Seismic monitoring of CO_2 injection: a multidisciplinary processing approach

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ABSTRACT

Geothermal power production may result in significant CO_2 emissions as part of the produced steam. CO_2 capture, underground storage and developments to exploit geothermal resources are therefore focal points for future clean- and renewable-energy strategies. The SUCCEED (Synergetic Utilisation Of CO_2 Storage Coupled With Geothermal Energy Deployment) project aims to demonstrate the feasibility of using produced CO_2 for re-injection as an action for climate change mitigation, to improve geothermal performance, while also storing the CO_2 through mineralisation. This study has the aim to develop innovative reservoir-monitoring technologies by active-source seismic data acquisition by a novel electric seismic vibrator source (E-Vibe), and recorded using permanently installed fibre-optic distributed acoustic sensors (DAS) in shallow-surface trenches, together with auxiliary multi-component (3C and 2C) geophone receiver arrays. The approach gives us the opportunity to compare and cross-validate the results using wavefields from different kinds of acquisition methods. We present the results of the first campaign of a time-lapse monitoring project at the Hellisheiði geothermal power plant in Iceland. We perform a shallow seismic data analysis by tomographic inversion of arrival times, and a deeper data analysis by seismic processing, to investigate both the shallower and the deeper basaltic rocks targets. The DAS and the 3C geophones stacked sections show good consistency, highlighting the same reflection zones at depth. The comparison of the new DAS technology with the well-known standard geophones acquisition proves the effectiveness and reliability of using broadside HWC DAS in surface monitoring applications.

1. INTRODUCTION

Although geothermal energy is generally considered a clean energy source in terms of environmental impact, large-capacity geothermal power plants may emit significant amounts of CO_2 as part of the produced steam. CO_2 capture, underground storage and developments for the utilization of geothermal resources are focal points for the future clean- and renewable-energy strategies. This study is being conducted as part of the SUCCEED (Synergetic Utilisation Of CO_2 Storage Coupled With Geothermal Energy Deployment) project (Durucan et al., 2021). The main objectives of the project are to explore and demonstrate the feasibility of utilising produced CO_2 for re-injection to enhance geothermal performance, while also storing the CO_2 through mineralisation, as an action for climate change mitigation. The study includes laboratory and field campaigns, and aims to develop innovative reservoir-monitoring technologies and to test and further demonstrate the industrial CCUS (Carbon Capture Utilization and Storage) opportunity for geothermal field operators to enhance geothermal performance. Active and passive seismic approaches, described in Stork et al. (2022), are used for this scope. The multidisciplinary project includes:

- Research into the geochemical, geomechanical and geophysical response of reservoirs to CO_2 injection.
- Computer models to investigate alternative injection and reservoir performance scenarios.
- Techno-economic assessment and optimisation of a field-wide/regional CO_2 injection strategy.
- Life-cycle assessment (LCA) models that reflect the engineering processes to evaluate the scalability of enhanced geothermal and CCUS systems considering environmental and resource constraints.
- Monitoring the CO_2 injection operations, site performance and reservoir behaviour at the Kizildere (Turkey) and Hellisheiði (Iceland) sites.
- Information on the changes in field parameters and in geochemistry and geomechanics of the geothermal field, as well as the fate of the CO_2 plume. Use of different, site-adjusted surface and downhole monitoring activities.
- Development and use of new and innovative seismic monitoring techniques and hardware (including an electric seismic vibrator and iDAS systems).

The last point is the subject of this paper. We present the results of the active-source seismic data acquisition and of the preliminary processing of surface-seismic monitoring data. The signals were obtained by a novel electric seismic vibrator source (E-Vibe), and recorded using permanently installed fibre-optic distributed acoustic sensors (DAS), together with auxiliary multi-component geophone receiver arrays (part provided by courtesy of ETH and OR). This multi-receiver configuration was used for the first campaign (conducted in July 2021) of a time-lapse monitoring project at the Hellisheiði geothermal plant in Iceland, one of the two sites studied in the framework of the SUCCEED project. The integration of datasets from different types of sensors resulted in improved quality control (QC) performance, and confirmed the consistency of the collected data. The subsequent analysis compares the signal-to-noise ratio (S/N) and the sensitivity in the broadside helically wound cable (HWC) seismic measurements, with the prediction and recognition of multi-component events in multichannel seismic data of different DAS and geophone systems obtained with co-located geometry.

In the interdisciplinary study, laboratory results from TU Delft (TUD) after geological field campaigns and the findings from seismic field data at Hellisheiði are jointly analysed and merged, including analysis of wavefields, multicomponent and subsurface velocity models by different wavefields. Seismic velocity measurements performed at the TUD laboratory (Janssen et al., 2022b) were used as initial input, and then updated using the seismic field data. This helps both the assessment of the shallower formation properties and deeper settings in the reservoir zone. The comparison and joint investigation of both real seismic signals and laboratory geological data includes numerical simulation and imaging, and subsurface model calibration along the main 2D monitoring line provided by the trenched HWC DAS sensors for the characterization and the time-lapse reservoir monitoring.

In this paper, we describe the processing workflow applied to the data acquired in the seismic campaign at Hellisheiði (Iceland) in the framework of the project in July 2021. The area we investigate in this study covers the surface projection of a fault which has been identified close to the OR-Reykjavìk Energy Geothermal Plant located in Hellisheiði. Multichannel seismic processing of the data, including tomographic inversion, was performed to better characterize the subsurface and improve the velocity model. This updated velocity model was used for a more reliable simulation of waves propagation in the studied area. In addition, a benchmark among the seismic responses from different types of sensors was performed and the different wavefields contents highlighted. Thus, the multidisciplinary features of the studies carried out at Hellisheiði offer an extraordinary opportunity for a joint analysis of the different types of acquired data, leading to a detailed characterization of the site and to develop a methodology to improve the efficiency of the monitoring campaigns.

1.1 Data integration

The work combines multidisciplinary methods, including laboratory experiments (Janssen et al., 2021), 2D numerical seismic modelling, field work to collect reference rock samples, or analogues, of the Hellisheiði geothermal reservoir, and seismic monitoring of CO_2 injection, as a key geophysical tool to investigate subsurface structural settings and conditions. Active-source acoustic transmission measurements have been done at field-representative stress conditions in the TUD laboratory, to estimate the seismic-response characteristics of the reservoir formations present at Hellisheiði. Reference seismic velocity models were estimated from literature and laboratory information. They were used as input to the 2D seismic wave propagation simulation, to define a subsurface model representing the project site. The seismic simulation results were used to design the source-receiver configuration and determine other parameters for the field acquisition and support the QC interpretation of the seismic-monitoring survey results. Synthetic wave-propagation simulation was also useful as a support for the initial analysis of real data.

1.2 Multi-tool acquisition approach

Using a multi-tool approach for the seismic survey, in addition to the DAS deployed in trench (Stork et al., 2020), multi-component sensors have been deployed for auxiliary signal analysis, enhanced monitoring, and quality control. These consisted of one line of 48 10Hz 2C geophones, recording the vertical and inline horizontal components, with 10 m spacing, and two lines of SmartSolo® 3C geophones, with 20 m spacing installed along the entire fibre-optic cable and along a line perpendicular to the fibre-optic cable to provide orthogonal information at depth. The SmartSolo® geophones were provided courtesy of ETH and OR.

2. GEOLOGICAL OVERVIEW

The Hellisheiði geothermal field is located south of the Hengill central volcano in the south-west of Iceland, close to the city of Reykjavik. The Hengill central volcano is part of the larger Hengill area (Figure 1), which lies on the Mid Atlantic Ridge and it is at the junction of Reykjanes Volcanic Zone (oblique rift), the Western Volcanic Zone (WVZ) (rift) and the South Iceland Seismic Zone (transform).

In this area, there are three important volcanic systems:

- one system is the Hengill central volcano, constituted by a north-northeast trending of normal faults and frequent magma intrusions (Bjornsson, 2004 and Bjornsson et al., 1986), which gives the name to the area;
- the Hrómundartindur, east of the Hengill central volcano;
- and the Grensdalur, south of Hrómundartindur, which is extinct, but still shows an intense geothermal activity (Li et al., 2019). The Hengill area extends over an area of about 112 km^2 and it is one of the largest geothermal areas in Iceland (Harðarson, 2014).

The Hellisheiði geothermal field has a temperature >300°C at depth of 1000 m below sea (Gunnarsson, 2013) and the steam combined heat and power plant is one of the biggest in the world by installed production capacity of 303 MWe and 210 MWth energy.

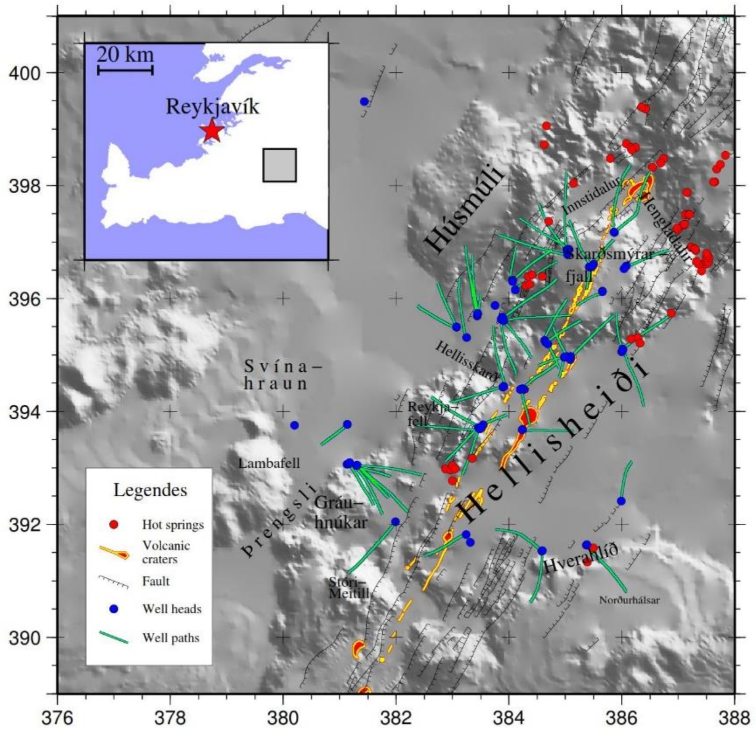


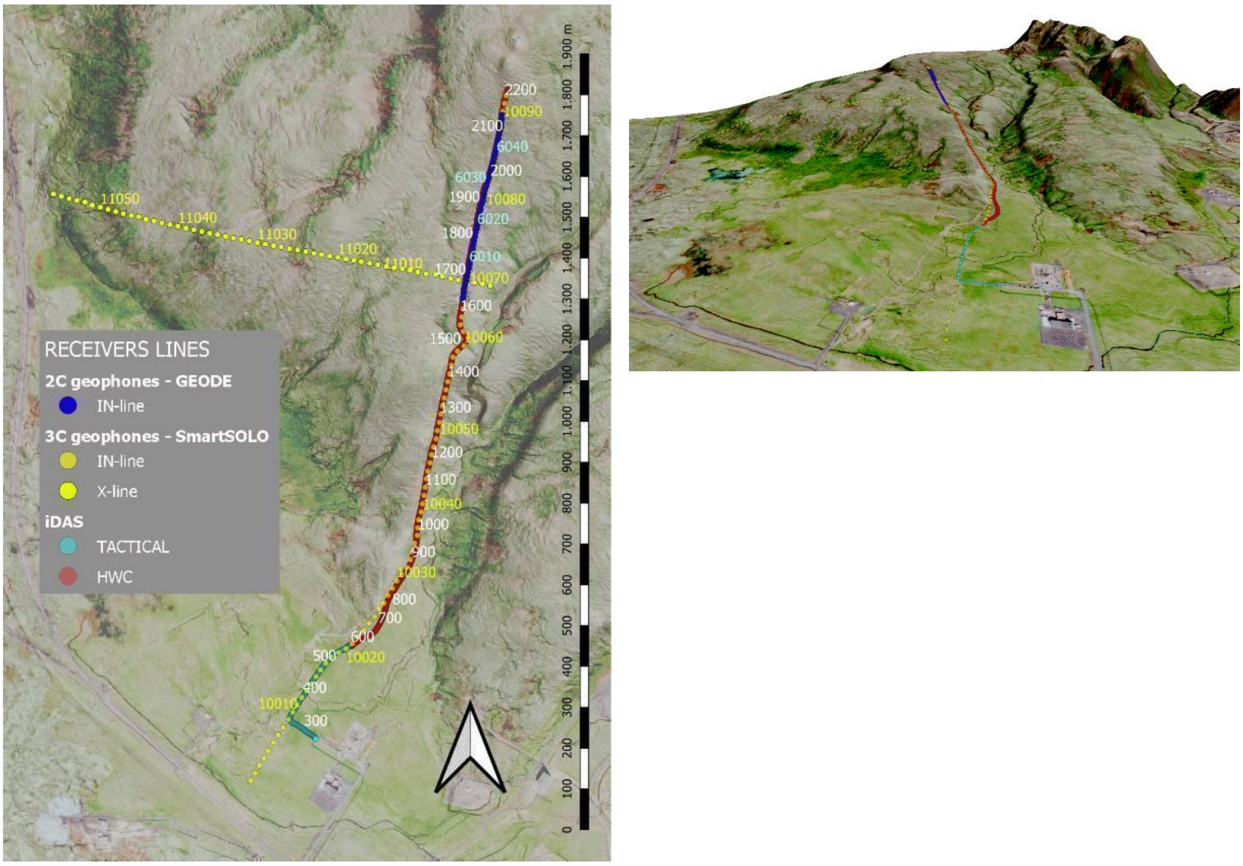
Figure 1: Location map of Hellisheiði Geothermal Field (from Gunnarson, 2013).

3. ACTIVE-SOURCE SEISMIC ACQUISITION

The area we investigate in this study covers the surface projection of a fault, which has been interpreted as close to the OR-Reykjavìk Energy Geothermal Plant located in Hellisheiði. The main targets of the survey are in a range of 0.7 to 2 km: the first, to monitor the CO_2 in the basaltic rocks of the volcanic system at 700 m depth, and, the second, a deeper target of basaltic rocks from a depth of about 2 km. The design of the receivers and sources acquisition lines was planned taking into account the complex surface logistic, topographic and access conditions. Due to the surface (environmental and topographic) constraints, the main seismic line is nearly parallel to the interpreted faults system (Figure 2). For this reason, to obtain additional lateral information, some auxiliary receiver and sample shot acquisition points were located along a perpendicular line crossing the main line.

The active source is the STORM-10 E-Vibe developed by Seismic Mechatronics and operated in vertical mode during this survey. The parameters for the source sweeps were decided after evaluating the initial QC results in the field, by analysis of the S/N in relation to the number of stacks per shooting point, to set the spacing of the vibration points (VPs), considering the operational resources available for the field campaign. The VPs are spaced at 40 m. They follow the path of the approximately 2-km-long trenched linear tactical and HWC DAS fibre-optic cable. This line was installed by Silixa, and suitable for passive- and active-source monitoring (Stork et al., 2020; Stork et al., 2022). The HWC cable was chosen for the project to improve the broadside sensitivity to P-waves (Kuvshinov, 2016). In fact, in addition to passive seismic (Stork et al., 2022), the active-source seismic target was to detect the compressional wavefields expected to emerge with near-vertical travel paths from deep structures, and to provide information on shear components. In the framework of the active-source seismic campaign, this configuration focused on the recognition of the reflected P- and S-waves for the investigation of the deeper formations. However, the active-source data obtained with the same setting were successfully used for velocity-analysis purposes by inversion of the first-arrival times of the signals travelling with slant travel paths in the shallow layers.

Simultaneous recording was performed with co-located geophones in addition to the main trenched DAS line (Stork et al., 2020), using multi-component sensors deployed for the auxiliary signal analysis, enhanced monitoring, and quality control based on prompt data interpretation, assisted in relevant time by remote support from headquarters. The geophone lines consisted of two types of sensors. One line of 48 10Hz 2C geophones, recording the vertical and inline horizontal components, was used with 10 m spacing in a shorter 500-m interval. Two longer lines of SmartSolo® 3C geophones were installed with 20 m spacing along the whole main HWC fibre-optic cable and along a line perpendicular to the fibre-optic cable to provide orthogonal information at depth relative to the main acquisition line, sub-parallel to the fault setting. The SmartSolo® geophones were provided by courtesy of ETH and OR. Figure 2 shows the layout of the multi-tool experiment, adopted for the first active-source seismic campaign at Hellisheiði. Because of the different functionality of the system with online and remote configurations, the data were available both in near-real time and deferred time after acquisition. The acquisition was performed in close cooperation, in field and at office by remote connection, between the partners (OGS, TUD, Silixa, Imperial College, Seismic Mechatronics, and OR-Reykjavík Energy).



a) **b)**

Figure 2: Surface seismic experiment layout. a) Line-geometry overview. b) 3D view, showing the topographic variations along the lines.

Recording parameters. The seismic source was operated for the production survey by Seismic Mechatronics in P-wave mode, i.e., it vibrated vertically. The source spacing during production was 40 m, stacked 16 times per VP. The sweep of the E-Vibe was 15 s length, sampled at 4000 µs, with a frequency range from 2 to 150 Hz and a start cosine taper of 0.3 s and an end taper of 0.6 s. The record length for DAS, TUD and SmartSolo® was of 20 s, with a sampling rate of 1000 µs, 500 µs and 1000 µs, respectively.

Real-time on-line data. DAS data were acquired on the entire cable length by the Silixa iDAS system and shot data were provided in SEGY format. The 48 2C geophones from TUD were acquired using the GEODE system. The output is a standard SEGY file with the collection of the entire daily records.

Deferred-time memory data. Memory data from the SmartSolo® geophones were retrieved only after acquisition, downloaded from the stations' memory, and then formatted and analysed at office.

Therefore, only the data from the DAS and 2C geophones were used for QC purposes during acquisition. The seismic campaign produced a large amount of data: 59 was the number of VPs, 16 was the number of stacks per VP in the production phase, 944 records each of 20 seconds for a total of 4225 Mega-traces, corresponding to 770 GB of data.

3.1 On-field operations and remote QC

OGS performed on-field and remote support, provided technical instrumentation, and mounted a remote radio system for triggering iDAS, to speed-up the collection of records during the early QC testing phase. An additional, radio trigger was installed on the E-Vibe to trigger the GEODE systems during production. The equipment included two laptop PCs, one of which running the acquisition control interface, and the other running QC jobs, i.e., data visualization and inspection. The remote QC was performed in near-real time, i.e., relevant time that allowed quick decisions on acquisition parameters with the aim to optimize resources. QC included the choice of source vibration parameters, VP interval, number of stacks per VP, sweep mode, frequencies and length, tuned during the survey based on the sweep and seismic results of initial and sample tests performed at the beginning of the survey. For this purpose, Seismic Mechatronics provided the source pilot signals. The data recorded shot by shot was made available in SEGY format at the end of each day, with all the information needed to build a consistent dataset, such as vibrator position and timestamp. Essential for the QC was the integration, formatting and editing of the different datasets with the same recording parameters, to be usable in relevant time during acquisition.

Figure 3 shows an example of a pilot-signal QC, which enables monitoring the source performance and highlighting any problems during the source vibration.

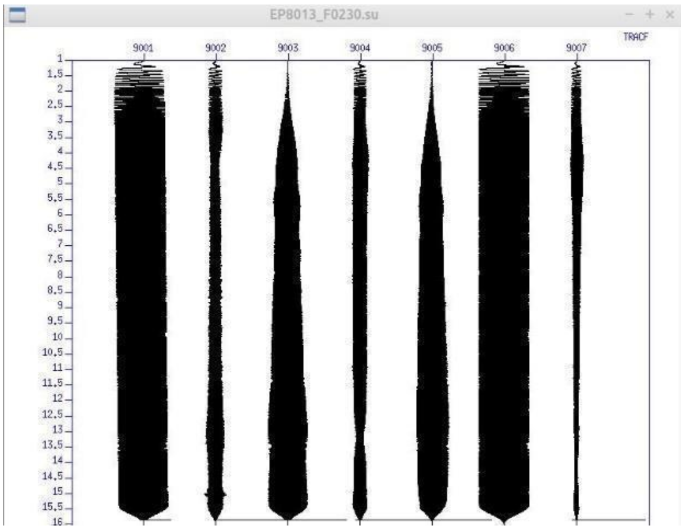


Figure 3: Example of a pilot-signal QC. The traces represent the theoretical signal, the measured acceleration signals and the calculated ground force for the selected shot and VP.

Cross-correlations of the data with the selected pilot trace were computed and stacked (vertical stack) to provide interpretable data during the field operations. This process, including data conversion, usually took the entire night, due to the large amount of data from the DAS, densely sampled both in space (with one optical receiver at about every m, and recording sampling of 1 ms). The correlated data were uploaded, during the night and the day after, to the remote-headquarter cloud and made available to the remote staff involved in the QC.

During the acquisition of each day, also on-field QC was performed on the data collected the day before, in order to provide some useful indication for the acquisition, following the feedback indications from remote headquarter where a deeper geophysical analysis was also performed during the acquisition campaign.

The remote QC was focused on evaluating and validating the preliminary seismic results obtained in the field, by evaluating the frequency spectrum of the signals, the quality of the pilots and the quality of the correlated data (seismic response and overall S/N). In this process, an analysis was performed to decide on the optimal number of vibrations per VP to improve the S/N in a cost-effective manner, thus to adjust and confirm the optimal operating parameters of the survey.

During the QC phase, only the data from the DAS and 2C geophones were used because the data from the SmartSolo® stations were not available in real-time.

Figure 4 shows common-source gathers obtained at VP EP8045 E-Vibe, recorded with both the DAS and 2C geophones as an example of provisional display utilized during the acquisition. The data are cross-correlated with the pilot signal from the E-Vibe and stacked. From left to right, the figure shows the panels of the 2C geophones (horizontal-inline and vertical components) and DAS signal extracted at the same line interval for comparison, taking into account the different spatial sampling of the two sensor lines. The data obtained with the different types of sensors show good consistency.

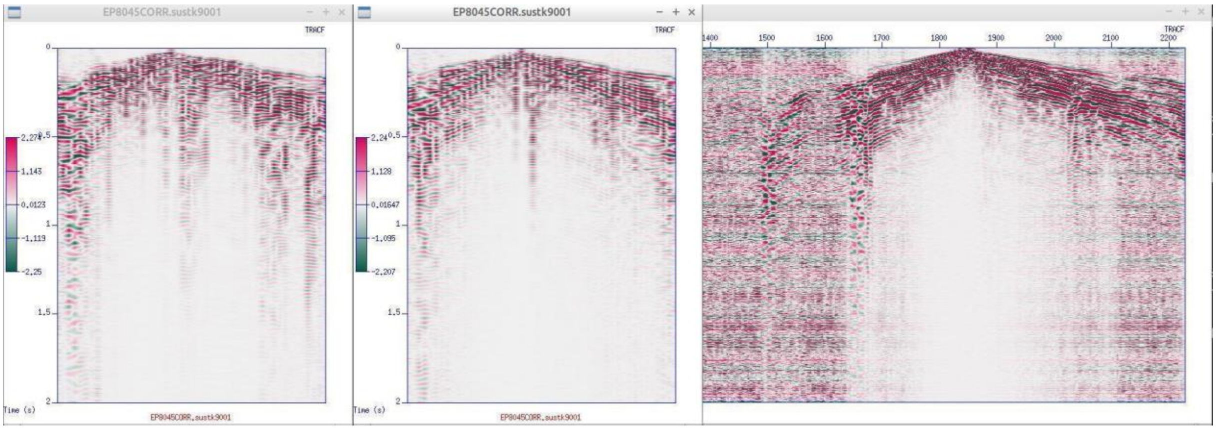


Figure 4: Common-source gather using (from left to right): horizontal-inline component of the 2C geophones, vertical component of the 2C geophones and DAS (with spatial sampling corresponding to the 2C geophones), as an example of provisional display utilized during acquisition.

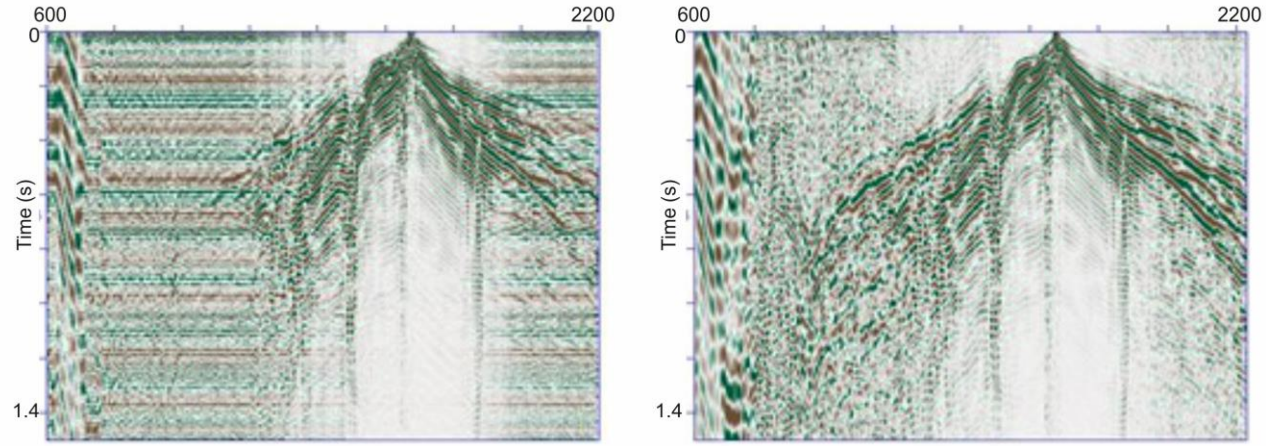


Fig. 5: DAS common-source gather with optical noise (left) before and (right) after noise removal.

4. SIGNAL PRE-PROCESSING

Prior to proceed with further signal analysis and multichannel data processing of the signals of the 2D seismic line, some pre-processing steps were applied to improve the S/N in the DAS data. The quality of the DAS data is in general good and satisfactory; however, coherent noise events were identified in the field shots and processed. The inspection of the field data showed that the DAS dataset was affected by optical noise crossing the entire shot records. This noise is interpreted as originated by the optical fibre system itself. This kind of noise consists in horizontal stripes of correlated noise in the correlated data (Figure 5a) that severely mask the seismic signal, already at short offsets. We developed a tool and analysis procedure to clean the signals and improve the S/N (Figure 5b). This tool is based both on selection of data before stacking, and on estimation and subtraction of the noise. The optical noise in the raw DAS data was estimated and subtracted from the DAS traces before correlation with the optical-noise-free pilot signal, i.e., the vibrator sweep.

5. NUMERICAL MODELLING

We calculated synthetic seismograms prior to acquisition and after seismic data collection. An analysis prior to the acquisition was done to evaluate and plan the acquisition parameters and settings with the aim of supporting the active- and passive-source seismic monitoring of the studied area, to provide data useful for the in-field quality control, and after model updates to drive the field-data processing and interpretation and to calibrate the laboratory-based velocity model. We performed the seismic elastic wave field modelling with a fourth-order in space and second-order in time two-dimensional finite-difference scheme based on a staggered grid formulation (modified after Levander, 1988). We used a 2D model designed along the DAS and SmartSolo® acquisition lines using a stratigraphic section in the vicinity of the Hellisheiði geothermal field (Janssen et al., 2022b), 4 km long and 3 km deep. The model was discretized with square pixels of 2 m side. Figure 6 shows the geometry of the subsurface model with the main individuated lithologies.

To analyse the wavefield produced by the E-vibe, we simulate the 2D wavefields emitted by a vertical (Z) and a horizontal (X) point sources acting at the topographic surface of the model, and we recorded both the vertical and the horizontal particle-velocity components. These data were used to study the source utilization (position and number of stacking), in terms of optimal use of wave components, and to select the acquisition parameters, considering also the DAS response. For the initial model, the compressional-wave velocity (V_P) was derived from average values properly assigned to each lithologies according to their depth; the density was calculated using the Gardener's relationship (Gardner et al., 1974). Shear-wave velocity (V_S) was derived using a V_P/V_S ratio of 1.8, estimated from the seismological profiles provided by the Coseismiq Project Hengill.

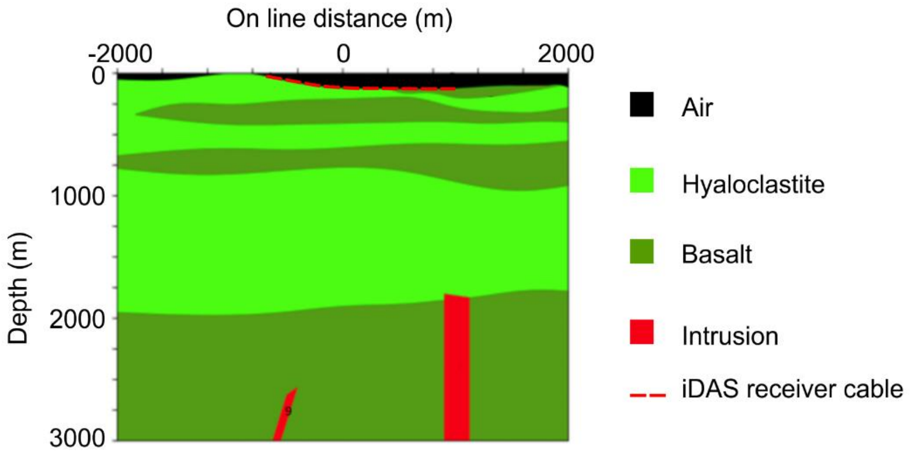


Figure 6: Hellisheiði subsurface model (NW-SE oriented), the main individuated lithologies are indicated in the legend, the receiver cable position is marked with a red dashed line.

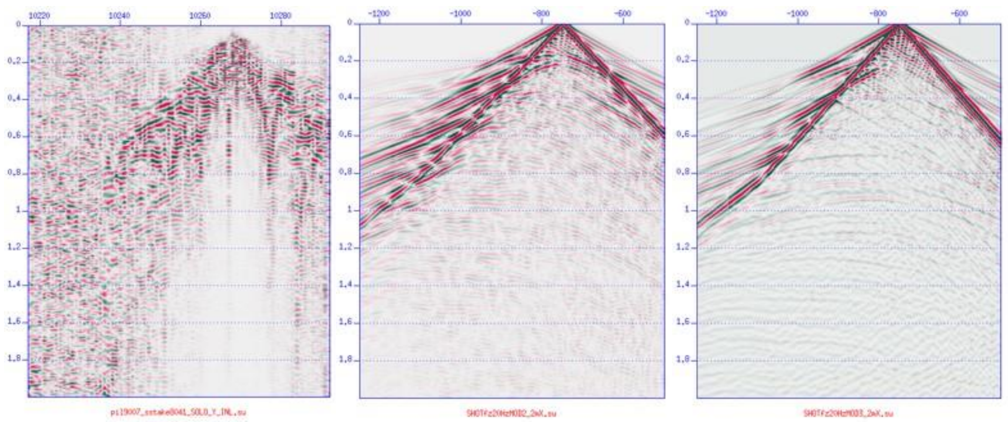


Figure 7: Common-source gathers: (a) Y-component of the SmartSolo® geophones, (b) corresponding synthetic response obtained using model MOD2 and (c) synthetic response obtained using model MOD3.

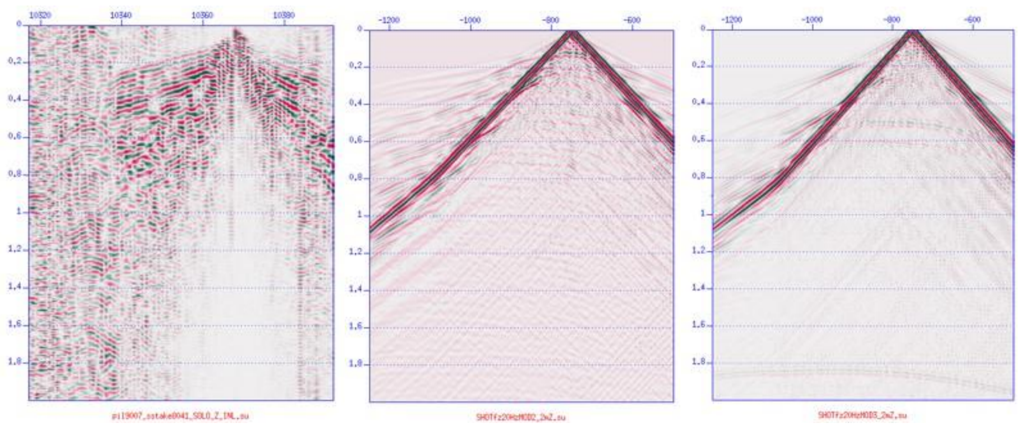


Figure 8: As in Figure 7 but for the Z-component of the SmartSolo® geophones.

We performed a model velocity analysis by comparing synthetic and field data, which resulted in updating the velocity and density models. A further update was performed after a re-calibration with the laboratory data. Figure 7 shows an example with the comparison between the Y-component of the SmartSolo® geophones and the corresponding synthetic responses obtained using two different models (MOD2 and MOD3), progressively updated and integrated with the laboratory results. Figure 8 shows the same results as in Figure 7, but for the Z-component. The figures show that the synthetic signals fit quite well with the field data.

The shallower part of model MOD2 was calibrated with the preliminary laboratory results of the geological study. The seismic properties of model MOD3, in terms of compressional and shear velocity and density, were modified with the final laboratory results presented by Janssen et al. (2022a). The compressional velocity of the shallower highly porous basaltic layers was less than that used in the previous models. A further model, MOD4, was considered after integration with the tomographic results obtained from the inversion of the first arrivals of the HWC DAS data, as described in the next section.

The comparison with the tomographic results, indeed, highlights an area of high velocity where a basaltic body is expected with a compressional velocity greater than that expected from laboratory measurements. One reason for this higher velocity might be the heterogeneities of the basalts. In addition, the shallow hyaloclastite unit seems to exhibit higher velocities than the laboratory measurements. Figure 9 shows the superposition of the tomographic inversion to the updated model along the receiver line along the SE-NW direction after the integration with the tomographic results.

6. SHALLOW SEIMIC SIGNAL INVERSION

The dense spatial sampling of the HWC DAS along the main line provides suitable data for tomographic inversion of the times of the first arrivals. The main results are shown in Figure 9. The analysis used a high number of DAS traces recorded with an optical gauge length of 10 m and a spatial sampling of less than 1 m. In fact, the DAS traces were suitable for refined signal analysis, while the geophone traces were available with less dense spacing and along a shorter line. The inversion results were obtained using the CAT3D OGS software, and provide velocity information and imaging in the shallower formations that was integrated with the MOD3 to update it to MOD4 (Figure 9). In MOD4, the shallow basaltic layer, where the tomography evidenced a high-velocity area, now has velocity of about 4200 m/s, Vs=Vp/1.8, while in MOD3, where values from Janssen et al. (2022a) were used, Vp=2600 m/s and Vs=14470 m/s.

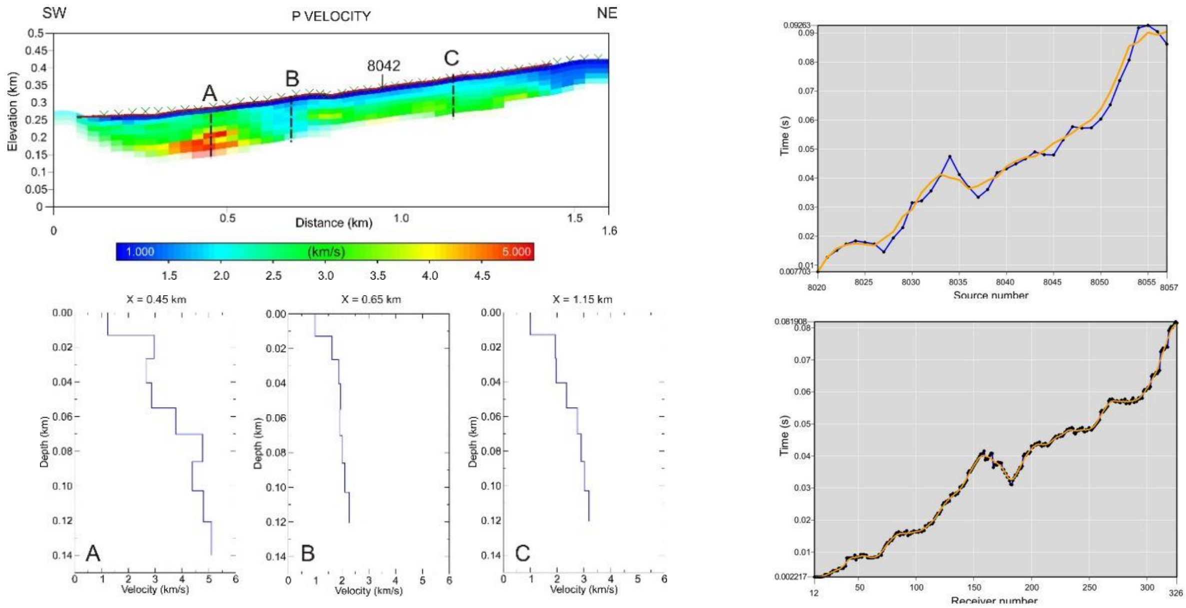


Figure 9: Compressional-velocity section obtained from inversion of first arrivals (top left), using the Simultaneous Iterative Reconstruction Technique (SIRT) algorithm (Stewart, 1991). Green crosses are the shot points, red line is the receiver cable (DAS). A, B, C are the positions corresponding to the vertical velocity functions shown in the bottom left panels. The right panels show the smoothed applied static corrections (yellow solid line) and in blue the punctual static corrections for sources (top) and receivers (bottom), respectively.

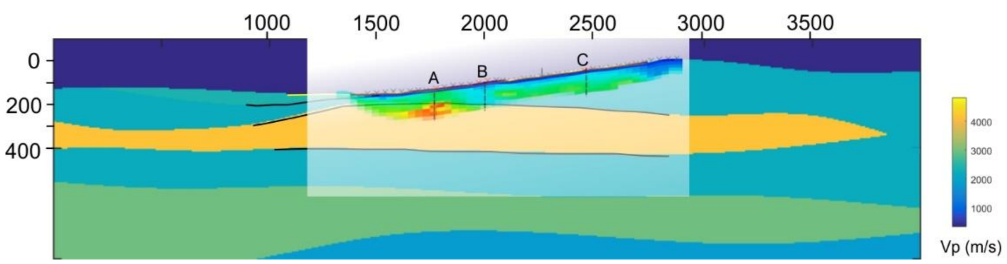


Figure 10: Superposition of the tomographic inversion to the updated model (MOD4) along the receiver line in the SE-NW direction, after the integration with the tomographic results.

7. 2D SEISMIC PROCESSING

The main goal of the acquisition and processing of the DAS and SmartSolo® surveys was to obtain detailed geophysical information about the subsoil of the study area, to demonstrate the feasibility and application of the DAS technologies for the monitoring campaigns. We focused the analysis on the S-N 2D line, which is nearly perpendicular to the fault. This acquisition with three types of sensors gave us the opportunity to compare the results from different kinds of acquisition methods, and to validate the results from the new DAS tool with those of the well-known geophones. Below, we describe the processing of the DAS and SmartSolo® data with comparison of their results, while the processing of 2C geophones and their comparison with the SmartSolo® and DAS data is not investigated here because of the limited extension of the 2C geophone line.

Apart from the initial processing dedicated to S/N improvement, the DAS and SmartSolo® data sets were processed using the same multi-channel processing flow for a more reliable comparison of the results. However, some steps, like trace editing and noise removal, were calibrated to the specific characteristics of each data. We used the same processing to compare in the same conditions the resulting stacked sections of the DAS and SmartSolo® acquisitions. Differently from data obtained by suitable receiver arrays, in the analysis of the individual trace signals, both datasets present low S/N. Along the line ranging from VP 8001 to 8059, due also to presence of coherent noise, the results are more disturbed in the first VPs, i.e., VP 8001-8019, where noise predominates. We removed these VP positions from the data set to reduce the amount of the noise and considered only the VPs from 8020 to 8057 for both datasets.

The DAS signal was spatially sampled with about 1 m trace-interval, with 1605 traces per VP. As a first step, to process a subset of the data, we extracted every fifth trace, obtaining an inter-trace interval of about 5 m, resulting in 326 traces per VP, which makes it easier to manage the data set and to compare it with the SmartSolo® acquisition. The single traces presented large amplitude variations versus offset. We normalized the dataset by dividing the traces amplitudes by their rms values (Figure 11 and Figure 12). In the gathering of the data, the first step was to define the geometry of the line, by designing a crooked line that smoothed the acquired 2D line, with a common midpoint (CMP) spacing of 2.5 m and a maximum fold of 44, higher than that of SmartSolo® geophones (Figure 13). Then we calculated the static elevation corrections, which are fundamental to correct the difference in the arrival times due to the relevant variation of the topography (up to 150 m) and velocity of the shallow layers. To get the static values at each geophone and VP position, we used the interval shallow velocities, obtained from the tomographic inversion of the first-break picking, using the Simultaneous Iterative Reconstruction Technique (SIRT) algorithm (Stewart, 1991), with Cat3D software (Figure 9).

We edited the traces in the CMP gathers, removing or reducing the noisier ones, i.e., those including different types of noise such as spikes and air wave. Before stacking, we applied an exponential gain correction to compensate for the signal attenuation and absorption in the subsoil, which is high in this volcanic environment (Shaw et al., 2008). A band-pass filter (5-16-70-80 Hz) was used to limit the frequency range in the comparison of the two types of signals.

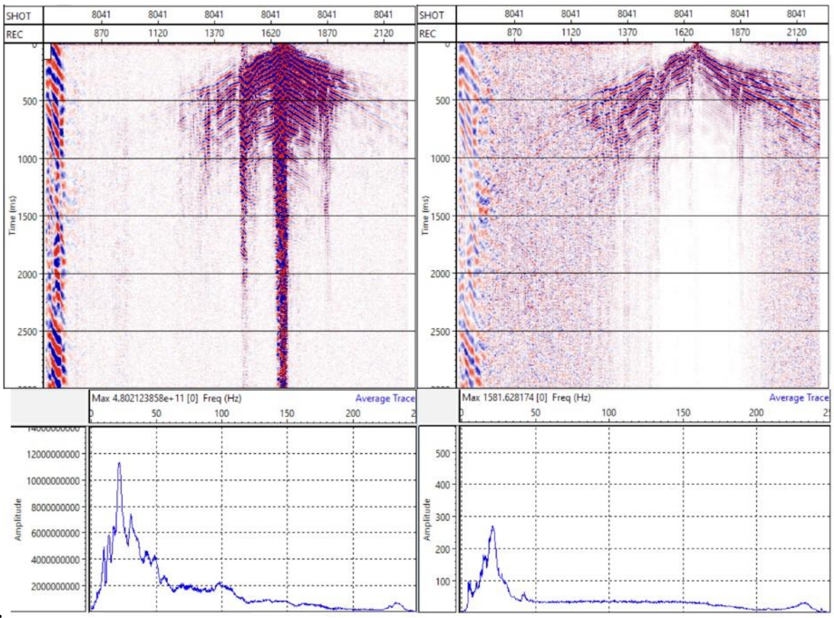


Figure 11: DAS gather for the VP 8041 before and after balancing.

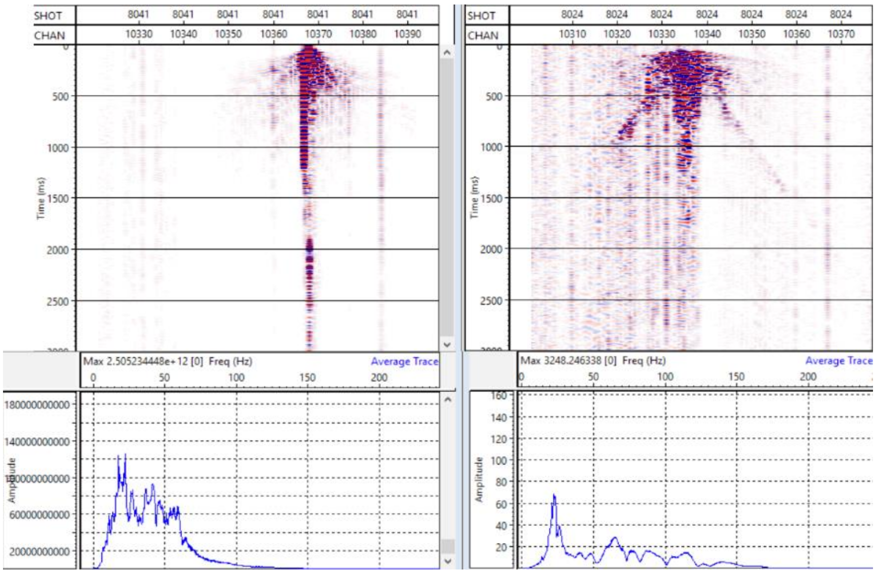


Figure 12: SmartSolo®s shot gather for the VP 8041 before and after balancing.

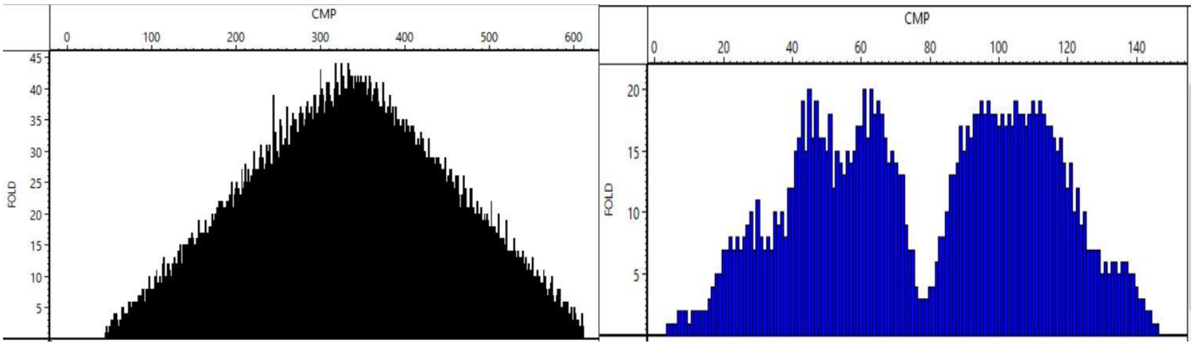


Figure 13: Fold of (left) DAS and (right) SmartSolo® CMP gathers along the 2D main line. The gap in the latter is due to the editing of the noisy traces.

We applied pre-stack predictive deconvolution, using a 400-ms-length operator and the second zero crossing as prediction lag, then repeated the same band-pass filter. The velocity analysis is one of the most important steps in the seismic data processing. In this survey, the low S/N and the high absorption by the subsoil lithology, together with velocity inversions in the numerical model, made it difficult to identify where to pick the stacking velocities. Notwithstanding this complexity, we identified a reference 1D velocity profile (Figure 14), through constant velocity stacks (CVS) and the semblances combined analysis, that was applied to obtain the time stacked section. The stacked result obtained with the DAS data, shown in Figure 15, was boosted by applying a weighted mix among the traces (0.6,1,1,1,0.6) and an automatic gain control (AGC) of 500 ms, the latter for display purposes only. Despite the complex environment, some reflected energy is visible between 500 ms and 1000 ms, but also later in time. A similar multi-channel processing was applied to the SmartSolo® data, which presented the same high-amplitude values seen in the DAS dataset. Also in this case, we balanced the amplitude values of the data (Figure 12). After that, we assigned the geometry to the CMP gathers, which resulted in 143 CMPs, spaced at 10 m, because the geophone spacing was 20 m, with a maximum fold of 20 (see Figure 13).

The elevation static-correction values to be applied at each geophone position were calculated from the same velocity model (see Figure 9) used for the DAS dataset, and the static-correction values are the same as those used for the DAS positions. After balancing, the dataset still showed some spikes, i.e., traces with high amplitude, which we removed shot-by-shot using an automated de-spiking tool. Also in this case, we run specific editing to reduce or remove other noises from the data, e.g., air wave. The next steps of the processing sequence were the same as used for the DAS dataset (i.e., exponential gain correction, band-pass filter, predictive deconvolution and stacking), with the same processing parameters and 1D velocity profile obtained from the DAS dataset (Figure 14). The final stacked time section obtained from the SmartSolo® data is shown in Figure 16 after application of AGC of 500 ms, for display purposes only. The stacked section from the SmartSolo® data is in general less noisy than the DAS stacked section, but with lower resolution. However, the two sections show a good agreement, and the same reflected energy is visible in both sections. Further analysis will involve the reprocessing of the DAS data with the complete dataset spatially sampled at 1 m, a more detailed velocity analysis at different CMPs. This task will be performed with the support of numerical seismic modelling. Other targets are the investigation of the different wave-fields in the DAS signals (acting as strain-rate sensors) and in the geophone signals (acting as velocity transducers), as well as the depth conversions of the time sections. These sections, according to the velocity profile in Figure 14, are estimated to range between the surface and depths greater than 2 km.

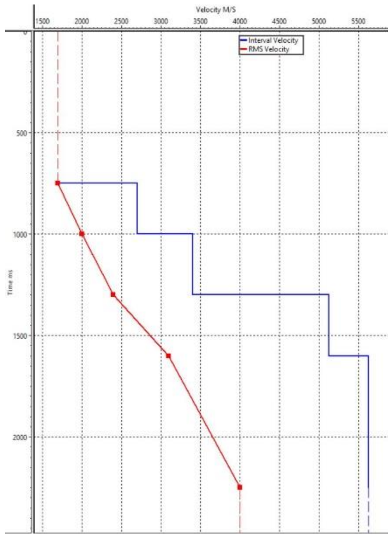


Figure 14: Stacking and interval velocity functions used in the processing of the 2-D data of the main seismic line.

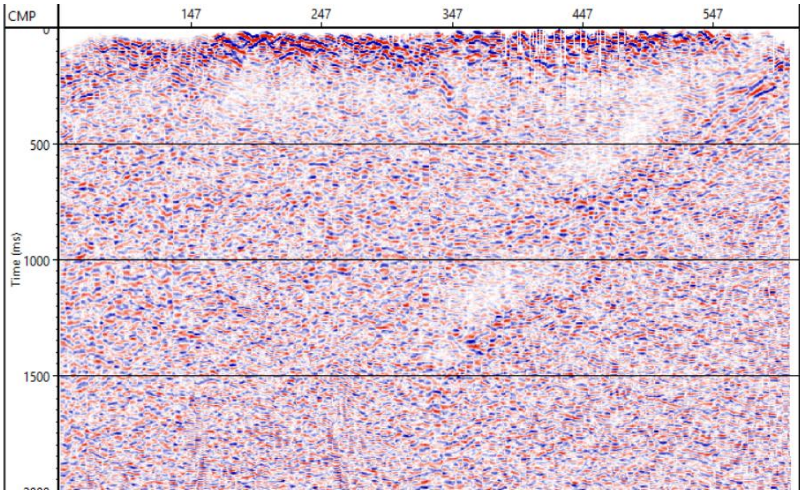


Figure 15: Bandpass-filtered DAS stacked time section.

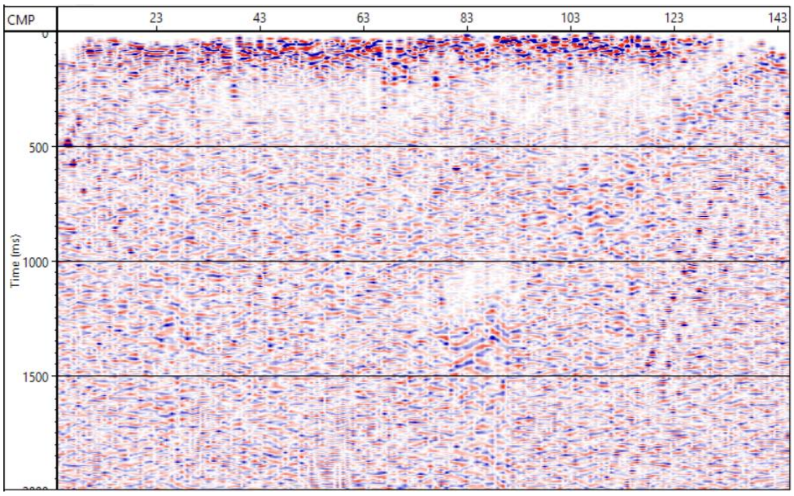


Figure 16: Bandpass-filtered stacked time section from the SmartSolo® data (vertical component).

8. CONCLUSIONS

This study presented the baseline active seismic acquisition using an innovative electric source (E-Vibe) and DAS system, and the data processing for seismic imaging and monitoring purposes for CO_2 re-injection at the Hellisheiði geothermal power plant in Iceland, in the framework of the SUCCEED project. The use of tree types of co-located sensors (DAS, 3C SmartSolo® geophones and 10Hz 2C geophones) gave us the opportunity to compare and cross-validate the results from different kinds of acquisition methods. The DAS and SmartSolo® stacked sections showed good consistency, highlighting the same reflection zones at depth. The comparison of the new DAS technology with the well-known standard geophones acquisition proved the validity of using broadside HWC DAS in monitoring applications. The subsequent processing of time-lapse data, acquired in June 2022, should demonstrate the monitoring capabilities of the DAS technology combined with the new E-Vibe source. In this work, we showed the processing of the extended lines acquired by DAS and SmartSolo® sensors with a comparison of their results, while the processing of and the comparison with the signals from the 2C geophones deployed along a shorter line interval was mainly used for wavefield analysis and QC purposes, gaining from their higher sampling properties and data availability in near-real time.

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