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Time-lapse seismic monitoring of CO_2 injection and storage at the Hellisheiði geothermal field, Iceland

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Abstract

Geothermal energy originates from the Earth's core and is stored in rocks and fluids underground. Although geothermal energy is generally considered a clean energy source in terms of environmental impact, large-capacity geothermal power plants can emit significant amounts of CO_2 as part of the generated steam. Carbon capture, utilisation and underground storage (CCUS) and developments for the use of geothermal resources are priorities for future clean and renewable energy strategies. One of the main objectives of the SUCCEED (Synergetic Utilisation of CO_2 storage Coupled with geothermal EnErgy Deployment) project is to provide a state-of-the-art, cost-effective, and low-environmental impact geothermal CO_2 storage monitoring technique. The feasibility of this system has been demonstrated at the Reykjavik Energy (OR) Hellisheiði geothermal field in Iceland, where re-injection of produced CO_2 is taking place to permanently store the CO_2 in the basaltic reservoir formation through mineralisation.

In this work, we focus on the time-lapse active seismic-reflection survey carried out at the Hellisheiði field. The baseline and the time-lapse surveys were conducted during the summers of 2021 and 2022, respectively. The aim of the time-lapse (4D) survey was to detect possible seismic differences that can be related to the migration of the CO_2 in the reservoir, demonstrating the effectiveness of a new, low-environmental-impact, electric seismic vibrator (E-Vibe) specially designed for the survey, and Helically Wound Cable (HWC) Distributed Acoustic Sensing (DAS) as a tool for CO_2 monitoring in a time-lapse perspective. This is a challenging task as conventional seismic-reflection techniques commonly deliver poor quality data in volcanic environments because of scattering, attenuation and static problems.

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1. Introduction

Geothermal energy derives from the Earth's core and it is stored in rocks and fluids in the subsurface. Generation of electricity from geothermal power dates back to the beginning of the 20th century and reached 95,098 GWh worldwide in 2020[1]. 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. Carbon capture, utilisation and underground storage (CCUS) and developments for the utilisation of geothermal resources are focal points for the future clean and renewable energy strategies. The main objectives of the SUCCEED project are to explore and demonstrate the feasibility of utilising produced CO2 for re-injection to enhance geothermal performance, while also storing the CO2 as an action for climate change mitigation. The studies have been carried out in two existing facilities, at Kizildere in Turkey [2] and Hellisheiði in Iceland, that present a uniquely active geology and natural conditions suitable for geothermal energy production. This multidisciplinary project includes geochemical, geomechanical and geophysical studies, fluid flow modelling, laboratory analysis (Janssen et al., 2022) as well as the development and use of innovative seismic monitoring techniques and hardware tools (including an electric seismic vibrator and Distributed Acoustic Sensing systems) for CCUS purposes.

Fibre-optic sensing cables (DAS) have been shown to be suitably robust for extended duration installations in geothermal fields [3], making them ideal to test and assess monitoring techniques at the Hellisheiði geothermal field to improve the long-term repeatable monitoring with a permanent installation. In fact, the DAS technology offers dense spatial and temporal sampling and measurements can be made on a single cable up to tens of km long. Another advantage of the fibre-optic technology over traditional seismic instruments (geophones) is that cables with polyimide coatings enable DAS measurements in high temperatures up to 300 °C, as often experienced in geothermal environments [4], with the great advantage that DAS cables can be used also in borehole seismic surveys.

First applications of DAS technology in geothermal reservoirs focused on passive monitoring., as microseismic, local, regional and teleseismic events can all provide useful information about a geothermal area on various scales (e.g., [5]). Recently, some authors used vertically installed fibre-optic cable in a geothermal injection well to record strain rates and detect earthquakes for monitoring purposes [6]. Standard DAS cables are not optimal for surface seismic acquisitions. In fact, a standard DAS has its highest sensitivity to P-waves when the angle of incidence ϑ of the wave is 0 degrees. The sensitivity decreases as $cos^2(\vartheta)$ as the angle of incidence increases, reaching its minimum when the wave propagation is orthogonal to the fibre (e.g., [7]). A broadside sensitivity version of the fibre optic cable is the Helically Wound Cable (HWC), where the sensitivity is significantly improved with the angle of incidence of a P-wave [8,9]. In recent years, passive monitoring of geothermal fields has been analysed utilising linear and HWC fibre-optic DAS deployed at the surface [10]. The use of HWC DAS for monitoring purposes in geothermal areas using an active source is still a topic under investigation, with the aim to understand its sensitivity to the different wavefields that can be recorded in a complex environment. Understanding the HWC DAS signals response could be of relevant importance for the development of a monitoring system in geothermal areas.

This work is focused on the Hellisheiði geothermal field and includes the description and the results of the active seismic monitoring campaigns, where the innovative HWC DAS system together with the electric seismic vibrator (E-Vibe) were used. We mainly focused on the time-lapse survey performed in June 2022, to investigate the capability of time-lapse seismic data to provide a reliable tool to highlight the migration of the CO_2 plume (dissolved in brine) in the reservoir, by the comparison with the baseline survey performed in July 2021.

2. Seismic surveys description

The Hellisheiði geothermal field is located in the southern part of the Hengill volcanic system in the southwest of Iceland, close to the city of Reykjavik. The Hengill volcanic system is constituted by a central volcano and a fissure swarm with a graben structure that extends to the northeast and southwest (e.g. [11]), and it is located at the junction of the Reykjanes Volcanic Belt, the Western Volcanic Zone and the South Iceland Seismic Zone. The area we investigate in this study covers the surface projection of a fault close to the Reykjavìk Energy Geothermal Plant in Hellisheiði. The DAS array used as a seismic sensor consisted of approximately 1.5 km of HWC and 350 m of linear tactical cable, permanently installed (Figure 1). For the baseline survey only, one line of 48 10 Hz geophones recording the vertical and horizontal components (2C), spaced 10 m apart, and a line of 92 SmartSolo® 3C geophones, spaced 20 m apart, were deployed along the main HWC line and the recorded data were used (Figure 1). The auxiliary well-known geophones were used as a benchmark to validate the signals from the innovative HWC [12]. Passive seismic approaches to study the behaviour of injected CO_2 in geothermal reservoirs using HWC have been described in [10]. Here, we describe the time-lapse active seismic approach for the monitoring of complex geothermal environments using HWC and the innovative eco-friendly E-Vibe. The advantage of HWC, besides the dense spatial and temporal sampling, is its broadside sensitivity, which makes it suitable for recording wavefields from deep structures, which is an objective of the study. There are, in fact, two main targets: the first one aims at monitoring the injected CO_2 in the basaltic rocks of the volcanic system at 700 m depth, while the second one is the deeper target of basaltic rocks from a depth of about 2 km, where the injected CO_2 is expected to migrate to.

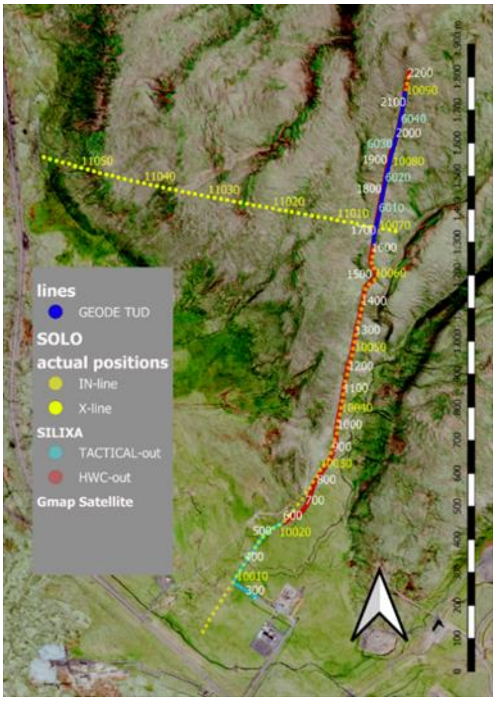
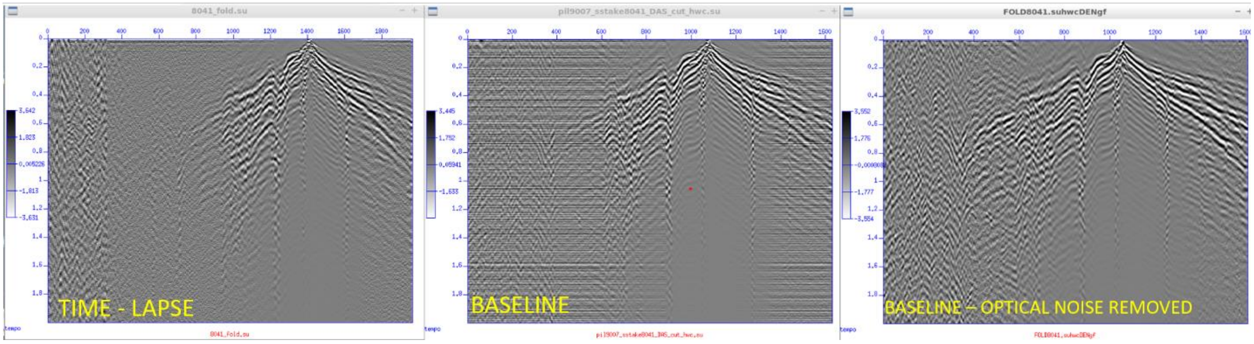


Fig. 1. Map of the seismic lines, including HWC, 2C and 3C geophones.

The baseline survey confirmed the consistency of the signal among the different kinds of sensors, validating the use of HWC [12] combined with the E-Vibe. After the baseline survey, about 12000 tons of CO_2 were injected in the reservoir, before the scheduled time-lapse survey. Figure 2 shows the comparison of the same shot gather (EP8041) from HWC recorded during the time-lapse and the baseline survey, before and after optical-noise removal. HWC baseline data were affected by optical noise, typical in DAS data, requiring an ad-hoc procedure to remove it in the pre-processing phase [12]. No optical noise removal was needed for the time-lapse data, accounting for less anthropic noise during the time-lapse acquisition.



a b c

Fig. 2. (a) HWC time lapse gather (recorded in June 2022), (b) baseline gather (recorded in July 2021), (c) baseline gather after optical noise removal.

Time-lapse seismic monitoring approach, including a baseline survey and a second (in general, more than one) survey performed after the injection of CO_2, whose migration must be detected, presents critical issues and precautions should be applied to avoid those that can be managed. Commonly, conventional seismic reflection techniques deliver poor quality data in volcanic environments due to diffractions, scattering, attenuation and static problems [13]. The repeatability of the baseline and the time-lapse surveys is of key importance in the acquisition phase.

Common events affecting the repeatability are: 1) different weather conditions, 2) different coupling of the seismic sources and receivers, 3) possible errors in the positioning of sources and receivers, 4) different S/N ratio due to environmental/anthropogenic noise. The use of permanent fibre optic installation avoids issues of receivers coupling and positioning. The data processing should be the same for both surveys, preserving amplitude and their relative ratios. Since it is impossible to recreate the identical environmental conditions (ambient noise) during acquisition over time, at least the denoising operations will differ in the two datasets. The seismic response data to the injected CO_2 is obtained by the difference of the time-lapse and baseline data. Unfortunately, results coming from subtraction of pre- and post-injection HWC data in this complex volcanic environment are of difficult interpretation, due to both the poor quality of seismic data in these areas and the non-perfect data repeatability (at least for weather/environmental conditions), notwithstanding the efforts done to replicate the same acquisition conditions.

3. Data analysis by non-standard approach

The poor quality of the HWC data recorded in this volcanic environment led to poor stacked sections, mainly due to the difficulties in picking the coherence spectra in the velocity analysis, to obtain reliable stacking velocities. To try overcoming these difficulties, we develop a new specific approach for such a challenging dataset.

As highlighted in the previous paragraph, in a time-lapse approach a first fundamental aspect is the repeatability of the baseline and time-lapse surveys, and a second important aspect is that both surveys' data need to be processed identically. As a metric of similarity between the two surveys we chose the normalized root mean square difference (NRMS), calculated trace by trace within a given temporal window, and expressed as a percentage [14]:

$$NRMS = \frac{200 * RMS(tl_t - b_t)}{RMS(tl_t) + RMS(b_t)}$$

where tl_t *and* b_t are the time -lapse trace and the baseline trace, respectively.

We applied the NRMS to the data, using both all the trace length and a selected temporal window. The results show that there is low similarity between the two surveys. Subtracting the two dataset, residual differences that are independent of changes in the subsurface conditions can be expected. These differences can be caused by different weather conditions during the two surveys, affecting in a different way the coupling of the source with the terrain, by, even small, errors in the positioning of the source, or by possible different environmental/anthropogenic noise. The collected data are, generally, affected by random and coherent noise. High signal amplitude differences are present inside every single shot and also among different shots. So, a critical point for the processing of these data is their normalization, keeping in mind that a true amplitude processing is desirable. To maintain as much as possible the amplitudes, we applied a normalization to the whole panel of each shot and the compensation for the spherical divergence only. Moreover, we tried an array simulation analysis thanks to the high dense spatial sampling of the HWC records. Array simulations enable to reduce noises and, consequently, improve the signal to noise ratio (S/N). Figures 3, 4 and 5 show the NRMS calculated both for the entire trace length and within a time window for data with no array simulation applied and for data with different array (pattern) simulations applied. We tried several array simulations, and eventually decided for a pattern simulation of 40 m (Figure 5).

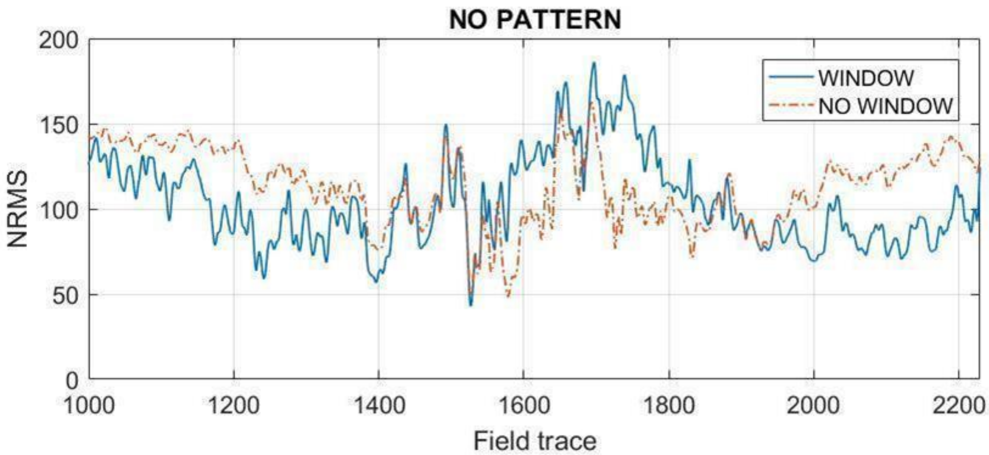


Fig. 3. NRMS of the data with no pattern simulation, calculated with the entire trace and within a window.

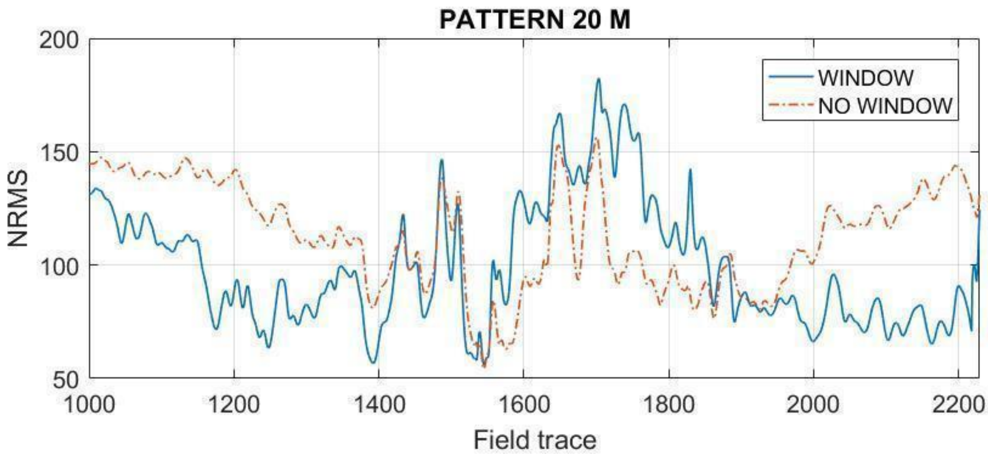


Fig. 4. NRMS of the data with pattern simulation of 20 m, calculated with the entire trace and within a window.

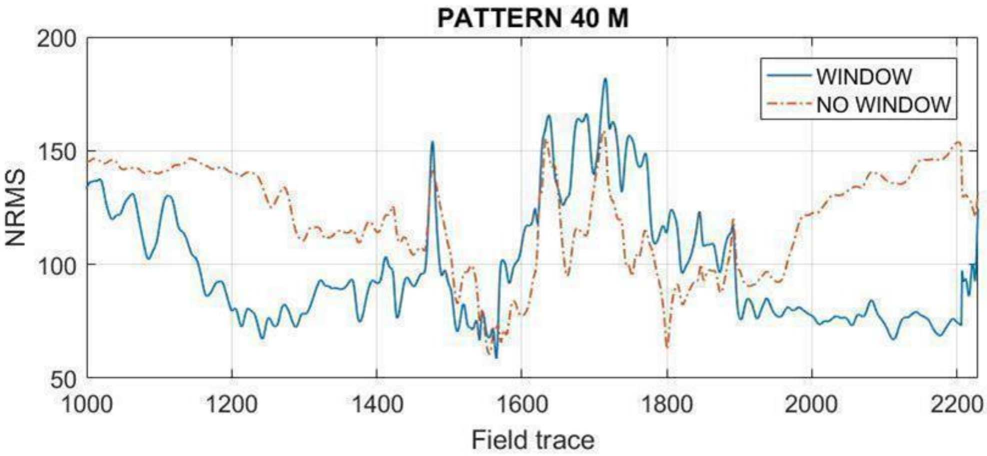


Fig. 5. NRMS of the data with pattern simulation of 40 m, calculated with the entire trace length and within a time window.

Thus, we focus our efforts on noise reduction with the objective to observe possible differences by comparison of the seismic response in selected areas of the two stacked sections, paying attention to preserve the relative amplitudes of the signals. A great advantage coming from the high spatial density of HWC DAS, about 1m, is the possibility to design array simulations, not possible with typical intertrace distances of conventional geophones. As previously stated, array simulations are beneficial for improving S/N, for example, in complex environments like volcanic areas.

We performed identically the 2D seismic processing of the HWC DAS baseline and time-lapse surveys, using the data with a pattern simulation of 40 m. We tried several other techniques for noise reduction, in different domains, but, due to the weak presence of reflected energy, they did not provide the expected results. To obtain the stacked sections, we did more than one velocity analysis, trying to spot and enhance the weak reflections, also supported by numerical modelling and laboratory measurements [15]. The velocity field applied to CMP is shown in Figure 6. The baseline and time-lapse stacked sections are shown in Figure 7.

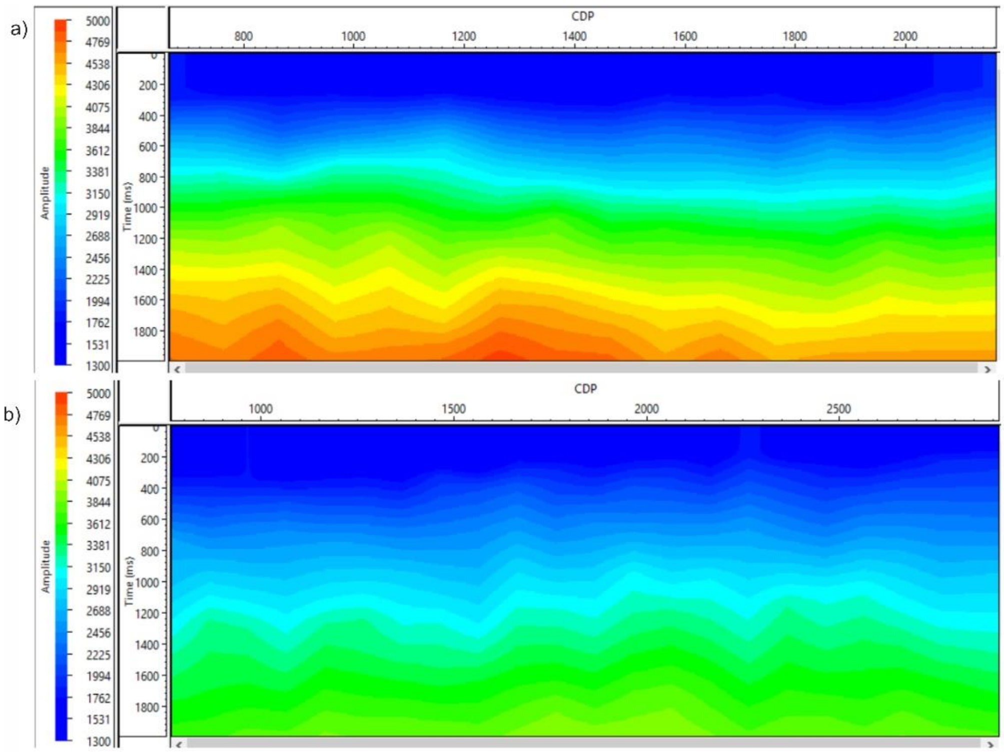


Fig. 6. Baseline velocity field (a) and time-lapse velocity field (b).

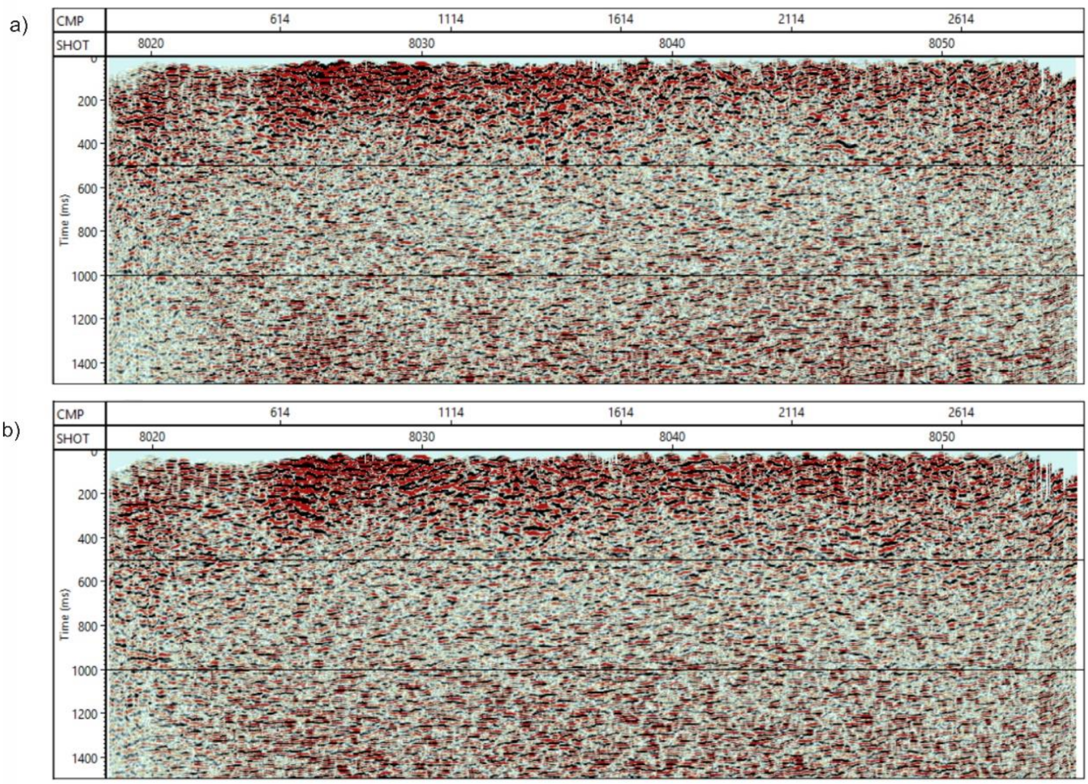


Fig. 7. Baseline stacked section (a) and time-lapse (b) stacked section, with amplitude normalization on CDP before stack.

Stated that the trace-by-trace subtraction of the baseline and time-lapse stacked sections would not be effective and reliable, the aim of the analysis figured to detect in the time-lapse stacked section one or more differences in the seismic response with respect to the baseline stacked section. A S/N analysis was performed in the sections to select the zones corresponding to a higher S/N, where the data analysis is more reliable. The results showed that the northern part of the section presents a higher S/N than the southern part. In the northern part of the line the events are better visible and so we focused on this area. We analysed the baseline and time-lapse sections, identically normalizing the data in a time window, to preserve the relative amplitude.

Some interesting differences emerge from the comparison of a detail of the two sections as shown in Figure 8. In the time-lapse section the red arrows indicate events between 0.9 s and 1.1 s that are not visible in the baseline survey. This is an important result, because it proves the effectiveness of the seismic method using HWC DAS to detect differences in the seismic response for monitoring purposes in time-lapse surveys. It also confirms the importance of the high spatial sampling of the HWC DAS cables, in order to improve the seismic signal enabling the pattern simulation, extremely important in complex environments as the volcanic ones. Moreover, the broadside sensitivity HWC DAS sensors have been validated by the comparison of the signals with the standard co-located sensors [12], commonly used in seismic campaigns.

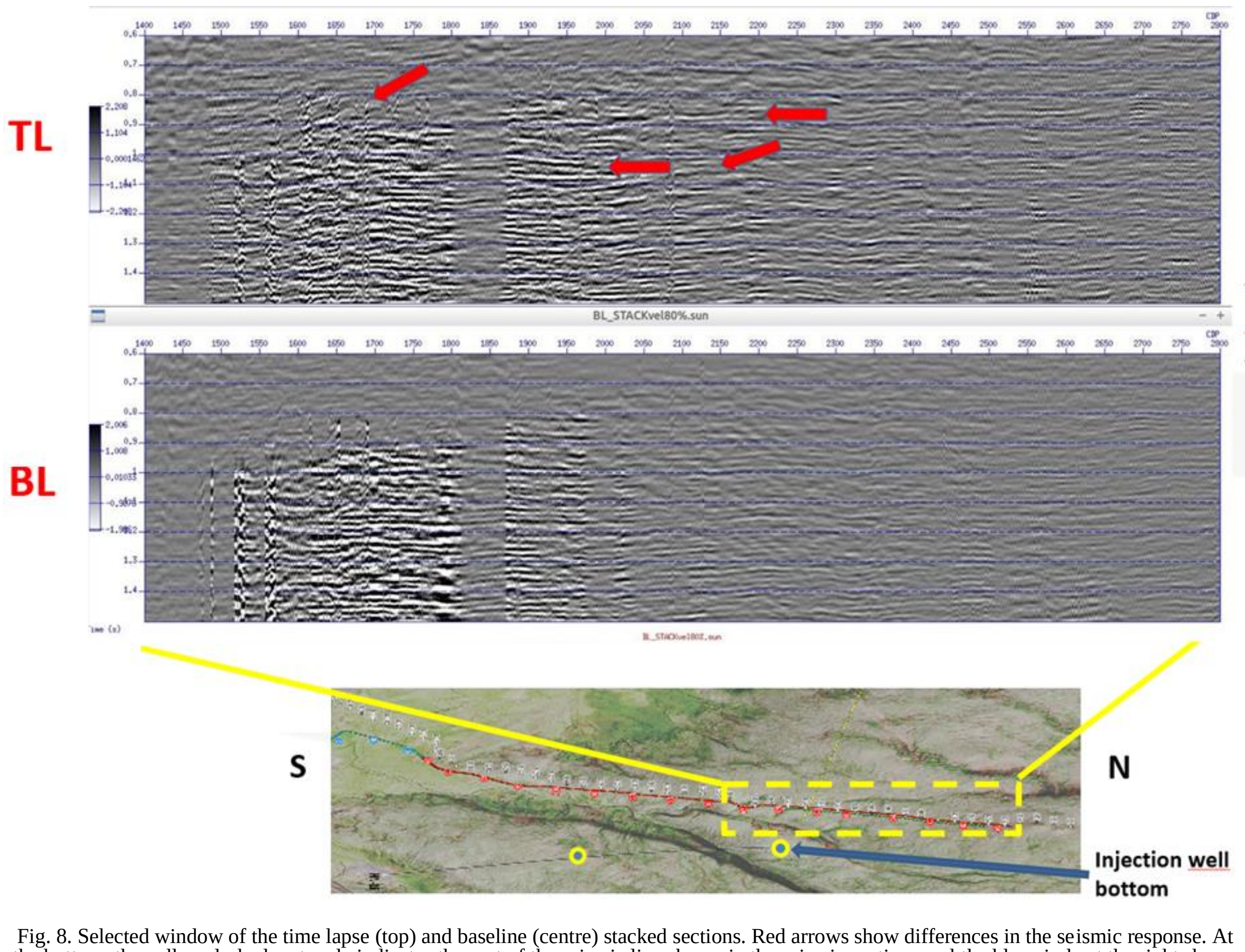


Fig. 8. Selected window of the time lapse (top) and baseline (centre) stacked sections. Red arrows show differences in the seismic response. At the bottom, the yellow dashed rectangle indicates the part of the seismic line shown in the seismic sections and the blue circle at the right shows the projection at the surface of the injection well bottom.

4. Conclusions

This study presents the results on the use of an environmentally friendly broadband active source (E-vibe) and HWC DAS for time-lapse monitoring purposes at a combined geothermal-CCUS power plant. Repeated seismic surveys provide valuable insight into how the reservoir changes through time, enabling fluid migration monitoring. Reservoir changes, however, have only a small impact on the seismic data and can be masked by environmental and other kind of issues of repeated surveys. Complex volcanic environments commonly led to seismic poor-quality data due to diffractions, scattering, attenuation and static problems. In this setting, the subtraction of the time-lapse and baseline sections to highlight seismic differences in not effective due to the low repeatability of the surveys confirmed by the NRMS analysis. We focused on improving the S/N ratio of the data through the array simulation technique, applied to the data of both surveys, which is possible due to the higher spatial sampling of the HWC compared to conventional geophones. The two stacked sections, obtained with the same processing steps, have been compared in a selected window where we identified a higher S/N ratio. The comparison shows differences in the seismic response of the two stacked sections. Considering the strongly noisy data and the different environmental conditions during the acquisitions, the meaning of these differences should be taken with caution, and it requires further investigations with an integrated approach with other types of data (i.e., well logs, petrophysical information, dynamic models) to validate the results. From a rough depth conversion, the penetration of the source turned out acceptable, confirming the effectiveness of the E-Vibe and HWC pairing as a monitoring tool.

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References

[1] Lund JW, Huttrer GW, Toth AN. Characteristics and trends in geothermal development and use, 1995 to 2020. Geothermics 2022;105:102522. https://doi.org/10.1016/J.GEOTHERMICS.2022.102522.
[2] Parlaktuna M, Durucan Ş, Parlaktuna B, Sinayuç Ç, Janssen MTG, Şentürk E, et al. Seismic velocity characterisation and survey design to assess CO2 injection performance at Kızıldere geothermal field. Turkish Journal of Earth Sciences 2021;30:1061–75. https://doi.org/10.3906/YER-2106-22.
[3] Mondanos M, Coleman T. Application of distributed fibre-optic sensing to geothermal reservoir characterization and monitoring n.d.
[4] Durucan Ş, Korre A, Parlaktuna M, Şentürk E, Wolf KH, Chalari A, et al. SUCCEED: A CO2 storage and utilisation project aimed at mitigating against greenhouse gas emissions from geothermal power production. 15th Greenhouse Gas Control Technologies Conference 2021, GHGT 2021 2021. https://doi.org/10.2139/SSRN.3819789.
[5] Foulger G. Geothermal exploration and reservoir monitoring using earthquakes and the passive seismic method. Geothermics 1982;11:259–68. https://doi.org/10.1016/0375-6505(82)90032-3.
[6] Blanck H, Jousset P, Reinsch T, Ryberg T, Clarke A, Aghayev R, et al. Passive Seismic Measurements using the Distributed Acoustic Sensing (DAS) Technology on the Reykjanes Peninsula, SW-Iceland. AGUFM 2019;2019:S41A-01.
[7] Willis ME. Distributed Acoustic Sensing for Seismic Measurements – What Geophysicists and Engineers Need to Know. Distributed Acoustic Sensing for Seismic Measurements – What Geophysicists and Engineers Need to Know 2022. https://doi.org/10.1190/1.9781560803850.

[8] Kuvshinov BN. Interaction of helically wound fibre-optic cables with plane seismic waves. Geophys Prospect 2016;64:671–88. https://doi.org/10.1111/1365-2478.12303.
[9] Poletto F, Finfer D, Corubolo P. Broadside Wavefields in Horizontal Helically-Wound Optical Fiber and Hydrophone Streamer 2015.
[10] Stork AL, Poletto F, Draganov D, Janssen M, Hassing S, Meneghini F, et al. Monitoring CO2 injection with passive and active seismic surveys: Case study from the Hellisheiði geothermal field, Iceland. Proceedings, 16th International Conference on Greenhouse Gas Control Technologies, GHGT-16, Lyon, France, 2022.
[11] Saemundsson K. Vulkanismus und Tektonik des Hengill-Gebietes in Südwest-Island. Acta Naturalia Islandica 1967;2:1–105.
[12] Bellezza C, Barison E, Farina B, Poletto F, Meneghini F, Böhm G, et al. Multi-Sensor Seismic Processing Approach Using Geophones and HWC DAS in the Monitoring of CO2 Storage at the Hellisheiði Geothermal Field in Iceland. Sustainability 2024;16:877. https://doi.org/10.3390/su16020877.
[13] Dell'Aversana P, Ceragioli E, Morandi S, Zollo A. A simultaneous acquisition test of high-density 'global offset' seismic in complex geological settings. First Break 2000;18:87–96. https://doi.org/10.1046/J.1365-2397.2000.00053.X.
[14] Kragh E, Christie P. Seismic repeatability, normalized rms, and predictability. Leading Edge (Tulsa, OK) 2002;21. https://doi.org/10.1190/1.1497316/ASSET/IMAGES/LARGE/640_1_F15.JPEG.
[15] Janssen M, Draganov D, Bos J, Farina B, Barnhoorn A, Poletto F, et al. Monitoring CO2 injection into basaltic reservoir formations at the Hellisheiði geothermal site in Iceland: laboratory experiments. 83rd EAGE Conference and Exhibition 2022 2022;3:1794–8. https://doi.org/doi.org/10.3997/2214-4609.202210474.