Exploration and monitoring with distributed acoustic sensing at the EGS site Groß Schönebeck

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ABSTRACT

Vertical seismic profiling has been performed at the Groß Schönebeck site in order to gain more detailed information on the structural setting and geometry of the geothermal reservoir. Data acquisition was performed using the novel method of distributed acoustic sensing, using hybrid wireline fiber-optic sensor cables deployed in two 4.3 km deep wells. During the four-day survey, data for 61 source positions was acquired. From the recorded data, accurate time-depth relationships, velocity and reflection profiles along the wells were derived. We show that structural elements near the boreholes can be imaged with high resolution, despite gaps in the data due to sparse coverage exist. The DAS method has enabled measurements at elevated temperatures up to 150 °C and has led to significant time and cost savings compared to deployment of a conventional geophone chain. Important new experiences for application of this non-standard method of acquisition have been gathered.

1. INTRODUCTION

The Groß Schönebeck site is located 40 km N of Berlin in the state of Brandenburg, Germany. It is a research platform that has been set up in order to test if production of geothermal energy from deep-seated reservoirs in the North German Basin is feasible. An enhanced geothermal system (EGS) has been created by hydraulic stimulation of low-permeability sedimentary and volcanic rocks of lower Permian (Rotliegend) age (Huenges et al. 2006; Zimmermann et al. 2010). For further development of the site, the implementation of a new stimulation concept and drilling of a new well have been proposed (Blöcher et al. 2015).

In order to gain more detailed information on the structural setting and geometry of the reservoir, a 3D seismic survey within an 8x8 km permit area has been carried out in February and March 2017 (Krawczyk et al. submitted). In addition, vertical seismic profiling (VSP) has been performed within the two 4.3 km deep research wells E GrSk3/90 and Gt GrSk4/05 existing at the site. The primary aims of the VSP survey were to establish precise time-depth and velocity profiles, and to image structural elements in the vicinity of the boreholes with higher resolution in three dimensions. A special challenge is imaging of structures within the reservoir interval of the Rotliegend at 4200 m depth, which is overlain by a 1400 m thick Zechstein salt complex.

The VSP measurement was performed using the novel method of distributed acoustic sensing (DAS). This method is based on optical time-domain reflectometry, and enables to register strain changes along optical sensor cables with high spatial and temporal resolution (Parker et al. 2014). Within recent years, a growing number of VSP surveys has been reported, where the DAS method has successfully been applied using sensor cables permanently installed behind casing or along tubing (e.g. Mestayer et al. 2011; Daley et al. 2013; Götz et al. 2018). In contrast to this, within this study the DAS data was acquired on wireline cables only temporarily deployed inside the wells, a method for which only very few experiences exist until now.

2. SURVEY DESIGN AND ACQUISITION

The target area was defined by the positions of the existing wells, the expected extent of the hydraulic fractures, and the trajectory of the proposed new well. It has a horizontal extent of approx. 700 x 500 m and a vertical thickness of approx. 300 m. A spiral pattern of 61 source points with offsets between 180 m and 2000 m from the wellheads was chosen, in order to achieve a good coverage of the target area and a uniform distribution of azimuths (Figure 1). Survey planning was based on well trajectories and geometry of the major geologic units (Moeck et al. 2009), taking into account DAS specific acquisition characteristics like directivity and signal-to-noise ratio. The source point positions were optimized based on ray tracing, using average acoustic properties of the major geologic units from a previous regional seismic survey (Bauer et al. 2010). The actual source point locations were then adjusted according to the conditions within the survey area, i.e. location of roads and agricultural areas, as well as required distances to sensible infrastructures like gas lines or buildings.

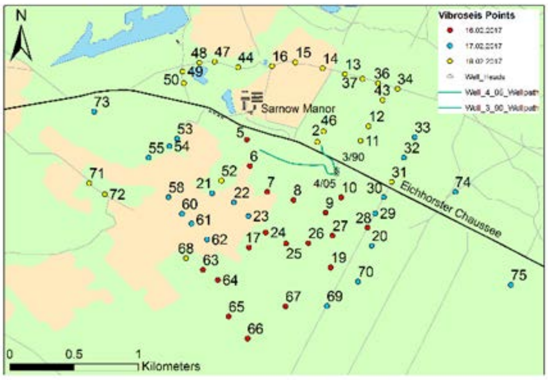

Figure 1: Survey area with VSP source point positions and borehole trajectories.

Field work was carried out within four days from Feb. 15-18, 2017. Energy excitation was performed with four Mertz M12 vibrator trucks simultaneously at each source position (45.100 lbs peak force). For acquisition of the DAS data in well E GrSk3/90 the GFZ hybrid borehole measurement system was used, which allows for deployment of fiber-optic sensors and electric downhole tools in parallel (Henninges et al. 2011). This well is near-vertical (maximum inclination 7.2°), and the fiber-optic data was acquired to a measured depth (MD) of 4256 m, which corresponds to a true vertical depth (TVD) of 4245.8 m below ground level. Within the well Gt GrSk 4/05, which is deviated up to 49° in the reservoir interval, a second wireline cable was deployed by Schlumberger (maximum DAS acquisition depth 4196 m MD / 4126.09 m TVD). Within this well additional measurements with a VSI (Versatile Seismic Imager) tool including a conventional three-component borehole seismometer were collected for comparison. DAS data was acquired using two Schlumberger hDVS (Heterodyne Distributed Vibration Sensing) units.

At the beginning a start-up test was carried out. Here suitable source and recording parameters were determined, including sweep frequencies, DAS gauge length and wireline cable tension. As a result, mainly a sweep with 10-112 Hz (linear) and 36 s duration was used during acquisition. For DAS data recording, a gauge length of 20 m was selected. This value was further adjusted for individual data sets during post-processing, based on the optimization procedure described by (Dean et al. 2017).

Within the following three days, acquisition was performed with a nominal number of 16 repeats for the 61 source positions distributed around the wells. The DAS measurements were recorded with a sampling rate of 2 ms and 5 m channel spacing across the entire length of the wells. Nevertheless, due to a technical problem during the second day of acquisition, only data for well GrSk3 could be recorded afterwards.

2.1 Basic seismic data processing

As one of the first processing steps, the DAS data recorded along the length of the sensor cables was correlated to well depths. Seismic pre-processing included stacking and correlation with the pilot sweep. The hDVS output strain data was then transformed to strain rate (time derivative), and further methods for conversion to geophone-equivalent data have been tested (Martuganova et al. submitted).

3. RESULTS

Shot gathers for a zero-offset position (VP 10) are displayed in Figure 2 and Figure 3. Over several intervals along the wells a specific noise with a zig-zag pattern can be recognized in the DAS data. Several approaches to reduce this ringing noise have been tested (Martuganova et al. submitted), e.g. using time-frequency domain (TFD) filtering, the result of which is displayed in Figures 2 and 3 for comparison.

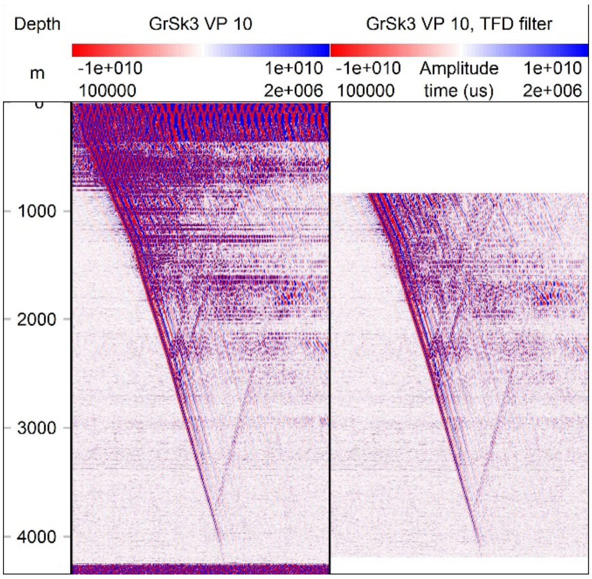

Figure 2: Zero-offset shot gathers for well GrSk3.

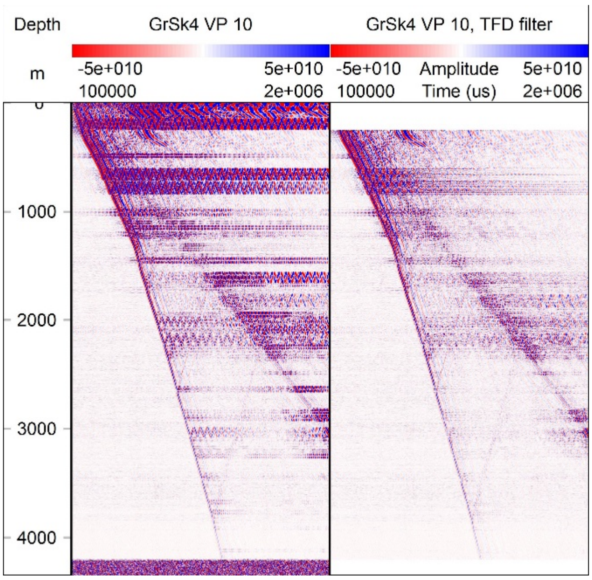

Figure 3: Zero-offset shot gathers for well GrSk4.

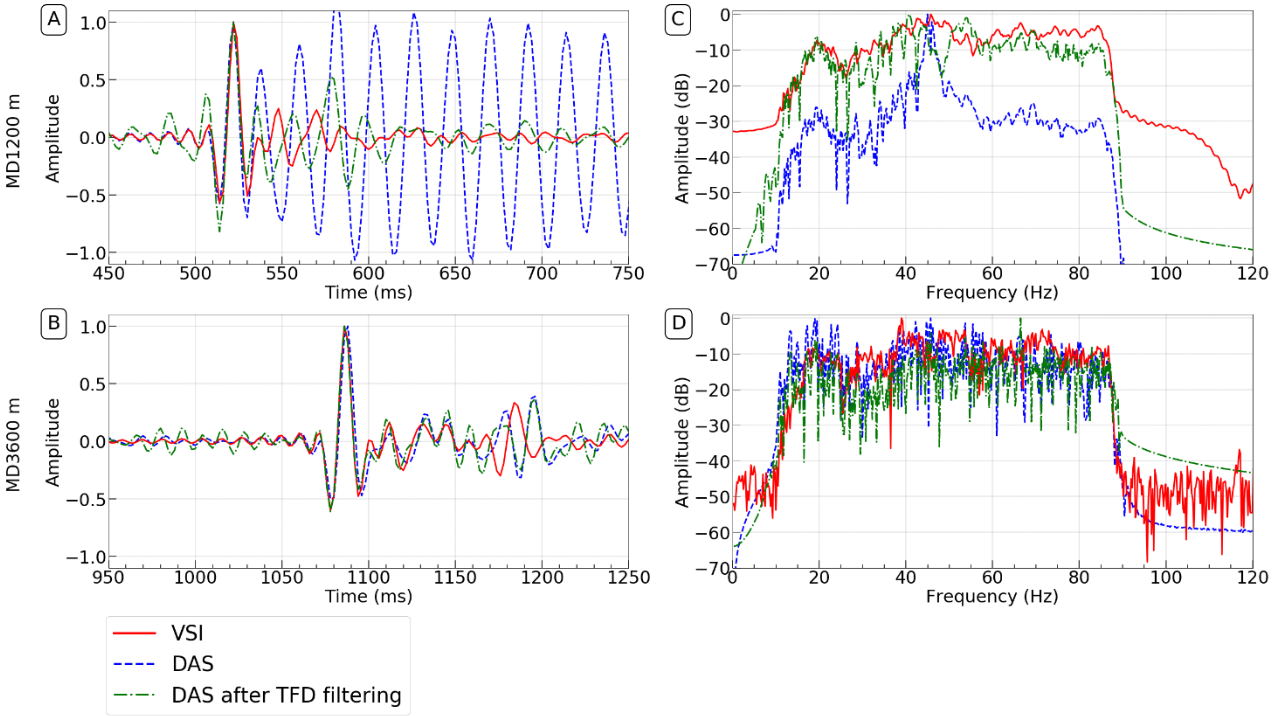

Figure 4: VSP traces and frequency spectra for VSI accelerometer and DAS strain-rate data recorded in well GrSk4 at 1200 m (A, C) and 3600 m (B, D) depth.

For well GrSk4, check shots at several depths were recorded with the VSI tool. A comparison between the vertical component of the VSI accelerometer data and the DAS data recorded at these depths is displayed in Figure 4. At 3600 m, the DAS strain-rate data shows very good agreement with the data from the accelerometer overall, which also applies to other depths recorded. At 1190 ms a temporary reversal of the polarity of the DAS signal compared to the accelerometer record is evident. At this time the signal is dominated by a strong reflection (see Fig. 3), originating from the base of the Zechstein interval.

The DAS trace for 1200 m depth is strongly influenced by the ringing noise described above, which is confined to a narrow frequency band between 40 and 50 Hz (Fig. 4c). The VSI tool data at this depth nevertheless shows a normal response, which suggests that the ringing noise in the DAS data is related to the different deployment methods of the acoustic receivers.

3.1 Zero-offset VSP processing

The arrival times of the direct down-going waves were picked in the zero-offset shot gathers. From these, time-depth relationships were established and interval velocities along the wells have been calculated (Figure 5). Variations within the VSP interval velocity profile show a good correlation to stratigraphy and the dominant lithologies. The calculated VSP interval velocities vary between about 2.8 and 5 km/s, and agree well to the compressional velocities of a sonic log previously recorded in the lower part of the well.

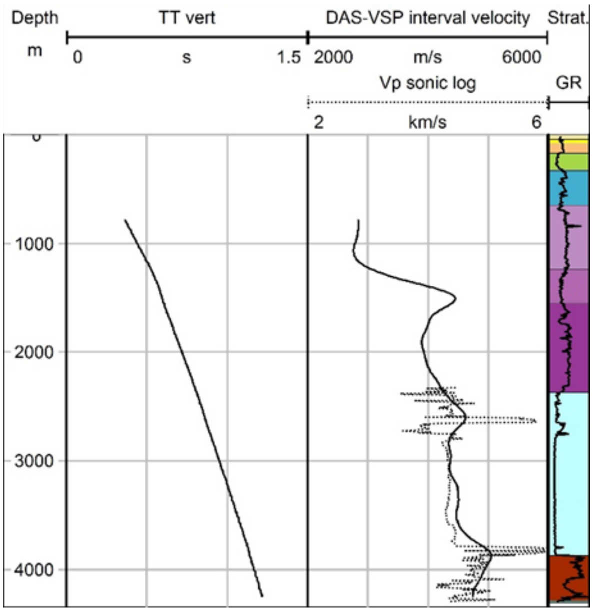

Figure 5: Vertical travel times (TT vert) and VSP interval velocities for well GrSk3. Stratigraphic units and a gamma-ray log (GR) are displayed in the track on the right.

Further processing steps included separation of up- and down-going wavefields, deconvolution, and transformation to two-way travel time. Afterwards vertical reflection profiles (corridor stacks) were generated from the separated upgoing wavefield data. A corridor stack for GrSk3 is displayed in Figure 6. The recorded reflections can be precisely assigned to logging data and lithological information from the wells using the time-depth relationships established before. The most prominent reflections occur near the top and the base of the Zechstein interval, and reflections within the Rotliegend reservoir interval are evident as well.

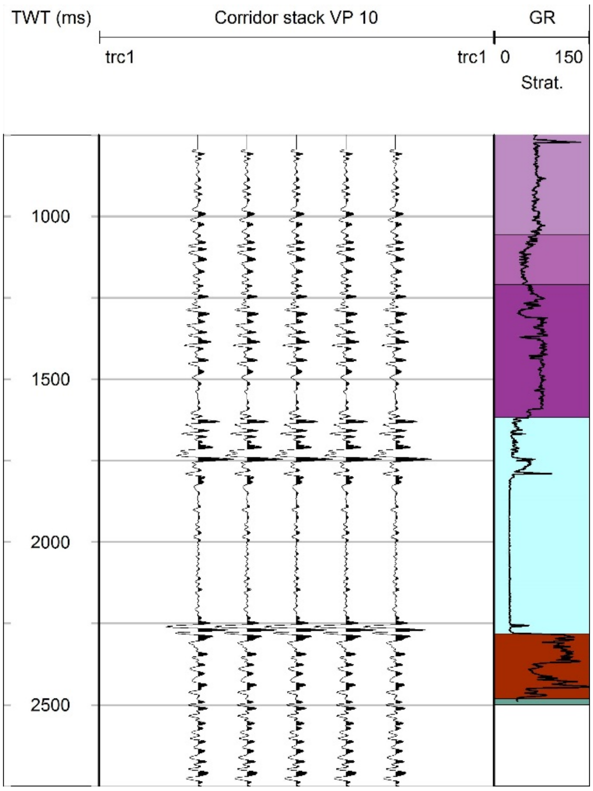

Figure 6: Corridor stack for well GrSk3 in two-way travel time (TWT). Right panel shows stratigraphic units and gamma-ray log (GR).

3.2 3D VSP imaging

As an input for 3D VSP imaging, the data from the other 60 offset positions recorded in well GrSk3 was processed in a similar way. The starting velocity model was based on previous information available, including well log data and a geological model based on vintage seismic data (Moeck et al., 2009), as well as post-stack time migration results of the 3D surface seismic data. The velocity model was then calibrated using the first-arrival travel times from the 61 VSP positions. The 3D VSP imaging was performed using a proprietary method based on beam-migration in combination with common depth-point mapping (VSProwess Ltd).

The generated seismic volume is displayed in Figure 7. It covers the target area around the wells which is imaged with high spatial resolution. As only data from one instead of two receiver wells could be used, zones with low coverage exist in the data volume. These low-fold zones were therefore blanked in order to exclude migration artefacts and avoid erroneous interpretations. The resulting data volume is therefore characterized by frequent gaps. Nevertheless important structural features can be identified, like an overall horizontal layering, different intervals with either parallel or divergent reflectors, and the absence of faults with larger vertical offsets.

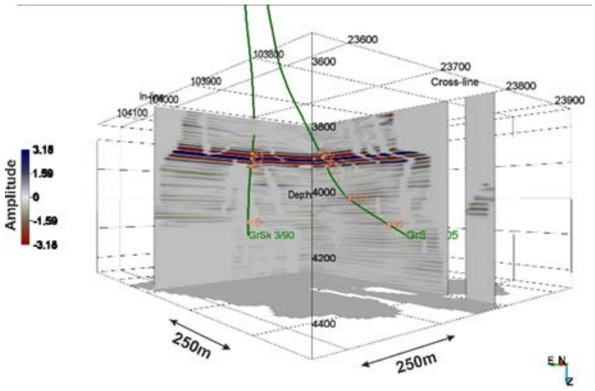

Figure 7: 3D VSP image, with vertical in-line and cross-line sections, well trajectories (green), and marker horizons (orange). Low-fold areas have been blanked (gray). Depths in meters below sea level (TVDSS).

4. CONCLUSIONS AND OUTLOOK

Based on this survey, important new experiences for DAS-VSP acquisition on wireline cable have been gathered. From the zero-offset data, accurate time-depth relationships and velocity profiles were derived. Integrated with other well data and geological information, these serve as input into the evaluation of the 3D surface seismic data set. We show that despite severe constraints during acquisition, structural elements near the boreholes can be imaged with high resolution using 3D-VSP processing. Further processing of the data is ongoing including processing of additional partial records available for well GrSk4, testing of different methods for noise suppression and wavefield separation, as well as other imaging techniques like Kirchhoff migration. The DAS method has enabled measurements at elevated temperatures up to 150 °C and has led to significant time and cost savings compared to deployment of a conventional geophone chain.

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