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Schlussbericht vom 07.12.2023

DEEPEN-CH

Improving passive seismic imaging capabilities for de-risking EGS projects in Switzerland

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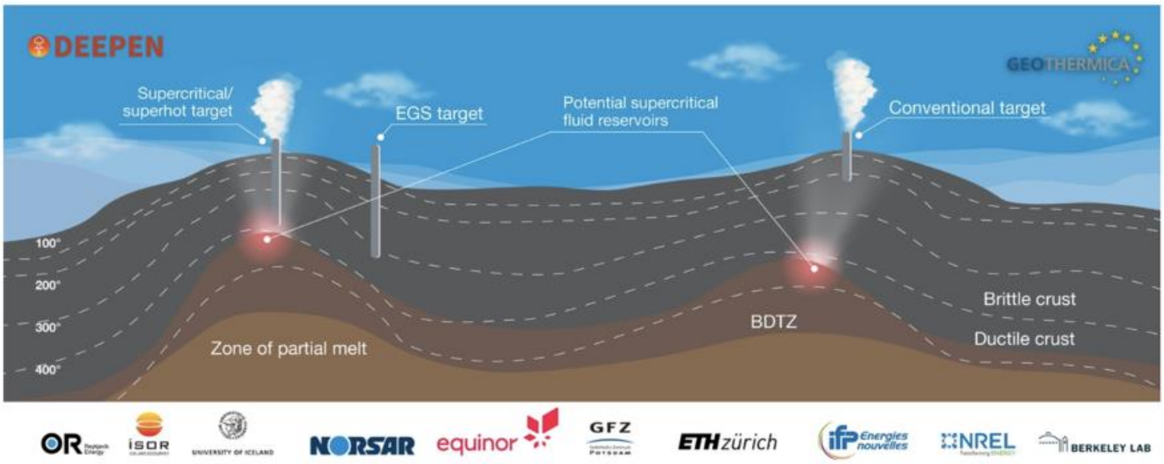

Figure 1: *Illustration of the DEEPEN target zones and partners.*

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Für den Inhalt und die Schlussfolgerungen sind ausschliesslich die Autoren dieses Berichts verantwortlich.

Zusammenfassung

Das Projekt DEEPEN-CH stellt den Schweizer Beitrag zum internationalen GEOTHERMICA-Projekt DEEPEN dar, koordiniert von Reykjavik Energy. DEEPEN begann offiziell im Dezember 2020 und endete im Dezember 2023. Weitere Informationen finden Sie unter: https://www.or.is/en/about-or/innovation/deepen/. DEEPEN zielt darauf ab, die Wurzeln magmatischer Geothermie Systeme durch Beobachtungen und Modellierung besser zu verstehen und Techniken und Arbeitsabläufe zu entwickeln, um solch tiefe und superheiße Ressourcen zu finden (Abb. 1). Bei dem Projekt handelt es sich um eine multinationale Zusammenarbeit mehrerer Universitäten, Institute und Energieunternehmen.Bei DEEPEN-CH nutzen wir die Chancen, die DEEPEN für den Schweizer Kontext bietet. Der Beginn der Produktion einer Ressource ist ein risikoreiches Unterfangen, da nur abgeleitete und unsichere Kenntnisse über den Untergrund vorliegen. Um das Risiko erfolgloser Bohrungen oder der Auslösung von Seismizität zu verringern, ist es von entscheidender Bedeutung, die seismischen Bildgebungsmethoden so zu verbessern, dass sie bei der a-priori-Ressourcencharakterisierung und seismischen Risikobewertung besser helfen können. DEEPEN-CH ist in drei Arbeitspakete unterteilt: Aufbau und Betrieb dichter seismischer Netzwerke in Island (WP1), Validierung und Verbesserung von Bildgebungsmethoden (WP2) und Wissenstransfer zu Zielanwendungen in der Schweiz (WP3).

Résumé

Le projet DEEPEN-CH représente la contribution suisse au projet international GEOTHERMICA DEEPEN, coordonné par Reykjavik Energy. DEEPEN a officiellement débuté en décembre 2020 et s'est terminé en décembre 2023. Pour plus d'informations, consultez : https://www.or.is/en/about-or/innovation/deepen/. DEEPEN vise à mieux comprendre les racines des systèmes géothermiques magmatiques grâce à des observations et à la modélisation, ainsi qu'à développer des techniques et des flux de travail pour trouver de telles ressources profondes et extrêmement chaudes (Fig. 1). Le projet est une collaboration multinationale entre plusieurs universités, instituts et sociétés énergétiques.

Chez DEEPEN-CH, nous exploitons les opportunités représentées par DEEPEN pour le contexte suisse. Se lancer dans la production de n'importe quelle ressource est une entreprise à haut risque car il n'existe qu'une connaissance inférée et incertaine du sous-sol. Pour réduire le risque d'échec du forage ou un niveau élevé de sismicité induite, il est d'une importance cruciale d'améliorer les méthodes d'imagerie sismique afin qu'elles puissent mieux faciliter la caractérisation a priori des ressources et l'évaluation des risques sismiques. DEEPEN-CH est divisé en trois work packages : Déploiement et exploitation d'un réseau sismique dense en Islande (WP1), validation et amélioration des méthodologies d'imagerie (WP2) et transfert de connaissances vers des applications cibles en Suisse (WP3).

Summary

The project DEEPEN-CH represents the Swiss contribution to the international GEOTHERMICA project DEEPEN, coordinated by Reykjavik Energy. DEEPEN started formally in December 2020 and ended in December 2023, more information is found at: https://www.or.is/en/about-or/innovation/deepen/. DEEPEN aims to better understand the roots of magmatic geothermal systems through observations and modeling, as well as to develop techniques and work flows to find such deep and superhot resources (**Fig. 1**). The project is a multinational collaboration among several universities, institutes, and energy companies.

In DEEPEN-CH, we exploit the opportunities represented by DEEPEN for the Swiss context. Embarking on production for any resource is a high-risk endeavor because there is only inferred and uncertain knowledge of the subsurface. To reduce the risk of unsuccessful drilling or induce seismicity, it is of

critical importance to improve seismic imaging methods such that they can better aid in a-priori resource characterizing and seismic risk assessment. DEEPEN-CH is divided into three work packages: Dense seismic network deployment and operation in Iceland (WP1), validation and improvement of imaging methodologies (WP2) and knowledge transfer to target applications in Switzerland (WP3).

Main findings

Dense nodal array

1. The recordings from a dense array of 500 three-component seismic nodes exceeded our expectations. Despite the nodes short battery time (2.5 months), **seismic clusters and Green's functions could be fully recovered**. From the Green's functions, clear dispersion curves from could be obtained **down to periods of 10 s**, allowing various imaging applications of the shallow crust (uppermost 5km).
2. The seismic nodes can be deployed at a fraction of the cost and effort needed for classical semi-permanent broadband stations and proved their highly valuable contribution to imaging and monitoring.
3. Anisotropic and isotropic imaging with the nodal data delineated lithological structures and potentially permeable pathways in the shallow crust.
4. Seismic catalogs obtained from the dense nodal deployment showed 7.5 times more events and the magnitude of completeness could be lowered by about 1 unit, compared with a broadband seismic network. Such a refined catalog can improve our understanding of the distribution of faults and state of stress

⇒ **Nodal array deployments should accompany future Swiss EGS project in the exploration and operation phase**. They have at present not the high-resolution of active 4D seismics, but can provide at low-cost information about lithological units and microseismicity.

Reservoir imaging and monitoring across the Hengill volcanic region

5. Various seismic methods were applied to the Hengill volcanic region. They substantially improved the understanding of seismicity and subsurface structure in the region and provide an **optimal test-site for benchmarking of further methodological improvements**.
6. The seismic velocity anomalies obtained from the tomographic imaging are in excellent agreement with resistivity anomalies, highlighting the capability of ambient seismic noise methods to image high-temperature reservoirs.
7. High Vp/Vs ratios and Gutenberg Richter b-value anomalies coincide with high-temperature areas.
8. Coda-wave interferometry proved its usefulness as a cost-effective method to indirectly sample the steam content in the subsurface, contributing to the **monitoring of the reservoir evolution.**

⇒ Coda-wave interferometry should also be applied in future Swiss plays during operation, to monitor potential pressure drops in the reservoir and ground subsidence early on.

Other observations

9. Seismic events recorded with distributed acoustic sensing (DAS) from a fibre match very well with the same events recorded by the nodal array.

⇒ The use of DAS recordings is also highly relevant for Switzerland. DAS cables can easily be inserted in boreholes and provide valuable information from depth adding to the information from 2D surface arrays.

1 Introduction

1.1 Background and Motivation of the Geothermica Project Deepen

High resource risk and high upstream exploration costs are key barriers to scaling up of geothermal energy development globally. Reducing the upstream risk has, for a long time, been a priority area of the sector on several fronts. The overall Geothermica DEEPEN project has contributed to this goal through increasing the probability of success when drilling for geothermal fluids in magmatic systems. This was achieved by developing improved exploration methods and improved framework for joint interpretation of exploration data using the Play Fairway Analysis (PFA) methodology.

The development of the PFA methodology is among the more notable developments towards reducing geothermal resource risk in the recent years. This methodology, which is inspired by best practices in the oil and gas industries, allows the estimation of the combined probability of encountering high-temperature fluids, their producibility and recharge, in a sub-volume of the crust through joint inversion of a number of geoscientific exploration data sets. Developing the PFA methodology for magmatic environments is a priority area for the sector as most geothermal resources, currently under production, belong to this play type. Improved understanding of subsurface conditions in these environments would improve success rate of drilling and thus have a direct positive impact on economic viability of geothermal power projects through reduced drilling cost. Furthermore, mounting evidence suggests that harvestable energy from magmatic geothermal reservoirs could be increased significantly by exploiting the bottom of convective geothermal reservoirs, towards the top of the magmatic heat sources, where superhot conditions prevail. In order to reach supercritical fluids (SCF) by deep drilling in an economically viable way, the methodology for defining well targets needs to be improved. The PFA methodology, as a framework to interpret a diverse portfolio of geoscientific data, could be a key tool to define drilling targets in the roots of magmatic geothermal systems.

The Geothermica DEEPEN project has: 1) developed a PFA methodology specific to magmatic plays that includes the root zones of geothermal systems in magmatic environments by combining the PFA methodology (developing training sites, statistical analysis of exploration data, fairway analysis) with the development of generalized conceptual models and numerical models for multiple plays within a single magmatic system, 2) developed new tools that will help with the subsurface imaging, building on the results of DEEPEN-CH and 3) demonstrated the PFA methodology at two magmatic systems, at Hengill, Iceland and at Newberry Volcano, in the U.S. Cascades.

The DEEPEN consortium consists of a group of industrial, academic, and national laboratory partners from Iceland, United States, Norway, Germany and Switzerland. The consortium includes Reykjavik Energy, an established geothermal developer in Iceland; National Renewable Energy Laboratory (NREL), U.S., the pioneers of the PFA methodology for geothermal, EQUINOR (formerly Statoil), an energy company with deep roots in the oil and gas sector and a strong tradition of joint inversion of multiple geoscientific exploration data sets, and seven research institutions with a long track record geothermal research: Iceland GeoSurvey (ÍSOR), Iceland; University of Iceland (UoI), Iceland; Norwegian Seismic Array (NORSAR), Norway; Lawrence Berkeley National Laboratory (LBNL), U.S.; Das Deutsche GeoForschungsZentrum (GFZ), Germany; Eidgenössische Technische Hochschule Zürich (ETHZ), Switzerland; and IFP Energies Nouvelles (IFPEN), France.

1.2. Project Goals of Deepen-CH

The Swiss contribution to DEEPEN focusses on the development and application of new tools for subsurface imaging of deep and hot bodies and fault systems. While the detection of deep and hot bodies is mainly relevant for the exploration of new resources in magmatic settings, the knowledge on nearby faults is highly relevant for safe operations in all plays. The importance of the ability to detect and characterize faults with respect to their safety relevance was already important for the St. Gallen Geothermal project in Switzerland, and has been again highlighted by the M5,4 Pohang (South Korea) earthquake in 2017 and the earthquake sequence near geothermal plants in Strasbourg in Nov. 2019.

For shallow high-temperature systems as well as hydrothermal systems such as St. Gallen, substantial experience exists on acquiring relevant datasets for encountering high-temperature fluids and detecting faults, for example through 3D seismic imaging, geochemical analysis of geothermal fluid reaching the surface, and resistivity imaging of the subsurface. However, it is much more difficult to estimate the recharge and producibility, which requires mapping out permeability within the crust. Where there are expressions of faults on the surface, those are targeted for drilling, but few tools are available for imaging faults in the subsurface in non-sedimentary regions.

Producing from deeper and even higher temperature plays in granitic and basaltic environments, is a high risk, but potentially much higher reward. In this environment, geothermal exploration still has a long way to go. It was part of this project to develop and test new techniques, such as noise-based interferometry combined with classical tomography. The ultimate goals are efficient and proven tools for imaging these low seismic contrast and high temperature regions.

While the main thrust of the GEOTHERMICA project DEEPEN is on opening up ultra-high temperature magmatic systems, many of the methodological improvements, can be readily transferred to EGS plays in granitic environments, such as the Haute Sorne project in the Jura, or to hydrothermal plays, such as the Genève Basin, or Energe-O projects in the Vaud. These projects are situated in areas with low levels of background seismicity and it will be of particular interest to lower the detection threshold and locate events as precisely as possible, to map potential faults in the area. We have seen that dense nodal deployments can help achieving this goal. Additionally, with noise-based imaging techniques, we can monitor the reservoir evolution (e.g., subsidence, stress changes, changes in steam content) accurately, which is essential from both operational and economic perspectives.

2 Description of the Hengill Geothermal field

The Hengill volcano and its associated geothermal fields (Fig. 2) represent Iceland's most productive harnessed high-temperature geothermal fields, where energy is provided by cooling magmatic intrusions connected to three volcanic systems. The crustal structure in this area is highly heterogeneous and shaped by the intricate interplay between tectonic forces and magmatic/hydrothermal activities, making detailed subsurface characterization challenging.
Currently, the two largest power plants in Iceland, and some of the biggest in the world are operated in the Hengill area by ON Power, a subsidiary of OR-Reykjavík Energy: The Nesjavellir plant to the north (120 MWe, 350 MWt) commissioned in 1990 and the Hellisheiði plant to the southwest of the volcano (303 MWe, 210 MWt), commissioned in 2006 (yellow

stars on Fig. 2A). Very powerful wells have been drilled in the Southern Hverahlíð area and in the Northern part of the Hengill geothermal field indicating reservoir temperatures in the range of 270–320°C and an enthalpy between 1,350 and 1700 kJ/kg (Biru, 2020). Near the Nesjavellir powerplant, *super-hot* geothermal resources (T>374 C) have been spotted that are currently considered for visionary future geothermal exploration. The power output from super-hot wells may be several times higher than from conventional wells.

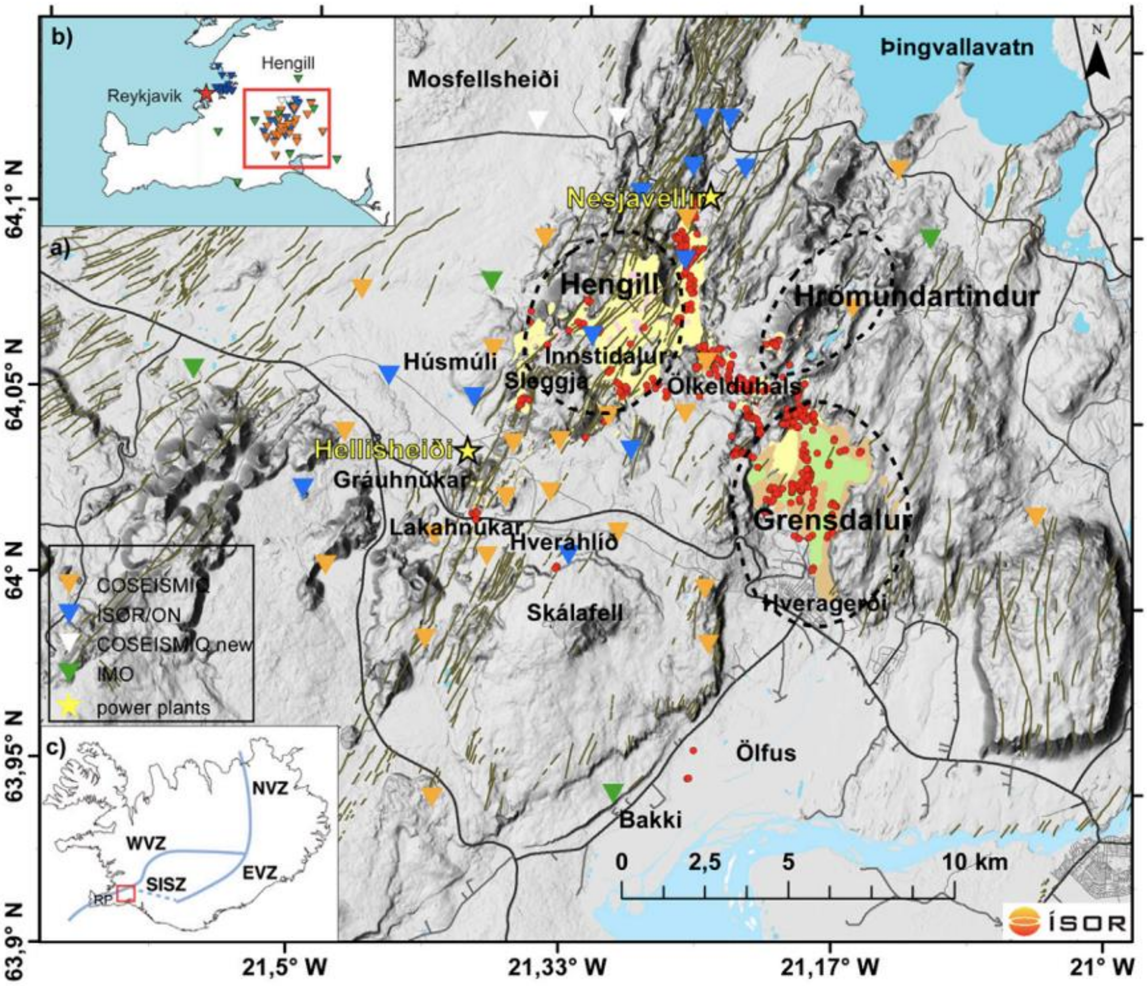

Figure 2: *The Hengill high-temperature geothermal area. Triangles mark broadband seismic stations in the area. The orange stations were operated by ETH during the COSEISMIQ and DEEPEN project and dismantled in August 2021. Red dots are fumaroles; regions with surface geothermal alteration are shown in yellow. Black dotted lines mark the three volcanic centers. Known faults and fractures are shown in grey, roads as black lines and yellow stars are the power plants at Hellisheiði (south) and Nesjavellir (north). The inset figures show (B) a zoom into the study area giving an overview of the extended seismic network and in (C) the location of the study area in the Hengill volcanic complex (red rectangle) at the triple junction of the Western Volcanic Zone (WVZ), the South Icelandic Seismic Zone (SISZ), and the Reykjanes Peninsula Oblique Rift (RP) (from Obermann et al. 2022b).*

Over the past decades, the Hengill volcanic complex has been studied with different geophysical methods. A Bouguer gravity map and an aeromagnetic map have been published and interpreted qualitatively (Björnsson et al., 1986; Hersir et al., 1990). GPS and satellite images have been used to observe surface deformation related to pressure changes in geothermal reservoirs (e.g., Budzinska, 2014; Juncu et al., 2017; Ducrocq et al., 2021). Surface faults are defined from field mapping and aerial photographs (e.g., Sæmundsson, 1992; Clifton et al., 2002; Sæmundsson et al., 2016). Resistivity methods have identified a shallow up-doming low resistivity layer, in the uppermost 1 km of the crust, related to smectite; a low temperature hydrothermal alteration mineral forming at 100–230°C (Árnason et al., 1986; Hersir et al., 1990; Árnason et al., 2010; Benediktsdóttir et al., 2021). Beneath this conductive clay cap, a high-resistivity core is associated with high-temperature alteration minerals (chlorite, epidote; formed at temperature >230° C). A deep conductive layer is observed in most, but not all, of the area (Árnason et al., 2010; Benediktsdóttir et al., 2021). The layer is shallow under and around the Hengill volcano (~3 km), stretching to the southeast. The anomaly is about 3.5 km wide and correlates well with a relatively positive residual Bouguer gravity anomaly reflecting high density at depth (Hersir et al., 1990). The deep conductor is believed to be due to hot solidified intrusions, related to the heat sources for the geothermal system above (Árnason et al., 2010). Inherent to these methods is a low spatial resolution, hindering an unambiguous determination of the shape of the intrusions. In the nineties, several local earthquake tomography studies have been performed in this region (Foulger, 1984; Foulger and Toomey, 1989; Foulger et al. 1995; Tryggvason et al., 2002; Jousset et al., 2011; Wagner,2019), revealing the main structures of the volcanic complex, but little more. The lack in resolution was mainly due to the sparse seismic networks used and the focus on earthquake-based methods. From October 2018 to July 2020, the permanent seismic network in the Hengill area consisting of 15 stations (blue and green triangles in Fig. 2A) was temporarily densified with 23 additional broadband seismic stations (blue triangles in Fig. 2A), as part of the EU funded project COntrol SEISmicity and Manage Induced earthQuakes (COSEISMIQ, http://www.coseismiq.ethz.ch/en/home/). Using this broadband network consisting of a total of 38 stations, the imaging resolution and earthquake location accuracy could already be much improved (Sanchez-Pastor et al. 2021, Obermann et al, 2022b).
Within DEEPEN-CH, we showed with the use of novel methodological and technological advances, such as noise-based imaging approaches and dense nodal arrays, the resolution gap becomes even smaller and tiny structures the subsurface (hectometer range) become visible.

3 Procedures and methodology

The work proposed in DEEPEN-CH was centered around three main work packages:

WP1: **Dense seismic network**
We extended the duration of the COSEISMIQ broadband network for one year, until August 2021. This gave us the possibility to install in parallel a dense dense nodal array consisting of 500 3 component geophones, from June-August 2021. An overview of the array and data quality has been published in SRL as Obermann et al. (2022), *Combined large-N seismic arrays and DAS fibre optic cables across the Hengill geothermal field, Iceland.* The data are made available via EIDA.

WP2: Methodological Advances
We investigated various topics focusing on the improvement of an automated seismic catalogue creation for large datasets as well as on high-resolution imaging and monitoring. Most of the results are already published/submitted and summarized in this report.

WP3: **Transfer to Swiss Play**
With Haute Sorne, a potential deep geothermal project in Northern Switzerland, being delayed, the direct transfer to Swiss Play conditions was not possible. Nevertheless, as we point out in section 4.3, the findings and methodological improvements are very relevant for the Swiss Play conditions.

Since the direct transfer to Switzerland was not possible, we spent much more time on the methodological advances and added several research angles on earthquake detection/location, coda-wave interferometry monitoring and a contribution to distributed acoustic sensing that had not been foreseen.

Milestones
All Milestones with exception of the application to Haute Sorne that was impossible due to the project delay (Milestone 3.1) have been completed.
Milestone 0 (before project start, 7/2020): Decision on network geometry based on COSEISMIQ results
Milestone 1.1: Network densification and continuation of real-time data streaming (M 4)
Milestone 1.2 One year of data collected (M14)
Milestone 1.3: Network de-installed (M18)
Milestone 2.1: Publication on seismic imaging potential submitted to Journal (M24)
Milestone 3.1: Result of Haute Sorne application submitted to Journal (M30)

Deliverables

D5.1.1 Data, Full event catalog
The nodal dataset is collected under the International Federation of Digital Seismograph Networks (FDSN) network code YM (Swiss Seismological Service [SED] at ETH Zurich, 2021) and is curated by the SED. The network information, with full metadata, is discoverable on European Integrated Data Archive (EIDA;
http://eida-federator.ethz.ch/fdsnws/station/1/query?net=YM&format=text&level=station&nodata=404).
The data are currently restricted and will be made available after the project end in January 2025 at this same site. Distributed acoustic sensing (DAS) data will as well be made available at the project end. We

aim to make a subset of spatiotemporally decimated time series publicly accessible via known seismological data repositories. However, in particular due to the data volume, a standardized format for the exchange of DAS data is still sought for by the scientific community. In the meanwhile, access and exchange of raw data can be organized upon request. The information about COntrol SEISmicity and Manage Induced earthQuakes (COSEISMIQ 2C) is available at 10.12686/sed/networks/2c. The information about OR - Reykjavik Energy is available at 10.7914/SN/OR. Information about SmartSolo Nodes is available at https://smartsolo.com. The information about Seismic Mechatronics is available at https://seismic-mechatronics.com/.
How to access the seismic catalogs from the 2C array is described in detail in Grigoli et al. 2022 (https://www.nature.com/articles/s41597-022-01339-w).

D5.1.2 Report on tomographic models, peer reviewed publication
We performed different tomographies using the broadband (BB) and nodal data. Three out of four studies are already published in peer-reviewed journals.

Body-wave tomography using the BB data: Obermann et al. 2022b, Frontiers
Ambient-noise Rayleigh wave tomography using the BB data: Sanchez-Pastor et al. 2021, Geothermics
Time-lapse tomography using the BB data: Sanchez-Pastor et al. 2024, Nature Com
Anisotropic and isotropic imaging using the nodal data: Wu et al, submitted, JGR

4 Results and Discussion

4.1 WP1 Network re-configuration and operation

Based on results of a noise-based Rayleigh wave tomography (Sánchez et al. 2021), observed seismic activity (Obermann et al, 2022b), and intense discussions with Reykjavik Energy on the location of the planned IDDP-3 site, Anne Obermann (SED), Pilar Sanchez-Pastor (SED) and Vala Hjoerleifsdottir (ON Power), identified regions of particular interest across Hengill geothermal field to set up a dense nodal array. Nodes are small, light geophones that typically come with an internal battery (Fig. 3e). These low-cost sensors are currently revolutionizing seismic data acquisition, since hundred to thousands of sensors can be deployed in areas, where until now seismic imaging relied on a handful of bulky, expensive sensors and equipment (Fig. 3 a,b,c).

For Deepen, we succeeded in securing 200 3-component nodes from the University of Geneva and 300 3-component nodes from the GFZ instrumental pool. We deployed these instruments across two regions of interest in Hengill from June to the beginning of August 2021 (Fig. 4). These regions are the northern region around the Nesjavellir power plant that showed anomalous swarm activity and highly productive wells, and the southern Hveralid volcano field that hosts some of the most powerful wells in Hengill. Fibre Optic cables across the Northern array (blue lines, Fig. 4) could be interrogated in an overlapping period by our project partners from NORSAR and GFZ. We could also extend the operational period of the GEOTHERMICA funded Coseismiq real-time broadband network (www.coseismiq.ethz.ch) by one year until August 2021. The costs for the extension were negligeable (one service run and data streaming) and covered by the SED. In August 2021, we decommissioned the Coseismiq network and the seismic nodes.

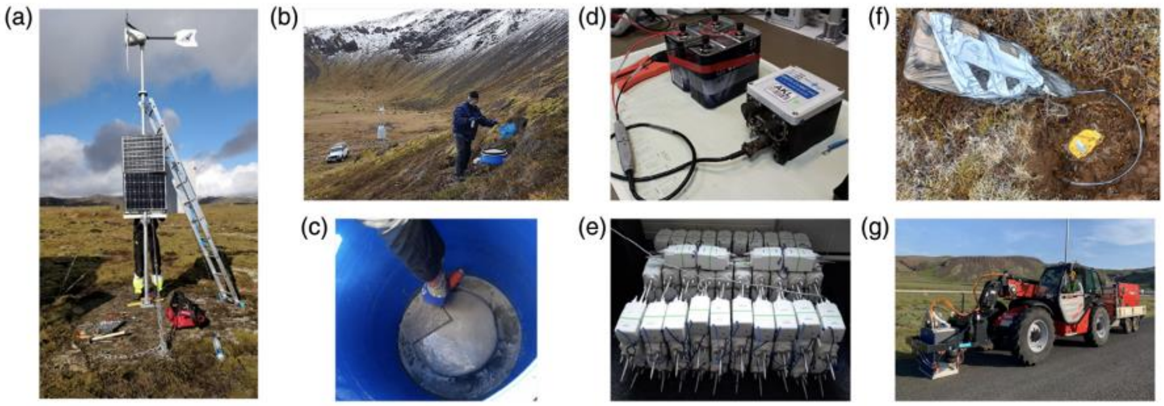

Fig 3 *(a–c) Impressions of the field installations for the 2C (coseismiq) network and (d–f) the YM (nodal) arrays. (a) Mast with wind turbine and solar panels for power supply to the sensor and digitizer. (b) Vault with seismic sensor at about 50 m distance from the mast. (c) Concrete socket within vault. (d) Cube with external batteries. (e) Seismic nodes. (f) Field installation of geophone and Datacubes. (g) Vibro-truck used around the Nesjavellir power plant. (from Obermann et al. 2022a).*

During the network operation time, we could observe a seismic swarm in the Northwestern part of our network, a meteorite impact and a well explosion within our network. In a collaboration effort with

Durucan Sevket from Imperial colleague London, we had a vibrotruck passing through the northern part of our array (Fig. 3). After data acquisition, we spent two months' time on quality checks (to a large part manual) of this massive dataset and the creation of a flawless meta database. The data was uploaded to EIDA, where it is available upon the request of a token. At the end of the project, it will be made available freely to the community. The recorded data quality is excellent, covering much larger than expected range of frequencies (10 s to 20 Hz).

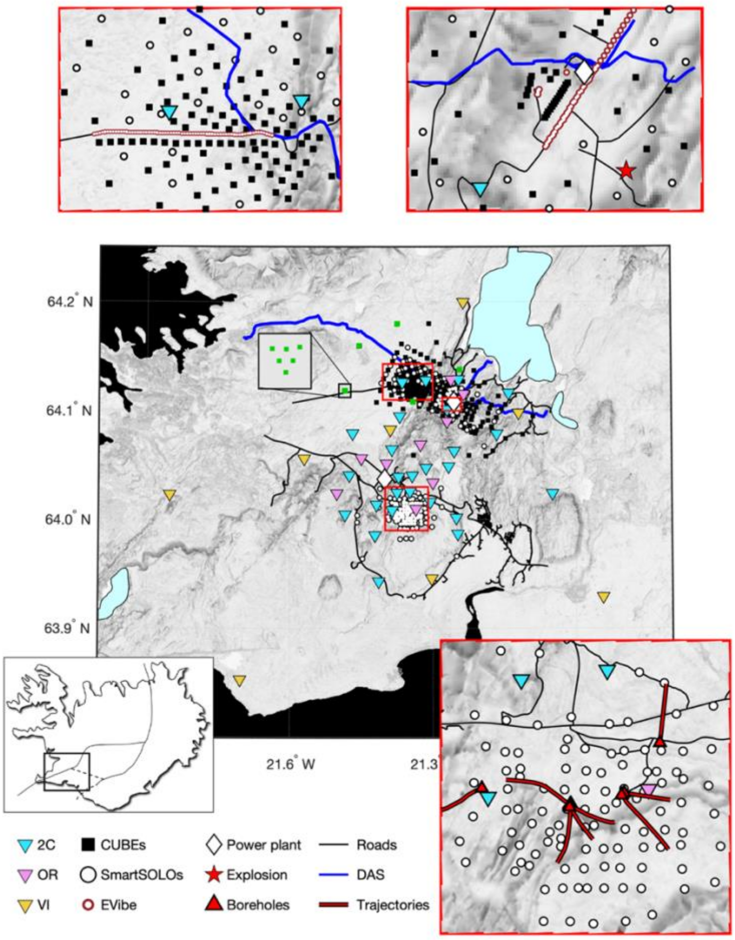

Fig. 4: *Overview map of the seismic network installations across the Hengill geothermal field. a) The location of the Hengill geothermal field at the triple junction. b) The permanent (OR, VI) and temporary (2C, nodal) seismic installations in Hengill and the location of the telecommunication fibre in the North. c,d) Zoom into the location of vibrotruck sweeps along the main road and around the Nesjavellir power plant, respectively. e) Zoom into the Southern nodal array in Hverahlíð and borehole locations. (From Obermann et al. 2022a).*

Time and money considerations: nodal vs broadband

The temporary installation of all 498 seismic nodes (buried at 20 cm depth at the designated location) was realized by 12 people within five days in complicated, hilly terrain, where distances of a few kilometers had to be covered by foot. Meaning that in the Hengill geothermal field a team of 2-3 people can install around 25 nodal stations a day. In accessible terrain, such as central and northern Switzerland, deploying 30 stations per day for a team of 2 people is realistic.

In comparison, the installation of 1 broadband station in the field (involving digging a 1 m hole for a barrel, cementing it, assembling the wind turbines and solar panels and placing the sensor) occupies a team of 3 people for 2 days plus 1 day to pre-assemble everything in the workshop and additional time to order all necessary material.

Costs broadband station: ~15-30000 CHF for sensor and digitizer and additional 3000 CHF for solar panels, wind turbine, barrel, cement etc, deployment (needs to be accessible): 1 station in 3 days for 3 people

Costs node: ~1000 CHF, deployment in difficult terrain: 75 stations in 3 days for 3 people

4.2 WP2 Methodological advances

The methodological advances are centered around two main topics; 1) Improving the seismic catalogues, 2) optimizing the seismic imaging and monitoring techniques.

1) Catalogues: we continued the efforts made during the Coseismiq project, and worked on integrating earthquake detections from the 3 years long recording time of the broadband stations into a homogeneous, high-quality catalog that is accessible on our server (Grigoli et al. 2021). We also analyzed in detail the seismicity patterns (Obermann et al, 2022b, section 4.2.1).

For the nodal deployment, given the large number of stations and recordings available, standard seismic processing tools such as Seiscomp3 reached their limitations. Here, recent developments using machine learning (ML) for automated seismic event detection and phase picking outperform traditional phase picking algorithms and even human experts in terms of picking efficiency and precision. We hence started an ETH internal collaboration with Dr. Shi Peidong and Dr. Federica Lanza, who are developing innovative seismic monitoring technologies in the GEOTHERMICA project DEEP (www.deepgeothernal.org), to adapt such methods for large nodal arrays (Shi in prep, section 4.2.2).

2) Seismic imaging and monitoring techniques: we investigated a large variety of seismic imaging and monitoring methods to shed light on the subsurface in the Hengill volcanic region.

- We used the broadband stations and earthquake data to perform a classical body-wave tomography resulting in 3D Vp, Vs and Vp/Vs models (Obermann et al. 2022b, section 4.2.3).
- We used the continuous recordings from the broadband stations for an ambient noise surface wave tomography resulting in a 3D Vs model (Sanchez-Pastor et al., 2021, section 4.2.4).
- We used the continuous recordings from the broadband and nodal stations to resolve the V_{VOIGT} isotropic and radially-anisotropic structures (Wu et al., submitted, section 4.2.5).
- We compared the outcome of the various models with DAS recordings (Baird et al. in prep, section 4.2.6).
- With time lapse monitoring we track the evolution of the steam cap in high-enthalpy reservoirs with seismic noise (Sanchez-Pastor et al., (2024), section 4.2.7).
- We attempted to image the brittle-ductile transition in the Nesjavellir geothermal field (Iceland) using seismic active and passive methods (Msc thesis Selina Wetter, section 4.2.8).

Determined by the spatial extent of the seismic networks, the resultant velocity models have a depth resolution of about 5 km. However, the lateral resolution could be substantially improved by the incorporation of the seismic nodes from >500 m to around 100m.

Given the richness of the nodal array dataset, we also started collaborations to investigate the following topics:

- We used passive recordings to image the CO2 reinjection reservoir with body-wave seismic interferometry (Hassing et al. (2023), Stork et al. (2022), section 4.2.9).
- The data acquired in the DEEPEN project also served for an off-topic research project on meteorites (Rodriguez et al. 2022, section 4.2.10).

4.2.1 Seismicity across the Hengill geothermal area

As a first step, we used a subset of 6,300 high-quality manually picked P- and S-phases, to compute a minimum 1-D model for the region. Our results suggest that the most consistent and accurate hypocenter locations are derived from a joint inversion of P and S arrival times for the Hengill area. We demonstrate that this minimum 1-D model in combination with SeisComP detection and location algorithms can be used to produce fully-automated yet high-quality earthquake catalogs. Our analysis established that both the induced and natural seismicity in the Hengill area occurs in several distinct, spatially constrained clusters (Fig. 5). In production and injection areas, the depth of the clusters is at about 2 km, near the bottom of the production and injection wells. These are most likely triggered by the injection and induced by the production, respectively. Outside of these clusters, the seismicity is generally deeper, with the depth of the deepest seismicity indicating the brittle-ductile transition zone. This zone is encountered at about 4 km near the center of the Hengill volcanic area and deepens with increasing distance from its volcanic center, to about 7 km in the southernmost region. A spatial analysis of b-values shows slightly increased values in areas with numerous injection wells and slightly decreased values in production areas.

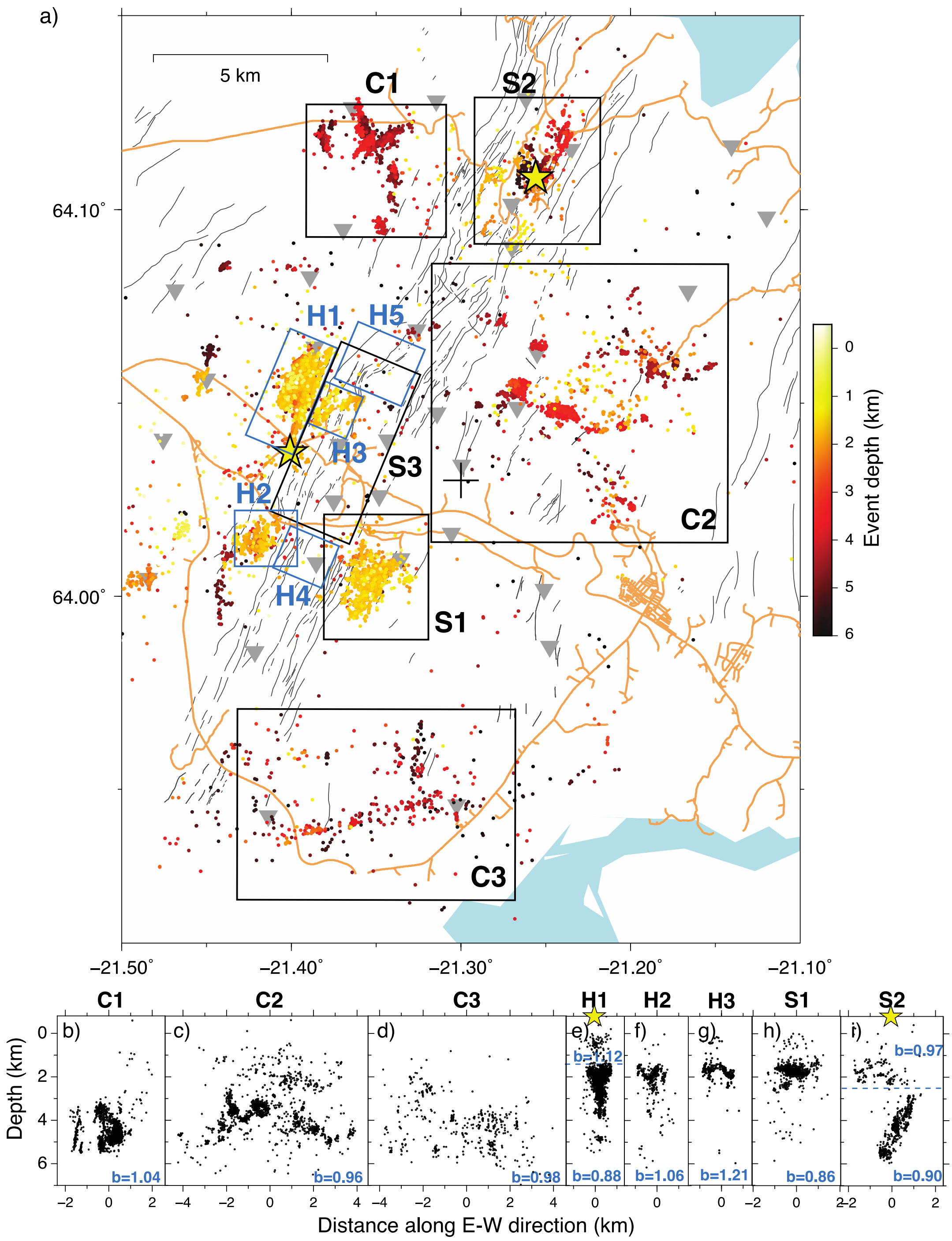

Fig 5 *(A) Double-difference relocated HQ earthquake catalog of the Hengill region from December 2018 to August 2021. The event's color indicates the focal depth. The seismicity occurs in clusters that we label as H1-H5 in the injection areas and S1-S3 in the production areas. Clusters C1-C3 are outside the main production areas, where fewer boreholes are located. (B–I) Vertical distribution of seismicity along E-W direction and b-values for each cluster*

4.2.2 Building an automatic seismic catalogue for large-N networks

We used tailored MALMI (Shi et al. 2022), a software based on machine learning and waveform migration (**Fig. 6a**), to automatically build a seismic catalogue from the continuous data collected by the DEEPEN nodal array. This new workflow does not require phase-detection nor association, instead the probabilities of P- and S-phases generated by ML models are directly migrated into the space and time domain to obtain source location and origin time. The whole framework is data-driven, thus does not have any explicit parameters to tune. The automated nature and parallel efficiency make it capable of real-time monitoring. Iceland is a perfect test site for the developed code, since the settings are known and a significant number of induced seismic events are recorded.

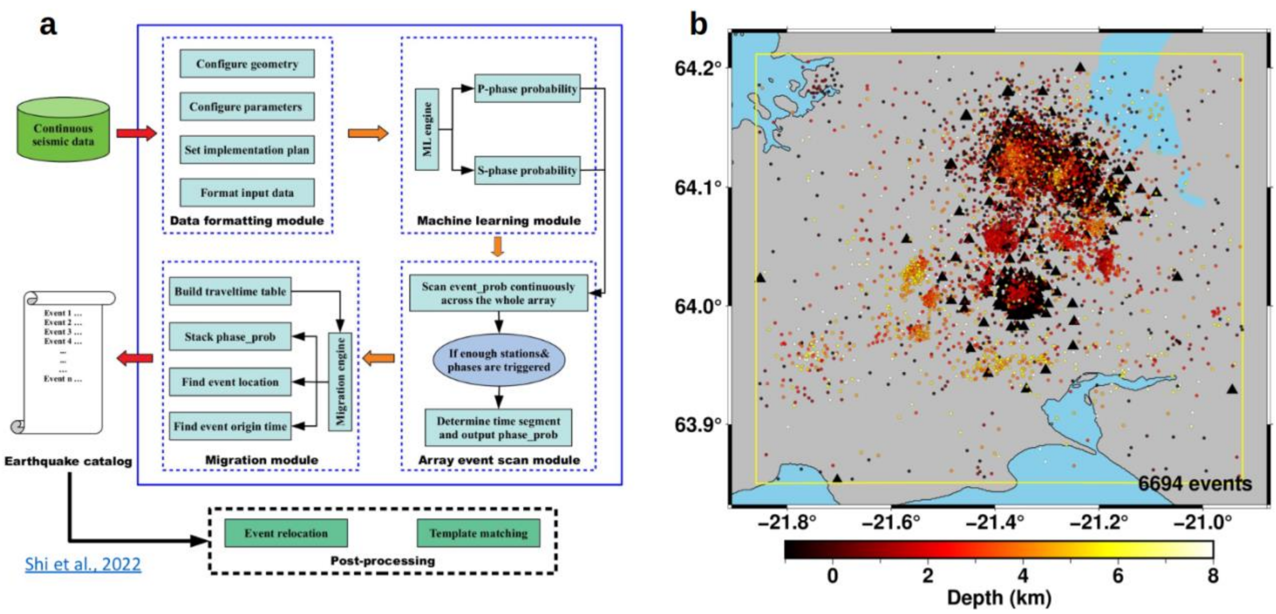

Fig 6. *(a) The MALMI workflow for automatically computing earthquake catalogues from continuous data. (b) The first order catalogue obtained by MALMI from the dense DEEPEN nodal array.*

A catalogue containing 6694 events has been obtained from the period between 2021 May 27 to 2021 August 31 (**Fig. 6b**). For comparisons, the COSEISMIQ low-quality and high-quality catalogues contain 1231 and 569 events during the same period. After additional quality control and relocation procedures we obtained a high-resolution catalogue containing 4071 well constrained events (Fig. 6b,7).

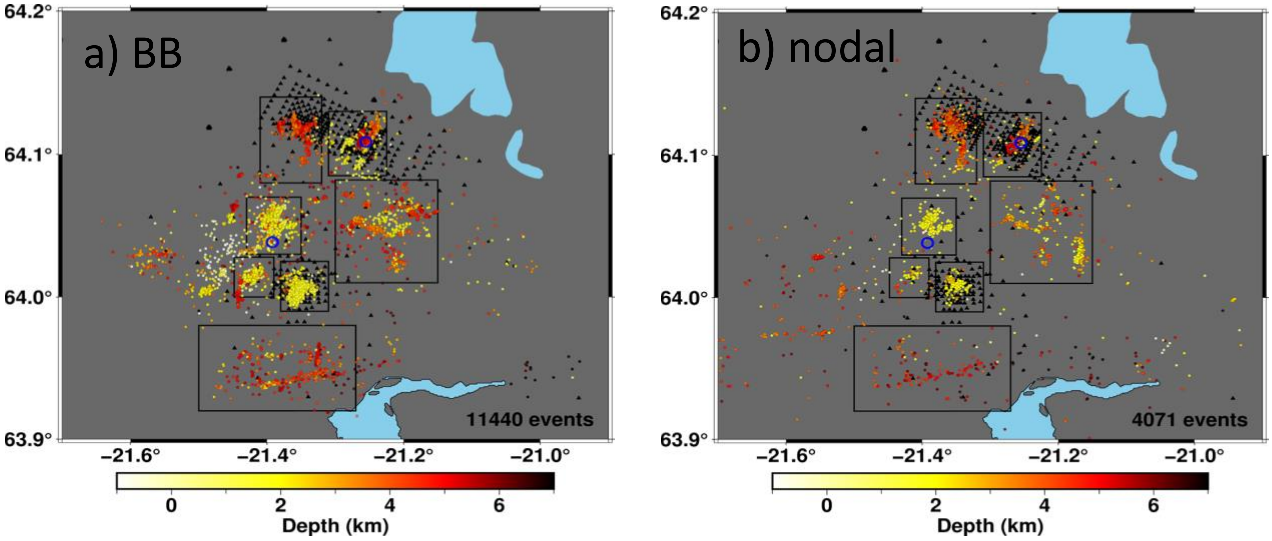

Fig 7 *Comparison of catalogues obtained from 3 years of broadband and 2.5 months nodal deployment.*

A comparison of catalogues obtained from 3 years of broadband and 2.5 months nodal deployment shows that all clusters could be fully recovered in the short duration of the nodal deployment (Fig. 7). Further, the magnitude of completeness Mc decreased from 0.7 to 0.1. At the same time, we detect 7.5 times the number of events compared with the detections of the broadband network in the same period. A factor of 1.3 can be attributed to the machine learning algorithm MALMI. The vast improvement by a factor of 6.2 is directly attributed to the network densification with the nodes.

A drawback during the processing was the high computational demand of a software such as MALMI to process the large datasets. Further improvement of the MALMI software, including parallel computing optimization and adaptive griding, is required to increase its computational efficiency on dense nodal arrays.

The MALMI software is open source and available on github https://github.com/speedshi/MALMI

4.2.3 Earthquake tomography with broadband data

We performed a Vp, Vs and Vp/Vs local earthquake tomography. At shallow depths (0–1 km), the Vp and Vs tomographic models indicate fast velocities along the postglacial fissure swarm as well as a SE-NW trend towards the Grensdalur volcanic center (Fig. 8). At greater depth these anomalies are not as pronounced. At 1–3 km, the relatively fastest velocity is observed in the NW corner of the Grensdalur volcanic center coinciding with a gravity high, likely reflecting dense solidified magmatic intrusion(s) in the volcanic center. This SE-NW anomalous velocity feature extending between the extinct Grensdalur volcanic center and the presently active Hengill volcanic center is also reflected in traces of geothermal surface manifestations, and other geophysical measurements, such as a shallow lying low resistivity anomaly and an aero-magnetic low—all three due to high temperature at some point in the geological history of the area and most likely caused by the migration of the crustal accretion and volcanic activity between the two volcanic centers. At greater depth (>4 km) a deep lying resistivity low is seen cutting through the northern part of the Hengill volcanic center and trending towards Grensdalur. It presumably reflects hot, solidified intrusions that are heat sources for the geothermal system.

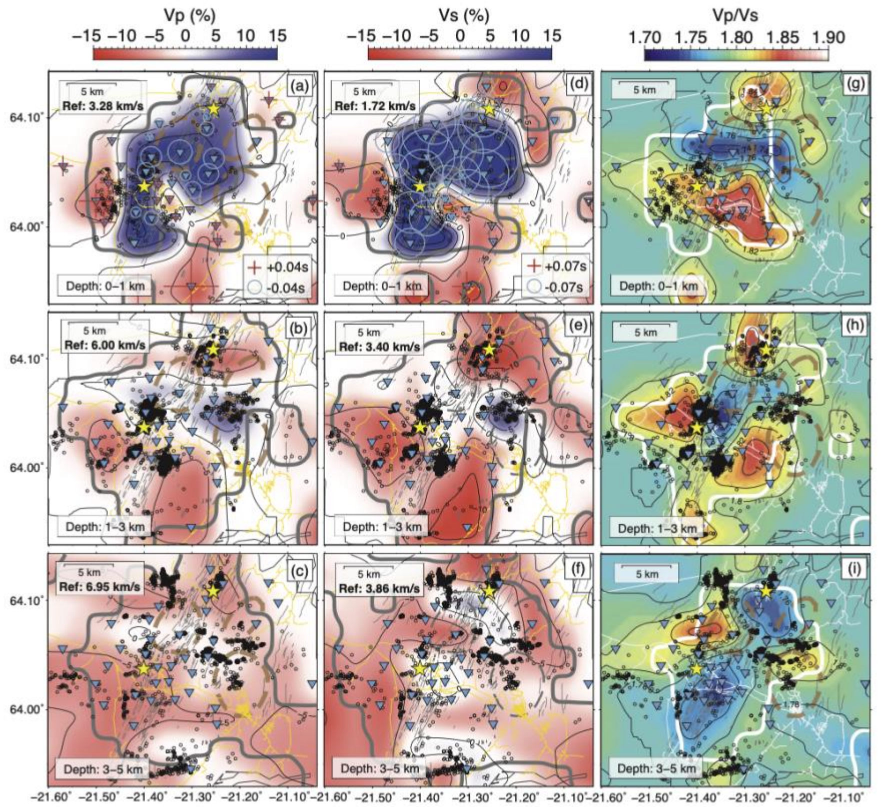

Fig 8 *Horizontal cross-sections of the Vp (A–C), Vs (D,–F) and Vp/Vs (G–I) velocity models at 0, 2 and 4 km depth presented as relative change (in %) with respect to reference 1-D model. The reference velocity of each layer is shown on the upper left-hand side of each figure. The average Vp/Vs is 1.79 in the study area. (From Obermann et al. 2022b).*

At 0–1 km depth, a zone of relatively low Vp/Vs ratios cuts through the Hengill volcanic center trending W-E, while at greater depth the low Vp/Vs ratio is mainly along the fissure swarm (Fig. 9). At 1–3 km depth the low Vp/Vs anomaly coincides with the main production field, located slightly NE of the Hellisheiði power plant, possibly caused by the extensive extraction which lowers the pressure in the field, and consequently increases the steam zone leading to lower Vp/Vs ratios. Most of the earthquakes are located within the Vp/Vs low and at the boundary of the high and low Vp/Vs anomalies, which might indicate a region with good permeability.

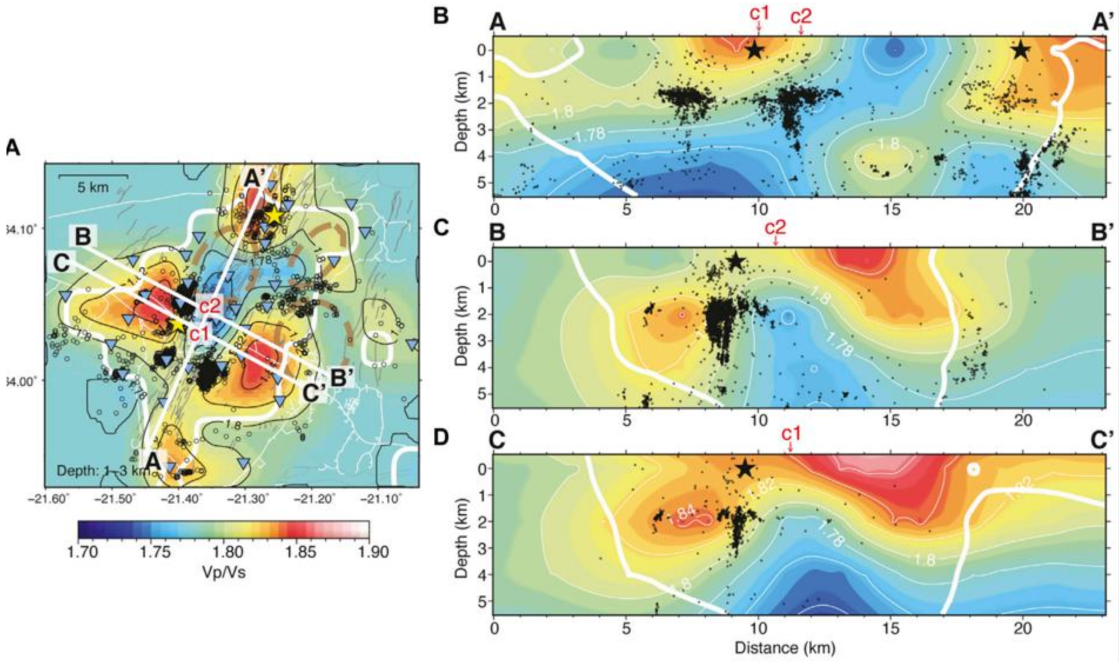

Fig 9 *Vertical cross-sections through the Vp/Vs model along the paths shown in (A). The stars mark the location of the power plants. The seismicity 2 km around each transect is superimposed on the figures and shown as black dots. The white thick lines mark the well resolved area with an RDE>0.7. (From Obermann et al. 2022b)*

4.2.4 Noise tomography with broadband data

In this study, we investigated the potential for ambient seismic noise tomography to be used as a geothermal exploration tool. The tomographic results are compared with different geophysical observables, of which resistivity modeling shows an excellent correlation with the results (Fig. 10). We also observed a prominent seismic velocity reduction to the south of Hverahlíð, where the most powerful boreholes in the region are located.

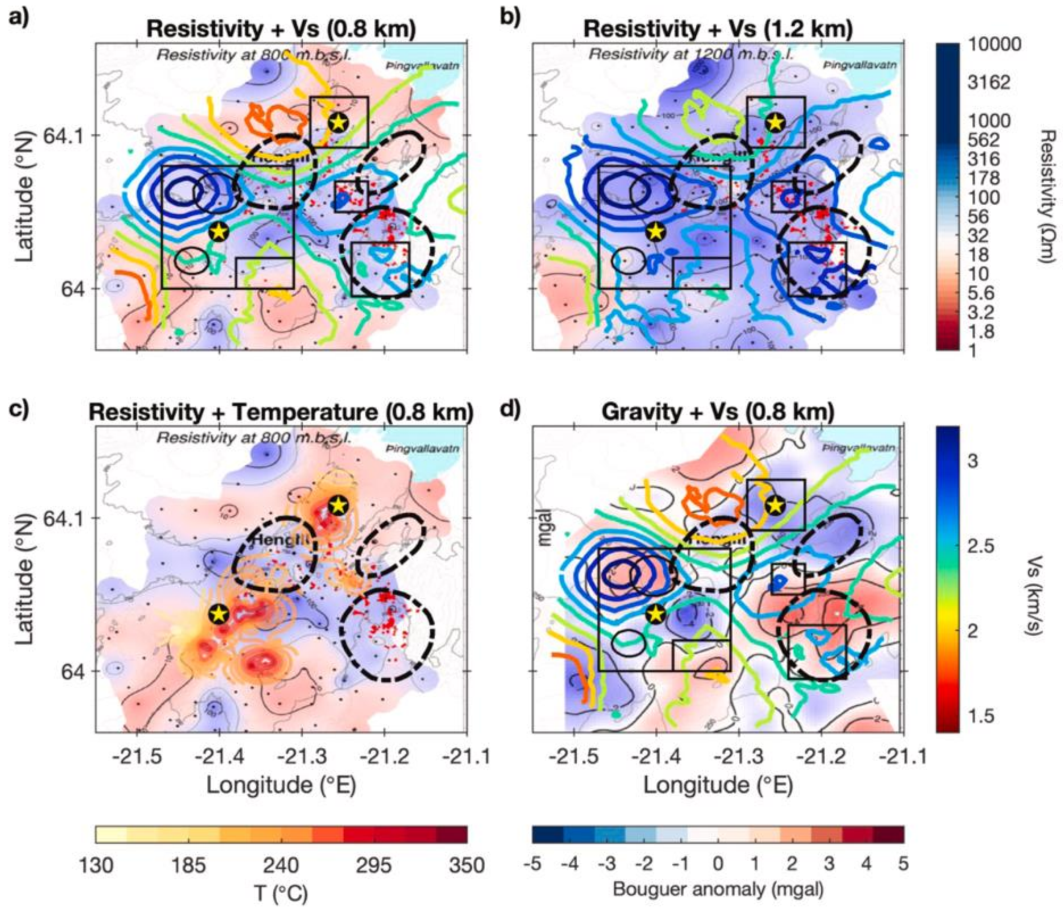

Fig 10 *Comparison between the 3D shear-wave velocity model (in all panels plotted as contour lines on top) and the joint 1D inversion of TEM and MT resistivity data at (a) 0.8 km and (b) 1.2 km depth. (c) Joint 1D inversion of TEM and MT resistivity data at 0.8 km depth and the formation temperature at 1 km depth. (d) Residual Bouguer gravity map and tomography model at 0.8 km depth. Note that the color scales corresponding to the resistivity and velocity estimations are equal for all panels. Red dots in a) - c) are geothermal surface manifestations and black dots indicate the location of the MT soundings. The geothermal fields and reinjection areas are represented in a) – c) as thin black lines. (From Sanchez-Pastor et al. 2021).*

4.2.5 Noise tomography with broadband and nodal data

We perform ambient noise Rayleigh and Love wave imaging by combining a 500-node dense geophone array and a 44-station sparse backbone seismic network (Fig. 11). We demonstrate that, even with a short duration of data (2 months), our seismic image is greatly enhanced in the top 5 km compared to the images retrieved from the sparse array only. In addition to the shallow structure, the dense sampling with good azimuthal coverage provides essential constraints on better depicting the deep structure. We observe a primary slow velocity anomaly ~4km depth associated with solidified magmatic intrusions that serve as a major heat source of Hengill. The trend of the anomaly is perpendicular to the major alignment of faults and fissure swarms, consistent with a previously found low-resistivity anomaly. In addition, we found that most of the earthquakes were located near the margin of velocity contrasts, likely indicating a structure or permeability change in the subsurface.

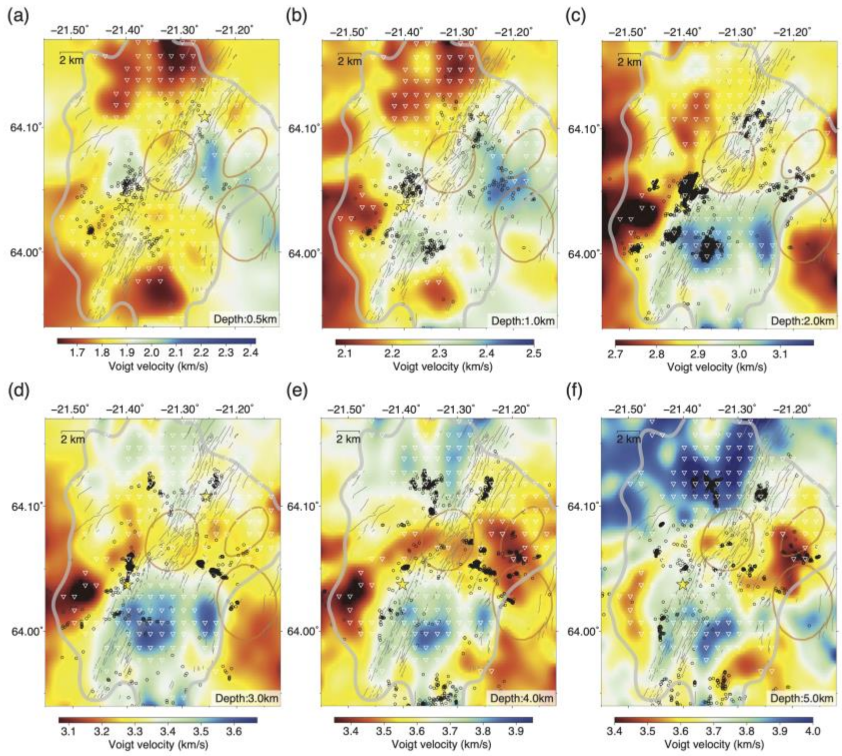

Fig 11 *(a–g) Voigt average velocity maps at different depths. The yellow stars and open triangles denote the locations of power plants and the bin centers. Seismicity near the corresponding depth is plotted as black dots. The orange lines mark the volcanic fields and the gray lines bound the areas with good ray coverage. The thin-gray lines outline the primary NE-trending faults and fissure swarms in Hengill.*

Jointly constrained by Rayleigh and Love waves, the difference between horizontally (V_{SH}) and vertically polarized (V_{SV}) wave speeds represents seismic radial anisotropy and is commonly indicative of the textural fabrics of the structure (**Fig. 12**). In Hengill, we observed a predominant fast direction along the vertical axis in the top 2 km of crust, implying an overall vertical crack formation resulting from extensional stress with ~10 mm/yr westward deformation. From 3 to 5 km depth, the fast direction transitions to the horizontal axis, broadly in agreement with the subhorizontal intrusions or lava deposits. This is supported by *in-situ* cores obtained in Nesjavellir, we see the intrusion density increases with depth, reaching 80-100% at 2 km depth. Anomalously, around the same depth, the southwestern Hengill geothermal field (Hverahlíð and south of Hellsheíði) remains in the vertically-fast direction. This area resides in the junction of distinct geologic, tectonic, and geodetic manifestations. We hypothesize the patch of the anisotropy anomaly is associated with crustal thinning that also promotes one of the powerful boreholes in Hverahlíð.

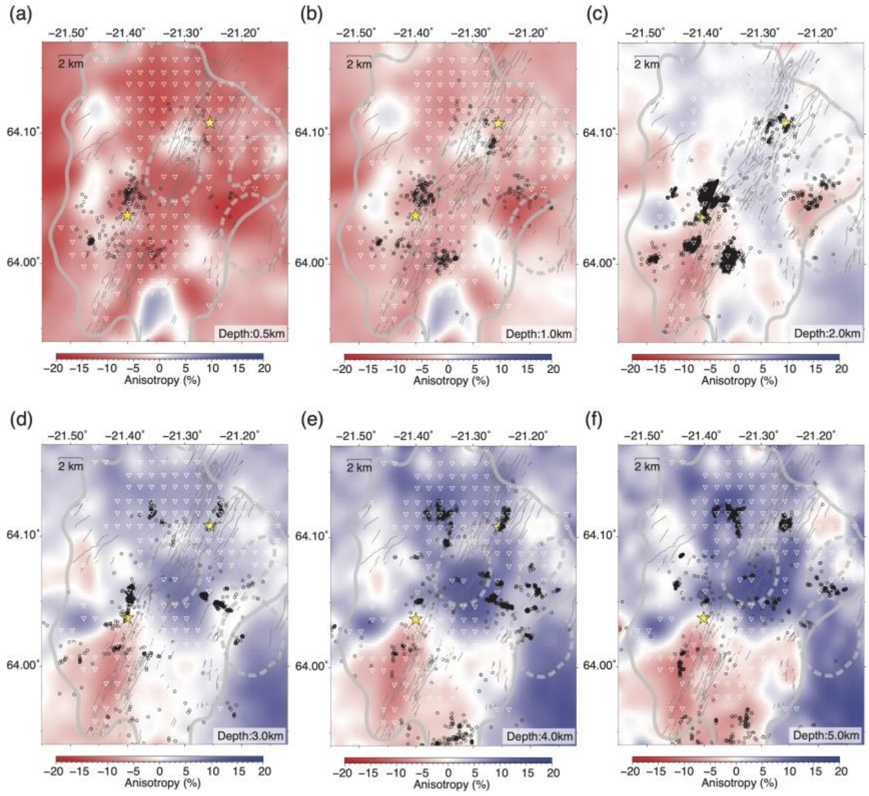

Fig 12 *(a–g) Radial anisotropy maps at different depths. The yellow stars and open triangles denote the locations of power plants and the bin centers. Seismicity near the corresponding depth is plotted as black dots. The dashed-gray lines mark the volcanic fields and the solid-gray lines bound the areas with good ray coverage. The thin-gray lines outline the primary NE-trending faults and fissure swarms in Hengill.*

4.2.6 Comparison of DAS recordings with velocity models

We compared the four different shear wave velocity models (Min 1D model, Body-wave tomography, Noise tomography, Noise tomography with nodes) with DAS recordings. While at a first glance, the body-wave velocity model appears to best fit, the noise-based tomographies capture details much better (Fig. 13). We are currently applying for additional funding to continue this work and further explore the use of DAS.

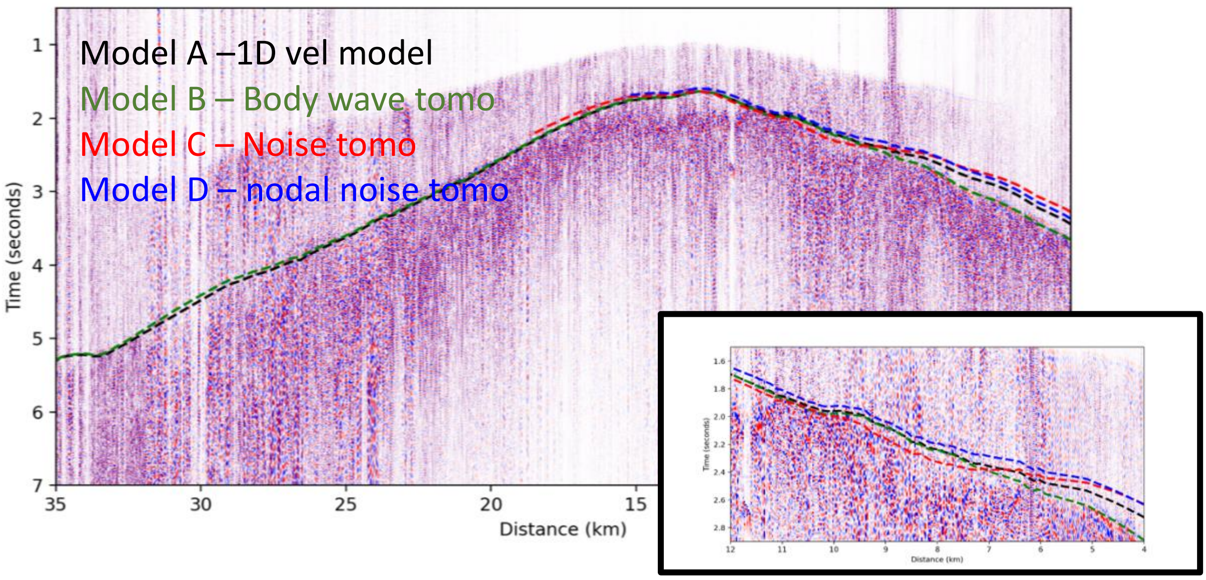

Fig 13 *Comparison of DAS recordings with the shear-wave velocity models obtained from the various tomographies*

4.2.7 Time Lapse Monitoring

Geothermal energy production entails massive fluid extraction from the subsurface. This causes a pressure drop in the reservoir that reduces the borehole productivity. Furthermore, the pressure decline can cause land subsidence and favor steam formation. Direct measurements within the production boreholes require production interruption and therefore, they are expensive and scarce. We investigated the potential of the surface and non-invasive seismic noise interferometry (SNI) approach to track the long-term evolution of geothermal reservoirs. We estimate seismic velocity changes in the Hengill geothermal field (Iceland) and compare them with ground deformation maps obtained with InSAR (Fig. 14). The seismic velocities decrease faster near production areas, where subsidence is larger and the steam formation prominent. We further modelled the expected seismic velocity evolution in this region with and without steam formation concluding that SNI allows clearly identifying steam as well as monitoring its time and spatial evolution.

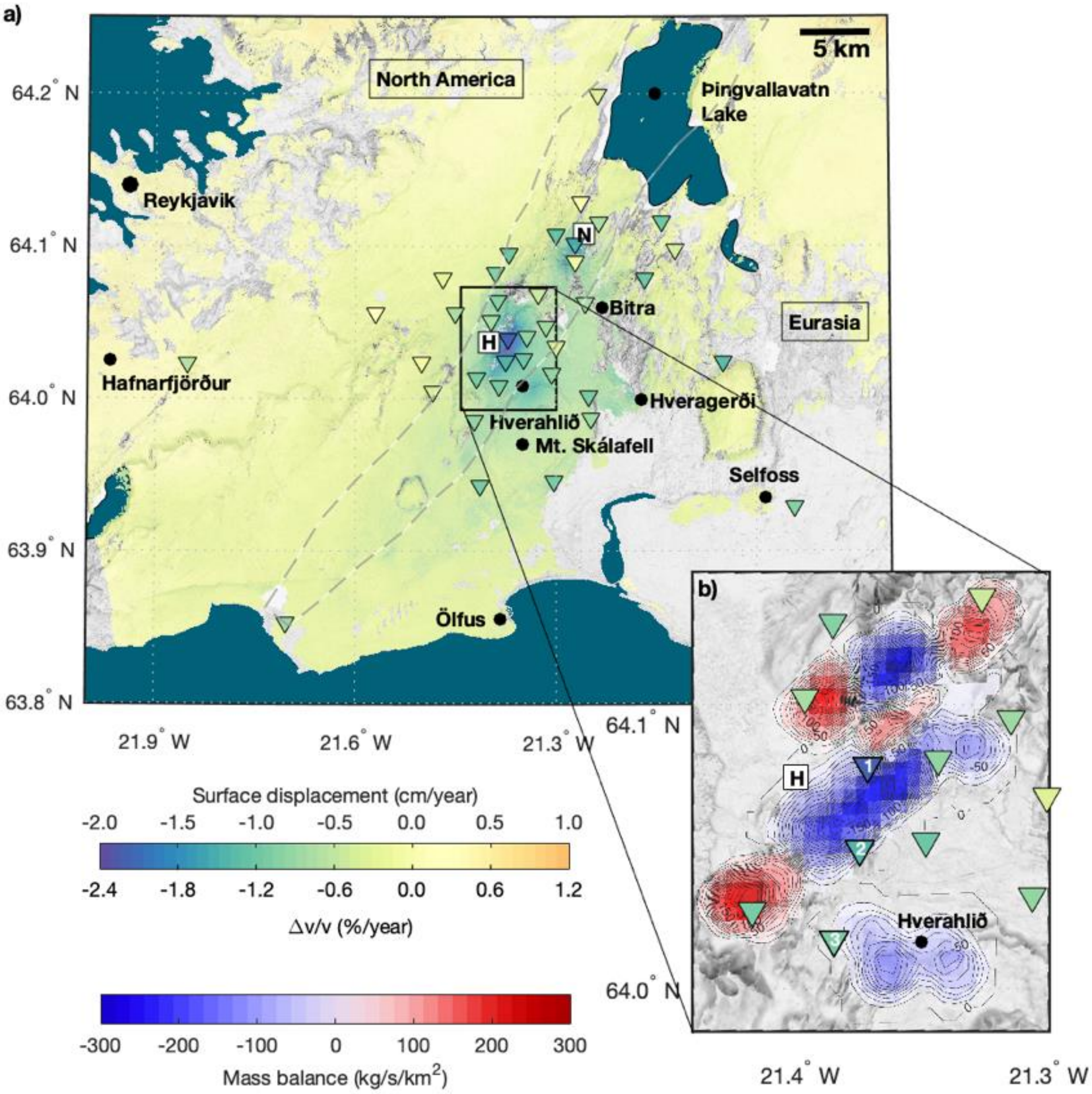

Fig 14 *Surface observations in the Hengill area. (a) Near-up surface displacement rates in the Hengill area. The location of the Nesjavellir and Hellisheiði power plants is represented with their corresponding initials within white squares. The location of the employed seismic stations is depicted by inverted triangles whose colors indicate the annual $\Delta v/v$ rate. The Hengill fissure swarm is delineated with a dashed gray line and places of interest are depicted with solid back dots (b) Mass balance in the Hellisheiði geothermal field, bluish colors (negative values) indicate production areas and reddish colors (positive values) injection fields (Sanchez-Pastor et al. (2024)).*

4.2.8 Imaging the brittle-ductile transition

The Hengill geothermal field is the next target for the Iceland Deep Drilling Project (IDDP) to find supercritical fluids and with that increase the geothermal energy production. Supercritical fluids are normally found below the brittle-ductile transition (BDT), which is expected at around 4 km depth in the Hengill geothermal field. The temperatures at the BDT are above the critical temperature. Thus, imaging the BDT with high resolution is of special interest in geothermal settings. The BDT can act as a single seismic reflector with a corresponding reflection coefficient. Therefore, it is possible to detect this transition zone with seismic methods. By single station auto-correlations of the ambient seismic noise records, it is possible to determine seismic reflectivity profiles. Using the seismic stations deployed in the Hengill area, we retrieved a reliable P-wave reflection response from Mosfellsheiði to the Hrómundartindur volcano (Fig. 13). A layer at around 5 km depth could be detected. We compared the results with the local seismicity and interpreted the layer as an indicator of the approximated depth of the BDT.

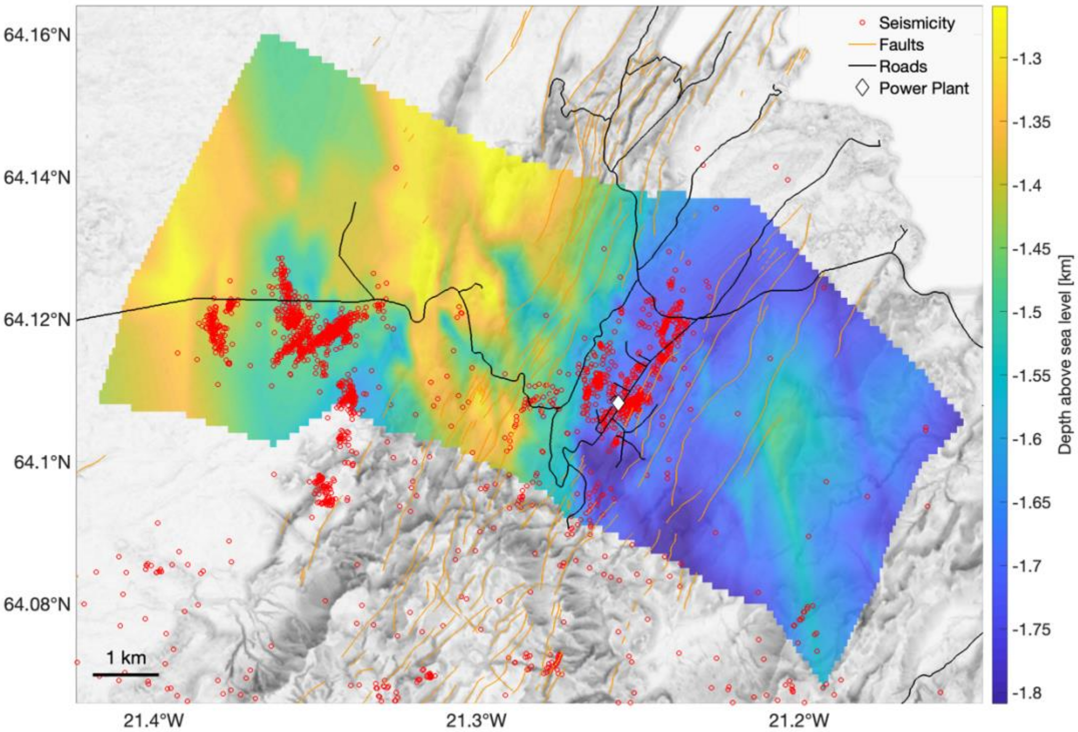

Fig 15 *Mapping the depth of the first reflector across the Hengill geothermal area.*

4.2.9 Imaging CO_2 reinjection into basalts with body-wave seismic interferometry

In collaboration with the SUCCEED project that investigates CO_2 reinjection with different seismic methods, we conducted active and seismic surveys at the geothermal power plant at Hellisheiði. During a survey in 2021, two lines with nodal geophones recorded noise for a week. We processed the passive-source data with seismic interferometry to image the subsurface structure around the CarbFix2 reinjection reservoir (Fig. 16). To improve image quality, we perform an illumination analysis to select only noise panels dominated by body-wave energy. The results show that most noise panels are dominated by air-wave energy arriving from the direction of the powerplant. We use panels with a near-vertical incidence to create a zero-offset image and a larger selection of body-wave-dominated panels to create virtual common-shot gathers. We process the gathers with a simple reflection seismology processing work-flow to obtain stacked images. The zero-offset images show a relatively lower signal-to-noise ratio and only horizontal reflectors. The stacked images show slightly dipping reflectors and possibly lateral amplitude variations around the expected injection region. This could indicate a region of interest for future research into the reinjection reservoir.

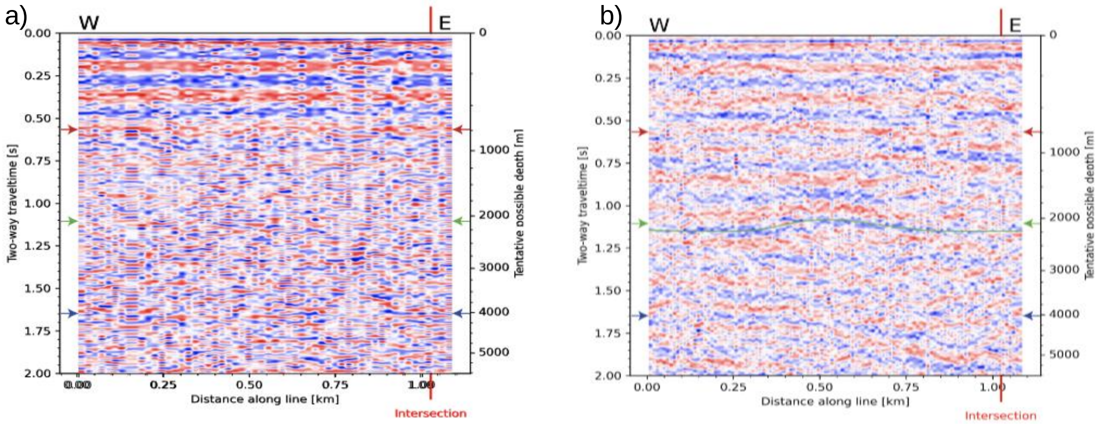

Fig 16 *The zero-offset image(a) and stacked image(b) for the crossline two-way travel time. The intersection with the main line is indicated with red lines outside of the axes. A large circular anomaly is visible around 0.25s two-way travel time and 450m along the line on the zero-offset section, while it is not visible on the stacked section.*

4.2.10 Acoustic Signals of a Meteoroid

A common challenge in acoustic meteoroid signal analyses is to discriminate whether the observed wavefield can be better described by line-source or point-source models. This challenge typically arises from a sparse availability of observations. Here, we had the outstanding record of ground-coupled waves from local large-N seismic and distributed acoustic sensing (DAS) observations of a meteoroid in Iceland. Our complete data set includes additional regional stations located within 300 km of the meteoroid's trajectory. The dense large-N and DAS data allow identification of acoustic phases that are almost impossible to discriminate on sparser networks, including a weak late arrival resolved mostly only by DAS. Using this data set with a new Bayesian inversion model, we estimate the trajectory parameters of one fragment from the meteoroid (Fig. 17). With these results we investigate its orbit in the solar system and propose a classification of the Icelandic event as a slow meteoroid of asteroidal origin with an energy on the order of 4–40 GJ, a probable size on the order of centimeters, and an orbit range consistent with the main asteroid belt.

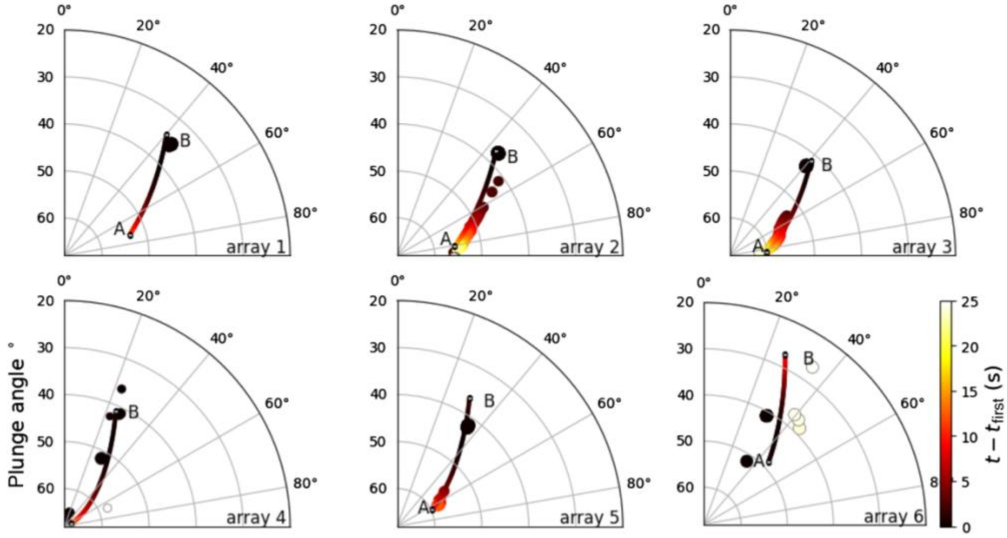

Fig 17 Analysis of meteoroid trajectory from array back-azimuth observations. Observed back-azimuth arrivals (azimuth and plunge, thick colored points) are compared to simulated arrivals (thin trajectories, initial and terminal points labeled by A and B, respectively). The color bar indicates the lag time after the first arrival. Array numbers are labeled.

4.3 WP3 Transfer to Swiss Play conditions

A pioneering geothermal project with a planned power output of 5 MW was supposed to start in Mid 2022 in Haute-Sorne, the Swiss Canton of Jura and contribute towards the implementation of Switzerland's 2050 energy strategy. However, due to legal processes initiated by opponents of the project the Haute-Sorne project start is delayed. As a substitute, we focused on methodological advances and expanded significantly the scope of WP2. Here, we point out how a transfer could look like.

Broadband backbone network: similar to the projects in St. Gallen and Basel, at least 5 broadband stations with real-time data streaming within 10 km of the injection site are mandatory for safety related permanent monitoring of induced seismicity (traffic light systems).

Dense nodal network: despite their limited battery duration of 2.5 months and offline data storage, we would strongly recommend to deploy a dense nodal network during various stages of the project. Ideally the deployment sites are clearly marked so that they can be used multiple times, limiting the perturbation on the waveforms to a minimum that is unavoidable when the sensor is collected to retrieve the data and charge the battery.

Following the lessons learnt in DEEPEN (Wu et al. 2024, Obermann et al. 2022), such an array would be regular spaced, yielding a homogeneous ray coverage and thus a harmonized spatial resolution. With dense arrays, the increased quantity and the homogeneity of ray paths are the key to enhancing resolution for seismic imaging. Within the network, at each site we would deploy multiple (2-3) nodes at meter distance. These mini arrays record essentially the same wavefield and can be used to enhance the signal to noise ratio significantly, which is highly relevant given the short recording duration of each survey. Such a setup will also help to average out small differences in the deployment (e.g., slightly different tilt or orientation) for time lapse surveys. Using all 3-components, high-resolution time-lapse images of the subsurface can be constructed (Wu et al. 2024) that should allow to monitor aseismic

deformations in much greater detail than the observations performed with a sparse network in Basel (Hillers et al. 2015) and St. Gallen (Obermann et al. 2015).
With such a dense array in place during the onset of the injection operations, there is also the realistic chance to monitor microseismicity in great detail, down to the illumination of fracture networks. The tools to process such large amounts of data are in place and ongoing work focusses on further improving the computation time.

5 Conclusions

Seismic nodes: We were very satisfied with the performance of the seismic nodes that proved to be a cheap and quick to install new instrument type that provides high-quality data over a large frequency range (10 s-20 Hz). The average costs are about~1000 CHF per node and a team of 2-3 people can deploy 25 nodes in difficult terrain per day.

High-quality data set: We created a very interesting high-quality seismic data set that is available with Metadata at EIDA (http://eida-federator.ethz.ch/fdsnws/station/1/query?net=YM&format=text&level=station&nodata=404) and has already sparked wide interest for collaborations.

Imaging: The dense nodal array deployment allowed us to obtain high-resolution images of the subsurface, using only 2.5 months of data. With an array aperture of about 30 km, we reach a depth resolution of about 5 km. The lateral resolution could be substantially improved by the incorporation of the seismic nodes from >500 m to around 100 m.

The stations in the dense network should be homogeneously distributed and ideally clustered in mini arrays of 2-3 stations to enhance the signal to noise ratio.

Seismicity: the nodal array allowed to retrieve all seismic clusters and lower the magnitude of completeness by one order of magnitude, resulting in 7 times more events. This is a substantial improvement allowing the delineation of faults with high-resolution.

Benchmarking: We showed the potential of ambient seismic noise methods to contribute to the exploration and monitoring of geothermal projects.

Hengill volcanic field: We significantly improved the knowledge of the subsurface across the Hengill volcanic area, rendering it an ideal testsite for testing of advanced methods.

The methodological improvements, as well as the lessons learnt from the nodal array deployments are directly applicable to Swiss settings. Beyond geothermal, high-resolution imaging and reflectivity imaging are also of interest for CO_2 storage applications.

6 Outlook and next steps

Despite these very positive outcomes, more work is needed to use seismic imaging methods reliably in a-priori resource characterizing and seismic risk assessment.
In magmatic settings in particular the Vp/Vs ratio and attenuation patterns are of interest, since they coincide with high-temperature anomalies. Enhanced Geothermal Systems (EGS) are situated in very varied geological settings, but face similar exploration and monitoring challenges. Despite the possible -though very expensive- application of 4D seismics, little is known about the exact distribution of faults and state of stress within and near the reservoir. Nevertheless, in particular near urbanized areas, the real-time processing and assessment of stress changes is of utmost importance to avoid the occurrence of felt induced seismic events and guarantee safe operations. For both, magmatic and enhanced geothermal systems, further innovation in terms of exploration and monitoring techniques at reservoir scale is needed.
Over the past years, seismic data are growing in size and variety at an exceptionally fast rate, opening new avenues for geothermal plays. As we have shown here, **new sensor technologies** make it possible to deploy extremely-dense seismic arrays including hundreds (to thousands) of reasonably broad-band geophones. Based on fiber optics technology, common telecommunication lines (dark and active) can be interrogated, generating extremely large and rich datasets with near continuous spatial sampling along the fiber line. Fibre cables can also be deployed along boreholes, with the objective to get below the main scattering heterogeneous surface layers and better image deeper structures. An integration of seismic data from fibres and body-waves retrieved from dense arrays could potentially overcome the limited depth resolution of surface-wave based imaging approaches.
With increased **computational capacities** and advances in data processing, machine learning (ML) tools have been adapted to the needs of the Earth Science community. ML tools can harvest vast amounts of information, such as large numbers of tiny earthquakes, and aseismic deformation processes from these massive datasets.
There have also been improvements in the **physical understanding of seismic scattering processes** in complex environments that open the door to the application of novel methods from other fields of physics (e.g., optics, ultrasound imaging) to seismic data, such as focal spot imaging (Hillers et al. 2016) and the use of reflection matrices to overcome imaging limitations induced by multiple scattering (Blondel et al. 2018) and the use of Machine Learning to incorporate scattering into the imaging procedure (Seydoux et al, 2020, O’ Brien et al, 2023)

7 National and international cooperation

The DEEPEN consortium consists of a group of industrial, academic, and national laboratory partners from Iceland, United States, Norway, Germany and Switzerland. The consortium includes Reykjavik Energy, an established geothermal developer in Iceland; National Renewable Energy Laboratory (NREL), U.S., the pioneers of the PFA methodology for geothermal, EQUINOR (formerly Statoil), an energy company with deep roots in the oil and gas sector and a strong tradition of joint inversion of multiple geoscientific exploration data sets, and seven research institutions with a long track record geothermal research: Iceland GeoSurvey (ÍSOR), Iceland; University of Iceland (UoI), Iceland; Norwegian Seismic Array (NORSAR), Norway; Lawrence Berkeley National Laboratory (LBNL), U.S.; Das Deutsche GeoForschungsZentrum (GFZ), Germany; Eidgenössische Technische Hochschule

Zürich (ETHZ), Switzerland; and IFP Energies Nouvelles (IFPEN), France.
For DEEPEN-CH, we directly collaborated with Reykjavik Energy, the German GFZ and NORSAR. Seismic nodes were also provided by the University of Geneva.

8 Publications

Publication from DEEPEN-CH

In Preparation

- Shi et al. Automatic Catalogue creation for large-N arrays using MALMI
- Baird et al. Comparison DAS recordings and tomographic velocity models

In Review

- Wu, S.-M., Sánchez-Pastor, P., Ágústsdóttir, T., Páll Hersir, G., Mordret, A., Hjörleifsdóttir, V., Obermann, A. (2024) *High-resolution seismic isotropic and anisotropic imaging across the Hengill geothermal fields using a large-N nodal array,* JGR

Published

- Bellezza, C., Barison, E., Farina, B., Poletto, F., Meneghini, F., Böhm, G., Draganov, D., Janssen, M., Otten, G., Stork, A., Chalari, A., Bos, J., Perry, W., Barnhoorh, A., Korre, A., Durucan, S., Brynjarsson, B., Hjörleifsdóttir, V., Schleifer, A., Obermann, A., & Sánchez-Pastor, P. (2023). *Seismic monitoring of CO2 injection: A multidisciplinary processing approach*. Proceedings World Geothermal Congress 2023.
- Gyger, Lea (March 2021) Searching for geothermal resources with active-source seismic imaging in Hengill, Iceland**,** Master thesis, ETH.
- Hassing, S., Draganov. D., Janssen, M., Barnhoorn, A., Wolf, K.-H., van den Berg, J., Friebel, M., Otten, G., Poletto, F., Bellezza, C., Barison, E., Brynjarsson, B., Hjörleifsdóttir, V., Obermann, A., Sánchez-Pastor, P., Durucan, S. (2023) *Imaging CO2 reinjection into basalts at the CarbFix reinjection reservoir (Hellisheiði, Iceland) with body-wave seismic interferometry*, Geophysical Prospecting, accepted
- Hjörleifsdóttir, V., Kolker, A., Hokstad, K., Stefánsson, A., Obermann, A., Dobson, P., Sonnenthal, E., Goertz-Allman, B., Vandyukova, E., Souque, C., Benediktsdóttir, A., Árni Guðnason, E., Dahm, T., Sörlie, C. (2023) *DErisking Exploration for geothermal Plays in magmatic Environments – Results and Perspectives from the DEEPEN Project*, GRC Transactions, Vol.47
- Obermann, A., Sánchez-Pastor, P., Wu, S-M., Wollin, C. Baird, A. F., Isken, M. P., Clinton, J., Goertz-Allmann, B.P., Dahm, T., Wuestefeld, A., Shi, P., Lanza, F., Gyger, L., Wetter, S., Hjörleifsdóttir, V., Langet, N., Brynjarsson, B., Jousset, P., Wiemer, S. (2022a) *Combined large-N seismic arrays and DAS fibre optic cables across the Hengill geothermal field*, Iceland, SRL, 9.
- Obermann, A., Wu, S.-M., Ágústsdóttir, T., Duran, A., Diehl, T., Sánchez-Pastor, P., Kristjansdóttir, S., Hjörleifsdóttir, V., Wiemer, S., Páll Hersir, G. (2022b) *Seismicity and 3-D body-wave velocity models across the Hengill geothermal area, SW Iceland*, Frontiers in Geosciences, 10

- Rodriguez, I., Isken, M. P., Dahm, T., Kraft, T., Lamb, O. D., Wu, S.-M., Kristjánsdóttir, S., Jónsdóttir, K., Sánchez-Pastor, P., Clinton, J., Wollin, C., Baird, A. F., Wüstefeld, A., Booz, B., Eibl, E. P. S., Heimann, S., Goertz-Allmann, B. P., Jousset, P., Oye, V., Hjörleifsdóttir, V., & Obermann, A., (2022) *Acoustic signals of a meteoroid recorded on a large-N seismic network and fibre optic cables*, SRL, 94.
- Sánchez-Pastor, P., Wu, S.-M., Hokstad, K., Kristjánsson, B., Drouin, V., Ducrocq, C., Gunnarsson, G., Rinaldi, A., Wiemer, S., Obermann, A. (2024) *Monitoring gas pockets in the crust with seismic noise*, Nature Communications Earth & Environment, accepted
- Stork, A., Poletto, F., Draganov, D., Janssen, M., Hassing, S., Meneghini, F., Böhm, G., David, A., Farina, B., Schleifer, A., Durucan, S., Brynjarsson, B., Hjörleifsdóttir, V., Perry, W., van Otten, G., Barnhoorn, A., Wolf, K.- H., Korre, A., Bos, J., Bellezza, C., Chalari, A., Obermann, A. & Sánchez-Pastor, P. (2022) *Monitoring CO2 injection with passive and active seismic surveys: Case study from the Hellisheiði geothermal field, Iceland*. Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16) 23-24 Oct 2022 https://doi.org/10.2139/ssrn.4273044
- Wetter, Selina (Sept 2022) *Imaging the brittle-ductile transition in the Nesjavellir geothermal field (Iceland) using seismic active and passive methods*, Master thesis, ETH.

Other References

Árnason, K., Eysteinsson, H., and Hersir, G. P. (2010). Joint 1-D inversion of TEM and MT data and 3D inversion of MT data in the Hengill area, SW Iceland. Geothermics 39 (1), 13–34. doi:10.1016/j.geothermics.2010.01.002

Árnason, K., Haraldsson, G. I., Johnsen, G. V., Thorbergsson, G., Hersir, G. P., Saemundsson, K., et al. (1986). Nesjavellir. Geological and geophysical surveys in 1985. Orkustofnun report. Icelandic, OS-86014JHD-02, 125.

Benediktsdóttir, Á., Árnason, K.,]Karlsdóttir, R., Vilhjálmsson, A. M., and Kristjánsson, B. R. (2021). Detailed resistivity models of sub-areas of the Hengill geothermal field, Iceland. Proc. World Geotherm. Congr. 2020+.

Biru, M. F. (2020). Well testing and power plant scenario analysis for hverahlid geothermal field, master's thesis, faculty of industrial engineering, mechanical engineering and computer science. University of Iceland. http://hdl.handle.net/1946/35842.

Björnsson, A., Hersir, G. P., and Björnsson, G. (1986). The Hengill high temperature area, SW-Iceland: Regional geophysical survey. Trans. Geotherm. Counc. 10, 205

Björnsson, A., and Hersir, G. P. (1981). Geophysical reconnaissance study of the Hengill high temperature qeothermal area, SW-Iceland. Geotherm. Res. Counc.Trans. 5, 55

Blondel, T., Chaput, J., Derode, A., Campillo, M., & Aubry, A. (2018). Matrix approach of seismic imaging: Application to the Erebus volcano, Antarctica. *Journal of Geophysical Research: Solid Earth*, *123*(12).

Budzinska, K. (2014). Man made deformation in the Hengill area between 2009-2013, M.Sc. thesis. Faculty of Earth Sciences, University of Iceland. Available at: https://skemman.is/bitstream/1946/19904/1/thesis1.pdf.

Clifton, A. E., Sigmundsson, F., Feigl, K. L., Guðmundsson, G., and Árnadóttir, T. (2002). Surface effects of faulting and deformation resulting from magma accumulation at the Hengill triple junction, SW Iceland, 1994–1998. J. Volcanol. Geotherm. Res. 115 (1-2), 233366–234255. doi:10.1016/s0377-0273(01)00319-5

Ducrocq, C., Geirsson, H., Árnadóttir, T., Juncu, D., Drouin, V., Gunnarsson, G., et al. (2021). Inflation-deflation episodes in the Hengill and hromundartindur volcanic complexes, SW Iceland. Front. Earth Sci. (Lausanne). 915, 725109. doi:10.3389/feart.2021.725109
Foulger, G. R. (1984). Seismological studies at the Hengill geothermal area SW Iceland. Durham theses, Durham University.
Foulger, G. R., and Toomey, D. R. (1989). Structure and evolution of the hengill-grensdalur volcanic complex, Iceland: Geology, geophysics, and seismic tomography. J. Geophys. Res. 94 (B12), 17511–17522. doi:10.1029/jb094ib12p17511
Foulger, G., Miller, A., Julian, B. R., and Evans, J. R. (1995). Three-dimensional vp and vp/vs structure of the Hengill triple junction and geothermal area, Iceland, and the repeatability of tomographic inversion. Geophys. Res. Lett. 22 (10), 1309–1312. doi:10.1029/94gl03387
Grigoli F, Clinton JF, Diehl T, Kaestli P, Scarabello L, Agustsdottir T, Kristjansdottir S, Magnusson R, Bean CJ, Broccardo M, Cesca S, Dahm T, Hjorleifsdottir V, Cabrera BM, Milkereit C, Nooshiri N, Obermann A, Racine R, Rinaldi AP, Ritz V, Sanchez-Pastor P, Wiemer S. (2022) *Monitoring microseismicity of the Hengill Geothermal Field in Iceland.* Sci Data, 19;9(1).
Hersir, G. P., Björnsson, G., and Björnsson, A. (1990). Eldstöðvar og jarðhiti á Hengilssvæði. Jarðeðlisfræðileg könnun 13095 Orkustofnun OS-90031/JHD-06 93. (in Icelandic)**.**
Hillers, G., Roux, P., Campillo, M., & Ben-Zion, Y. (2016). Focal spot imaging based on zero lag cross-correlation amplitude fields: Application to dense array data at the San Jacinto fault zone. *Journal of Geophysical Research: Solid Earth*, *121*(11), 8048-8067.
Jousset, P., Haberland, C., Bauer, K., and Árnason, K. (2011). Hengill geothermal volcanic complex (Iceland) characterized by integrated geophysical observations. Geothermics 40, 1–24. doi:10.1016/j.geothermics.2010.12.008
Juncu, D., Árnadóttir, T., Hooper, A., and Gunnarsson, G. (2017). Anthropogenic and natural ground deformation in the Hengill geothermal area, Iceland. J. Geophys. Res. Solid Earth 122 (1), 692–709. doi:10.1002/2016jb013626
O' Brien G, Bean C.J., Meiland H. & Witte P. Imaging and seismic modelling inside volcanoes using Machine Learning, Scientific Reports 13 (1) 630, 2023
Seydoux, L., Balestriero, R., Poli, P., De Hoop, M., Campillo, M., & Baraniuk, R. (2020). Clustering earthquake signals and background noises in continuous seismic data with unsupervised deep learning. *Nat. Communications*, 11(1), 1-12.
Sánchez-Pastor, P., Obermann, A., Reinsch, T., Ágústsdóttir, T., Hjörleifsdóttir, V., Wiemer, S. (2021) *Imaging high-temperature geothermal reservoirs with ambient seismic noise tomography, a case study of the Hengill geothermal field, SW Iceland*, Geothermics, 96.
Sæmundsson, K., and Saemundsson, K. (1992). Geology of the thingvallavatn area. OIKOS (a J. Nord. Ecol. Soc.) 64, 40–68. doi:10.2307/3545042
Sæmundsson, K., Sigurgeirsson, M. A., Hjartarson, A., Kaldal, I., and Kristinsson,S. G. (2016). Reykjavík: Iceland GeoSurvey. 2nd ed., 1. Geological Map of of Southweast Iceland, 100
Shi, P., Grigoli, F., Lanza, F., Beroza, G. C., Scarabello, L., & Wiemer, S. (2022). MALMI: An automated earthquake detection and location workflow based on machine learning and waveform migration. *Seismological Society of America*, *93*(5), 2467-2483.
Tryggvason, A., Rögnvaldsson, S. T., and Flóvenz, O. G. (2002). Three-dimensional imaging of the P and S-wave velocity structure and earthquake locations beneath Southwest Iceland. Geophys. J. Int. 151 (3), 848–866. doi:10.1046/j.1365-246x.2002.01812.x
Wagner, F. (2019). Toward fully automatic earthquake detection and processing for tomography in the Hengill area, doctoral dissertation. Acta Universitatis Upsaliensis.