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Interim report dated 14 February 2024

DemoUpStorage

Demonstration and Upscaling of Carbon Dioxide storage for a net zero Switzerland

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DEMO UP STORAGE

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Eidgenössische Technische Hochschule Zürich
Rämistrasse 101, 8092 Zurich, Switzerland
www.ETHZ.ch

Ecole Polytechnique Fédérale de Lausanne
BatimentCE 3316 Station 1, 1015 Lausanne, Switzerland
www.epfl.ch

University of Geneva
24 rue du General-Dufour 1211, Geneve, Switzerland
www.unige.ch

Eidgenossische Anstalt für Wasserversorgung, Abwasserreinigung und Gewasserschutz
Uberlandstrasse 133, 8600 Dubendorf, Switzerland
www.eawag.ch

Authors:
Alba Zappone, ETHZ, alba.zappone@SED.ethz.ch
Stefan Wiemer ETHZ, stefan wiemer@SED.ethz.ch
Lyesse Laloui, EPFL, lyesse.laloui@epfl.ch
Andrea Moscariello, University of Geneva, andrea.moscariello@unige.ch
Rolf Kipfer, EAWAG, rolf.kipfer@eawag.ch
Anne Obermann, ETHZ, anne.obermann@sed.ethz.ch
Jonas Junker, ETHZ, jonas.junker@sed.ethz.ch
Stefanie Zeller, ETHZ, stefanie.zeller@sed.ethz.ch
Irina Dallo, ETHZ, irina.dallo@sed.ethz.ch
Eleni Stavropoulou, EPFL, eleni.stavropoulou@epfl.ch
Chuan Wang, EAWAG, chuan.wang@eawag.ch
Ovie Eruteya University of Geneva,Ovie.Eruteya@unige.ch
Pascal Graf, ETHZ, Pascal.Graf@sed.ethz.ch
Urs Fassler, ETHZ, Urs.Fassler@sed.ethz.ch

SFOE project coordinators:
Men Wirz, Men.Wirz@bfe.admin.ch
Florence Bégué, Florence.Begue@bfe.admin.ch

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The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.

Zusammenfassung

Das primäre Ziel des Forschungsprojekts DemoUpStorage "Lösungen zur Speicherung von Kohlendioxid für eine Netto-Null-Schweiz" ist die Demonstration der sicheren Speicherung von CO2 in isländischem Basalt mit Hilfe modernsten kombiniertem geophysikalischem und hydrochemischem Monitoring an der CARBFIX-Injektionsstelle in Helguvik, Island.

Die Schweizer Roadmap für die geologische CO2-Speicherung wird auch durch das Sammeln und den Austausch von Wissen vorangetrieben. Im Rahmen von DemoUpStorage, einem P&D Projekt, welches parallel zu DemoUpCARMA läuft, werden bis zu 1000 Kilotonnen Schweizer CO2 nach Island transportiert, wo das Unternehmen Carbfix das Gas in basaltischen Formationen nahe der Nordküste der Halbinsel Reykjanes dauerhaft speichern wird. Mittels geophysikalischer und hydrochemischer Methoden wird die Migration und Mineralisierung des CO2 im Laufe der Zeit überwacht.

Aufgrund starker Verzögerungen bei der Vorbereitung der Injektionsstelle in Helguvik geriet die In-situ-Überwachung generell ins Stocken, aber die Labor- und Modellierungsarbeiten wurden wie geplant fortgesetzt. Die Ergebnisse eines Laborversuchs zeigen, dass sich die Kohlenstoffmineralisierung auf die Durchflusseigenschaften des Basalts auswirkt, vor allem durch die Reduzierung der Mikroporosität. Die erfolgreiche Umsetzung der Technologie in grossem Massstab erfordert eine Injektion an Stellen mit hoher Porosität, idealerweise in geklüfteten Zonen, wo der Durchfluss gewährleistet werden kann, und die Mineralisierung nicht zur Verstopfung der Poren führt.

Kommunikations- und Outreach-Aktivitäten sind ebenfalls ein wichtiger Teil des Projekts und werden in enger Zusammenarbeit mit dem Parallelprojekt DemoUpCARMA durchgeführt. Die Schweizer Öffentlichkeit ist nachweislich nicht gut über Kohlenstoffspeicherung und Mineralisierungsprozesse informiert, zeigt sich offen und neugierig gegenüber dieser Technologien. Wichtig für die Bevölkerung in der Schweiz ist auch, dass die CO2-Speicherung in Island von der dortigen Bevölkerung akzeptiert wird. Im Allgemeinen sieht die Schweizer Öffentlichkeit verschiedene Vorteile, aber auchRisiken im Zusammenhang mit diesem Prozess (z.B., die Möglichkeit, die schwer abbaubaren Emissionen zu neutralisieren, CO2-Leckagen und Umweltverschmutzung)

Résumé

L'objectif principal du projet de recherche DemoUpstorage, "Demonstration und Upscaling von Lösungen zur Speicherung von Kohlendioxid für eine Netto-Null-Schweiz" est de démontrer le stockage sécurisé du CO2 dans le basalte islandais en utilisant des techniques de pointes combinant la surveillance géophysique et hydrochimique sur le site d'injection CARBFIX à Helguvik, en Islande. La stratégie suisse pour le stockage géologique du CO2 progressera également grâce à la collecte et à l'échange d'informations et au développement des capacités. A l'aide du projet parallèle DemoUpCARMA, DemoUpStorage transporte jusqu'à 1000 kilotonnes de CO2 suisse vers l'Islande, où Carbfix stockera le gaz de manière permanente dans des formations basaltiques près de la côte nord de la péninsule de Reykjanes.

Des méthodes géophysiques et hydrochimiques sont utilisées pour surveiller la migration et la minéralisation du CO2 au cours du temps. Les variations de la vitesse sismique, la résistivité électrique et les gaz dissous sont surveillés avant, pendant et après l'injection de CO2 afin de détecter la migration et la minéralisation des carbonates. En parallèle, des échantillons de roche représentant la zone d'injection à Helguvik sont exposés à de l'eau enrichie en CO2 en laboratoire. On y observe les variations micro-texturales, mécaniques, minéralogiques et chimiques ainsi que les variations de la vitesse sismique à l'échelle du centimètre. Des modèles numériques, à la fois prédictifs et de validation, sont utilisés pour permettre une interprétation des observations in situ et en laboratoire.

D'importants retards dans la préparation du site d'injection à Helguvik ont entraîné une interruption de la surveillance in situ, mais les expériences en laboratoire et la modélisation se sont déroulées comme prévu. Les résultats de l'étude à l'échelle du laboratoire montrent que la minéralisation du CO2 a un impact sur les propriétés d'écoulement du basalte, principalement par la réduction de la micro-porosité. La mise en œuvre réussie de la technologie à grande échelle nécessite une injection dans des endroits à forte porosité, idéalement dans des zones fracturées où l'écoulement est assuré et où la minéralisation n'entraînera pas le blocage des pores.

Les activités de communication et de sensibilisation constituent une partie importante du projet et sont menées en étroite collaboration avec le projet parallèle DemoUpCARMA.

Il s’est avéré que le public suisse est mal informé sur les processus de stockage et de minéralisation du CO2, mais souhaite en savoir plus. Il a également été démontré que l'acceptation par la population islandaise du stockage du CO2 dans son pays est un élément clé. En général, le public suisse perçoit divers avantages et risques liés à ce processus (neutralisation des émissions difficiles à éliminer, fuites de CO2 et pollution de l'environnement

Summary

The primary goal of the research project DemoUpstorage, “Demonstration und Upscaling von Lösungen zur Speicherung von Kohlendioxid für eine Netto-Null-Schweiz” is to demonstrate the secure storage of CO2 in Icelandic basalt using cutting-edge combined geophysical and hydrochemical monitoring techniques at the CARBFIX injection site in Helguvik, Iceland. The Swiss Roadmap for geological CO2 storage will also advance through the gathering and sharing of knowledge and the development of capacity. Utilizing the DemoUpCARMA parallel P&D project, DemoUpStorage transports up to 1000 kilotons of Swiss CO2 to Iceland, where the company Carbfix will permanently store the gas in basaltic formations close to the Reykjanes peninsula's northern coast. Geophysical and hydrochemical methods will be used to monitor CO2 migration and mineralisation over time. Before, electrical resistivity, dissolved gas levels, and seismic velocity variation are all monitored.

Time-lapse CO2 migration monitoring is performed by combining geophysical and hydrochemical techniques. Seismic velocity variation, electrical resistivity and dissolved gasses are monitored before, during and after CO2 injection to detect migration and mineralisation of the carbonates. In parallel rock samples representative of the injection zone in Helguvik are exposed to CO2-enriched water at the laboratory scale, and the micro-textural, mechanical, and mineralogical-chemical variations are observed, together with seismic velocity variations on cm-scale samples. Numerical modeling both as predictive and as validation tools are performed to offer key interpretation of the in-situ and lab observations.

Large delays in the preparation of the injection site at Helguvik caused a general stall in the in situ-monitoring, but laboratory and modeling activities proceeded as planned. The results of the lab-scale study show that carbon mineralization impacts the flow properties of the basalt, mainly by reduction of the micro-porosity. Successful implementation of the technology at large scales requires an injection in locations of high porosity, ideally in fractured zones where the flow can be ensured and mineralization will not result in pore clogging.

Communication and outreach activities are also an important part of the project and are conducted in close collaboration with the parallel project DemoUpCARMA. The Swiss public has been found not well informed about carbon storage and mineralization processes, but is willing to know more. It was also evidenced that the acceptance of the Icelandic population on CO2 storage in their country is a key element. In general, the Swiss public perceives various benefits and risks related to this process (e.g., able to neutralize the hard-to-abate emissions, CO2 leakage, and environmental pollution).

Contents

Abbreviations

CC	Carbon Capture
CCS	Carbon Capture and Storage
CCTS	Carbon Capture, Transportation, and Storage
CCUS	Carbon Capture, Utilization, and Storage
CDR	Carbon Dioxide Removal
CO2	Carbon dioxide
DACCS	Direct Air Carbon Capture and Storage
DAS	Distributed Acoustic Sensing
DemoUpCARMA	Demonstration and Upscaling of CARbon dioxide MAnagement solutions for a net-zero Switzerland
DemoUpStorage	Demonstration and Upscaling of carbon dioxide Storage solutions for a net-zero Switzerland
FO	Fiber optics
FOEN	Federal Office for the Environment
GHG	Greenhouse gas emissions
IPCC	Intergovernmental Panel on Climate Change
NET	Negative Emission Technologies
SED	Swiss Seismological Service
Q&A	Questions and answers
SFOE	Swiss Federal Office of Energy
TdLab	Transdisciplinarity Lab at ETH Zurich
VSP	Vertical Seismic Profiling
XRCT	X-Ray Computed Tomography

1 Introduction

1.1 Background information and current situation

Rapid decarbonization is necessary to achieve "net zero emissions" and reduce global warming to 2°C above pre-industrial levels (IPCC, 2022). The removal of CO2 from the atmosphere is necessary because society will not be able to completely eradicate carbon emissions, i.e. from hard-to-abate industries like steel, cement, petrochemicals and fertilizers production, that are responsible for around 22 percent of global CO2 emissions (Bataille, 2019). Negative Emission Technologies (NETs) and Carbon Capture, Transportation, Utilization, and Storage (CCTS/CCUS) must therefore be promoted in order to meet the climate targets by 2050 and keep global warming to 2°C (IPCC, 2022).

A bottle neck in the CCUS chain is still in the storage capacity: as a result of expanding plans to outfit facilities with CO2 capture, a discrepancy between the demand for CO2 storage space and the rate of development of storage facilities is emerging. The availability of CO2 storage could thus constitute an impediment to CCUS deployment (IEA, 2023). As a response, a growing number of diverse unconventional storage technologies are being tested around the world. The development of CO2 mineral storage, which uses highly reactive mafic rocks to sequester CO2, is accelerating. In the United Arab Emirates, the 44.01 company announced the launch a commercial scale pilot project. In Iceland CARBFIX is proposing large scale injections of seawater enriched in CO2 into basaltic formations and is moving from pilot to commercial scale.

To achieve the net zero aim by 2050, the Swiss Energy Strategy foresees CO2 capture and subterranean storage (CCS), also potentially considering possibilities of storage abroad. The partner project of DemoUpStorage, DemoUpCARMA (https://www.aramis.admin.ch/Texte/?ProjectID=49400) investigates the transportation and storage of Swiss biogenic CO2 in Icelandic basalt as well as the possibilities for scaling up this pathway. DemoUpCARMA will transport kilo- tons of Swiss biogenic CO2 to Iceland, where the company Carbfix will use a new injection technique (using seawater instead of fresh water) to permanently store CO2 at a site selected because of its potential for up-scaling. This represents a key step towards a CO2 storage hub in Icelandic basalts made available also for Swiss emitters.

Because secure and long-term storage of the CO2 is an essential prerequisite, DemoUpStorage takes the lead in closely monitoring the injection and the fate of the CO2 in the Icelandic underground. DemoUpStorage wants to demonstrate the safe storage of CO2 in Icelandic basalt with novel, dense and combined geophysical and geochemical monitoring techniques. The results of DemoUpStorage will advance the Swiss Roadmap for geological CO2 storage through capacity building and knowledge sharing.

1.2 Purpose of the project

Main purpose of the project is demonstrating and benchmarking monitoring strategies to track the mineralization happening in basalts. DemoUpStorage concentrates on monitoring the storage operations to ensure the reservoir integrity, the effectiveness of activities, and the respect of safety conditions. Because secure and long-term storage of the CO2 is an essential prerequisite for the success of the project, DemoUpStorage takes the lead in closely observe the fate of the Swiss CO2 in the Icelandic underground. DemoUpStorage wants to demonstrate the safe storage of CO2 in Icelandic basalt with novel, dense and combined geophysical and geochemical monitoring techniques.

For a decade, Iceland has been injecting CO2 dissolved underground. Correlated mineralization processes have been widely researched in labs and observed in natural analogues. However, the mineralization has never been continuously tracked in situ using geophysical and geochemical techniques. Through our field experiments at the Helguvik site, we investigate whether it is possible to picture the fluid migration in the storage reservoir and whether this migration is accompanied by micro-seismicity.

Monitoring of the CO2 plume in the underground is often realized with time-lapse seismic methods. These methods typically include 3D or 2D surface seismic, 2D multi-azimuth walk-away borehole vertical seismic profiles, cross-hole seismic. More and more distributed acoustic sensing (DAS) fiberoptic (e.g. Jenkins et al.,2015) are used in parallel to hydrophones, geophones or acoustic receivers. Seismic techniques are used both in active and passive mode, i.e. recording waves from natural earthquakes or artificial sources (sparkers in boreholes, etc.). Also Electrical Resistivity Tomography (ERT) is a useful geophysical tool, often used to complement seismic techniques to estimate the CO2 mobility because of the ERT high sensitivity to the composition of pore-fluids. Due to the increase of conductivity of CO2-enriched fluids, as comparison with the formation fluids, the method is extremely valuable for CO2 injection and storage monitoring.

In DemoUpStorage we combine surface-based geophysical approaches with borehole-based monitoring techniques to observe the mineralization process from close distance. We use active and passive seismic measurement techniques, and geoelectric resistivity measurements both in borehole-based and in surface to borehole-based arrays. The final goal is to establish from geophysical measurements that mineralization has taken place, and hence that CO2 is permanently stored. In parallel, we use fibre optics, and we evaluate the performance of different fibers/interrogators.

The main challenge of these methods source the amount of the main challenge for all these methods lies in the amount of mineralised ore that will be deposited in the pores of the reservoir. If the mineralization is limited to a few percentage units or distributed in highly inhomogeneous manner, it will be difficult to translate it into a change in seismic velocity or electrical resistivity. It will be necessary to collect a solid baseline in order to subtract effects such as tides, or seismic noise that could mask the small change in properties to be attributed to carbonate precipitation.

One of the primary concerns in storing CO2 is that it may rise from the injection depths to surface aquifers, polluting them, or even reaching the atmosphere. This is typically monitored by sampling from injection and monitoring wells. This straight forward-technique has the drawback that the monitoring points are generally small in number and may lead to a very incomplete network geometry. Although the possibility of upraise of gaseous CO2 is remote given the method used in Iceland, which involves mixing only small percentages of CO2 below the threshold of water saturation, one of the purposes of DemoUpStorage is to screen any rising to the surface. we monitor shallow CO2 migration through an innovative technique that measures dissolved gases in low-depth aquifers using a portable mass spectrometer connected to a shallow borehole. The mass spectrometer will detect the presence of CO2 in shallow aquifers, i.e. covering an area with wide lateral extension. It can be considered a sort of “early warning” system to rule out the possibility of leakage in the vicinity of the injection well. Moreover, the mass spectrometer connected to a deep borehole at large distance from the injection point will provide a precious dataset to understand the hydrodynamic of the deep reservoir, and complement the geochemical observations that the Icelandic colleagues will perform by point sampling the water at depth. Often tracers, such as natural isotopes (12C, 13C and 18O) or artificial additives (noble gasses, compounds based on carbon contents, or salts) are mixed to CO2, and are used to detect the mobility of CO2 both in the reservoir and in the atmosphere. Since CO2 storage mechanisms vary depending on the reservoir (e.g. depleted oil and gas fields, saline aquifers in clastic or carbonate reservoirs), it is necessary to carefully consider the different breakdown/absorption properties. In general, tracer detection methodologies in CCS applications are still in their early development stages (Zang et al., 2021). We will use He as tracer and will mix it to CO2, following the experiences we have done in similar, but at smaller scale, experiments (Weber at al., 2023).

The portable mass spectrometer developed by EAWAG will monitor continuously dissolved CO2 (and He as tracer) in the storage aquifer and right on top of it. So far, measurements of CO2 flux from injections have been periodic, while continuous measurements allow for a thorough assessment of the dynamic of the aquifer and of possible leakage.

An important component of DemoUpStorage is the support of laboratory analysis, which is crucial for improving the understanding of the mineralisation process and for the interpretation of field observations. Using the lab resources at EPFL, we test the effects of the water-dissolved CO2 on the basalt's micro- and meso-structure and on its hydromechanical characteristics. By exposing basalt samples to CO2-enriched water under conditions that resemble the in situ underground, we improved the understanding of the mineralization process and have a close look at the effects of mineralization on rock physical properties. By testing the main parameters in the lab, e.g. by measuring seismic wave propagation in mineralized basalt samples we have a key interpretation of the seismic signature we detect at the Helguvik site. Rigorous lab-testing under controlled boundary conditions (stress, flow rates, chemical composition, temperature etc.) is therefore indispensable for the interpretation of large-scale results but also for model calibration. One of the main limitations in lab testing is to define the representativeness of samples, characteristically a few cm in size, to represent the conditions of the entire aquifer, at the scale of hundreds of meters or kilometers. The situation is even more complicate when key parameters (such as permeability and porosity), are extremely heterogeneous, as in the Helguvik environment. Borehole logs of surrounding wells, and detailed analysis of the Helguvik borehole cuttings will be used to overcome this limitation, and build up numerical models of the underground.

Together with experimental tests, we carry out numerical simulations on mineralization, seismic imaging, and hydromechanical changes at EPFL in collaboration with the University of Iceland. Reservoir modeling, risk and safety analysis, and upscaling issues are all driven by numerical simulations.

Another objective of DemoUpStorage is the knowledge transfer io the Swiss contest. The validation and establishment of safety procedures, together with tracing the fate of the CO2 up to permanent mineralization is crucial for onshore storage, both in 'pristine' (and popular tourist destination) Iceland, but also in populated areas where there is no option for off-shore storage, like Switzerland. The attitude of the Icelandic media towards on-shore CO2 storage via mineralization is also explored and will be compared with the Swiss context.

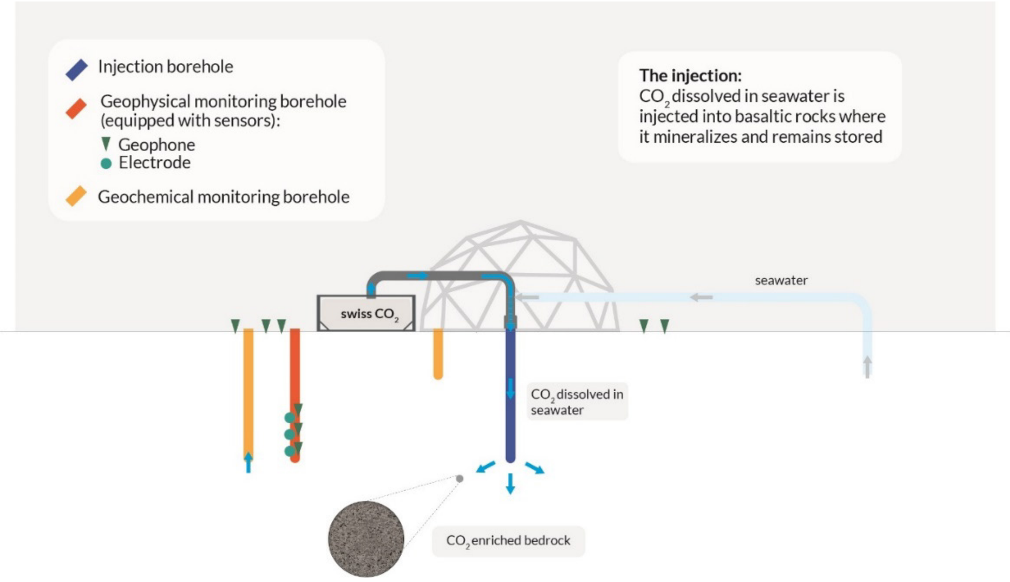


***Figure 1**: DemoUpStorage Main Graphic*

1.3 Objectives

The main goals of DemoUpStorage are:

- to objectively assess if injecting CO2 dissolved in seawater into basalts on the coast of Iceland represents a secure, long-term, and environmentally friendly pathway for CO2 sequestration. DemoUpStorage will further assess, in collaboration with DemoUpCARMA, if this strategy has the potential to be scaled up in future, and would enable the storage of tens of kilotons/year of Swiss CO2 in basalts, starting already in 2024.
- To advance and benchmark borehole- and surface-based monitoring techniques and computational modeling tools to reliably track and forecast the migration of CO2 in different geological settings, including those relevant for future CO2 injection tests in Switzerland.
- To establish and validate safety procedures. While improbable based on prior research, accidents like leakage, freshwater contamination, or induced seismicity have the potential to damage the reputation of CCTS technologies and erode public acceptability on a worldwide scale. It is insufficient to leave safety and accident issues to injection site operators alone, because the Nations and companies that distribute the CO2 are also perceived by the public as being accountable, and so suffer a severe reputational risk.
- To build up within Switzerland an interdisciplinary competence in monitoring and modeling CO2-injection with the ultimate goal of being ready for future projects in Switzerland.

2 Description of facility

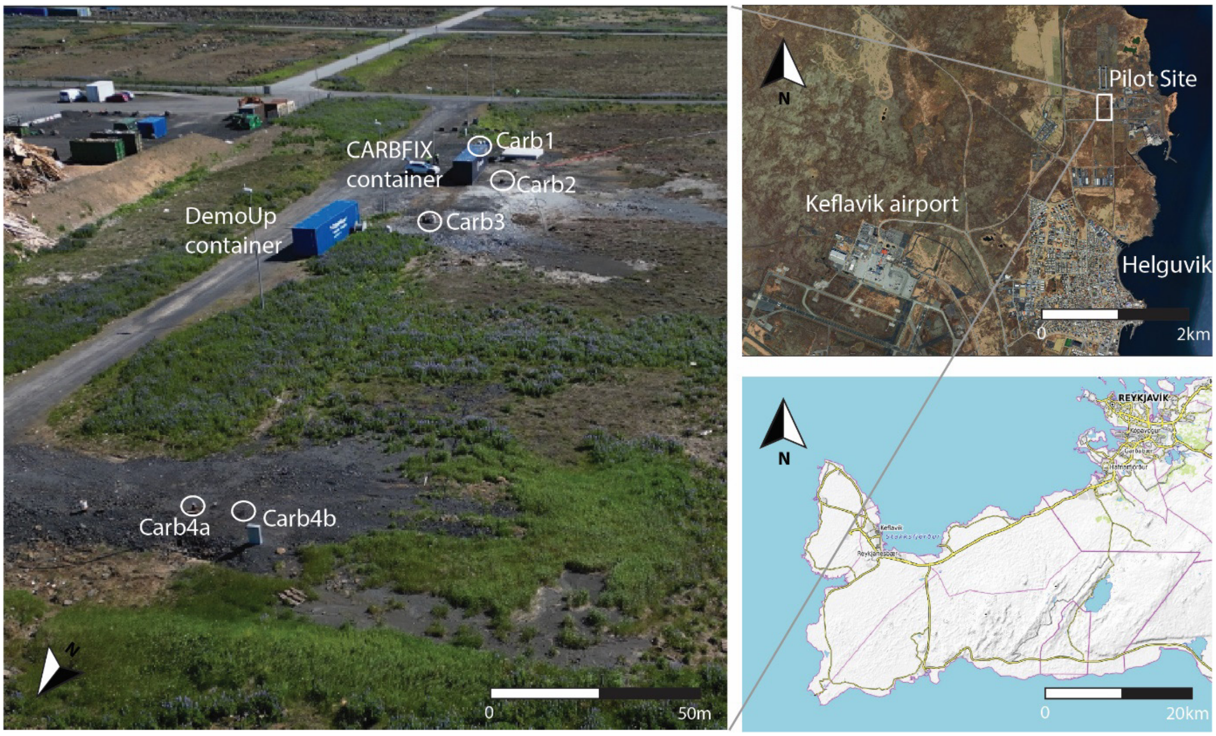


Figure 2: *Location of the experimental site.*

Considerations on accessibility to developed infrastructures (e.g. electricity), and on scale-up potential lead to the selection of an industrial site in Helguvik as pilot site of DemoUpStorage (figure2).

The site is on the north side of the Reykjanes Peninsula, a few km from the Keflavik International Airport and at less than 1 km from an industrial harbor. The area is easily accessible by a paved road a few kilometers from the center of the village of Helguvik and is surrounded by a large shed of an abandoned steel factory to the north and an active inert waste landfill to the east. The area is pretty flat and shows outcrops of lava partially covered by debris or moss.

Three wells, c.a. 420 m deep, have been drilled along a NNW-SSE alignment c.a.100 m long, for injection (CARB1) and monitoring (Carb3: geophysical, Carb4: geochemical) purposes. A 37 m deep well (CARB2) has been placed slightly towards W, with the purpose to offer independent access to the shallowest aquifer. The drilling operations were conducted by CARBFIX from August 2022 to June 2023. Logging (televiewer, caliper, Optical Borehole Imager, Acoustic Borehole Imager, Resistivity, Neutron and gamma ray) was conducted by ISOR upon request of CARBFIX in CARB1 and CARB4 (data available upon request at CARBFIX). Drill cuttings were collected every 2 m along the total depth for CARB1 and CARB4. The only available stratigraphy is for CARB4, and indicates that the whole underground is composed of basaltic rock types, dominantly with olivine-tholeiite composition and some minor picrite. Below 300 m tholeiite may be present. Lava flows are dominant, and no hyaloclastite is found. Low-temperature alteration is minor and no calcite was identified.

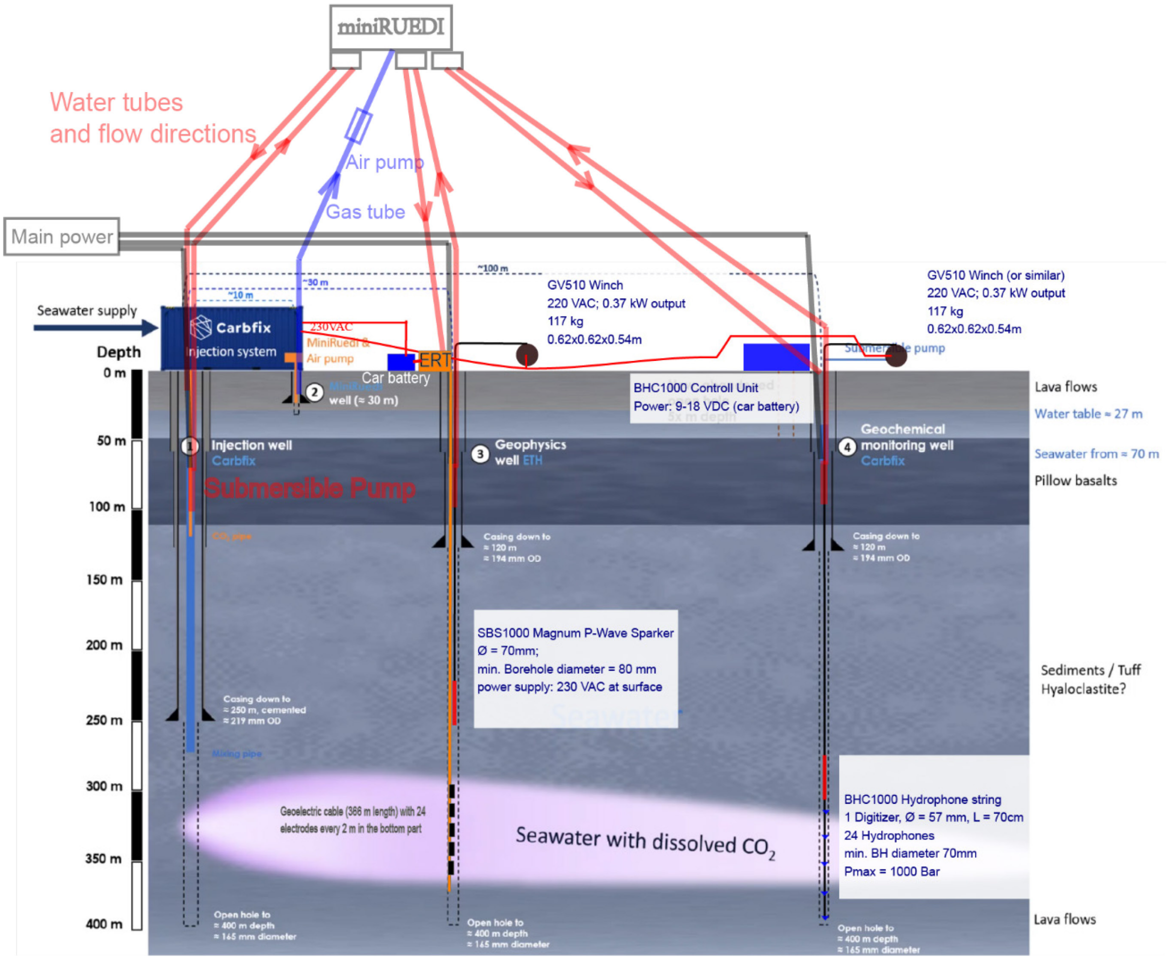


***Figure 3:** Schematic experimental setup at the Helguvik site.*

A container (Figure 4) has been positioned between CARB1 and CARB3, to host the injection system designed by Carbfix. Together with the injection pumps and a mixing device to enrich the injected water with tracers. The container is also hosting the mass spectrometer (miniRUEDI, Brennnwald et al., 2016) to detect in continuous the dissolved gasses in the underground water. Together with the conservative tracers (salts) selected by CARBFIX, we will enrich the injected water with Helium. The board connecting the He bottles to the CARBFIX mixing system has been designed and realized by Solexpert AG and is shown in Figure 5.

Figure 4: *CARBFIX Container*

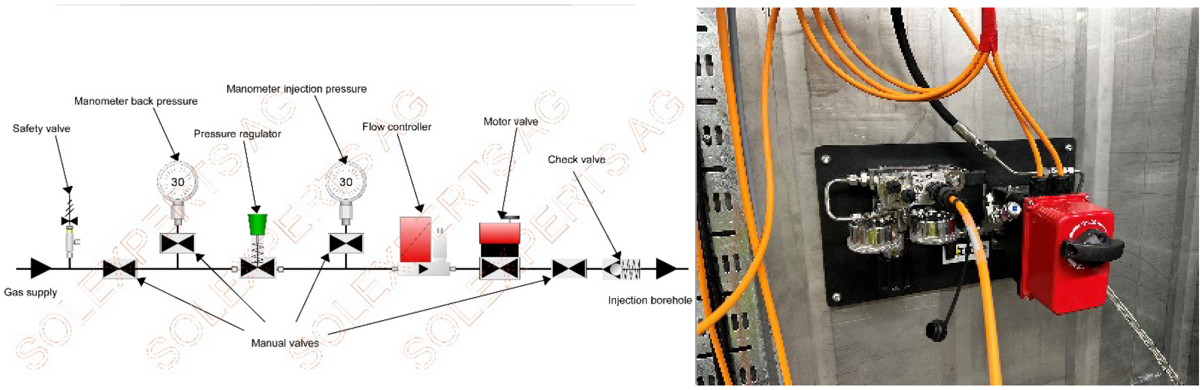


Figure 5: *Helium board layout. The board is mounted in the Carbfix container and connected with the CO2 mixing unit*

An integral part of the DemoUpStorage project is being developed ex-situ in the laboratories in EPFL Lausanne and University of Geneva. The EPFL lab deals with testing hydromechanical properties on basalts before and after exposures to CO2-enriched fluid, accompanied by 3D x-ray computed tomography (XRCT) to detect the impact of eventual mineralisationon the pore space of the material The contribution of the university of Geneva lab is the characterization of the mineralogical composition of the basalt with the aid of a scanning electron microscopy facility (QEMSCAN QUANTA 650F).

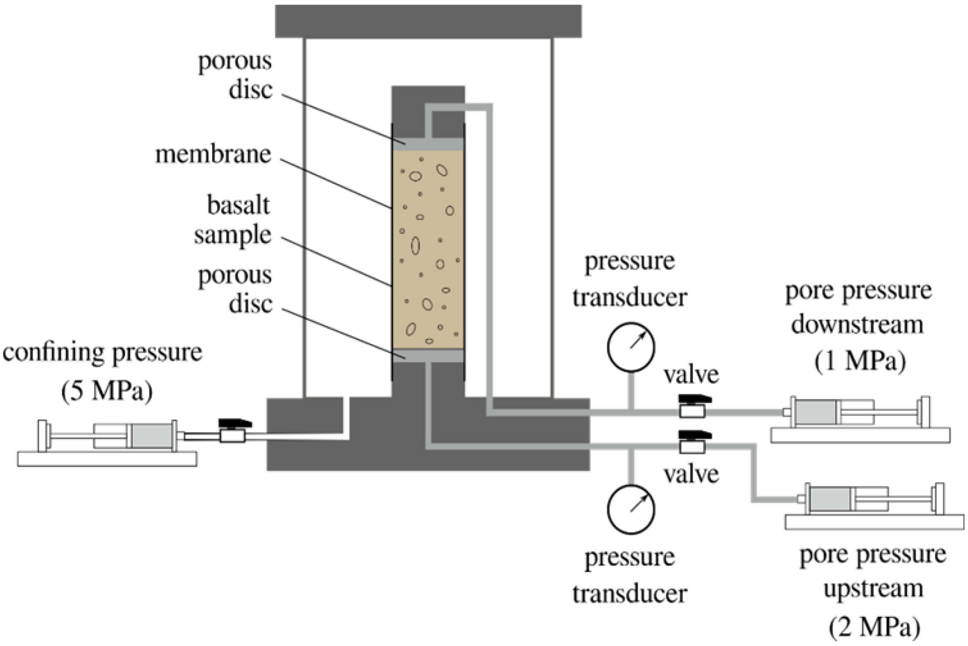


Figure 6: *Experimental setup at the Laboratory for Soil Mechanics (LMS) for flow characterisation; CO2-rich seawater permeability is measured by applying a 1 MPa pressure difference between up- and down-stream sides of the sample. Details in 4.4.1.*

3 Procedures and methodology

The approach used in DemoUpStorage to reach its objectives has four main components:

1. Combined geophysical and geochemical techniques for in situ detection of the path of CO2 in the underground water and above the reservoir.
2. Laboratory testing of the effect of mineralization on the microstructure and on the hydromechanical properties of the basalts.
3. Numerical simulations of in situ and in lab tests both in scoping and in validation mode.
4. Open, transparent and continuous communication of storage-related safety and environmental issues.

The project is organized into 5 working groups, closely inter-correlated, and working together to reach the above-mentioned objectives:

WP1: Project management; Leader: ETH-SED (Dr. Alba Zappone); Participants: All partners. This WP is responsible for providing an organizational framework, for financial and administrative management, for implementing measures to timely achieve the objectives, for contributing to the dissemination of results, for quality control, and reporting on deliverables.

WP2: Time-lapse CO2 migration monitoring; Leader: ETH-SED (Dr. Anne Obermann); Participants: University of Geneva (UniGe) (Dr. Ovie Eruteya, Prof. Dr. Andrea Moscariello), EAWAG (Prof. Dr. Rolf Kipfer, Dr. Matthias Brennwald, Chuan Wang), ETH-SED (Jonas Junker, Katinka Tuinstra). The WP assesses the mobility of CO2 enriched water and the mineralization processes through changes in seismic velocity, electrical conductivity, and gas analyses of water around the injection. It provides a high-resolution imaging of the subsurface at the reservoir scale as input to the 3D reservoir model (WP3). Benchmarking and knowledge transfer of monitoring technologies to the Swiss context is also in the objectives of the WP.

WP3: Geophysical & Geological modeling at Reservoir Scale; Leader: UniGe (Dr. Ovie Eruteya, Prof. Dr. Andrea Moscariello); Participants: EPFL (Prof. Dr. Lyesse Laloui, Dr. Eleni Stavropoulou); ETH (Dr. Antonio Pio Rinaldi). Combining geophysical, geochemical, and geological data collected by WP2 the WP3 realizes and calibrates 3D static models. It also integrates petrophysical properties of reservoir rocks obtained from the laboratory activities carried out in WP4. Enabling numerical simulations of injection upscaling at the target site, or at other sites it provides knowledge transfer of modelling tools for Swiss conditions.

WP4: Laboratory characterization and validation of processes; Leader: EPFL (Prof. Dr. Lyesse Laloui, Dr. Eleni Stavropoulou); Participants: UniGe (Dr.Ovie Eruteya, Dr. Antoine de Haller, Prof. Dr. Andrea Moscariello), ETH (Dr. Claudio Madonna).The WP provides mineralogical, petrophysical and hydromechanical characterization of basalt reservoir rocks, evaluates their geomechanical and geochemical response of CO2-rich seawater injection, and quantify the time-dependent response of mineral trapping. Through measurements of wave propagation on the same rocks, it provides a key for interpretation of the seismic observations in WP2

WP5: Integration with other projects, upscaling, and application to Switzerland; Leader: ETH (Prof. Dr. Stefan Wiemer); Participants: All. The WP independently investigates societal acceptance of ‘foreign’ CO2 storage in Iceland, and provides feedback on storage-related aspects to DemoUpCARMA, thus allowing an assessment if Iceland can be suitable for larger Swiss CO2 storage. It also provides knowledge transfer on CO2 migration monitoring and risk assessment technologies to Swiss conditions and to Swiss pilot projects.

The structure of the project is illustrated in Figure 7

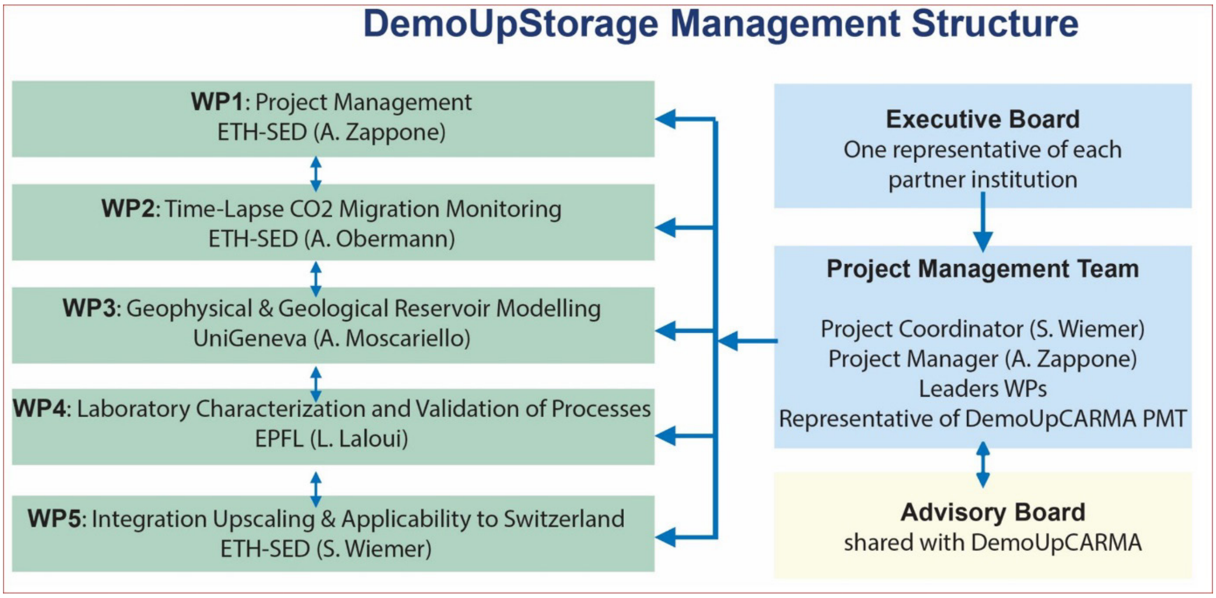


Figure 7: *Organization chart of the project.*

4 Activities and results

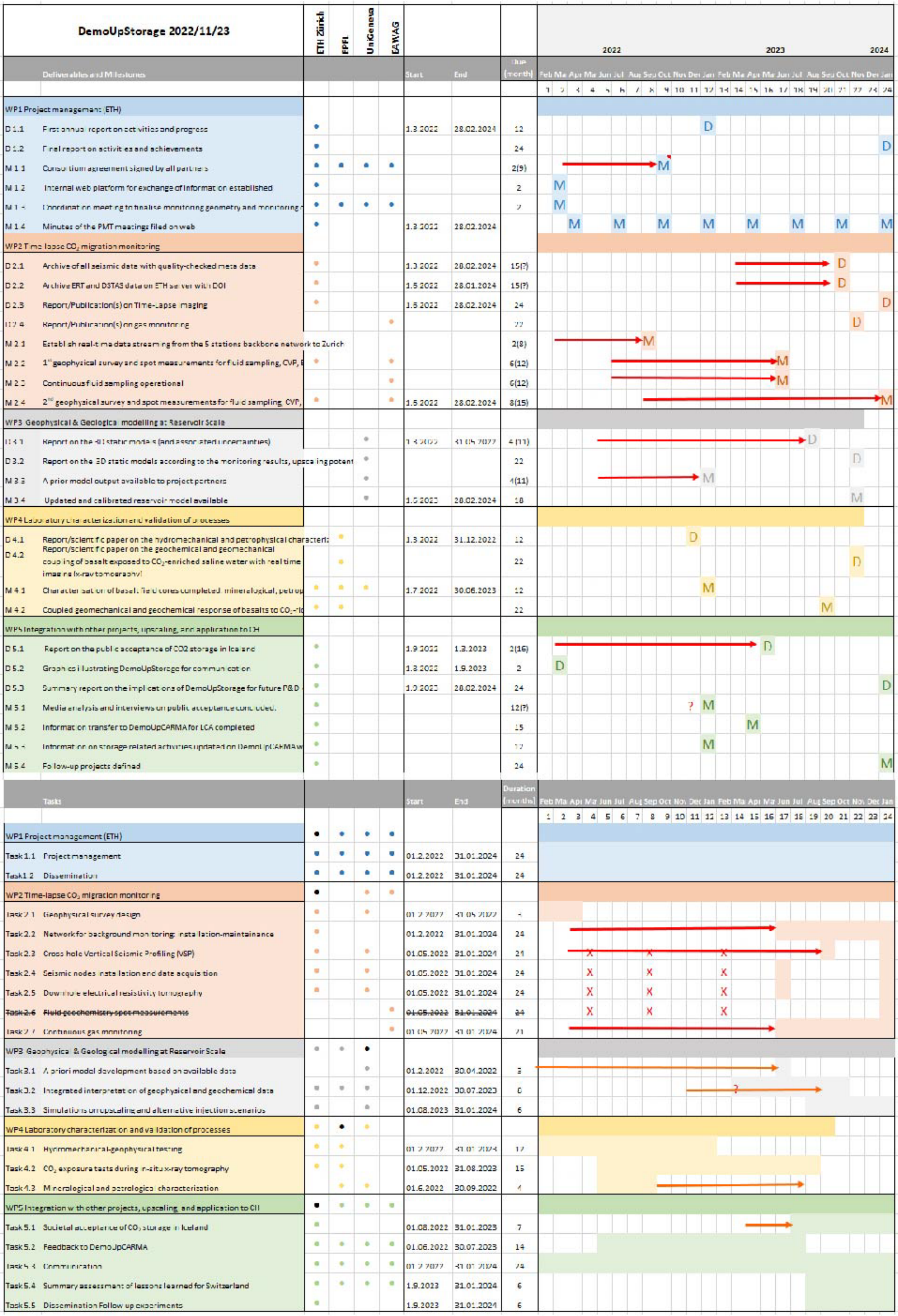
Due to substantial delays at the selected site in Iceland, both in the definition of the exact drilling site, in the acquisition of the permitting to access the area for drilling and for monitoring, and finally in the preparation and completion of the boreholes, most of our activities were postponed. The timeline of the major elements of DemoUpStorage is presented below.

1. Spring 2022: finalization of the Consortium Agreement following the EC DESCA example, preparation of a platform to share data, announcements and information. (https://demoupstorage.sp.ethz.ch/_layouts/15/start.aspx#/Lists/Contact%20list/AllItems.aspx
2. September 2022 (originally planned February 2022): Backbone Network: ETH/SED installed a backbone network of five seismic stations for micro-seismicity monitoring, that operate and transmit data independently year-round, using solar panels and wind generators.
3. March 2022-June 2023 (originally planned Feb - April 2022): Finalize drilling and monitoring design. The design of the monitoring and of the drilling has been extensively discussed with CARBFIX and the University of Iceland in a series of meetings in the spring/summer 2022. Unfortunately, the selected site did not have any pre-existing borehole that would allow to build a first computational reservoir model. Nevertheless, synthetic seismic modeling was performed on the basis of literature data and will be described in detail below.
4. March-April 2022: Arrival of basaltic cores from a site near Helguvik in EPFL and 3D micro-structural characterisation (porosity, micro-fissures) of their initial state (pre-exposure) with x-ray tomography (XRCT).
5. August 2022-May 2023: (originally planned March - June 2022): Site preparation. The drilling operation, under the responsibility of CARBFIX, started on August 29 with CARB4. This borehole was abandoned a few days later at a depth of 60 m, due to technical difficulties. The well CARB4b was started 5 m west from the previous one and it was decided to use CARB4 as a source for water to be injected. The drilling company completed the last borehole,

CARB3 in May 2023 just a few days before the arrival of the ETH team for the first cross-hole monitoring campaign.

6. May 2022 - July 2023: Start of laboratory experiments at EPFL. Preparation of basaltic samples for hydromechanical testing and CO2 exposure: minimum exposure duration of 1 month. From October 2022 longer exposure duration was chosen for the last 3 cores (2-3 months). The hydromechanical campaign was concluded in July 2023.
7. January 2023 - August 2023: Numerical simulation at EPFL of the flow properties and mineralisation of the cores (lab scale) with pore network modeling based on the acquired XRCT images before and after CO2 exposure.
8. June 2023 (originally planned June 2022): Installation of monitoring equipment in boreholes and at the surface, background measurements. Main monitoring components (mass spectrometer, fiber optics, seismic nodes, electrode chain, flow-board for injection of Helium) were purchased in Autumn-Winter 2022. Further components e.g. hydrophone chain and digital speaker, and the interrogator for FO were rented during the first monitoring campaign in June 2023. Active seismic measurements using sparker shots, the hydrophone chain and the surface nodal array have been conducted in June 2023 and will be completed in the last week of August 2023. The mass spectrometer has been connected to borehole CARB1 and CARB2 and is transmitting data in continuous mode.

Table 1: Deliverables and milestones



DemoUpStorage 2022/11/23		ETH Zürich	EPFL	UniGeneva	EAWAG				2022											2023												2024
	Deliverables and Milestones					Start	End	Due (month)	Feb	Ma	Apr	Ma	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Ma	Apr	Ma	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
									1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
WP1 Project management (ETH)																																
D 1.1	First annual report on activities and progress	●				1.3.2022	28.02.2024	12												D												
D 1.2	Final report on activities and achievements	●						24																								D
M 1.1	Consortium agreement signed by all partners	●	●	●	●			2(9)									M															
M 1.2	Internal web platform for exchange of information established	●						2		M																						
M 1.3	Coordination meeting to finalise monitoring geometry and monitoring	●	●	●	●			2		M																						
M 1.4	Minutes of the PMT meetings filed on web	●				1.3.2022	28.02.2024				M			M			M			M			M			M			M			M
WP2 Time lapse CO_2 migration monitoring																																
D 2.1	Archive of all seismic data with quality-checked meta data	●				1.3.2022	28.02.2024	15(?)																					D			
D 2.2	Archive ERT and DSTAS data on ETH server with DOI	●				1.5.2022	28.01.2024	15(?)																					D			
D 2.3	Report/Publication(s) on Time-Lapse imaging	●				1.5.2022	28.02.2024	24																								D
D 2.4	Report/Publication(s) on gas monitoring				●			22																						D		
M 2.1	Establish real-time data streaming from the 5 stations backbone network to Zurich							2(8)								M																
M 2.2	1st geophysical survey and spot measurements for fluid sampling, CVP,	●			●			6(12)																	M							
M 2.3	Continuous fluid sampling operational				●			6(12)																	M							
M 2.4	2nd geophysical survey and spot measurements for fluid sampling, CVP,	●			●	1.5.2022	28.02.2024	8(15)																								M
WP3 Geophysical & Geological modelling at Reservoir Scale																																
D 3.1	Report on the 3D static models (and associated uncertainties)			●		1.3.2022	31.05.2022	4 (11)																			D					
D 3.2	Report on the 3D static models according to the monitoring results, upscaling potent			●				22																						D		
M 3.3	A prior model output available to project partners			●				4(11)												M												
M 3.4	Updated and calibrated reservoir model available			●		1.5.2022	28.02.2024	18																						M		
WP4 Laboratory characterization and validation of processes																																
D 4.1	Report/scientific paper on the hydromechanical and petrophysical characteriz		●			1.3.2022	31.12.2022	12											D													
D 4.2	Report/scientific paper on the geochemical and geomechanical coupling of basalt exposed to CO_2-enriched saline water with real time imaging (x-ray tomography)		●					22																						D		
M 4.1	Characterisation of basalt field cores completed: mineralogical, petrop	●	●	●		1.7.2022	30.06.2023	12												M												
M 4.2	Coupled geomechanical and geochemical response of basalts to CO_2-fl	●	●					22																				M				
WP5 Integration with other projects, upscaling, and application to CH																																
D 5.1	Report on the public acceptance of CO2 storage in Iceland	●				1.9.2022	1.3.2023	2(16)																D								
D 5.2	Graphics illustrating DemoUpStorage for communication	●				1.3.2022	1.9.2023	2		D																						
D 5.3	Summary report on the implications of DemoUpStorage for future R&D	●				1.9.2022	28.02.2024	24																								D
M 5.1	Media analysis and interviews on public acceptance concluded.	●						12(?)											?	M												
M 5.2	Information transfer to DemoUpCARMA for LCA completed	●						15															M									
M 5.3	Information on storage related activities updated on DemoUpCARMA w	●						12												M												
M 5.4	Follow-up projects defined	●						24																								M
	Tasks					Start	End	Duration (months)	Feb	Ma	Apr	Ma	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Ma	Apr	Ma	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
									1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
WP1 Project management (ETH)		●	●	●	●																											
Task 1.1	Project management	●	●	●	●	01.2.2022	31.01.2024	24																								
Task1.2	Dissemination	●	●	●	●	01.2.2022	31.01.2024	24																								
WP2 Time-lapse CO_2 migration monitoring		●		●	●																											
Task 2.1	Geophysical survey design	●		●		01.2.2022	31.05.2022	4																								
Task 2.2	Network for background monitoring: installation-maintainance	●				01.2.2022	31.01.2024	24																								
Task 2.3	Cross hole Vertical Seismic Profiling (VSP)	●		●		01.05.2022	31.01.2024	21				X				X					X											
Task 2.4	Seismic nodes installation and data acquisition	●		●		01.05.2022	31.01.2024	24				X				X					X											
Task 2.5	Downhole electrical resistivity tomography	●		●		01.05.2022	31.01.2024	24				X				X					X											
~~Task 2.6~~	~~Fluid geochemistry spot measurements~~				●	~~01.05.2022~~	~~31.01.2024~~	~~24~~				X				X					X											
Task 2.7	Continuous gas monitoring				●	01.05.2022	31.01.2024	21																								
WP3 Geophysical & Geological modelling at Reservoir Scale		●	●	●																												
Task 3.1	A priori model development based on available data			●		01.2.2022	30.04.2022	3																								
Task 3.2	Integrated interpretation of geophysical and geochemical data	●	●	●		01.12.2022	30.07.2023	8														?										
Task 3.3	Simulations on upscaling and alternative injection scenarios	●		●		01.08.2023	31.01.2024	6																								
WP4 Laboratory characterization and validation of processes		●	●	●																												
Task 4.1	Hydromechanical-geophysical testing	●	●			01.2.2022	31.01.2023	12																								
Task 4.2	CO_2 exposure tests during in-situ x-ray tomography	●	●			01.05.2022	31.08.2023	15																								
Task 4.3	Mineralogical and petrological characterization		●	●		01.6.2022	30.09.2022	4																								
WP5 Integration with other projects, upscaling, and application to CH		●	●	●	●																											
Task 5.1	Societal acceptance of CO_2 storage in Iceland	●				01.08.2022	31.01.2023	7																								
Task 5.2	Feedback to DemoUpCARMA	●	●	●	●	01.06.2022	30.07.2023	14																								
Task 5.3	Communication	●	●	●	●	01.2.2022	31.01.2024	24																								
Task 5.4	Summary assessment of lessons learned for Switzerland	●	●	●	●	1.9.2023	31.01.2024	6																								
Task 5.5	Dissemination Follow up experiments	●				1.9.2023	31.01.2024	6																								

The following tasks and milestones are planned for the next month as described below

1. Autumn 2023 (originally planned July 2022): Start of injection,
2. Winter 2023: 2nd measurement campaign. We will repeat active and passive cross-hole seismic methods, resistivity measurements, a few months after the injection has started. The exact time will be decided on the observations we have from the dissolved gasses in water.
3. Spring 2024 (originally planned December 2022): 3rd measurement campaign.
4. To be decided (originally planned March 2023): 4th measurement campaign.
5. To be decided (originally planned June 2023): Stop of injection, 5th measurement cycle. Retrieve equipment, unless a follow-up project and scale-up funds and requires continued operation.
6. Spring 2024 (originally planned July - Feb. 2024): Finalize scientific analyses and publications, define drilling targets for core recovery, if possible.

Below are the major activities carried out in the project to date, broken down by WPs.

4.1 Project management (WP1)

This work package carries out all activities related to project management.

A Consortium Agreement was prepared in cooperation with the legal office of ETH, UniGe, and EPFL. It was signed by all parties in November/December 2022.

A kickoff meeting was organized on 11.03.2022 at ETH Zurich, where all the activities on the work packages were discussed. It was followed by a Consortium Meeting on 26 August 2022 at ETH, a project meeting together with DemoUpCARMA on 12 September 2022 and a workshop on 13 September 2022 in Reykjavik, when we had the opportunity to discuss with the CARBFIX colleagues the various technical aspects of the installation. Representatives of demoUpStorage presented the progress of the projects in the DemoUpCARMA Consortium meetings on 08.06.2022, 24.01.2023 and 10.07.2023. Minutes and presentations of the meetings are available at the SharePoint of DemoUpStorage in folder Documentation/ConsortiumMeetings: https://demoupstorage.sp.ethz.ch/_layouts/15/start.aspx#/Documentation/Forms/AllItems.aspx.

The next consortium meeting is planned on 4 September 2023 in Zurich.

Various work packages meetings were held in between the above-mentioned consortium meetings to plan their specific and overall project’s objectives. Most of these meetings, especially related to WP2 and 3, involved the colleagues from CARBFIX. The project coordinator meets regularly via Teams, the project coordinator of DemoUpCARMA and the contact person of CARBFIX on a weekly basis to keep all the parties updated on the project development.

The Advisory Board is shared with the DemoUpCARMA board and consists of representatives of the scientific community, industrial sector, broad society (including students), and administration (e.g., BFE, BAFU, Swisstopo). The board met in January 2023 when the substantial delay of the activities at Helguvik was discussed and a new timeline was defined. The representatives of BFE were informed of the delay and the deadline for the affected tasks, milestones and reporting was postponed.

DemoUpStorage results are communicated in scientific conferences:

- 20th Swiss Geoscience Meeting 18-20 November 2022 | Lausanne Switzerland
- 23rd EGU General Assembly 23–28 April 2023 | Vienna, Austria & Online
- 9th International Congress on Environmental Geotechnics, 25-28 June 2023 | Chania, Greece

The public outreach activities are fully embedded into DemoUpCARMA, newsletters are regularly published on the DemoUpCARMA webpage. more details are given in the following Chapter 5.

4.2 Time-lapse CO2 migration monitoring (WP2): Combined geophysical and geochemical techniques.

One integral part of the DemoUpStorage pilot project in Iceland are geophysical and geochemical time-lapse surveys to monitor subsurface changes due to the precipitation of secondary carbonate minerals.

4.2.1 Synthetic Seismic Modeling

Design Optimisation for Seismic Monitoring of Carbon Dioxide Mineralization in Basalt

The best spatial resolution for such an undertaking can be achieved by a seismic cross-hole survey where travel times between two wells are used to invert for the subsurface velocity structure. The travel time differences between a baseline survey prior to the injection and a timelapse survey after the injection can be used in a differential inversion to image the velocity anomaly.

We investigated the sensitivity and feasibility of imaging subsurface velocity anomalies with two different wave propagation forward modeling methods: eikonal first arrival solver and spectral element modeling (SEM). As the effect of carbonate mineralization on the elastic parameters in basaltic formation and its corresponding velocity anomaly amplitude can only be estimated, we model the velocity anomaly with amplitudes of 1% and 5% respectively to study the sensitivity of the setup. Further, forward scenarios of distances of 25 m, 50 m and 75 m between the wells are tested to gain insights into the extent of areas that can be imaged with reasonable resolution in the context of field planning, field condition, as well as data processing.

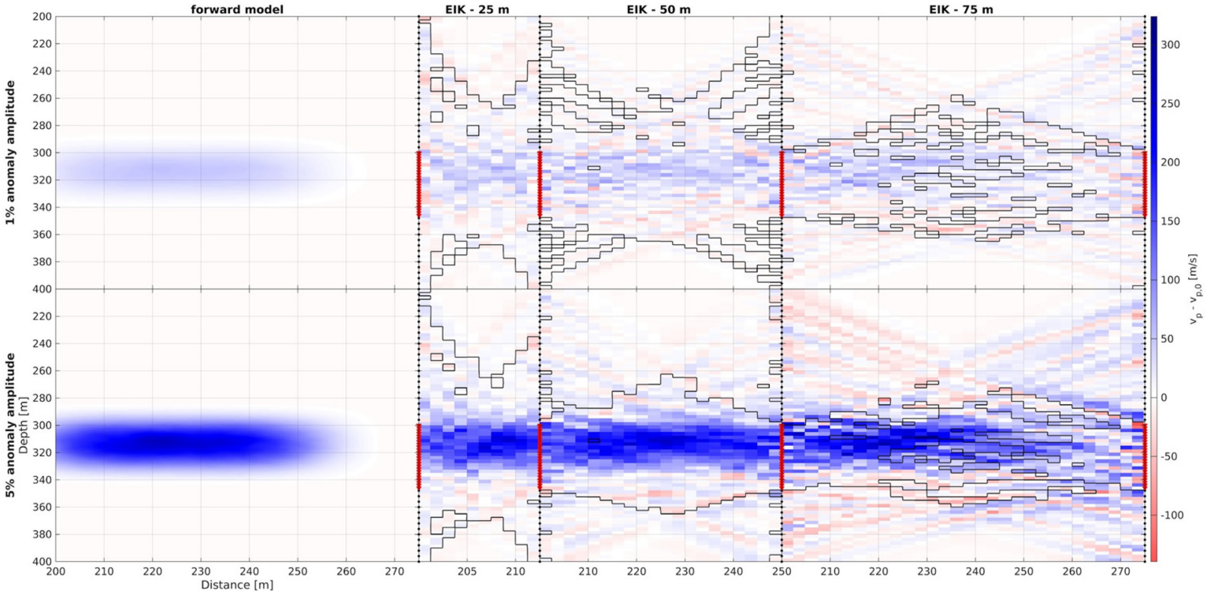


Figure 8: *Results from the synthetic seismic modelling study. Shown are the 1% (top row) and the 5% (bottom row) velocity anomaly studies with the eikonal solver data. The leftmost column shows the true anomaly as designed for the input. The second column shows the inverted anomaly for the 25m*

inter-well distance scenario followed by the 50m and the 75m scenario. Source locations are shown as black dots, receiver locations as red triangles.

The simulations (figure 8) show that the expected velocity anomalies can be successfully imaged in the 25 and 50-m scenarios, both shape- and amplitude-wise. The 75 m scenario also detects the anomaly but resolves its shape unsatisfyingly. Tests showed that the amplitude has only a minor effect on the quality of the inversion; however, the differential inversion is highly sensitive to the implemented noise level. The ray paths and the performed resolution tests demonstrate the necessity of having receivers placed at the depths of the expected anomaly. The model recovery exacerbates within a few meters above and below the receivers. Both forward modeling methods have a good agreement in travel-time calculation sensitive to the implemented small velocity perturbation with a correlation coefficient of 99.97 %. Although SEM is computationally significantly more expensive, it calculates the full wavefields and thus shows the potential of full waveform inversion for future work.

Numerical Study on the Effect of Carbonate Precipitation on Basalt

As a consequence of establishing a new site, we had barely any in-situ subsurface knowledge for defining the well locations for the crosshole seismic monitoring. The search for the optimal well locations was further complicated given that the effects of carbonate precipitation on the elastic properties of the basaltic host rock are poorly studied. The only data available is - to our knowledge - the laboratory study by (Adam and Otheim, 2013) who found a vp velocity increase of 9 to 22% as a result of the reactions between CO2 and basalt. However, as they performed laboratory measurements in the ultrasonic frequency range, these results do not need to relate directly to seismic frequencies (e.g. Moos and Zoback, 1983). This gap of information makes an estimation of the in-situ seismic velocity changes due to the CO2 injection difficult.

To estimate the range of possible velocity variation due to mineralization, in the absence of experimental data, we decided to perform calculations using mTex (Bachmann et al., 2010). mTex is an open-source MATLAB toolbox for analyzing and modeling crystallographic textures. It allows the calculation of seismic velocities of mineral aggregates based on the stiffness tensors and the relative volumetric fractions. For our calculations, we take the averaged volumetric mineral fractions of the core samples provided by Carbfix to Uni Lausanne and literature values for the stiffness tensors . This allows us to calculate an average stiffness tensor for the basaltic host rock. To study the effects of the CO2 injections, we introduce the effects of porosity and pore saturation on the stiffness tensor based on Li and Zhang (2011) and Gassmann (1951). With this, we can now calculate the seismic velocities of the basalt as a function of porosity and calcite content (Figure 9).

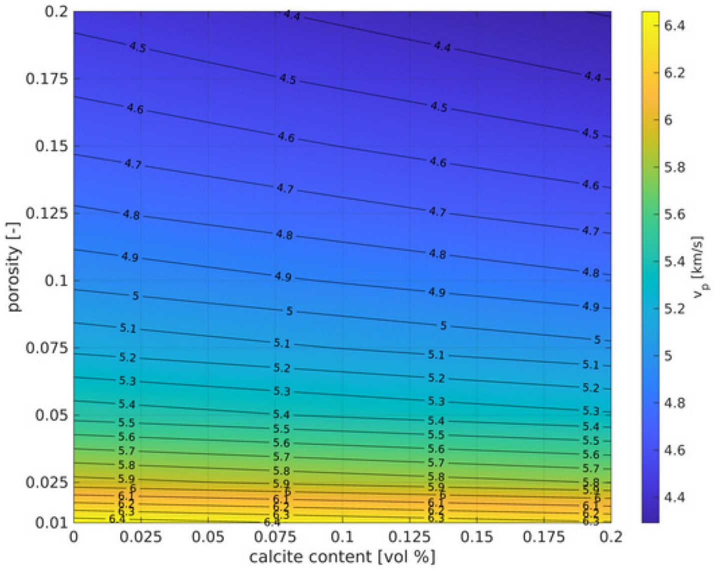


Figure 9: *Seismic velocity Vp as function of porosity and calcite content. A fully saturated medium is assumed.*

We expect two processes to occur in the subsurface: First, the injection of acidic, CO2-enriched water causes the host rock to partially dissolve (Snæbjornsdottir et al., 2018) which leads to an increase in porosity. This effect causes an upwards movement of the seismic velocity along the vertical axis of the plot. Second, the carbonates precipitate and decrease the porosity (Snæbjörnsdottir et al., 2018). This causes a shift of the seismic velocity parallel to the northwest-southeast diagonal of the plot. This is due to the fact that the carbonates do not replace other minerals but fill up the available pore space. Based on the geochemical modeling of Carbfix’s Hellisheidi site by Aradottir et al. (2012), we estimate that the velocity changes that we can expect to lay in the order of +3% Vp relative to the pre-injection state, which lays in between the initial guesses of +1% and +5% that we used for our synthetic seismic modeling study.

The calculations with mTex have multiple limitations: (i) we had to assume a homogeneous medium; (ii) the model does not include fractures or any other heterogeneities; (iii) the implementations of the effects of the pores on the elastic stiffness tensor and the pore saturation is only valid for seismic frequencies (Gassmann, 1951; Mavko et al., 2009) and only for porosities up to 0.2 (Li and Zhang, 2011). However, we think that our calculation gives a first-order-of-magnitude estimate of the velocity changes to expect and also gives room for further investigations. Further investigations may include: (i) studying the effect of variable dissolution velocities for individual minerals as seen in (Arad´ottir et al., 2012), (ii) introducing formulation of the pore-fluid effects for higher frequencies (e.g. Biot, 1956) and (iii) the validation of the findings with laboratory measurements (e.g. from Adam and Otheim (2013) or our own ones).

4.2.2 Geophysical Monitoring

Seismic Backbone Stations

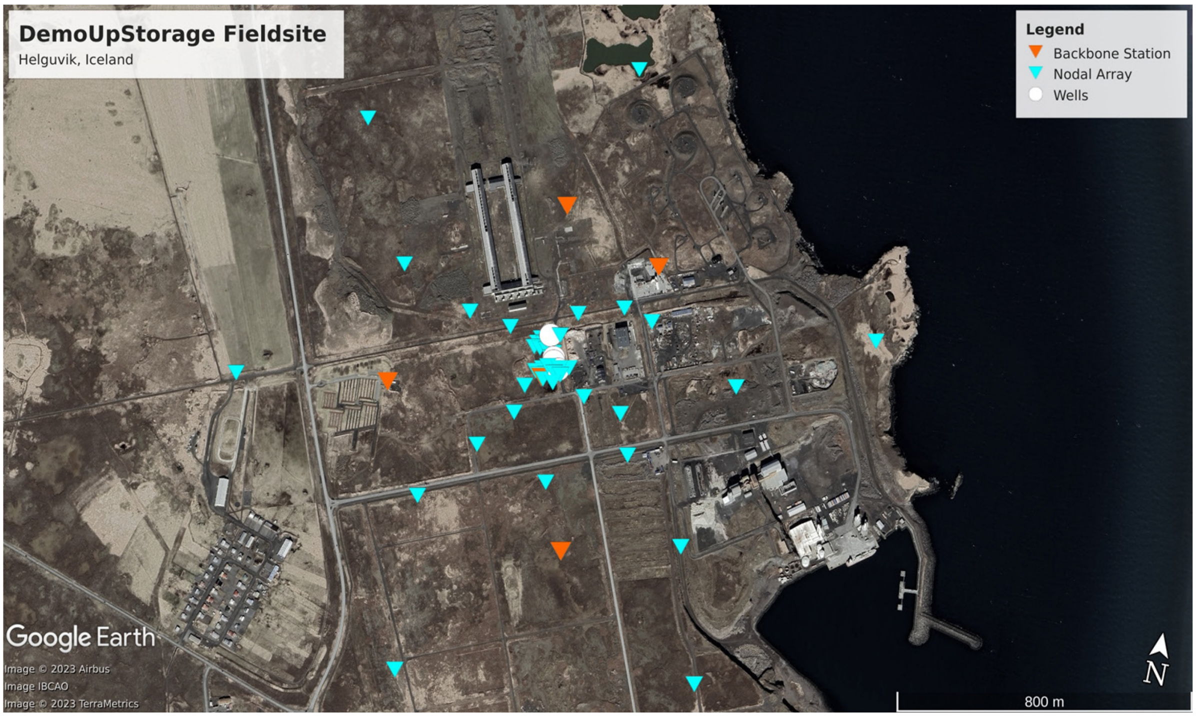


***Figure 10**: Overview of the Helguvik site with the location of the wells and the backbone seismic stations shown (orange). Further, the deployment locations of the nodal array for the baseline measurements are also shown (light blue). Please note that one of the backbone station is placed just in the middle of the nodal array.*

Since September 2022, we have received continuous data from 5 backbone seismic stations (Lennartz 5s), spread across the area (see Figure 10). An analysis of the noise field (see Figure 11) shows anthropogenic contamination in the frequency >7 Hz. The high noise around the first microseism (7s) are typical for Iceland and related to strong winds in the ocean.

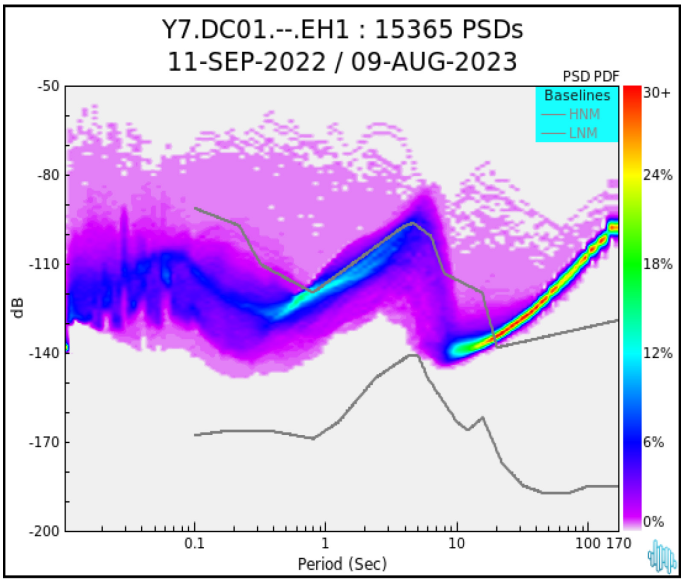


Figure 11: *Example of PSD Plot of the DC01 backbone station. DC01 is located 50m south-west of the injection well Carb1.*

4.2.3 Characterisation Campaign

We performed the first geophysical survey between June 5th and June 18th 2023 at the field site in Helguvik. 11 people from ETH and EAWAG were involved. In the following, we present an overview of the acquired data and the first conclusions drawn from it. Note that due to a technical failure of the borehole source we were not able to conduct the crosshole seismic survey but had to adjust our measurements (details below).

Crosshole seismic

We rented a digital sparker from Geotomographie GmbH that has the advantage of not losing power along the cable length compared to the more common analogue sparker. The first 5 shots showed very clear signals recorded between the injection and geophysical monitoring well at 30 m distance (Figure 12). Unfortunately, we could not wrap up the campaign in June since the sparker's capacitors broke. A flown-in technician from Geotomographie could only confirm that the sparker was beyond repair on site.

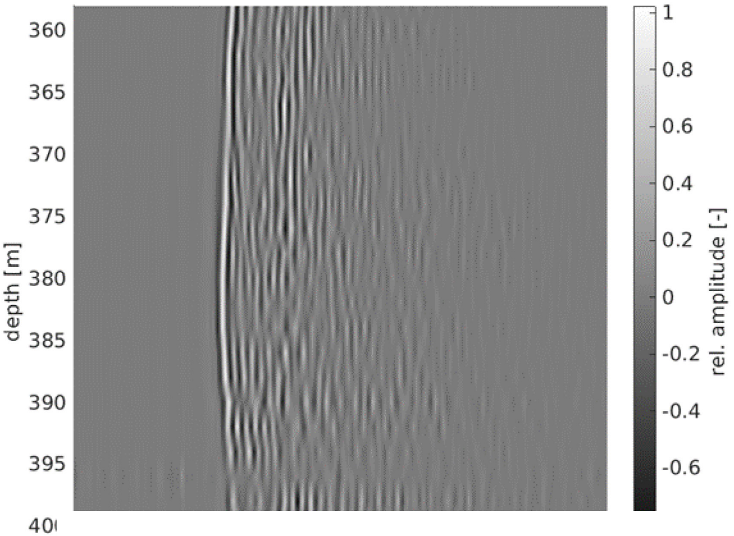


Figure 12*: Example of a sparker shot in Carb3 well at 388m depth, recorded by the hydrophone string in Carb1.*

Vertical Seismic Profiling (Hammer Seismic)

As a backup plan, we conducted a Vertical Seismic Profiling (VSP) survey. For that we use primarily a hammer as a seismic source at the surface and record the generated seismic waves with the hydrophones and the fiber optics in Carb1. The data quality is not comparable to the crosshole data. This is expected due to the weaker source and the significantly greater source-receiver offset. However, the hammer shots are still visible in the recordings at depths of 400m and shot location offsets of up to 40 m from Carb1. Further processing is needed to separate the tube wave from the direct arrivals and to build a proper 1D velocity model of the site. This model can afterwards be used to define the starting model for the inversion of the crosshole seismic data once it is recorded.

Refraction seismic profile and weight drops

We also had the possibility to perform additional measurements with a 370 Kg concrete weight as a seismic source. 14 shots were performed along the road parallel to the Boreholes and recorded on DAS and 15 surface nodes that were placed in a line between Carb1 and Carb3. The source-receiver offset is here up to 180 m so this data is more suitable for refraction seismic. Due to the generally high noise level of the site, the signal-to-noise ratio is low. However, several arriving wave trains can be seen in the data. Further processing is needed in this dataset to obtain a velocity model of the near subsurface.

Fiber Optics

In the first field campaign in June, we deployed 450m of fiber-optic cable inside borehole CARB-1. It was hanging inside the borehole for the duration of the experiment and it has been used to record the active shots of the sparker, hammer and weight drop experiments conducted. We have also monitored during a period of 24 hours to record background noise and potential nearby events. The fiber-optic recordings were made to make an additional cross-hole survey or profile using the sparker. The hammer shots that were taken are well-recorded and are being processed to make a one-dimensional velocity profile along the well. However, the required signal is hidden beneath a very strong noise from the casing of the borehole, so it remains to be seen if velocities can be recovered.

Nodal Seismic Network:

Towards the end of the first field campaign, we started to deploy the passive seismic array using 43 SmartSolo 5Hz 3 channel geophones. For a map of deployment see Figure 10. The geophones record continuous seismic data for approximately 30 days. The data will be downloaded from the stations in the next field campaign (August 19th to August 29th 2023) and shall be used to construct an approximate S-wave velocity model of the subsurface.

Geoelectric Measurements (Electrical Resistivity Tomography, ERT)

During the June field campaign, we conducted ERT profiles in Carb3 and Carb4 (see Figure 13). Both ERT profiles show a comparable structure with several distinct features seen in both profiles. However, due to lacking stratigraphic information, a concluding interpretation of the data is difficult to make. Two features may be linked to observations from the stratigraphic column, provided by ISOR. ISOR reports that the light gray basalt becomes “somewhat denser” below 300m. This is the area where we see an increase in resistivity. This could be linked to a decrease in porosity that could coincide with the report that the basalt gets denser. Further down at 325m depth, we see a significant decrease in resistivity in both boreholes. This could be caused by the higher clay content reported by ISOR. Additional logging information needs to show whether these first interpretations are valid.

At the end of the field campaign, we installed the electrode chain at a depth of between 312m and 360m depth and performed daily measurements since then. The first few days showed rather stable measurements but we could not access the data since mid-July due to technical reasons.

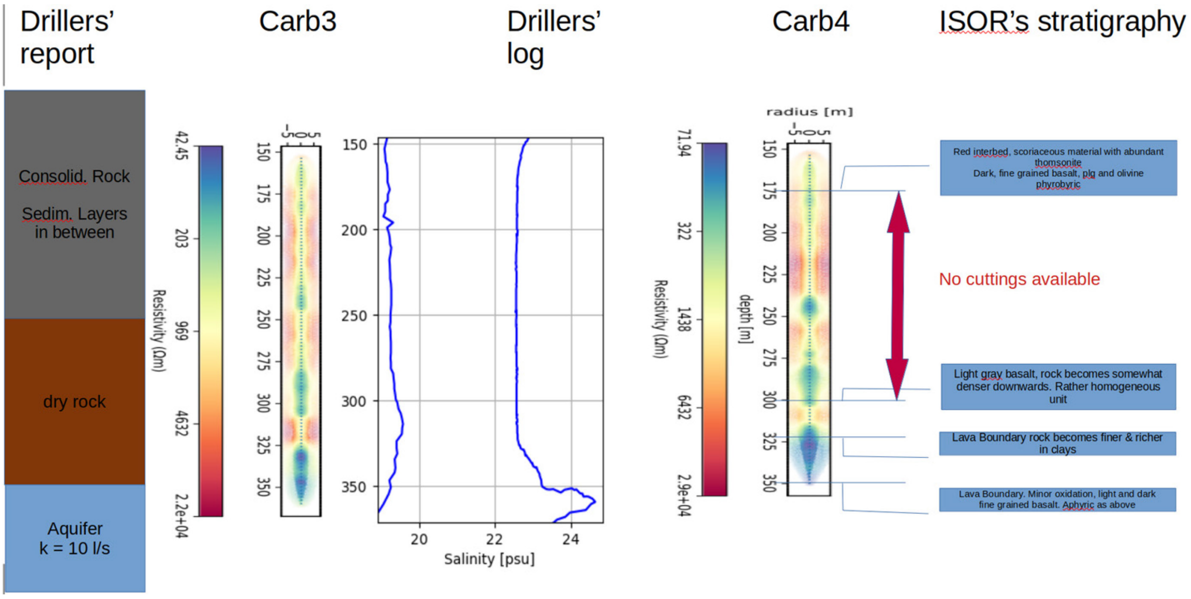


Figure 13: *Summary of the ERT data acquired during the June 2023 field campaign. From left to right, we show: Drillers' Report: The stratigraphy as orally reported by the drillers to us; Carb3: Inverted ERT profile for Carb3; Drillers' Log: Salinity as logged during the June 2023 field campaign (the right curve is from the down-going measurement, the left one from the up-going measurement, Carb4: Inverted ERT profile for Carb4; ISOR's stratigraphy: Relevant information from the stratigraphic column acquired by ISOR in December 2022*

Dissolved gasses monitoring

The "miniRUEDI" is a portable mass spectrometric system for quantification of partial pressures of gas species (e.g., He, Ar, Kr, O2, N2, CO2, and CH4) in gaseous and aqueous matrices (Brennwald et al., 2016). In this project, miniRUEDI is experimentally designed for continuous measurement of dissolved gas concentrations in the boreholes located downstream of the injection site. By analyzing the temporal variations of dissolved gas concentrations at these specific boreholes, we aim to gain insights into the carbon transportation and transformation processes. Consequently, this analysis will shed light on the evolution of injected CO2 in the subsurface environment. We note that long-term monitoring of this carbon sequestration site will significantly add to our mechanistic and process-oriented understanding of the complete life cycle of carbon storage in the local subsurface environment.

The main focus of the fieldwork campaign in June 2023 was the implementation of a miniRUEDI system to enable continuous, on-site monitoring of dissolved gas concentrations in both Carb-2 and Carb-3 wells. The miniRUEDI was successfully installed within the CARBFIX container, which acts as the central hub for data collection and monitoring activities. The CARBFIX container is placed ~10 m from the Carb-2 well and ~30 m from the Carb-3 well (see Figure 14). During the fieldwork, we used an excavator to dig two trenches, extending from the miniRUEDI site to Carb-2 and Carb-3 wells. To ensure long-term deployment and protection, we inserted the water tubes and electrical cables into PVC tubes and buried them together within the trenches (see Figure 15).

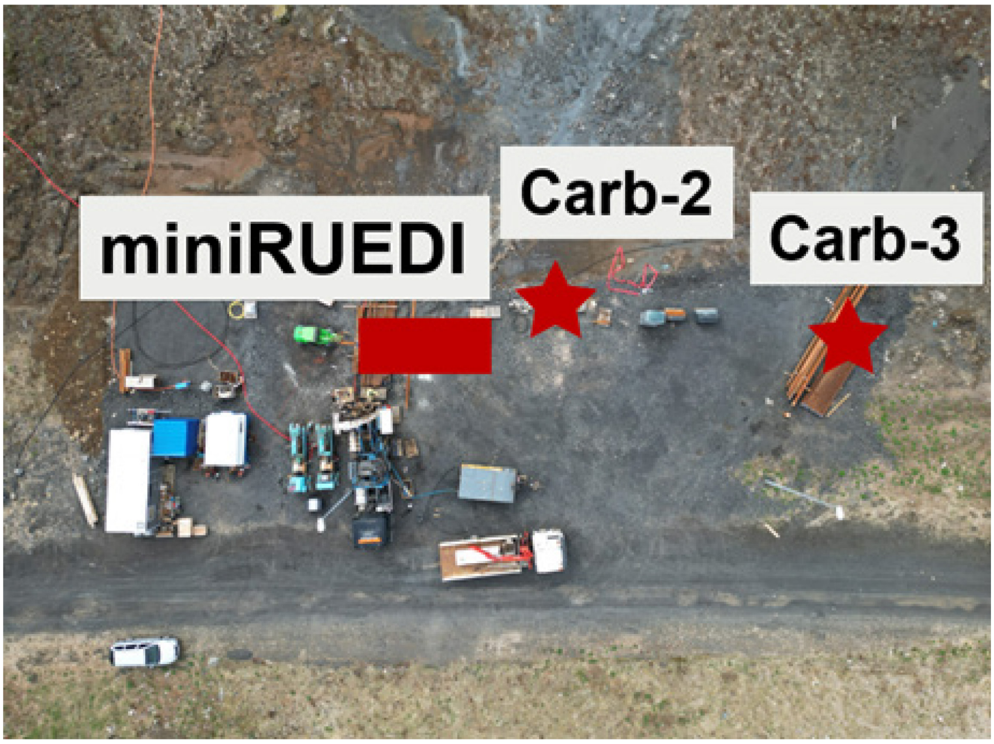


Figure 14: *The aerial view of locations of miniRUEDI, Carb2 well, and Carb3 well*

Figure 15: *The trenches for burying water tubes and electrical cables extend from the miniRUEDI site to Carb2 (left) and Carb3 (right) wells.*

For continuous groundwater monitoring, we installed two submersible pumps in each well (~30m below the ground surface). The extracted groundwater is then directed into the container through water tubes. Before entering the miniRUEDI's membrane module, the groundwater undergoes initial filtration using a metal mesh to remove small particles preventing obstruction of the miniRUEDI's analysis (see Figure 16). Subsequently, the filtered groundwater is exposed to air-water equilibration within the miniRUEDI system. Once gas-water equilibrium is achieved, the miniRUEDI accurately quantifies the partial pressures of various gas species present in the equilibrated headspace. Additionally, combining temperature and pressure measurements in the equilibrium module allows for the calculation of dissolved gas concentrations through Henry's Law.

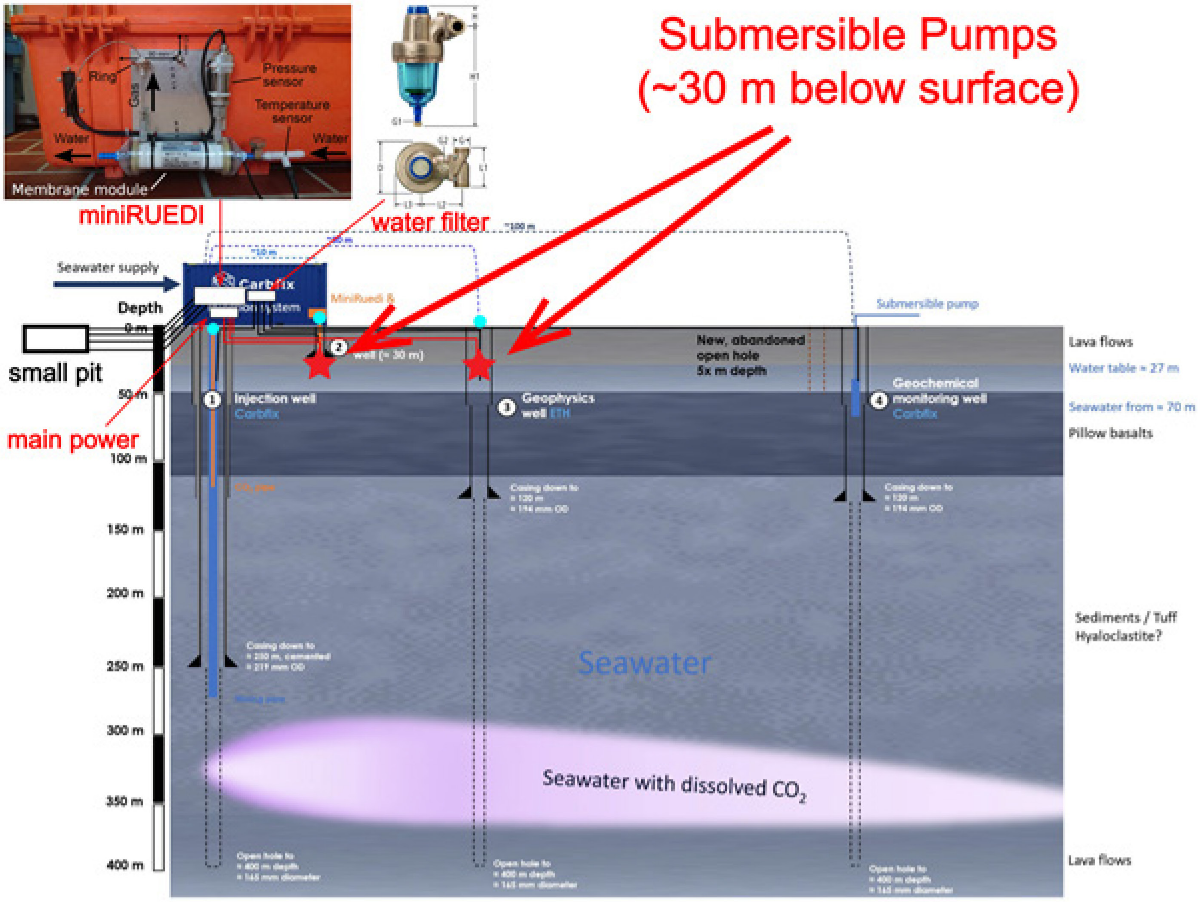


Figure 16: *The cross-section diagram of miniRUEDI setting in the field site.*

Since its installation in June 2023, the miniRUEDI system has been continuously monitoring dissolved gas concentrations (He, Ar, Kr, N2, O2, and CO2) in Carb2 and Carb3 wells, as illustrated in Figure 16-17. The real-time monitoring result from miniRUEDI is depicted in Figure 18, revealing distinct differences between the two wells in temperature, total dissolved gas pressure, and dissolved gas composition. Notably, Carb-3 well exhibited higher temperature compared to Carb-2 well (19.4 versus 12.7 degrees Celsius, see Figure 18). Additionally, Carb-3 well showed higher total dissolved gas pressure than Carb-2 well (1.12 versus 0.97 bar, see Figure 18). The miniRUEDI measurements further indicate that the dissolved gas composition in Carb-2 closely resembled ambient air, with slightly lower O2 and CO2 partial pressures (see upper left panel in Figure 18). In comparison, Carb3 well displayed significantly higher partial pressure of noble gasses (He, Ar, and Kr) and N2, but lower O2 and CO2 partial pressures than Carb-2 well.

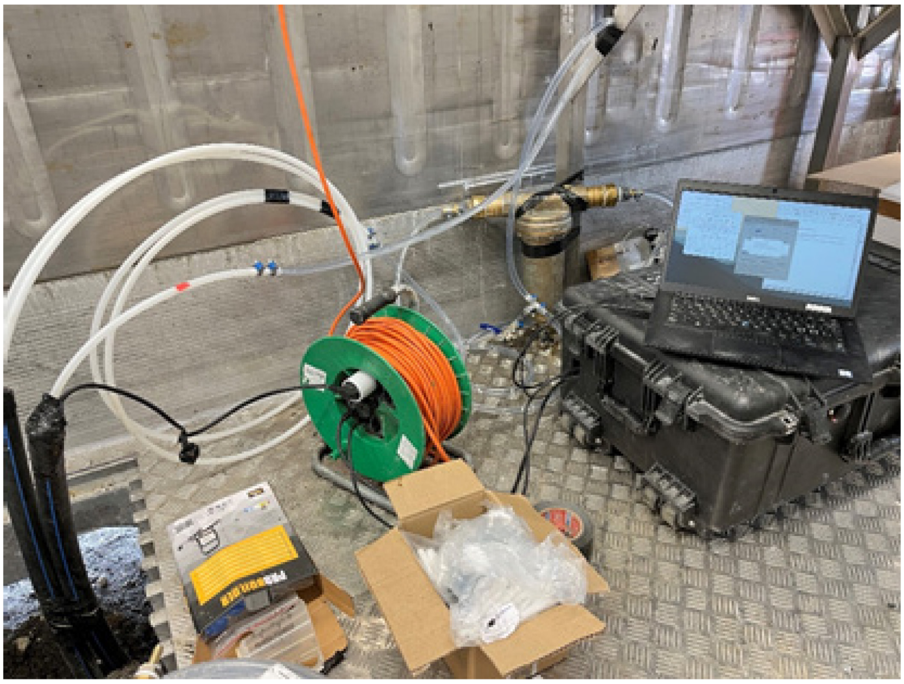
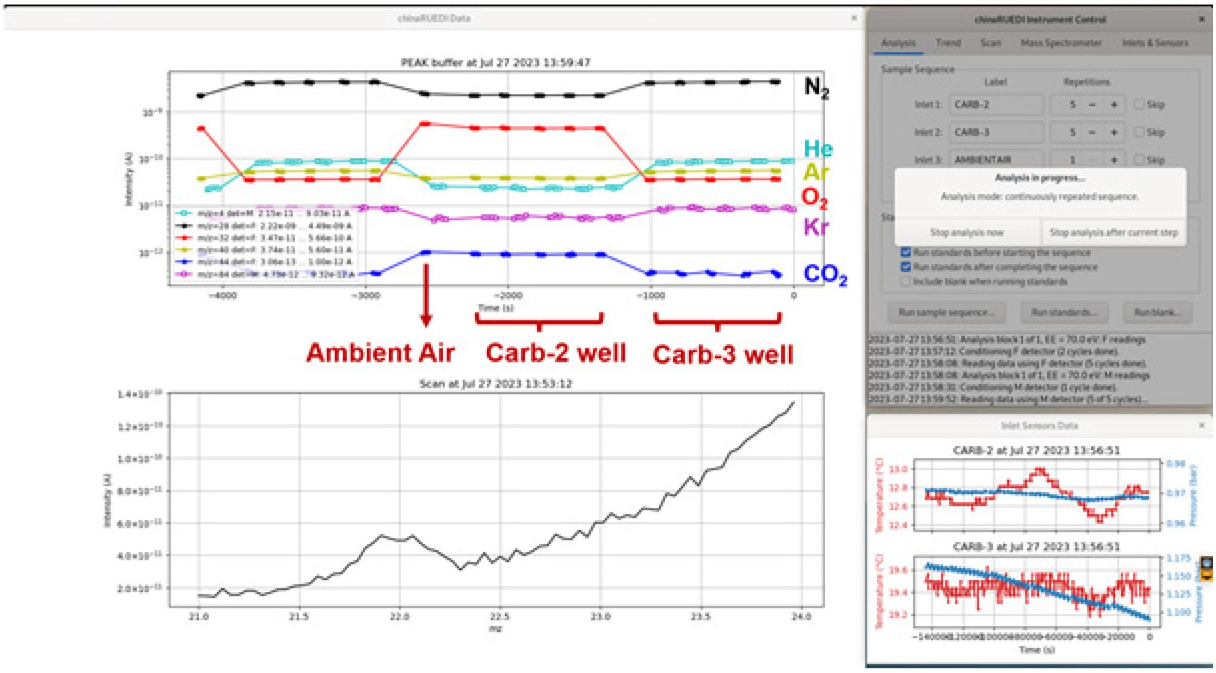


Figure 17: *The miniRUEDI is continuously running inside the CARBFIX container. The black suitcase is the miniRUEDI, and the computer serves as a screen displaying real-time monitoring results.*



Sample Sequence

	Label	Repetitions	
Inlet 1:	CARB-2	5	☐ Skip
Inlet 2:	CARB-3	5	☐ Skip
Inlet 3:	AMBIENTAIR	1	☐ Skip

Analysis mode: continuously repeated sequence.

☑ Run standards before starting the sequence
☑ Run standards after completing the sequence
☐ Include blank when running standards

```
2023-07-27 13:56:51: Analysis block 1 of 1, EE = 70.0 eV: F readings
2023-07-27 13:57:12: Conditioning F detector (2 cycles done).
2023-07-27 13:58:08: Reading data using F detector (5 cycles done).
2023-07-27 13:58:08: Analysis block 1 of 1, EE = 70.0 eV: M readings
2023-07-27 13:58:31: Conditioning M detector (1 cycle done).
2023-07-27 13:59:52: Reading data using M detector (5 of 5 cycles)...
```

Figure 18*: The real-time monitoring results of miniRUEDI. The upper left panel shows the intensity of different gas species, the lower left panel indicates the intensity at different m/z ratios, the upper right panel is the controlling interface of miniRUEDI, and the lower right panel is the temperature and total dissolved gas pressure result*

4.3 Geophysical & Geological modeling at Reservoir Scale (WP3)

4.3.1 Subsurface modeling database

A key step prior to the generation of a 3D geological reservoir model is the establishment of the subsurface database regarding the CO2 injection site at Helguvik (Figure 19; Table 2). For this purpose, the software Petrel (SLB 2022 version) was used. To start, the database contains the surface location of the 4 boreholes which will be drilled in this project and the high-resolution topographic surface of the study area extracted from the site was also loaded in the Petrel database.

To date, only the well logs acquired from the Carb-4 borehole have been incorporated in the database (Figure 20; Table 2). The data from the remaining three boreholes will be added as soon as they will be logged. Moreover, critical borehole information such as lithology and optically derived porosity logs (Davis, 2022) from the HB-05, HB-06 and HB-07 boreholes have been added to our database for a more robust reservoir modeling.

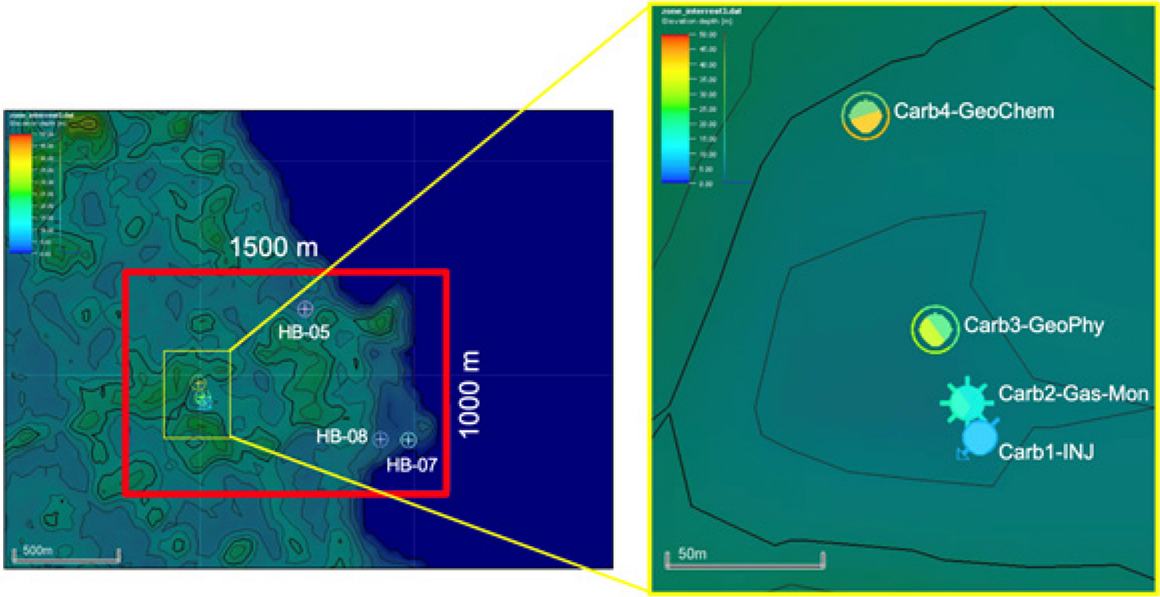


Figure 19: *Study Area and Model Boundary. The red polygon indicates the grand modeling boundary, and the yellow boundary denotes the sector scale boundary encapsulating the Carb 1-4 boreholes. The purple arrow indicates the approximate south-north groundwater flow direction in the study area.*

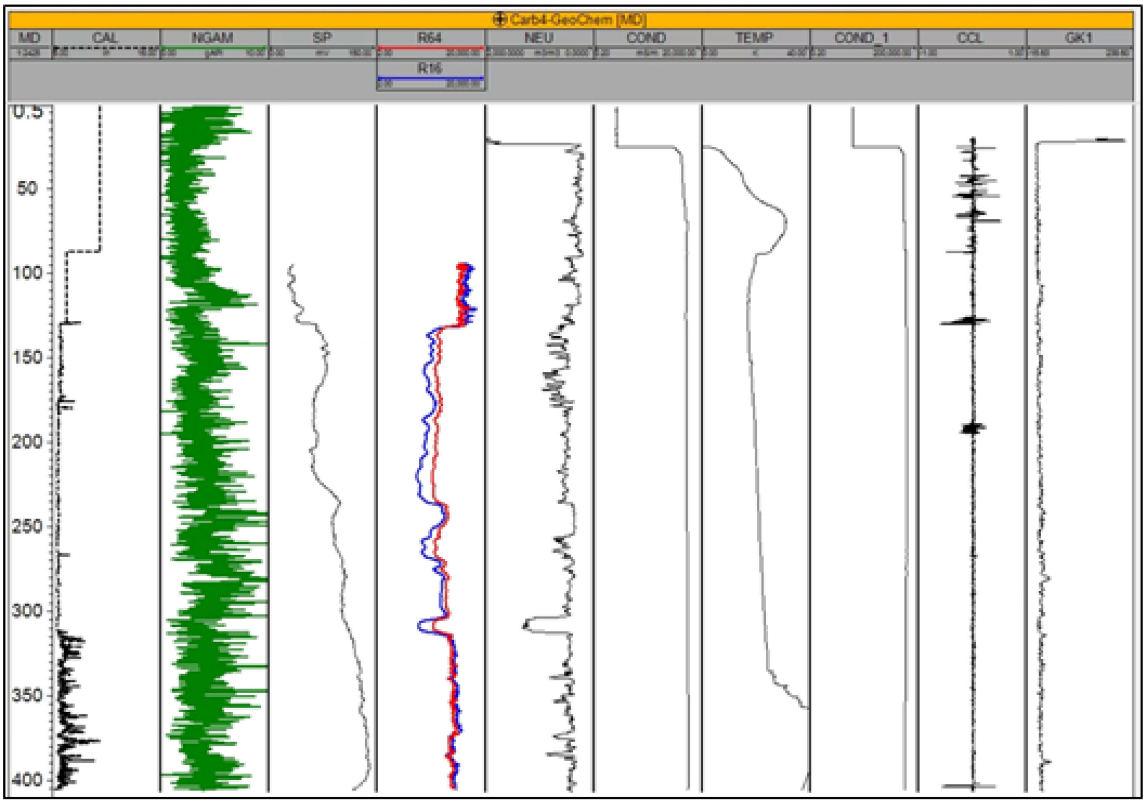


Figure 20: *Suite of well logs available in Carb-4 Geochem borehole.*

Borehole	Depth (m)	Log Types	Cuttings/Core	Comments	Source
Carb-1	0-420	N/A	N/A	N/A	ISOR
Carb-2	0-37	N/A	N/A	N/A	ISOR
Carb-3	0-420	N/A	Cuttings	N/A	ISOR
Carb-4	0- 420	Litho, neut, dens, temp, cond, res.	Cutting	BHI also available not yet incorporated	ISOR
HB-05	0-60	Litho Phi	core	Phi derived from core photos optical analysis	Vikigsson and Kristinsson, 1982 Davis, 2022
HB-07	0-60.25	Litho Phi	core	Phi derived from core photos optical analysis	Vikigsson and Kristinsson,1982 Davis, 2022
HB-08	0- 60.1	Litho Phi	core	Phi derived from core photos optical analysis	Vikigsson and Kristinsson,1982 Davis, 2022

Table 2*: Subsurface database showing the borehole data available for this study.*

4.3.2 Reservoir Rock Typing

Reservoir Rock Typing (RRT) of the storage formation is necessary to classify basaltic reservoirs based on the reservoir quality and predict their reservoir behavior and specifically their controls and influence on CO2 injection, subsurface flow and storage. Rock typing is performed by integrating a high-resolution mineralogical, geochemical and petrophysical analysis. This is important since rock heterogeneities in the storage formation will control injectivity, subsurface fluid-flow and CO2 mineralization. RRT was initially performed on five original 5 core samples from the boreholes HB-05, HB-06 and HB-07 of 3.9 cm in diameter. They have been trimmed to obtain 7.6 cm-high cylinders (Figure 21). Six stubs (ca 50 gr of residual material) have been recovered for geochemical analysis (XRF).

Figure 21: *Overview of samples used for the compositional, textural and rock property analysis of basalt samples from boreholes HB-05, HB-07 and HB-08. Core plug samples received from CARBFIX are considered to be representative of the storage formation.*

Textural Analysis

The textural study was performed on one thin section for each sample except for sample 08-03 where two thin sections. The texture of each core sample is typical of basaltic rocks and consists of fine-grained basic igneous rock. Macroscopic description based on outcrops, core and cutting description indicate the presence of several textural varieties such as glassy, massive, porphyritic, vesicular and scoriaceous. Individually the texture of core samples are generally relatively homogeneous whereas if compared to each other they change in texture and rock properties. In the case of sample 08-03 high degree of heterogeneity was observed at the core sample scale where the texture of bottom and top of the core varied considerably (Figure 22).

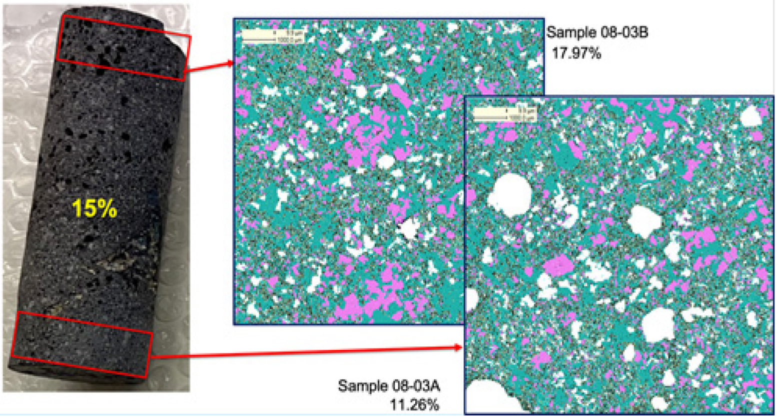


Figure 22: *Petrographic analysis performed with QEMSCAN of basalt sample from the HB-08 borehole comparing the value of porosity (Phi) measured with conventional core analysis (3D Phi) and on thin section (2D Phi). Note the difference of texture and Phi values at the top and bottom side of the core cylinder attesting for high degree of heterogeneity of this rock type.*

Mineral assemblage analysis

The basalt samples analyzed in this study from the HB wells, consist mostly of calcic plagioclase feldspar and pyroxene (usually Augite), with or without olivine. Rock samples also contain silica (i.e., glass and/or quartz), chromite, hornblende, biotite, pyroxene (i.e., Enstatite and Ferrosilite) and feldspathoids.

The thin sections prepared were scanned at 15 kV with a grid of 10 µm using the QEMSCAN. Pyroxene, olivine, and chromite minerals were added or adapted into the standard 15kV database based on scans and optical microscopy cross-check.

A high content of unclassified minerals was observed in some samples likely accounting for the presence of a higher amount of devitrified volcanic glass (Figures 23-26). Volcanic glasses, especially if partially devitrified, are difficult to resolve with the QEMSCAN because they consist of very fine-grained mixtures. As commonly found in dolerite dikes, a trace amount of quartz is present in the samples, but part of it shows mixed signal (not pure quartz) and might account for residual silicic volcanic glass (Figure 4.5-4.8). Relatively high amount of Chlorite found in sample 07-03 will be validated by XRD or Raman and it could be related to a product of basaltic glass alteration within cracks. Sample 07-03 is the only one showing a significant amount of basaltic volcanic glass. Importantly, the amount of background (white) is a broad estimate of the optically derived porosity of the sample (Figure 22-26).

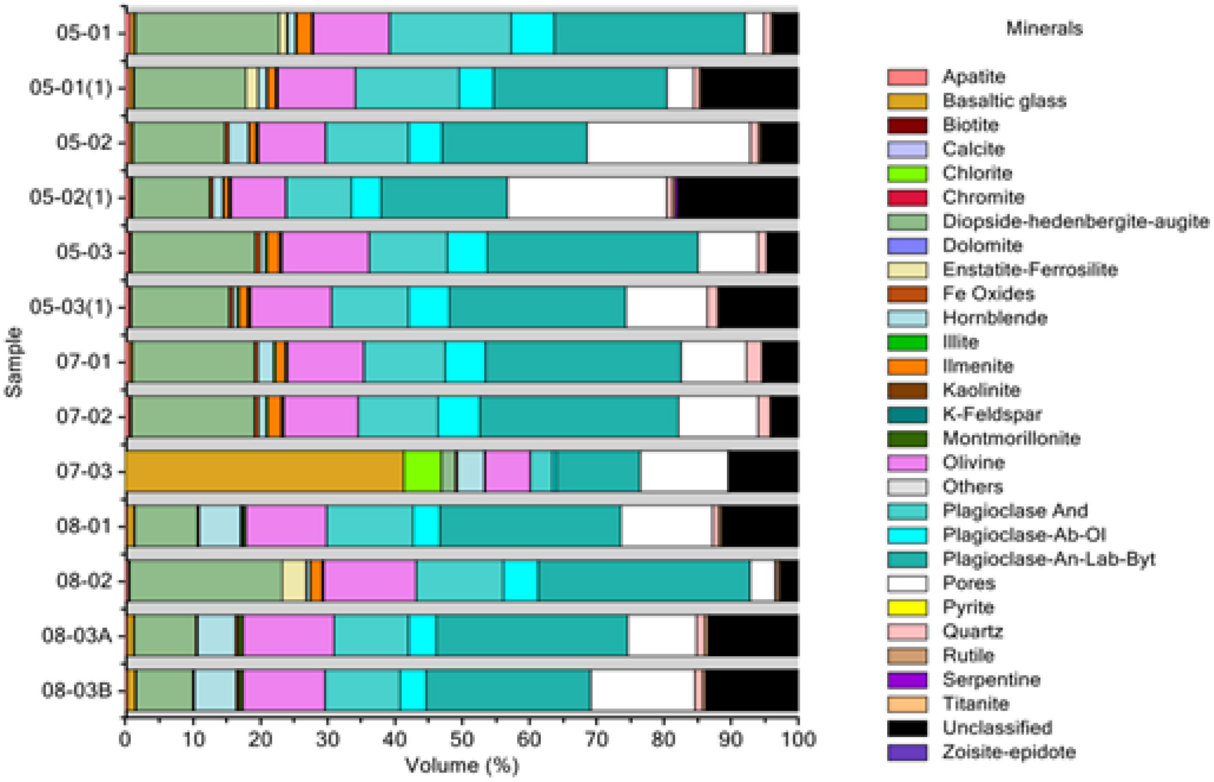
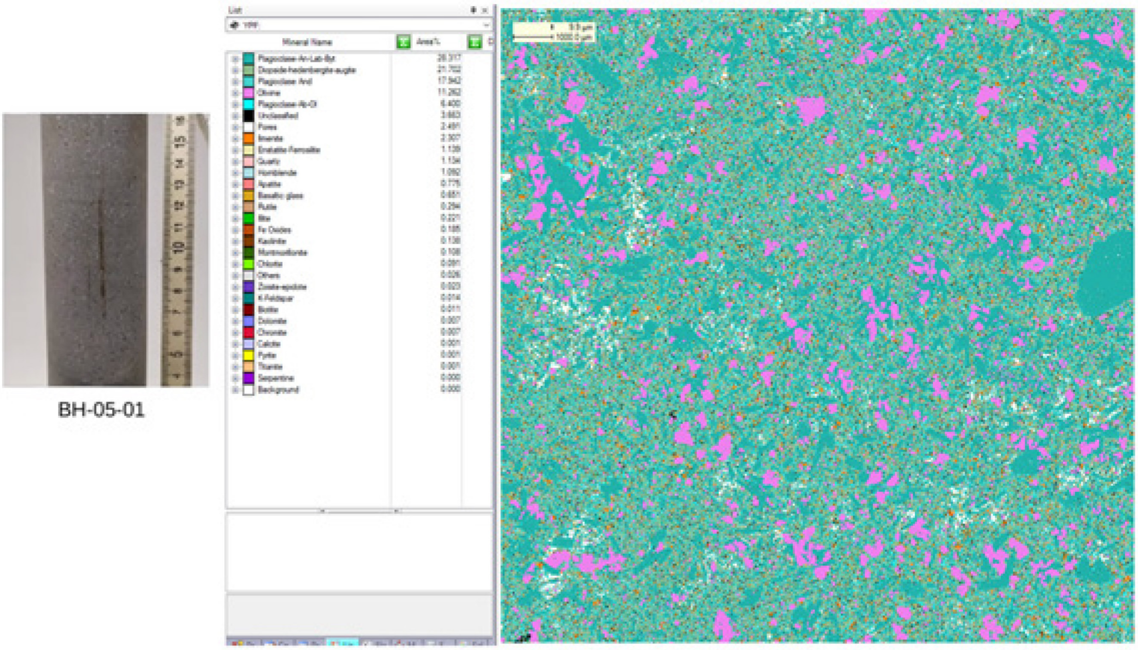


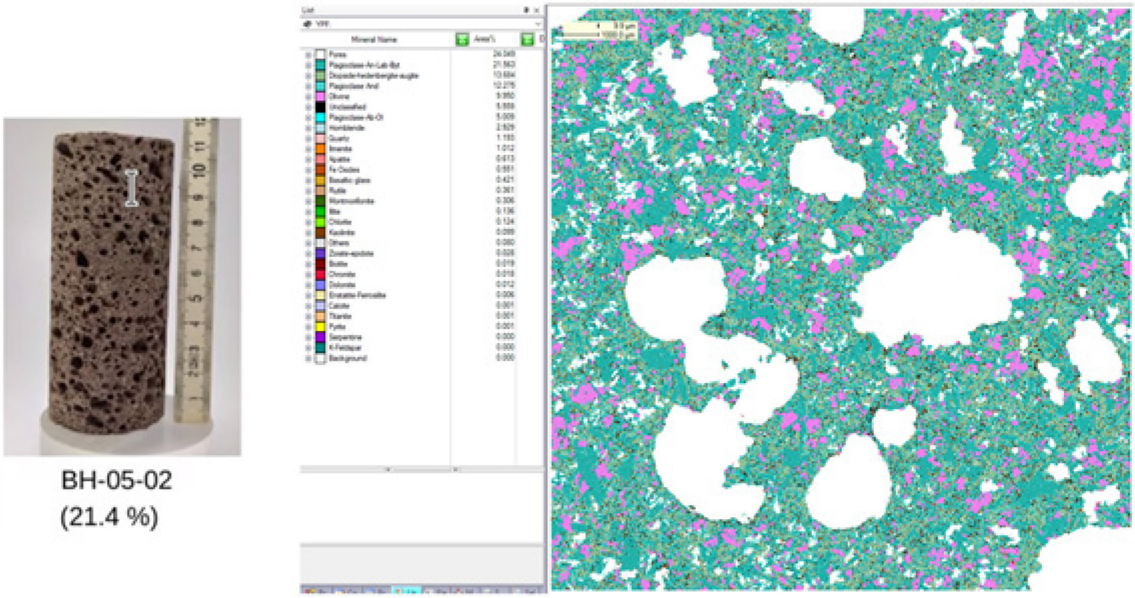
***Figure 23**: Mineral assemblages of all samples analyzed by QEMSCAN with indication of 2D porosity (white bar).*



BH-05-01

Mineral Name	Area%
Plagioclase-An-Lab-Byt	26.317
Diopside-hedenbergite-augite	21.702
Plagioclase And	17.942
Olivine	11.262
Plagioclase-Ab-Ol	6.400
Unclassified	3.663
Pores	2.491
Ilmenite	2.307
Enstatite-Ferrosilite	1.139
Quartz	1.134
Hornblende	1.092
Apatite	0.775
Basaltic glass	0.651
Rutile	0.294
Illite	0.221
Fe Oxides	0.185
Kaolinite	0.138
Montmorillonite	0.108
Chlorite	0.091
Others	0.026
Zoisite-epidote	0.023
K-Feldspar	0.014
Biotite	0.011
Dolomite	0.007
Chromite	0.007
Calcite	0.001
Pyrite	0.001
Titanite	0.001
Serpentine	0.000
Background	0.000

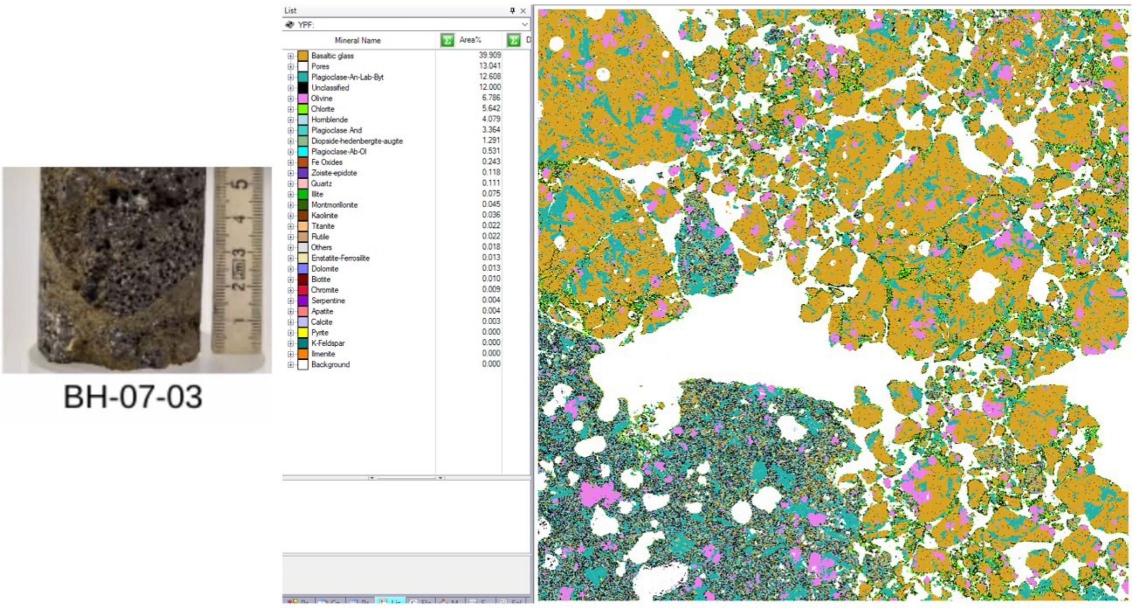
Figure 24: *Petrographic analysis performed with QEMSCAN of basalt sample from the HB-05-01.*



BH-05-02
(21.4 %)

Mineral Name	Area%
Pores	24.349
Plagioclase-An-Lab-Byt	21.563
Diopside-hedenbergite-augite	13.684
Plagioclase And	12.275
Olivine	9.850
Unclassified	5.859
Plagioclase-Ab-Ol	5.009
Hornblende	2.929
Quartz	1.193
Ilmenite	1.012
Apatite	0.673
Fe Oxides	0.551
Basaltic glass	0.421
Rutile	0.361
Montmorillonite	0.306
Illite	0.136
Chlorite	0.124
Kaolinite	0.099
Others	0.080
Zoisite-epidote	0.028
Biotite	0.019
Chromite	0.018
Dolomite	0.012
Enstatite-Ferrosilite	0.006
Calcite	0.001
Titanite	0.001
Pyrite	0.001
Serpentine	0.000
K-Feldspar	0.000
Background	0.000

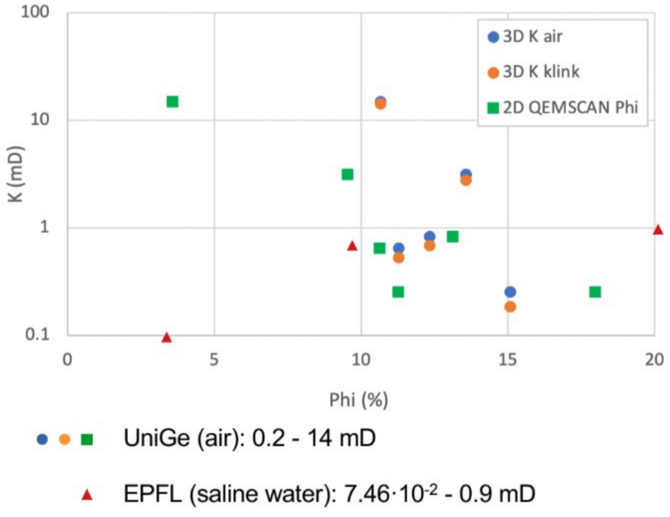
Figure 25: *Petrographic analysis performed with QEMSCAN of basalt sample from the HB-05-02, note the vuggy pores.*



Mineral Name	Area%
Basaltic glass	39.909
Pores	13.041
Plagioclase-An-Lab-Byt	12.608
Unclassified	12.000
Olivine	6.786
Chlorite	5.642
Hornblende	4.079
Plagioclase And	3.364
Diopside-hedenbergite-augite	1.291
Plagioclase-Ab-Ol	0.531
Fe Oxides	0.243
Zoisite-epidote	0.118
Quartz	0.111
Illite	0.075
Montmorillonite	0.045
Kaolinite	0.036
Titanite	0.022
Rutile	0.022
Others	0.018
Enstatite-Ferrosilite	0.013
Dolomite	0.013
Biotite	0.010
Chromite	0.009
Serpentine	0.004
Apatite	0.004
Calcite	0.003
Pyrite	0.000
K-Feldspar	0.000
Ilmenite	0.000
Background	0.000

Figure 26: *Petrographic analysis performed with QEMSCAN of basalt sample from the HB-07-03, note the high amount of basaltic glass (light brown/yellow color).*

4.3.3 Petrophysical characterization



Petrophysical analysis of porosity (Phi) and Permeability (K) performed both on core samples using conventional core analysis (CCA) with a optically-derived (from QEMSCAN) porosity (phi) and permeability (k) and core plug-derived measurements were performed on the available samples. For all samples analyzed, porosity ranges between 10.6 - 15 %, while permeability ranges between 0.2-14mD (Figure 27).

Figure 27*: Phi-K cross plot for the five basaltic samples derived from CCA.*

4.3.4 Reservoir Modelling

Conceptual model of Helguvik site

The definition of a conceptual model depicting a possible configuration of the subsurface geological conditions at the Helguvik site is necessary (Figure 28) in order to establish the key architectural elements and compositional characteristics which will be quantified in the reservoir model. In this context, a 3D conceptual reservoir model incorporating the four drilled boreholes (Carb 1-4), and their completion strategy together with possible reservoir layering and zonation is presented (Figure 28). Also, an envisaged fracture system is added to the model which has implications for controlling subsurface fluid-flow dynamics and mineralization. Furthermore, the groundwater flow direction in the area from south to north is added (Figure 28). In all, CO2 mixed with seawater will be injected via Carb1 into the storage formation for example layer 4c, likely composed of basaltic lavas interbedded with hyaloclastite layers This conceptual model will be iteratively revised as soon as more information from the borehole is available, such as cuttings, borehole images (fractures orientation) temperature and pressure gradient.

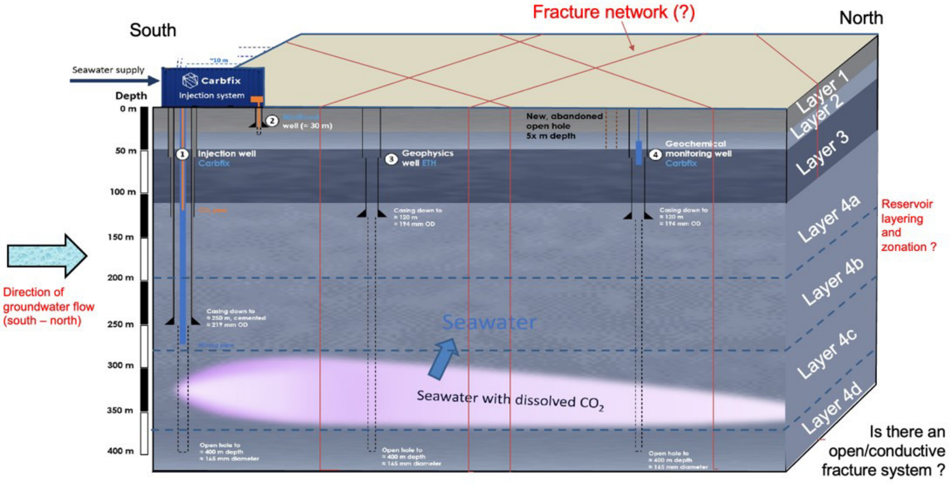


Figure 28: *3D conceptual reservoir model of the Helguvik site (modified by UNIGE from the initial 2D reservoir conceptual reservoir model presented by CARBFIX).*

Definition of model boundary

We have decided to extend the model to incorporate three pre-existing wells HB05, HB08, HB07 in addition to the four wells drilled (Figure 19). Importantly this new model boundary captures the cliffs and outcrop exposure which will enable an understanding of the fracture system. The geological characteristics such as strata and bed geometry of the cliff's outcrops have been drawn from offshore and reported in a ISOR report (Vikigsson and Kristinsson,1982) whereas the outcrop along a road cut has been photographed by a drone (Prof Tom Michell, personal comm.). The integration of all outcrops data in the 3D model is part of an ongoing MSc project at UNIGE.

Building the 3D static reservoir model

A new modeling area of interest has been defined spanning 1500 m x 1000 m to capture subsurface heterogeneities (Figure 29). The model was extended from the initial boundary (yellow polygon) to benefit from additional borehole data (HB-05, HB-07 and HB-08). Importantly, it also incorporates the outcrop exposure along the cliffs where valuable information on the subsurface fracture network can be derived and incorporated in subsequent (discrete fracture network modelling) DFN modelling. Importantly, the model boundary has been aligned in the same direction of the ground water flow south-north in the study area (Figure 28).

3D static model development

Firstly, a volume of interest (area of interest * model depth) was built spanning 1500 m (length) x 1000 m (width) x 400 m (depth) and gridded using a cell size of 5 m x 5 m (the wellbore domain can further be refined to 1 m by 1m) (Figure 29). At this stage, we are yet to implement a layering and zonation strategy into the 3D model. This will be done once a clear lithological, facie modelling and flow zonation is completed as soon as we receive the drilling report for the Carb1-4 borehole. Also, petrophysical properties and DFN will be added to the 3D model. Eventually, refinement and upscaling will be performed ensuring essential heterogeneities are respected prior to numerical modelling.

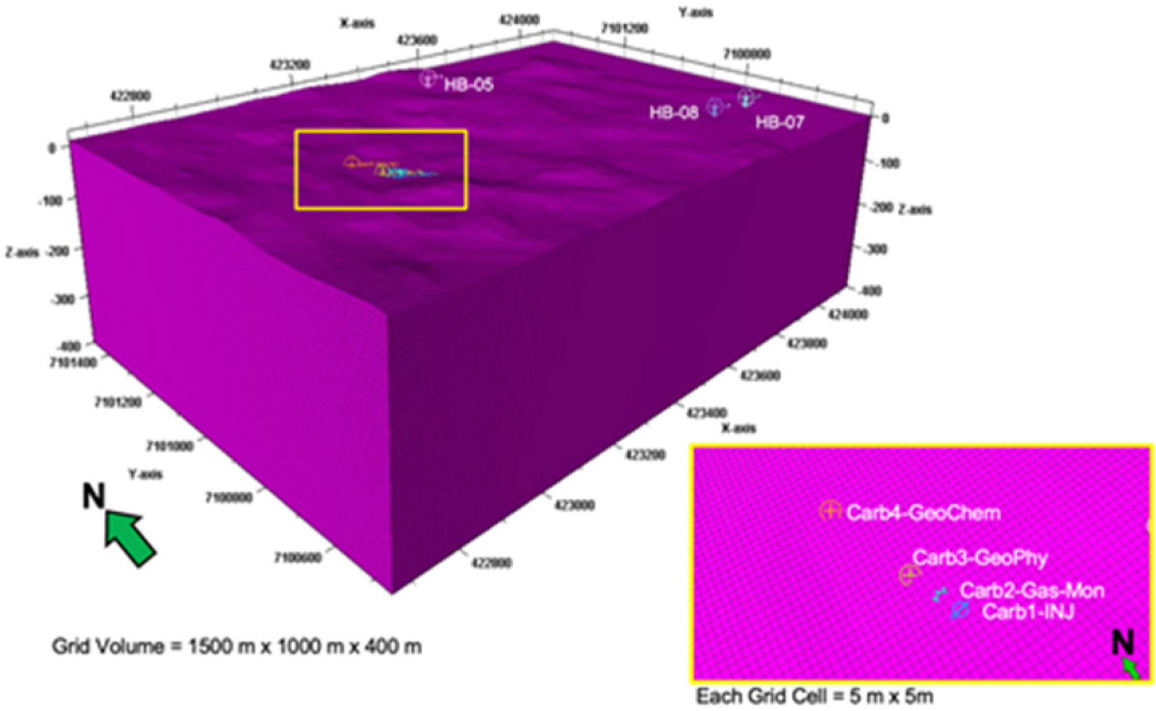


Figure 29: *Unattributed 3D static grid for the Helguvik site.*

4.4 Laboratory characterization and validation of processes (WP4)

4.4.1 Laboratory testing

Laboratory testing aims at providing a better insight into the efficiency of CO2 mineralization in the basaltic material and its impact on the material's hydromechanical properties. Injection and therefore trapping efficiency relies on the flow properties of the basaltic material. Eventual porosity reduction (clogging) can significantly limit the storage potential of the material (Callow et al., 2018), which in the case of injection under a constant flow rate, can lead to a local increase of pore pressure, reduction of effective stress and triggering of micro-seismicity.

The transport properties of the material before and after exposure to dissolved CO2 are targeted under pressure conditions representative of the field. The impact of eventual mineralization on the pore space of the material is investigated with 3D with x-ray tomography. Finally, a pore network model (PNM) is employed to simulate fluid flow and understand the impact of carbon mineralization on the connected porosity of the material.

Hydromechanical testing and CO2 mineralisation

Basaltic cores from a borehole located in the vicinity of the Helguvík site were used, where a distinct lava flow bedding has been identified. More precisely, the studied core originates from a shallow depth of ~20 m (BH-08) in the Hólmsberg cliff. The cores have been sized down to a diameter equal to 38 mm and a height of 78 mm. The flow properties of the basaltic sample were tested in the lab using the experimental setup illustrated in Figure 6. The sample was first confined at a pressure level of 5 MPa and saturated with synthetic saline water similar to the composition used by Voigt et al., 2021. The flow properties of the sample were then evaluated in terms of permeability and hydraulic conductivity. The measurement of hydraulic conductivity was performed with the constant head method (Darcy, 1856; Renard et al., 2001), applying a water pressure difference equal to 1 MPa between the upstream (2 MPa) and downstream (1 MPa) sides of the sample.

After the establishment of the initial flow properties of the sample, injection of CO2 dissolved into saline water was performed. CO2 has been dissolved in the saline water in a reservoir at a pressure of 2 MPa and a volume of at least equal to the pore volume of the sample was injected. The two pore pressure valves (upstream and downstream) were then closed and the sample was left under no flow CO2 exposure over a minimum period of 1 month, at confining pressure 5 MPa and pore pressure 1.5 MPa, i.e. differential pressure equal to 3.5 MPa. The flow properties of the sample were finally measured after CO2 exposure by applying the same constant head method (ΔP = 1 MPa) and eventual carbon mineralisation was evaluated.

4.4.2 Micro-structural analysis and pore network modeling

Carbon mineralization is expected to alter the pore structure of the basaltic material. Mineral precipitation will result in reduction of the porosity and consequently reduction of the transport properties of the material. To understand the impact of mineralization on the pore structure of the material, the tested sample has been scanned in the x-ray tomography (50 μm/px) before and after CO2 exposure. Figure 30 shows the reconstructed 3D volume of a basaltic sample with XRCT and the 3D volume of the pores. Overall, XRCT images of the different samples showed a high heterogeneity of the pore space, with large pores at the bottom and denser zones at the top of the sample. Regardless of the existence of very large pores (in the range of a few millimeters), flow is dominated by the connected porosity of the material; it is therefore of crucial importance to understand the connectivity of the tested sample.

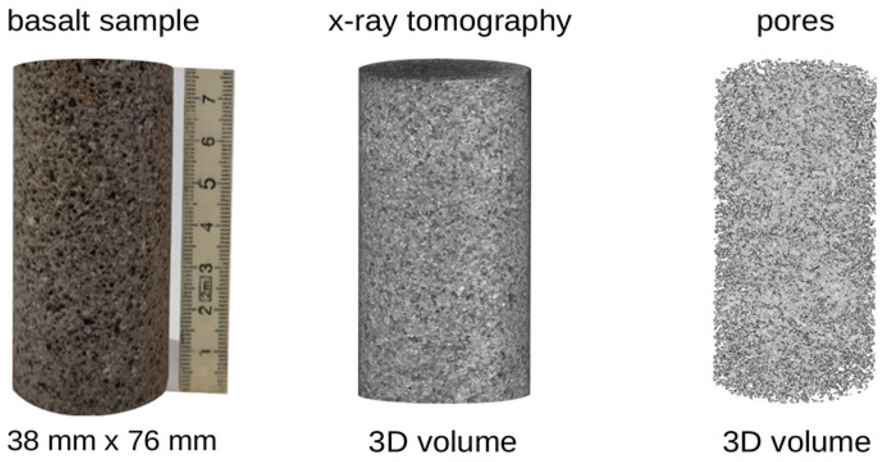


***Figure 30:** left: Cylindrical basaltic sample; middle: reconstructed 3D volume with XRCT; right: calculated 3D pore space*

To better understand the correlation between the pore structure of the material and the experimentally measured flow properties, a pore network model (PNM) has been employed using the open source openPNM code (Gostick et. al, 2016). The 3D pore network was extracted directly from the x-ray image based on the snow algorithm (Gostick, 2017). More precisely, a binary image of the pores/solid matrix structure was used as input data (similar to Figure 30 right). This algorithm uses a watershed segmentation method that defines the pore regions based on a calculated distance from the solid matrix. The pore space is then described as a network of pores connected by throats that are represented by a spherical and cylindrical geometry respectively. Fluid flow simulation was then performed and the absolute permeability of the network was calculated based on the Darcy law, considering single-phase laminar flow.

An initial characterisation of the micro-structure of the cores has been performed with XRCT scans. The porosity of the basaltic samples is measured in 3D with an average resolution of 50μm. The calculated porosity of the used samples is plotted in Figure 31 with depth of origin and the measured hydraulic conductivity in the lab (black points). It is obvious from these plots that basalts, unlike sedimentary rocks, have a varying porosity with depth without a given trend. Most importantly their total porosity does not correlate with their flow properties that are driven by the connected porosity which can be significantly smaller.

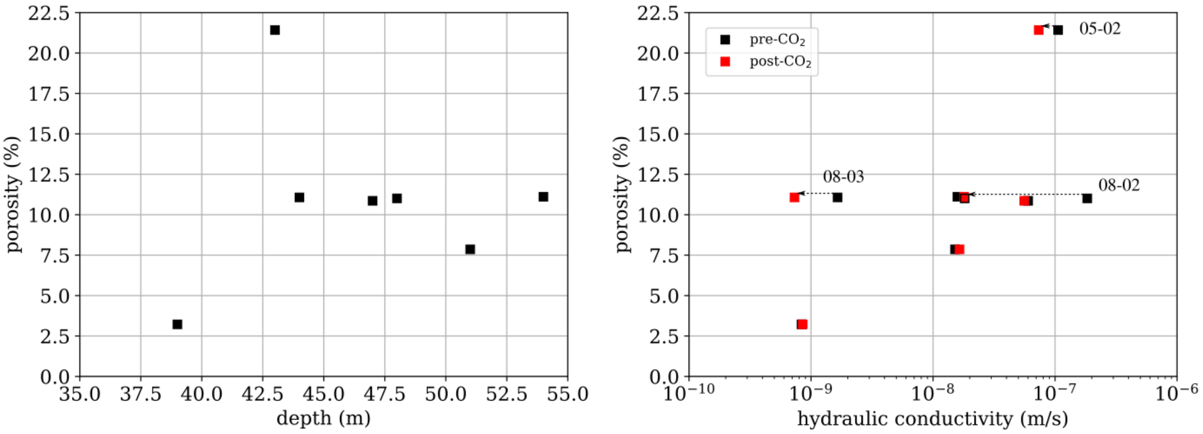


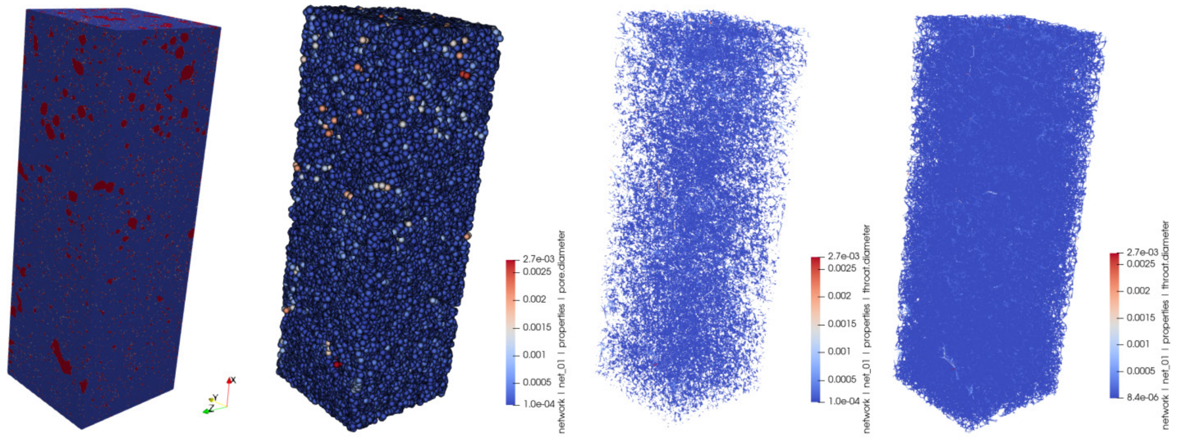
***Figure 31**: Initial porosity of the seven basaltic cores as a function of depth (left) and hydraulic conductivity before and after CO2 exposure (right)*

The experimental results of hydromechanical testing before and after CO2 exposure are plotted in Figure 31 (red points) and summarized in Table 3. One month of exposure did not result in a significant change of hydraulic conductivity, except for sample 05-02 which exhibited a 30% lower conductivity after CO2 exposure. Sample 05-02 was the only sample with a significantly higher porosity > 20%, but most importantly the only sample including a pre-existing fracture. Even though micro-structural analysis of the sample has not yet been conclusive due to resolution limitations, this result demonstrates the importance of fissured zones for the efficiency of mineralization: higher reactive surface area.

The last three samples were exposed to CO2 for a longer duration (2 to 3.5 months) in order to better understand the timing of mineralization under no flow conditions. A significant conductivity decrease by one order of magnitude (from 1.83·10-7 m/s to 1.81·10-8 m/s) was obtained for sample 08-02 that was exposed to CO2 over the longest period duration of 3.5 months. Sample 08-03 presented a considerable decrease in conductivity by half an order of magnitude already after two months of exposure, from 1.65·10-9 m/s to 7.32·10-10 m/s. These results suggest that mineral precipitation has taken place over the exposure period, leading to a reduction of the connected porosity and consequently flow. Carbon mineralization is directly dependent on the mineralogical composition of the exposed core, which is quite variable between the tested cores; this is obvious already from the different color of the samples. For instance, sample 08-03 is the only sample that contains a high percentage of volcanic glass that is known to be very reactive with CO2 and thus important for mineralization. Reduced flow properties of sample 08-03 are supported by the porosity measurements from XRCT. Based on the acquired x-ray images, an initial 3D porosity of 11.07 % is measured which decreases to 8.61% after two months exposure to dissolved CO2. At the given resolution, it has not been possible to distinguish precise localized regions where pore size modification has taken place. Thus, to gain a better insight in the evolution of the pore network from potential mineral precipitation, flow simulations are performed in the pore network extracted from each image, i.e. before and after CO2 exposure.

Sample	CO_2 exposure duration	K pre-exposure (m/s)	K post-exposure (m/s)
05-01	33 days	$8.35 \cdot 10^{-10}$	$8.55 \cdot 10^{-10}$
05-02	28 days	$1.06 \cdot 10^{-7}$	$7.35 \cdot 10^{-8}$
05-03	31 days	$6.02 \cdot 10^{-8}$	$5.59 \cdot 10^{-8}$
07-01	28 days	$1.51 \cdot 10^{-8}$	$1.65 \cdot 10^{-8}$
07-02	85 days	$1.58 \cdot 10^{-8}$	$1.79 \cdot 10^{-8}$
08-02	110 days	$1.83 \cdot 10^{-7}$	$1.81 \cdot 10^{-8}$
08-03	60 days	$1.65 \cdot 10^{-9}$	$7.32 \cdot 10^{-10}$

Table 3: *Experimental results of flow tests on seven basaltic cores before and after CO_2 exposure*



(a) (b) (c) (d)

Figure 32: *Initial pore structure before CO2 exposure. (a) Binary input volume of pores (red) and solid (blue) from x-ray tomography, (b) Pore network created from the input x-ray image (color bar: pore diameter in m), (c) Initial connectivity (throats) of the pore network (color bar: throat diameter in m), (d) Fully connected network (color bar: throat diameter in m)*

A pore network is assigned based on the input porosity image, and according to their size, a distance of the fitted pores connecting throats is additionally assigned. In both images, the pore architecture at the given resolution results in a poorly connected network in which flow throughout the entire height of the sample is not possible. For this reason, the isolated pores, i.e. the non-connected pores are manually connected to the rest of the network by assigning a fixed throat diameter. This throat diameter represents the porosity of the solid matrix of the material that cannot be detected from the scan resolution. In this way the connectivity of the material is represented by a double-scale porosity: macro-porosity (pores > 50 μm) and micro-porosity (solid matrix). A reduced number of connecting throats, i.e. connected pores, is calculated after CO2 exposure, confirming a reduced connectivity in the network. The different steps for the creation of the fully connected network before initiating the flow simulation are presented in Figure 32.

Single-phase flow simulation is then performed under conditions similar to the hydromechanical tests in the lab. The resulting flow rates and permeability for both states of the sample are presented in Table 4 and are in good correspondence with the experimental values for a solid matrix throat diameter equal to 8.40 μm.

	Initial number of pores/throats	Final number of pores/throats	Hydraulic conductivity (m/s)	Flow rate (m^3/s)
Pre-CO_2 exposure	164815/85066	164815/356968	$1.649 \cdot 10^{-9}$	$3.895 \cdot 10^{-9}$
Post-CO_2 exposure	105208/43959	105208/211978	$7.294 \cdot 10^{-10}$	$1.722 \cdot 10^{-9}$

***Table 4:** Flow rates and permeability before and after CO_2 exposure*

To confirm how the measured porosity reduction from the two x-ray images affects flow, the pore diameter of the fully connected pore network (pores > 50 μm) before CO2 injection is decreased by the measured amount, i.e. by 2.4%. Flow simulation of the modified network results only in a very slight reduction of permeability from 1.649·10-9 to 1.637·10-9 m/s. This response suggests that potential mineralization in the macro-pores of the material does not impact flow in a significant way. Indeed, an additional reduction of micro-porosity, i.e. solid matrix porosity, is necessary to acquire the post-exposure flow response, from 8.40 μm to 6.85 μm. This result reveals that mineralization is more prone to take place in the micro-pores, affecting the flow properties of the material by reduction of half an order of magnitude already after 2 months of exposure.

5 Evaluation of results to date

5.1 Time-lapse CO2 migration monitoring (WP2): Combined geophysical and geochemical techniques

Geophysical Observations

Since the CO2 injection has not started yet, it is too early to comment on the geophysical capacity to perform time lapse CO2 migration monitoring. However, the first measurements, in particular the ERT measurements look highly repeatable, which is promising with regard to the changes that we hope to detect after CO2 injection.

Dissolved gasses observations

The results obtained with the miniRUEDI provide valuable insights into the background and characteristics of dissolved gasses in both wells, contributing to a deeper understanding of the surface environment and the effectiveness of the CARBFIX's carbon sequestration efforts. Dissolved gas composition in Carb-2 well is close to air, suggesting that the groundwater in Carb-2 well resembles air-saturated water. This finding points towards precipitation as the primary source of water in this unconfined aquifer (see Figure 18). During the field investigation, we observed rapid water dissipation after injecting water into Carb-2 well, indicating high permeability and a well-connected pore space. These interconnected pores created an open-air condition in the unsaturated zone, allowing infiltrated precipitation to reach equilibrium with the air before reaching the water table, reasonably explaining the observed air-like dissolved gas composition. In comparison, the significantly higher He, Ar, Kr, and N2 partial pressures in Carb-3 well could be attributable to excess air dissolution in the confined groundwater (see Figure 18). While the consistent decreases in O2 and CO2 partial pressures in the Carb-3 well may be caused by hydro-biochemical processes, such as nitrification, sulfate oxidation, and CO2 fixation (Vachon et al., 2020).

The field site is near the ocean. Thus, the local atmospheric pressure is ~1.01 bar. Interestingly, the total dissolved gas pressure in Carb-2 groundwater was ~4% lower than the atmospheric pressure, while Carb-3 exhibited a higher total dissolved gas pressure of ~10% above the atmospheric pressure. The lower total dissolved gas pressure in Carb-2 well can be attributed to reduced O2 and CO2 partial pressures, which may result from biogeochemical reactions in the shallow unconfined aquifer. In contrast, the significantly higher total dissolved gas pressure in Carb-3 may be a result of both excess air dissolution at recharge and biogeochemical reactions in the groundwater. The comprehensive quantitative analyses will help discern the primary driving forces shaping the total dissolved gas pressure in Carb-3 well. Additionally, both Carb-2 and Carb-3 wells exhibited significantly higher temperatures than the annual average air temperature (~5 degrees Celsius), indicating geothermal heating of the local groundwater. Long-term monitoring of dissolved gas measurements will reveal the ongoing gas dynamic and evolution at this site.

5.2 Geophysical & Geological modeling at Reservoir Scale

The results from the rock typing and petrophysical analysis of basaltic samples representative of the storage formation reveals that:

- Phi-K values from core plugs show low to medium reservoir connectivity for the matrix scale (0.2-14 mD).

- Mineralogical composition shows differences which can explain reservoir properties (occurrence of widespread micro-crystalline volcanic glass).
- Some basalt layers might behave as sealing unit.
- The number of samples measured for K and Phi is not statistically significant and to date does not constitute a solid base for reservoir modeling. Alternatively, the use of analogue Phi and K database from Oil & gas industry – if accessible - could be a viable solution.
- Fracture porosity is not assessed to date but likely affecting the reservoir fluid-flow behavior and storability.
- Need to land on key decisions for fit-for-purpose 3D modeling (static & dynamic).

5.3 Laboratory characterization and validation of processes

The impact of carbon mineralization on the transport properties of a basaltic material have been investigated with combined laboratory flow tests and micro-structural modeling. The obtained experimental and modeling results provide an important insight into the occurrence of preferential mineralization in the pore structure of the intact material by considering two distinct macro- and micro-porosity scales.

The following main findings can be summarized:

- Reduction of flow properties by 30% after one month of CO2 exposure in the only fissured sample demonstrates the importance of increased reactive surface for the efficiency of mineralization.
- Significant decrease of hydraulic conductivity by one order of magnitude after 3.5 months of CO2 exposure
- Carbon mineralization in the sample with high content of volcanic glass occurs already after a 2-month exposure of CO2-rich seawater. Mineralization is confirmed by means of permeability reduction before and after CO2 exposure in the lab (it decreases by half an order of magnitude).
- Mineral precipitation is additionally indicated from 3D image analysis of x-ray tomographies of the tested sample before and after exposure. A reduction of total porosity by 2.4 % has been measured for an image resolution of 50 µm/px.
- To reproduce the flow properties of the tested sample from the pore network extracted from the sample’s x-ray image, a double porosity must be assigned. In addition to the connected macro-pores, a micro-porosity representing the solid matrix pore size is set to 8.4 µm in order to reproduce a fully connected network.
- Reduction of the macro-pores by 2.4 % in the pore network simulation, i.e. porosity reduction from image analysis at the given resolution, does not have any significant impact on the acquired fluid flow. Reduction of the micro-porosity by 18.5 % is required to reproduce the post-CO2 experimental results. This response suggests that carbon mineralisation is more prone to take place in the micro-pores of the material rather than the large pores.

The results of this lab-scale study show that carbon mineralization can impact the flow properties of the basaltic material, mainly by reduction of the micro-porosity. Successful implementation of the technology at large scales requires an injection in locations of high porosity, ideally in fractured zones where flow can be ensured and mineralization will not result in pore clogging.

6 Next steps

The project's ambitious objective is to showcase, on a field scale, the effective and enduring storage of CO2 underground. Employing geophysical techniques, we aim to identify carbonate precipitation resulting from the interaction of injected CO2 and available basalt cations (Mg, Fe, Ca, etc.) by monitoring seismic velocity changes. Detecting mineral carbonation involves observing substantial precipitation of solid phases in pores and fractures at depth. We may also identify specific locations of precipitation. Continuous detection of dissolved gases in the formation water by the miniRUEDI will inform and optimize the seismic campaign while revealing the aquifer's dynamics at depth.

The miniRUEDI's ability to detect the initial arrival of dissolved CO2 and the Helium tracer allows to detect when CO2 arrives at boreholes 3 and 4. This, combined with the injection data and the additional periodic sampling by Carbfix of fluids from borehole 4, will allow us to calibrate our reservoir and flow model of the basaltic layers. The speed of the ground water migration through the reservoir is a key unknown in our modelling and in defining a quantitative understanding of the mineralisation process. Additionally, the miniRUEDI, connected at shallow depth (Borehole 2), serves as a detector for potential gaseous CO2 leakage into the atmosphere. It effectively monitors shallow aquifers and acts as an early warning system in case of unexpected upward migration of the injected CO2, dissolved in fluid or, possible, after degassing.

The most challenging task will be to verify the mineralisation and ultimate long-term storage of the CO2. One key to achieving this goal is to compute the mass balance of injected CO2 and quantifying the fraction that precipitates in the rock formation based on isotope analysis. This task will mainly be tackled by Carbfix, supported by the miniRUEDI data; data and results are freely shared between Carbfix and the Swiss partners. The real-time geophysical data from the ERT, and the differential tomographic imaging should allow to identify and estimate the changes in resistivity and seismic velocity and allow to approximate mineralisation volumes. We will also then use the lessons learned from laboratory studies and combine all information into a dynamic reservoir model including chemical reactions that hopefully will allow us to constrain mineralisation. However, DemoUpStorage is breaking new ground in this respect and before obtaining and analysing the data, it is difficult to predict how successful and how uncertain we will be in verifying mineralisation. No monitoring system can easily been installed in the nearby coastal environment, making it difficult to rule out migration of dissolved CO_2 into the nearby ocean as part of ground-water flow. The most conclusive evidence confirming basalt carbonation would involve acquiring rock samples near the injection well. This could be achieved by drilling a new boreholes one or two years after the start of the injection; alternative, it may be possible to retrieve cores from small side-track to the existing wells. Our aspiration is to obtain such samples in the future, possibly as part of upcoming scientific collaborations between Switzerland and Iceland.

More specific steps in the monitoring activities, planned for the next months are described below.

6.1 Time-lapse CO2 migration monitoring (WP2): Combined geophysical and geochemical techniques

Geophysical Techniques

After the injection starts, we will conduct daily ERT measurements. The next and final cross hole seismic easement campaign is planned in 6-12 months from the injection start, depending on the progress in injecting and based on the analysis of measurement results obtain in real-time. Parallel to that we will analyze all the gathered seismic and ERT data. This includes:

- Use the weight drop seismic data to build a rough velocity model of the subsurface

- Use this velocity model to invert the crosshole seismic data using either traveltime- or full waveform tomography
- Compare the crosshole data to the synthetic seismic modelling data obtained in the planning phase of the survey. What did we predict right? Where do we need to adjust? Was it worth doing such in-depth simulations for the planning of the survey?
- Continue the daily ERT measurements and also do multiple surveys a day to study potential tidal effects.
- Interpret the data with the help of stratigraphic and logging data

Dissolved gasses

To better understand the local gas dynamics and to better capture the carbon transportation and transformation processes, we plan to extend our dissolved gas monitoring as follows:

- Monitor the time-series of dissolved gas concentrations at the more downstream site (Carb-4 well, geochemistry well);
- Capture the temporal variations of dissolved gas concentration in these wells after CO2 sequestration in the injection well;
- Measure the electrical conductivity, pH in these wells for better understanding the origin and hydrochemical evolution of groundwater in the two aquifers.

6.2 Geophysical & Geological modeling at Reservoir Scale

The next steps foreseen are:

- Perform more rock typing and petrophysical analysis of cuttings from the Carb1-4 boreholes. This will afford a comprehensive understanding of the actual reservoir characteristics of the storage site.
- Complete geochemical and petrographic analysis of cuttings from Carb1-4 boreholes to identify possible vertical reservoir layering using a chemostratigraphic approach.
- Perform well log analysis, especially focusing on the lithofacies analysis of the basalt and the image logs that can give insight into the facture network at the storage site.
- Add layers and zones, based on the results of the preceding tasking to the unattributed model. Furthermore, the 3D model will be populated with petrophysical properties and other temperature and pressure information in preparation for numerical modeling.

6.3 Laboratory characterization and validation of processes

The next steps foreseen are:

- Fracture analysis of sample 05-02.
- Further (and longer) CO2 exposure of selected samples?
- Micro-structural analysis of a micro-sample (5 mm x 5 mm) after long-term exposure with XRCT (optional/bonus)

7 National and international cooperation

Collaboration within and outside of Switzerland are an important componenzt of DemoupStorage.

- We collaborated closely with Carbfix, and this collaboration – in partnership with the companion project DemoUpCarma, is now developing also into potential follow up and uo-scaling project. DemoUp* may thus open up a first pathway to commercial storage of Swiss CO2 in Iceland.
- In the context of the EuroStars project CO2SeaStone, we are collaborating with the University of Iceland and University College London.
- The work of DemoUpStorage has been important in shaping the CITRu project (CO2 storage in Trüllikon), a first injection test of CO2 in Switzerland explored by Swisstopo and ETH.

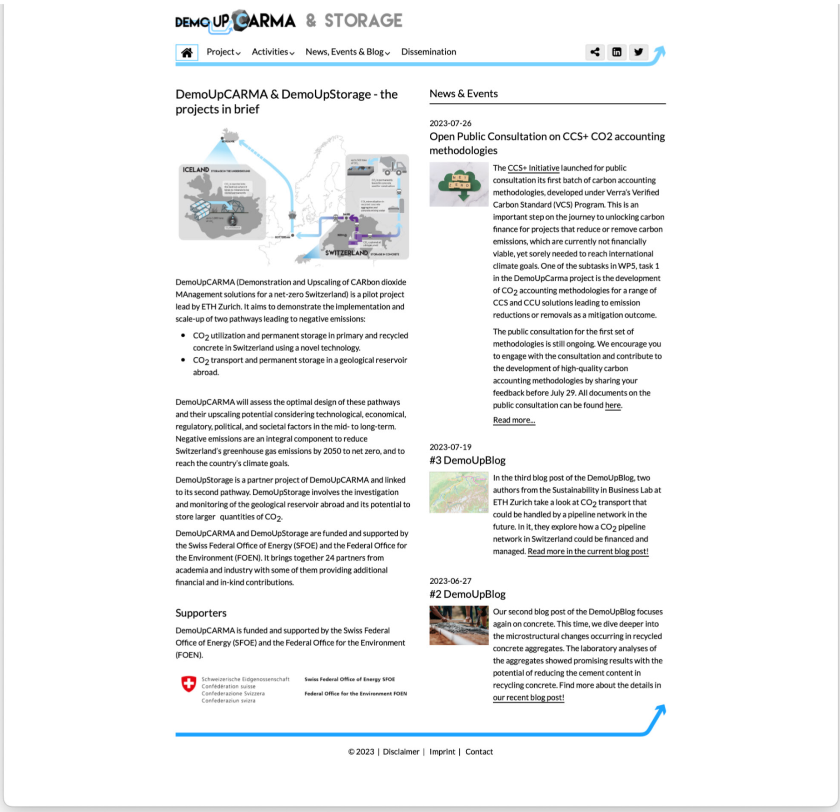
8 Communication

WP5, among others, focuses on the societal perspective of the project (e.g., public perception) and the communication of the project results to a wide audience including professional stakeholders and the general public. To this end, we closely collaborated with the DemoUpCARMA project team and built on their gained expertise. In the following, we summarize the main achievements in the last year.

A key element of communication to the informed public as well as to project stakeholders was the DemoUpCarma dn DemoUp storage joined web site at www.demoupcarma.ethz.ch. We regularly updated the web site with news and events as well as with additional background information on the project.

For the web site, and for general communication, we developed also a number of key graphics that explain the concept of DemoUpStorage (see for example Figure 33).

A highlight of the project in the past year was the visit of the President of the Swiss Confederation, Alain Berset to the Hellisheiði plant (Figure 34), where the initial four shipments of CO2 (80 tons in total) from Switzerland are currently being injected underground. The plant, operated by Carbfix, a partner of DemoUpStorage, injects CO2 mixed with water for permanent mineralization at its existing wells by the geothermal power plant in Hellisheiði. Marco Mazzotti, coordinator and head of the DemoUpCARMA project at ETH Zurich, attended the visit as the project representative to offer insights. see https://www.admin.ch/gov/en/start/documentation/media-releases.msg-id-95116.html for the press release related to this visit.



DEMO UP CARMA & STORAGE

DemoUpCARMA & DemoUpStorage - the projects in brief

DemoUpCARMA (Demonstration and Upscaling of CARbon dioxide MAnagement solutions for a net-zero Switzerland) is a pilot project lead by ETH Zurich. It aims to demonstrate the implementation and scale-up of two pathways leading to negative emissions:

- CO_2 utilization and permanent storage in primary and recycled concrete in Switzerland using a novel technology.
- CO_2 transport and permanent storage in a geological reservoir abroad.

DemoUpCARMA will assess the optimal design of these pathways and their upscaling potential considering technological, economical, regulatory, political, and societal factors in the mid- to long-term. Negative emissions are an integral component to reduce Switzerland's greenhouse gas emissions by 2050 to net zero, and to reach the country's climate goals.

DemoUpStorage is a partner project of DemoUpCARMA and linked to its second pathway. DemoUpStorage involves the investigation and monitoring of the geological reservoir abroad and its potential to store larger quantities of CO_2.

DemoUpCARMA and DemoUpStorage are funded and supported by the Swiss Federal Office of Energy (SFOE) and the Federal Office for the Environment (FOEN). It brings together 24 partners from academia and industry with some of them providing additional financial and in-kind contributions.

Supporters

DemoUpCARMA is funded and supported by the Swiss Federal Office of Energy (SFOE) and the Federal Office for the Environment (FOEN).

Schweizerische Eidgenossenschaft
Confédération suisse
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Swiss Federal Office of Energy SFOE
Federal Office for the Environment FOEN

News & Events

2023-07-26
Open Public Consultation on CCS+ CO2 accounting methodologies

The CCS+ Initiative launched for public consultation its first batch of carbon accounting methodologies, developed under Verra's Verified Carbon Standard (VCS) Program. This is an important step on the journey to unlocking carbon finance for projects that reduce or remove carbon emissions, which are currently not financially viable, yet sorely needed to reach international climate goals. One of the subtasks in WP5, task 1 in the DemoUpCarma project is the development of CO_2 accounting methodologies for a range of CCS and CCU solutions leading to emission reductions or removals as a mitigation outcome.

The public consultation for the first set of methodologies is still ongoing. We encourage you to engage with the consultation and contribute to the development of high-quality carbon accounting methodologies by sharing your feedback before July 29. All documents on the public consultation can be found here.

Read more...

2023-07-19
#3 DemoUpBlog

In the third blog post of the DemoUpBlog, two authors from the Sustainability in Business Lab at ETH Zurich take a look at CO_2 transport that could be handled by a pipeline network in the future. In it, they explore how a CO_2 pipeline network in Switzerland could be financed and managed. Read more in the current blog post!

2023-06-27
#2 DemoUpBlog

Our second blog post of the DemoUpBlog focuses again on concrete. This time, we dive deeper into the microstructural changes occurring in recycled concrete aggregates. The laboratory analyses of the aggregates showed promising results with the potential of reducing the cement content in recycling concrete. Find more about the details in our recent blog post!

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***Figure 33**: The DemoUpCARMA & Storage website*

***Figure 34:** the visit of the President of the Swiss Confederation, Alain Berset in April 2023*

8.1 Information exchanges

In close collaboration with WP3 in DemoUpCARMA, updates on the drilling site, the monitoring concept and the lab experiments (EPFL) were presented at the consortium meetings in January and July. This encouraged the dialogue between researchers and industry representatives from the consortium and helped the project partners to understand the full CCTS chain including the scientific aims of DemoUpStorage.

To ensure further information exchange between both projects and within both consortia, an internal newsletter has been sent three times. For each issue, DemoUpStorage project members contributed with short reports about the project's status.

The website of DemoUpStorage has been integrated in the DemoUpCARMA website. We also created an infographic to explain the monitoring setup of DemoUpStorage.

Overall, from the insights in DemoUpCARMA, we know that people want specific examples and different expert opinions (Dallo et al., 2023). In our communication, we thus aim to always provide explanations of tangible processes and investigations and to give experts from different disciplines the chance to report their findings. This allows the public and professional stakeholders to build informed opinions. We also follow the advice to provide structured information (Dallo et al., 2023), thus simplifying information at the top of the website page and more detailed information when scrolling down.

8.2 Societal acceptance of CO2 storage in Iceland

Besides technological assessments, societal issues must be addressed too since public opposition can hinder projects, as we have seen in the context of other technologies such as geothermal power plants (Stauffacher et al., 2015). Therefore, it is key to involve the public from the beginning of the project to address their questions and concerns (Dechezleprêtre et al., 2022; Offermann-van Heek et al., 2020). Through transparent communication (see section 8.1), the public should be continuously informed about the findings of the projects, including the benefits and possible risks of the processes.

To this end, it is crucial to consider that various personal, social, and local factors influence public perception of, acceptance of, and support for CCTS/CCUS efforts. For example, Merk et al. (2022) have shown that Norwegians have a higher acceptance of CCTS/CCUS when the CO2 is domestically sourced and not foreign. Further, higher trust in industry, science, and government increases public support (Jobin & Siegrist, 2020). In comparison, perceived uncontrollability (Arning et al., 2020), preferences for other climate mitigation measures (Oltra et al., 2010), perceived risks and tampering with nature (Jobin & Siegrist, 2020) decrease public acceptance.

Regarding the specific CCTS process in DemoUpStorage, we in the first step assessed Swiss public familiarity with, acceptance of, and support for the pathway which captures CO2 at a biogas plant in Switzerland, transports and stores it durably in a geological reservoir in Iceland (see Figure 35; Dallo et al., 2023). In this study, we found out that the Swiss public (i) does not know much about this process but wants to know more; (ii) agrees that the Icelandic population must accept the CO2 storage in their country; (iii) prefers that CO2 is transported by train or pipelines; and (iv) perceives various benefits and risks related to this process (e.g., able to neutralize the hard-to-abate emissions, CO2 leakage, environmental pollution).

In parallel, we have started assessing the Icelandic public's and stakeholders' perception of the CO2 storage efforts in their country and the upscaling plans. These studies are delayed because we wanted to coordinate with the efforts of other research groups, namely Risiko-Dialog and the Transdisciplinarity Lab (TdLab) at ETH Zurich; primarily, to avoid bothering professional stakeholders and the general public in Iceland twice and to take into account Carbfix's role and position in the country. Carbfix has already conducted a survey with the public to assess their opinions and perceptions, thus they can be contacted directly for more information.

What we have done so far was to add some questions related to the DemoUpCARMA CCTS pathway to the interview guideline of Risiko-Dialog. They conducted as part of the CDR PoEt project interviews with various Icelandic stakeholders (e.g., industry, NGOs, and administration) to understand their perception of the Direct Air Carbon Capture and Storage (DACCS) efforts, and added some questions also about the CCTS process. Overall, the options were mixed across the interviewees. Some prefer the existing CCS efforts in Iceland and question the carbon footprint of transportation (which is in line with the Swiss public's concerns). They further critically reflected on the energy needed to operate the CO2 storage process, also in the light of their national energy strategy. Some also wondered if they should not rather support, with their knowledge and expertise, other countries to implement CO2 storage in their own countries

In addition, we collaborate with a doctoral student from the TdLab at ETH Zurich who has already conducted a media content analysis and interviews with some stakeholders. She further plans to conduct focus groups with professional stakeholders and the public to assess their perception of the CO2 storage efforts and upscaling plans. Thus, we aim at integrating these insights into this task too.

The deliverable with the insights on the Icelandic public perception will be submitted by the springf 2024.

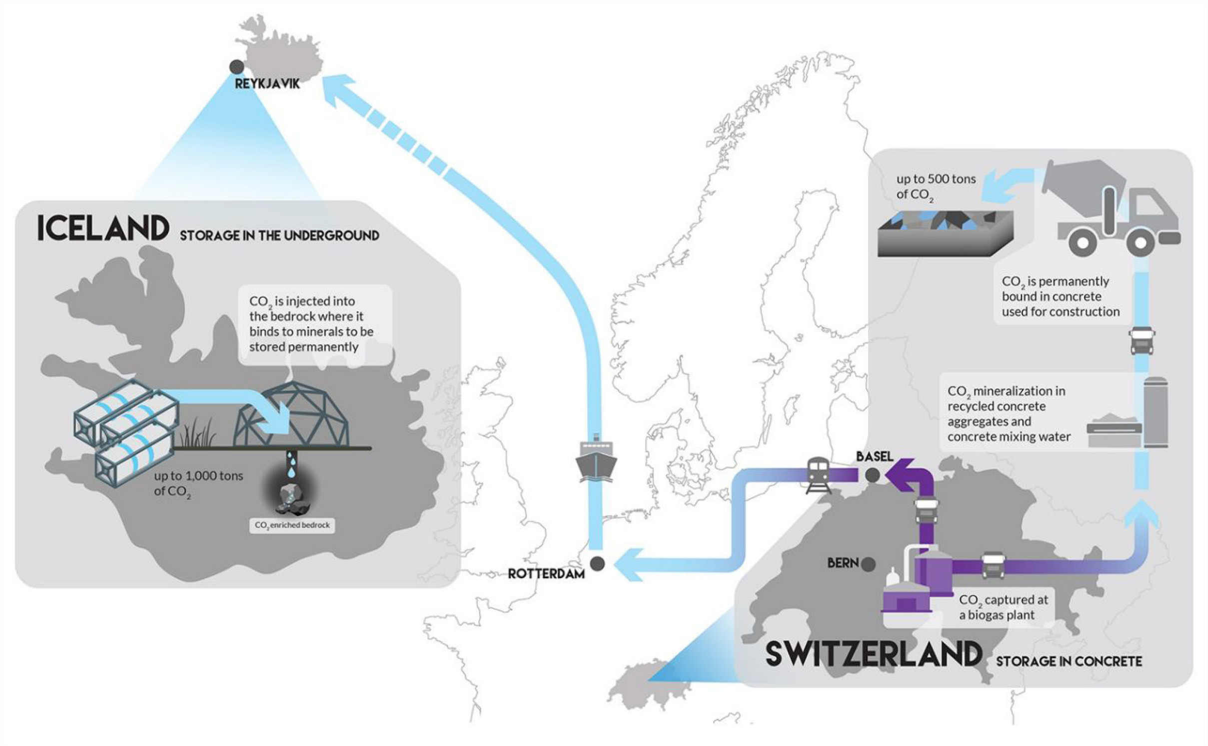

Figure 35: *The infographic we showed to participants in an online survey to inform them about the pathway that involves capturing CO2 in Switzerland and storing it in Iceland (Dallo et al., 2023)*

9 Publications

Dallo, I., Marti, M., Kuratle, L., Ly, C., Zaugg, S., & Zeller, S. (2023). Deliverable D5.6: Report on the current knowledge and public perception of the Swiss public towards CCTS and CCUS. Demonstration and Upscaling of CARbon dioxide MAnagmenet solutions for a net-zero Switzerlan ‘DemoUpCarma’. ETH Zurich. Switzerland.

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11 Appendix

The complementary material consists of few notes about the preparation and realization of the first measuring campaign in September 2022 and June 2023

11.1 2022: Seismic Backbone Stations

In summer 2022 we prepared the equipment necessary for the Seismic Backbone Stations at ETH in Zürich (Figure A1).

The shipment consisted of housings, sensors, recording and data transmission devices for five stations. And also special cabling equipment and Antennas for GPS and Power Supply of the Tools. The scope of supply included a total of two pallets with a total weight of about 200 kg, which were transported to Iceland by air freight.
We sourced the basic supplies such as plastic barrels, insulation material and cement in Iceland.
Some of the stations work on power outlets, others have an autonomous power supply which is rented in Iceland.
Each station consists of a mast with a small wind turbine and solar panels. This combination comes from the often changing weather and short days in Winter. The described masts are installed near a measurement station as you can see in (Figure A2)

Figure A1: *Prepared measurement boxes with equipment in Zurich.*

To install a sensor, a barrel is cut in half and partially buried. Then it is filled with cement to get a smooth and level floor which is well connected to the ground. In there the sensor is placed and adjusted. The barrel is filled with thermal insulation material to reduce the influence of temperature changes to the sensor signals.
The measurement equipment and communication devices are then placed in a box just beneath the sensor.

Figure A2: *Installed mast with wind turbine and solar panels.*

Figure A3: *Sensor with thermal insulation installed.*

Figure A4: *Installed measuring station.*

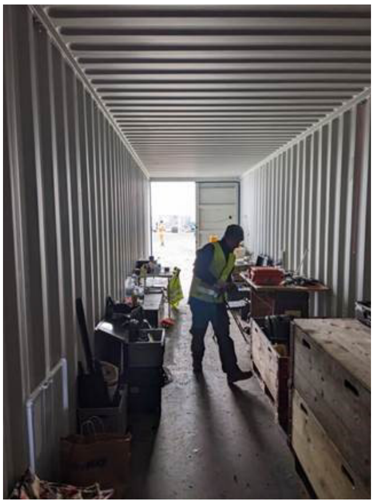
11.2 2023: Characterisation Campaign

The preparation of the measurement campaign in summer 2023 required the transportation of measurement technology, instruments and accessories for five different measurement systems. The Equipment for the Electrical Resistivity Tomography (ERT), the Ground Penetrating Radar (GPR) as well as the measuring instruments for the Nodal Array were brought from Zurich to Iceland together with specialized tools and materials. The equipment for crosshole seismics and the geophone chains were delivered from Germany, while the interrogator for measurements with fiber optics came from France.

In Zurich, nine pallets with a total mass of over one ton were prepared. The logistical processing, including appropriate packaging for air transport, stretched over several weeks. Various challenges had to be addressed, including the requirements for air transport of lithium-ion batteries, the dimensions and weight restrictions of the freight as well as safe packaging of the fragile instrument and customs formalities.

Figure A5*:* *Palettes ready to be shipped in Zürich.*

The shipment from Zurich reached the site with a one-day delay, as the final size of the cargo required another flight.



On site, both the equipment storage and the working office were set up in a 40-foot container for the duration of the campaign.

Figure A6*: Container with workplaces and storage space at the construction site.*

After the measurements, a partial return shipment was prepared on site in Iceland. The equipment was successfully collected from the site and delivered to ETH after ten days.

Figure A7: Palettes ready to be shipped back to Zürich.

Despite minor delays due to aircraft changes and no relevant damage, the entire process has gone smoothly so far.

Another piece of equipment will be sent back to Zürich by the end of August. The ERT and miniRUEDI will be sent back at the end of the campaign.