., Zimmermann, G., and Huenges, E.: Hydraulic history and current state of the deep geothermal reservoir Groß Schönebeck, *Geothermics*, 63, 27–43, <https://doi.org/https://doi.org/10.1016/j.geothermics.2015.07.008>, enhanced Geothermal Systems: State of the Art, 2016.
- Booth, A. D., Christoffersen, P., Schoonman, C., Clarke, A., Hubbard, B., Law, R., Doyle, S. H., Chudley, T. R., and Chalari, A.: Distributed Acoustic Sensing of Seismic Properties in a Borehole Drilled on a Fast-Flowing Greenlandic Outlet Glacier, *Geophysical Research Letters*, 47, e2020GL088 148, <https://doi.org/https://doi.org/10.1029/2020GL088148>, e2020GL088148 2020GL088148, 2020.
- 470 Brisbourne, A. M., Kendall, M., Kufner, S.-K., Hudson, T. S., and Smith, A. M.: Downhole distributed acoustic seismic profiling at Skytrain Ice Rise, West Antarctica, *The Cryosphere Discussions*, 2021, 1–18, <https://doi.org/https://doi.org/10.5194/tc-2021-1>, 2021.
- Burg, J.: Maximum Energy Spectral Analysis, Ph.D. thesis, Stanford University, 1975.
- Burg, J. P.: The relationship between maximum entropy spectra and maximum likelihood spectra, *Geophysics*, 37, 375–376, <https://doi.org/https://doi.org/10.1190/1.1440265>, 1972.
- 475 Carrara, S., Shortall, R., and Uihlein, A.: Geothermal Energy - Technology Development Report 2020, <https://doi.org/10.2760/16847> (online),10.2760/0517 (print), 2020.
- Constantinou, A., Farahani, A., Cuny, T., and Hartog, A.: Improving DAS acquisition by real-time monitoring of wireline cable coupling, in: 86th SEG Annual Meeting, Expanded Abstracts, pp. 5603–5607, <https://doi.org/https://doi.org/10.1190/segam2016-13950092.1>, 2016.
- 480 Correa, J., Pevzner, R., Bona, A., Tertyshnikov, K., Freifeld, B., Robertson, M., and Daley, T.: 3D vertical seismic profile acquired with distributed acoustic sensing on tubing installation: A case study from the CO2CRC Otway Project, *Interpretation*, 7, SA11–SA19, <https://doi.org/https://doi.org/10.1190/INT-2018-0086.1>, 2019.
- Dean, T., Cuny, T., and Hartog, A. H.: The effect of gauge length on axially incident P-waves measured using fibre optic distributed vibration sensing, *Geophysical Prospecting*, 65, 184–193, <https://doi.org/https://doi.org/10.1111/1365-2478.12419>, 2017.
- 485 Dillon, P. B. and Thomson, R. C.: OFFSET SOURCE VSP SURVEYS AND THEIR IMAGE RECONSTRUCTION\*, *Geophysical Prospecting*, 32, 790–811, <https://doi.org/https://doi.org/10.1111/j.1365-2478.1984.tb00739.x>, 1984.
- Dou, S., Lindsey, N., Wagner, A. M., Daley, T. M., Freifeld, B., Robertson, M., Peterson, J., Ulrich, C., Martin, E. R., and Ajo-Franklin, J. B.: Distributed Acoustic Sensing for Seismic Monitoring of The Near Surface: A Traffic-Noise Interferometry Case Study, *Scientific Reports*, 7, 11 620, <https://doi.org/10.1038/s41598-017-11986-4>, 2017.
- 490 Elboth, T., Geoteam, F., Qaisrani, H. H., and Hertweck, T.: De-noising seismic data in the time-frequency domain, in: 78th SEG Annual Meeting, Expanded Abstracts, pp. 2622–2626, <https://doi.org/https://doi.org/10.1190/1.3063887>, 2008.

- Guterch, A., Wybraniec, S., Grad, M., Chadwick, A., Krawczyk, C., Ziegler, P., Thybo, H., and De Vos, W.: Crustal structure and structural framework, in: *Petroleum Geological Atlas of the Southern Permian Basin Area*, pp. 11–23, EAGE Publications b.v., Houten, The Netherlands, 2010.
- 495 Göthel, M.: Lithologische Interpretation und stratigraphisches Niveau der reflexionsseismischen Horizonte im Untergrund Brandenburgs einschließlich Berlins, *Brandenburgische Geowiss. Beiträge*, 23, 85–90, 2016.
- Götz, J., Lüth, S., Hennings, J., and Reinsch, T.: Vertical seismic profiling using a daisy-chained deployment of fibre-optic cables in four wells simultaneously – Case study at the Ketzin carbon dioxide storage site, *Geophysical Prospecting*, 66, 1201–1214, <https://doi.org/https://doi.org/10.1111/1365-2478.12638>, 2018.
- 500 Hennings, J., Baumann, G., Brandt, W., Cunow, C., Poser, M., Schrötter, J., and Huenges, E.: A Novel Hybrid Wireline Logging System for Downhole Monitoring of Fluid Injection and Production in Deep Reservoirs, in: *73rd EAGE Conference & Exhibition, Expanded Abstracts*, <https://doi.org/https://doi.org/10.3997/2214-4609.20149727>, 2011.
- Hennings, J., Martuganova, E., Stiller, M., Norden, B., and Krawczyk, C. M.: Wireline distributed acoustic sensing allows 4.2 km deep vertical seismic profiling of the Rotliegend 150 °C geothermal reservoir in the North German Basin, *Solid Earth*, 12, 521–537, 505 <https://doi.org/https://doi.org/10.5194/se-12-521-2021>, 2021.
- Hudson, T., Baird, A., Kendall, J., Kufner, S., Brisbourne, A., Smith, A., Butcher, A., Chalari, A., and Clarke, A.: Distributed Acoustic Sensing in Antarctica: What we can learn for studying microseismicity elsewhere, *Conference Proceedings, EAGE GeoTech 2021 Second EAGE Workshop on Distributed Fibre Optic Sensing*, pp. 1–5, <https://doi.org/https://doi.org/10.3997/2214-4609.202131037>, 2021.
- Humphries, M., Vidal, J., and de Dios, J.: VSP Monitoring for CO<sub>2</sub> Migration Tracking in Fractured Rock Massifs, in: *77th EAGE Conference and Exhibition*, no. 1 in *Expanded Abstracts*, pp. 1–5, European Association of Geoscientists & Engineers, 510 <https://doi.org/https://doi.org/10.3997/2214-4609.201412672>, 2015.
- IEA Geothermal: The 2019 Annual Report, IEA Geothermal, 2020.
- Jiang, T., Zhan, G., Hance, T., Sugianto, S., Soulas, S., and Kjos, E.: Valhall dual-well 3D DAS VSP field trial and imaging for active wells, in: *86th SEG Annual Meeting, Expanded Abstracts*, pp. 5582–5586, <https://doi.org/https://doi.org/10.1190/segam2016-13871754>, 2016.
- 515 Krawczyk, C. M.: Wie Glasfaserkabel als Geosensoren zur Erkundung und Überwachung des Untergrunds genutzt werden können – Anwendungen und Potenzial von ortsverteilten faseroptischen Messungen (How fibre optic cables can be used as geosensors to explore and monitor the subsurface – Applications and Potential of distributed acoustic sensing), *Brandenburgische Geowiss. Beiträge*, 2022.
- Krawczyk, C. M., Stiller, M., Bauer, K., Norden, B., Hennings, J., Ivanova, A., and Huenges, E.: 3-D seismic exploration across the deep geothermal research platform Groß Schönebeck north of Berlin/Germany, *Geothermal Energy*, 7, 15, 520 <https://doi.org/https://doi.org/10.1186/s40517-019-0131-x>, 2019.
- Lellouch, A., Schultz, R., Lindsey, N., Biondi, B., and Ellsworth, W.: Low-Magnitude Seismicity With a Downhole Distributed Acoustic Sensing Array—Examples From the FORGE Geothermal Experiment, *Journal of Geophysical Research: Solid Earth*, 126, e2020JB020462, <https://doi.org/https://doi.org/10.1029/2020JB020462>, e2020JB020462 2020JB020462, 2021.
- Li, Z. and Zhan, Z.: Pushing the limit of earthquake detection with distributed acoustic sensing and template matching: a case study at the 525 Brady geothermal field, *Geophysical Journal International*, 215, 1583–1593, <https://doi.org/10.1093/gji/ggy359>, 2018.
- Lim, T., Fujimoto, A., Kobayashi, T., and Mondanos, M.: DAS 3DVSP Data Acquisition for Methane Hydrate Research, in: *EAGE Workshop on Fiber Optic Sensing for Energy Applications in Asia Pacific, Expanded Abstracts*, pp. 1–5, European Association of Geoscientists & Engineers, <https://doi.org/10.3997/2214-4609.202070014>, 2020.



- Lior, I., Sladen, A., Rivet, D., Ampuero, J.-P., Hello, Y., Becerril, C., Martins, H. F., Lamare, P., Jestin, C., Tsagkli, S., and Markou, C.: On the  
530 Detection Capabilities of Underwater Distributed Acoustic Sensing, *Journal of Geophysical Research: Solid Earth*, 126, e2020JB020925,  
<https://doi.org/https://doi.org/10.1029/2020JB020925>, e2020JB020925 2020JB020925, 2021.
- Lizarralde, D. and Swift, S.: Smooth inversion of VSP traveltimes data, *GEOPHYSICS*, 64, 659–661,  
<https://doi.org/https://doi.org/10.1190/1.1444574>, 1999.
- Martuganova, E., Stiller, M., Bauer, K., Hennings, J., and Krawczyk, C. M.: Cable reverberations during wireline dis-  
535 tributed acoustic sensing measurements: their nature and methods for elimination, *Geophysical Prospecting*, 69, 1034–1054,  
<https://doi.org/https://doi.org/10.1111/1365-2478.13090>, 2021.
- Miller, D., Coleman, T., Zeng, X., Patterson, J., Reinisch, E., Wang, H., Fratta, D., Trainor-Guitton, W., Thurber, C., Robertson, M., Feigl,  
K., and Team, T.: DAS and DTS at Brady Hot Springs: Observations about Coupling and Coupled Interpretations, in: 43rd Workshop on  
Geothermal Reservoir Engineering, Proceedings, 2018.
- 540 Moeck, I., Schandelmeier, H., and Holl, H.-G.: The stress regime in a Rotliegend reservoir of the Northeast German Basin, *International  
Journal of Earth Sciences*, 98, 1643–1654, <https://doi.org/10.1007/s00531-008-0316-1>, 2009.
- Nishimura, T., Emoto, K., Nakahara, H., Miura, S., Yamamoto, M., Sugimura, S., Ishikawa, A., and Kimura, T.: Source location of volcanic  
earthquakes and subsurface characterization using fiber-optic cable and distributed acoustic sensing system, *Scientific Reports*, 11, 6319,  
<https://doi.org/10.1038/s41598-021-85621-8>, 2021.
- 545 Norden, B., Bauer, K., and Krawczyk, C. M.: The 3D structural model of the geothermal research platform Groß Schönebeck in the Northeast  
German Basin: new insights based on 3D seismics, in preparation.
- Reinsch, T., Hennings, J., Götz, J., Jousset, P., Bruhn, D., and Lüth, S.: Distributed Acoustic Sensing Technology for Seismic Exploration  
in Magmatic Geothermal Areas, in: Proceedings World Geothermal Congress, 2015.
- Schleicher, J., Hubral, P., Tygel, M., and Jaya, M. S.: Minimum apertures and Fresnel zones in migration and demigration, *Geophysics*, 62,  
550 183–194, <https://doi.org/10.1190/1.1444118>, 1997.
- Shultz, W. and Simmons, J.: 3D DAS VSP in unconventional: A case study, in: 89th SEG Annual Meeting, Expanded Abstracts, pp. 979–  
983, <https://doi.org/https://doi.org/10.1190/segam2019-3214518.1>, 2019.
- Spica, Z. J., Nishida, K., Akuhara, T., Pétrélis, F., Shinohara, M., and Yamada, T.: Marine Sediment Characterized by Ocean-Bottom Fiber-  
Optic Seismology, *Geophysical Research Letters*, 47, e2020GL088360, <https://doi.org/https://doi.org/10.1029/2020GL088360>, 2020a.
- 555 Spica, Z. J., Perton, M., Martin, E. R., Beroza, G. C., and Biondi, B.: Urban Seismic Site Characterization by Fiber-Optic Seismology, *Journal  
of Geophysical Research: Solid Earth*, 125, e2019JB018656, <https://doi.org/https://doi.org/10.1029/2019JB018656>, 2020b.
- Stiller, M., Krawczyk, C. M., Bauer, K., Hennings, J., Norden, B., Huenges, E., and Spalek, A.: 3D-Seismik am Geothermieforschungs-  
standort Groß Schönebeck, *BBR - Fachmagazin für Brunnen- und Leitungsbau*, 1, 84–91, 2018.
- Sun, J.: Limited-aperture migration, *Geophysics*, 65, <https://doi.org/10.1190/1.1444754>, 2000.
- 560 The European Commission: Report from the commission to the European parliament and the council. Progress on competitiveness of clean  
energy technologies. Part 4/5, Publications Office of the European Union, Brussels (Belgium), 2021.
- Thomsen, L.: Weak elastic anisotropy, *GEOPHYSICS*, 51, 1954–1966, <https://doi.org/10.1190/1.1442051>, 1986.
- Trainor-Guitton, W., Guitton, A., Jreij, S., Powers, H., Sullivan, C. B., Simmons, J., and Porotomo Team: 3D Imaging from vertical DAS  
fiber at Brady’s Natural Laboratory, in: Proceedings, 43rd Workshop on Geothermal Reservoir Engineering, 2018.

- 565 Trautwein, U. and Huenges, E.: Poroelastic behaviour of physical properties in Rotliegend sandstones under uniaxial strain, *International Journal of Rock Mechanics and Mining Sciences*, 42, 924–932, <https://doi.org/https://doi.org/10.1016/j.ijrmms.2005.05.016>, *rock Physics and Geomechanics*, 2005.
- Wilson, G. A., Willis, M. E., and Ellmuthaler, A.: Evaluating 3D and 4D DAS VSP image quality of subsea carbon storage, *The Leading Edge*, 40, 261–266, <https://doi.org/https://doi.org/10.1190/tle40040261.1>, 2021.
- 570 Yu, G., Cai, Z., Chen, Y., Wang, X., Zhang, Q., Li, Y., Wang, Y., Liu, C., Zhao, B., and Greer, J.: Walkaway VSP using multimode optical fibers in a hybrid wireline, *The Leading Edge*, 35, 615–619, <https://doi.org/https://doi.org/10.1190/tle35070615.1>, 2016.
- Yuan, S., Lellouch, A., Clapp, R. G., and Biondi, B.: Near-surface characterization using a roadside distributed acoustic sensing array, *The Leading Edge*, 39, 646–653, <https://doi.org/https://doi.org/10.1190/tle39090646.1>, 2020.
- Zhan, G. and Nahm, J.: Multi-well 3D DAS VSPs: Illumination and imaging beyond the wellbores, in: 90th SEG Annual Meeting, Expanded Abstracts, pp. 3798–3802, <https://doi.org/https://doi.org/10.1190/segam2020-3426032.1>, 2020.
- 575 Zimmermann, G., Moeck, I., and Blöcher, G.: Cyclic waterfrac stimulation to develop an Enhanced Geothermal System (EGS)—Conceptual design and experimental results, *Geothermics*, 39, 59–69, <https://doi.org/https://doi.org/10.1016/j.geothermics.2009.10.003>, the European I-GET Project: Integrated Geophysical Exploration Technologies for Deep Geothermal Reservoirs, 2010.