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DOI
10.3997/2214-4609.202210474

Publication date
2022

Document Version
Final published version

Published in
EAGE Annual Conference & Exhibition 2022

MONITORING CO2 INJECTION INTO BASALTIC RESERVOIR FORMATIONS AT THE HELLISHEIÐI GEOTHERMAL SITE IN ICELAND: LABORATORY EXPERIMENTS.

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Summary

In the ACT Consortium funded project SUCCEED, researchers study the potential for monitoring the process of (re-)injecting produced and captured CO2 into the Hellisheiði geothermal field for the aid of enhancing geothermal deployment as well as permanently storing CO2 through mineralization. The Hellisheiði site provides an excellent opportunity for demonstrating an innovative seismic monitoring technique. Prior to conducting an active-source monitoring survey, we perform acoustic transmission measurements, on Hellisheiði rock samples, at field-representative stress conditions to obtain the seismic-response characteristics of all present formations. Subsequently, we use the acquired velocity data as an input for simulating 2D seismic surveys using a subsurface model representing the Hellisheiði site. Results show that the impact of increasing depth, i.e., stress, on seismic velocities is most apparent for the porous basalt layers due to their relatively large portion of open pore space, allowing for substantial compaction, increasing their bulk density and thus velocity. The poorly-consolidated hyaloclastites reveal a negligible effect of increasing depth on their velocity as the material already reached its maximum compaction at low stresses, thus at shallow depths. Comparison of synthetic and field geophone data reveal that the velocity profiles have to be updated for the shallow depths in the model.

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Introduction

Though it is commonly assumed that geothermal energy is a clean and renewable form of energy, the majority of the geothermal power stations do emit carbon dioxide (CO_2), and other greenhouse gases, as part of the produced geothermal fluid (Bayer et al. 2013; Bravi and Basosi, 2014; O'Sullivan et al. 2021). However, as shown by a report published by World Bank in 2016, CO_2 emissions related to geothermal power generation sites are, on average, relatively small compared to traditional coal and gas fired plants (Fridriksson et al. 2016). Nevertheless, CO_2 releases due to geothermal energy production can be quite significant in some areas like in Italy (Bravi and Basosi, 2014), Turkey (Bayer et al. 2013), and in Iceland (Ármannsson, 2018). For example, the Hellisheiði co-generation power plant in Iceland, commissioned in 2006, has a 303 MWe electrical production capacity and a 133 MWth thermal capacity. The latter resulting in the production of 417,000 tonnes of CO_2 and approximately 114,000 tonnes of H_2S from the basaltic reservoir formation over its entire production history (Sigfússon et al. 2018), equivalent to average annual emissions of 41,000 and 10,000 tonnes for CO_2 and H_2S, respectively (Gunnarsson et al. 2018).

With our work, we aim to study and validate the feasibility of monitoring the (re-)injection of produced, and captured from the atmosphere, CO_2 (at the Hellisheiði geothermal plant in Iceland) into the geothermal field for pressure maintenance, i.e., enhancing geothermal production, whilst permanently storing the CO_2 through mineralization. This provides a state-of-the-art, cost-effective, and low-environmental impact coupled geothermal-CO_2 storage monitoring technique. At first the CO_2, that got released as a by-product of geothermal energy production, is captured in water, yielding acidic gas-charged re-injection water (Gislason and Oelkers, 2014; Clark et al. 2020). During its re-injection into the basaltic reservoir formation, the acidic water accelerates the dissolution process of the basalts, resulting in the release of divalent cations, i.e., Ca^{2+}, Mg^{2+}, and Fe^{2+}, to the injected aqueous phase. Subsequently, the dissolved CO_2 is now able to react with the freshly added cations, yielding the formation of stable carbonate minerals (Power et al. 2013; Gislason and Oelkers, 2014; Clark et al. 2020). For permanently storing CO_2 inside the Earth's subsurface, carbon mineralization is seen as the safest storage technique (Gislason and Oelkers, 2014; Clark et al. 2020). The aforementioned (re-)injection strategy has been practised at the Hellisheiði site since 2014. Mass balance calculations performed since then show that bulk of the injected CO_2 was mineralized within a time frame of a few months to a year after injection was initiated (Gunnarsson et al. 2018; Clark et al. 2020). The Hellisheiði site provides a perfect opportunity for demonstrating innovative seismic monitoring techniques using a distributed fibre-optic acoustic sensing system (iDAS) in combination with an electric linear synchronous motor (LSM) seismic vibrator (e-vib). The LSM-based seismic vibrator consists of a 673 kg reaction mass, 265 kg baseplate, maximum driving force 10 kN, and dimensions of 950×1440×1170 mm. Sweeps starting from 2 Hz can be generated. The novel e-vib can be used for generating both compressional and shear waves.

In this work, we combine various scientific methods including laboratory experiments, numerical 2D seismic modelling, and fieldwork for i) collecting reference rock samples, or analogous, of the Hellisheiði geothermal reservoir and ii) seismic monitoring of CO_2 injection. We perform laboratory active-source transmission measurements at field-representative stress conditions on rock samples to obtain the seismic-response characteristics of all formations present at Hellisheiði. Subsequently, we use the acquired seismic velocity data as an input for simulating 2D seismic surveys using a subsurface model representing the project site. The simulation results are then used for defining the field acquisition geometry, but are also used to aid the interpretation of the seismic monitoring survey results. Where in this study we mainly focus on laboratory experiments, in our other contribution to this Conference (Meneghini et al. 2022) we discuss the preliminary results from the multi-tool active-source seismic acquisition. This work is closely related to our previous work where we assessed the velocity characterisation of geothermal reservoir rocks of the Kızıldere geothermal field in Turkey (Janssen et al. 2021).

Methods and Materials

Figure 1 presents an overview of the workflow we use in our study. We sourced several rock samples from various fresh outcrops in the area around the Hellisheiði geothermal site. These included hyaloclastites, dikes/intrusions, and basalts with varying porosities (ranging from 22 to 47%, reflecting different depths within the subsurface where the magma cooled off). After coring the collected samples, we determine several physical properties, i.e., porosity, matrix, and bulk density, for each of the cores. Subsequently, we place the cores in a triaxial Hoek cell (Hoek and Franklin, 1968) for obtaining the seismic velocity characteristics as a function of stress (i.e., depth below surface). A detailed description of the coring and experimental procedures is given in sections 2.2 and 2.4 of Janssen et al. (2021).

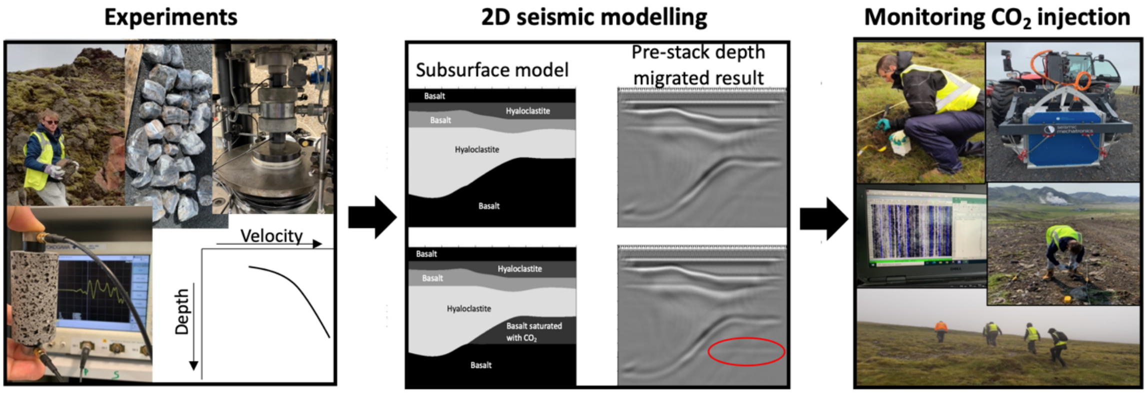

Figure 1 Overview of the workflow. First, we conduct experimental work including sample collection from fresh outcrops and seismic-response characterisation of representative samples (left). Second, we use the obtained velocity profiles as an input for simulating 2D seismic active-source surveys (centre). Finally, we carry out a field acquisition campaign for monitoring the CO_2 injection (right).

Figure 2 shows the results, i.e., compressional (P-)wave velocity (V_p) and shear (S-)wave velocity (V_s) as function of axial stress (σ_1), of the active-source acoustic-assisted confined compressive strength experiments. Results indicate that the effect of increasing depth on V_p is most prominent for the shallow, porous, basalt layers: ~1350 m/s per km. It reflects closure of open pore space due to compaction, yielding an increased mineral-to-mineral contact area, thus increasing V_p. Within the basalt samples studied, the rate of increase in V_p gradually reduces to ~217 m/s per km for the, relatively, low-porous basalt at >2 km depth. For the hyaloclastites assessed, the effect of increasing stress on V_p seems to be negligible. Most likely, the porous, not well-consolidated, hyaloclastite was already maximum compacted at low absolute stress levels, resulting in negligible amount of compaction at greater depths, thus a fairly constant V_p.

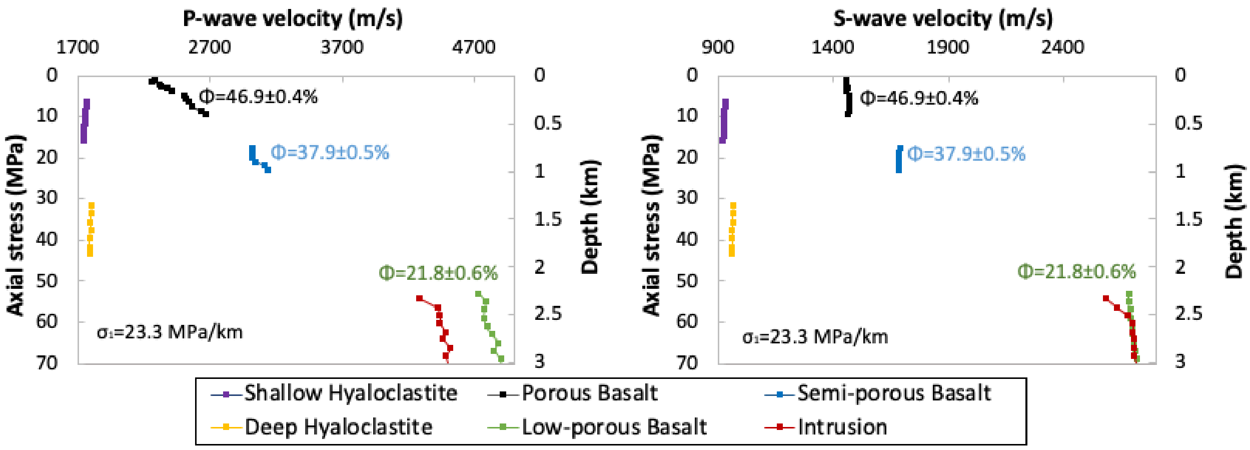

Figure 2 P-wave velocity (left) and S-wave velocity (right) as function of axial stress (σ_1), and thus depth below the surface, for all Icelandic formations studied. Radial stress ($\sigma_2=\sigma_3$) was kept constant at their respective field-representative values: 1 (for depths <153 m) and 5 (depths between 210-412 m) MPa for porous basalt, 7 MPa for shallow hyaloclastite, 18 MPa for semi-porous basalt, 32 MPa for deep hyaloclastite, 53 MPa for low-porous basalt, and 53 MPa for the intrusion. Stress-depth relationships are taken from Batir et al. (2012).

The obtained laboratory results shed light on the stress-dependency of the seismic velocities for all lithologies present at the Hellisheiði geothermal field. The acquired velocity-depth (or velocity-stress) relationships per rock type (**Figure 2**), which reflect dry pore space conditions, can subsequently be applied to any given stratigraphic section in the vicinity of the Hellisheiði geothermal field for constructing a velocity profile. We do the latter for the area of interest which represents the CO_2 injection location at Hellisheiði (**Figure 3**). The left part of **Figure 3** shows the developed subsurface model, where CO_2 is injected in the basaltic formation at a depth of around 2500±300 m; the centre presents seismic velocity profiles at lateral positions in the model of -2000 m and 1000 m; the right part presents the ratio of V_p over V_s. Note the significant increase in V_p, as function of depth, for the two shallow (<500 m) porous basalt layers, resulting in a similar increase in V_p/V_s ratio as V_s remains relatively constant as function of σ_1 (**Figure 2**).

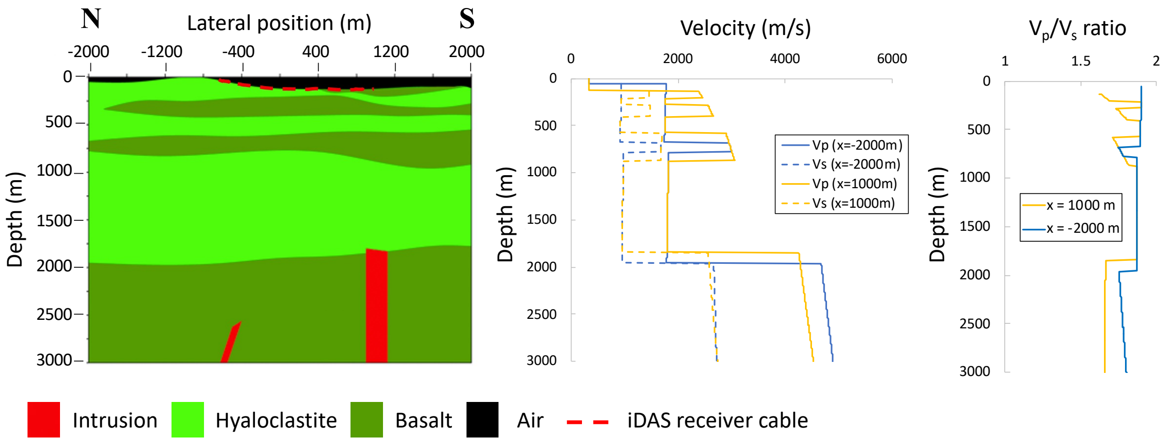

***Figure 3** Hellisheiði subsurface model (left), seismic velocity profiles (centre), and V_p/V_s (right) at lateral positions (x) -2000 m and 1000 m.*

We then use the obtained stress-dependency of the seismic velocities (**Figure 2**) for the formations we study as an input for 2D finite-difference modelling (Thorbecke and Draganov, 2011) using the subsurface model presented in **Figure 3**. Using the preliminary results of the active-source seismic acquisition performed in July 2021 at Hellisheiði (Meneghini et al. 2022), we did some calibration for a revision of the velocity profiles. We used these data as provisional quality-control results. We calculated synthetic seismograms with a 2D finite-difference elastic code (for detail, see Meneghini et al. 2022). Comparison of synthetic and field geophone data revealed that the velocity profiles had to be updated to some extent for the shallow depths in the subsurface model.

Conclusions

We carried out an extensive active-source acoustic-assisted experimental study at field-representative stress conditions in order to obtain the seismic-response characterisation of all rock formations present at Hellisheiði. Results showed that the impact of increasing depth on seismic velocities is most apparent for the shallow porous basalt layers due to its relatively large portion of open pore space, allowing for substantial amounts of compaction. The hyaloclastite formations revealed a negligible effect of increasing depth, thus stress, on its seismic velocity as, most probably, the poorly-consolidated material already reached its maximum compaction at low absolute stress levels, thus at shallow depths. Comparison of synthetic and field geophone data revealed that the velocity profiles had to be updated to some extent for the shallow depths in the model. The processing of the field data is ongoing, and will be used to update the pre-acquisition subsurface model.

Acknowledgements

This project is funded through the ACT – Accelerating CCS Technologies (Project No 294766), the Department for Business, Energy & Industrial Strategy UK (BEIS), the Ministry of Economic Affairs and Climate Policy, the Netherlands, the Scientific and Technological Research Council of Turkey (TUBITAK), Orkuveita Reykjavíkur/Reykjavik Energy Iceland (OR) and Istituto Nazionale di Oceanografia e di Geofisica Sperimentale Italy (OGS). The authors thank Marc Friebel (TU Delft), Jens van den Berg (TU Delft), and Karel Heller (TU Delft) for their technical support.

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