Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Federal Department of the Environment,
Transport, Energy and Communications DETEC

Swiss Federal Office of Energy
Energy Research and Cleantech

Interim report from 26 November 2025

CO2LPIE
CO2 long-term periodic injection) Experiment

Project activities 2023-25

Source: D. Jaeggi, swisstopo, 2024

Publisher:
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Berne
www.energy-research.ch

Co-financing:
Cemsuisse, Marktgasse 53, 3011 Bern
VBSA, Wankdorffeldstrasse 102, 3014 Bern

Subsidy recipients:
Eawag
Überlandstrasse 133
8600 Dübendorf
www.eawag.ch

Bundesanstalt für Geowissenschaften und
Rohstoffe (BGR)
Geozentrum Hannover
Stilleweg 2
30655 Hannover

ETH Zürich
Schweizerischer Erdbebendienst
Sonneggstrasse 5
8092 Zürich ETH-Zentrum

Authors:
Rolf Kipfer, Eawag, Rolf.Kipfer@eawag.ch
David Jaeggi, Mont Terri Project, David.Jaeggi@swisstopo.ch

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

SFOE contract number: SI/502693-01

Summary

The CL-Experiment investigates, hydraulic, mechanical, and chemical (HMC) effects of CO_2-injection into intact, yet heterogeneous Opalinus Clay of sandy facies under in-situ conditions at the Mont Terri rock laboratory. The aim is to enhance our general understanding of caprock behaviour and its integrity with a focus on CO_2. The innovative experimental concept consists of four monitoring boreholes drilled to 17.5 m depth in the edges of a 2x2 m square. These four boreholes are equipped with a newly developed Modular Multi-sensor Monitoring System (MMMS) which allows for high resolution temporal and spatial active and passive seismic tomography, electrical resistivity tomography (ERT), longitudinal strain monitoring, T-sensing and pore water pressure monitoring. The 14.5 m deep boreholes for injection and the extraction were drilled into this experimental volume of 24 m^3 at a distance of 1 m from centre to centre. Both boreholes are equipped with a five-fold hydraulic multi-packer system (MPS). Due to a failure of the MPS in borehole BCL-10 during the baseline monitoring phase in May 2025, a new identical system was manufactured and installed at reduced distance of 0.7 m from the injection borehole in a new drilled borehole BCL-11. This reduction in distance makes it possible to make up for lost time to a certain extent. The old borehole BCL-10 was abandoned and sealed with resin. At the MPS two different depth levels of the injection borehole can be used for injection of CO_2-enriched brine. Injection is achieved over a circulation system allowing for diffusive exchange between the formation and the porewater in the circuit/interval. CO_2-dissolution happens through a membrane. The flux of CO_2 injected into the system is controlled by temporal pressure decay in two connected pressure vessels and an additional gas flow meter in between. On the extraction side 3 intervals are connected to water circuits with membrane systems connected to gas loops and a custom-made gas spectrometer, a so called MiniRuedi. For the initial characterization of the experimental volume and the base-line monitoring phase the MMMS arrangement proved to be very valuable. The sensitivity and spatial resolution of the seismic system, ERT and FO sensing system proved to be adapted to the scale of the experiment and the expected effects in the system during the future injection. An extensive lab analysis programme on rock core samples is being carried out and yielded some first datasets. Modelling works with a special focus on the system understanding of CO_2LPIE are running in parallel. The CO_2 injection through a circulation system allowing for the assessment of diffusive exchange between CO_2 dissolved in brine and pore water/rock is used here for the first time in the CCS-context. We expect much more system understanding and data of the geochemical exchange with this new setup than in former in-situ experiments. Hydraulic testing will be finalized soon and the last in-situ tests of the cabinets and system performance are underway. The experiment will be operational in October 2025 and the injection of CO_2 can be started. According to the first interim report, we are on schedule to complete the project in line with the original application. This provides the basis for the SFOE to release the remaining funds as planned.

Zusammenfassung

Das CL-Experiment untersucht hydraulische, mechanische und chemische (HMC) Auswirkungen der CO_2-Injektion in intakten, jedoch heterogenen Opalinuston mit sandiger Fazies unter In-situ-Bedingungen im Felslabor Mont Terri. Ziel ist es, unser allgemeines Verständnis des Verhaltens des Caprock und seiner Integrität mit Schwerpunkt auf CO_2 zu verbessern. Der innovative Versuchsaufbau besteht aus vier Beobachtungsbohrungen, die in den Ecken eines 2 x 2 m großen Quadrats bis zu einer Tiefe von 17.5 m gebohrt wurden. Diese vier Bohrungen sind mit einem neu entwickelten modularen Multisensor-Messsystem (MMMS) ausgestattet, das eine hochauflösende zeitliche und räumliche aktive und passive seismische Tomographie, elektrische Widerstandstomographie (ERT), Längsdehnungsmessung, Temperatur- und Porenwasserdruckmessung ermöglicht. Die 14.5 m tiefen zentralen Bohrlöcher für die Injektion und die Entnahme wurden in diesem Versuchsvolumen von 24 m^3 in einem Abstand von 1.0 m von Achse zu Achse gebohrt. Beide Bohrlöcher sind mit einem fünffachen hydraulischen Multipackersystem (MPS) ausgestattet. Aufgrund eines Ausfalls des MPS in Bohrung BCL-10 während der Ausgleichsphase im Mai 2025 wurde ein neues identisches System hergestellt und in einem reduzierten Abstand von 0.7 m zur Injektionsbohrung in einer neu gebohrten Bohrung BCL-11 installiert. Durch diese Verringerung des Abstands kann die verlorene Zeit bis zu einem gewissen Grad aufgeholt werden. Die alte Bohrung BCL-10 wurde aufgegeben und mit Harz versiegelt. Beim MPS können zwei verschiedene Tiefen des Injektionsbohrloches für die Injektion von CO_2-angereichertem künstlichem Porenwasser genutzt werden. Die Injektion erfolgt über ein Zirkulationssystem, das einen diffusiven Austausch zwischen der Formation und dem Porenwasser im Kreislauf/Intervall ermöglicht. Die CO_2-Auflösung erfolgt durch eine Membran. Der in das System injizierte CO_2-Fluss wird durch einen zeitlichen Druckabfall in zwei miteinander verbundenen Druckbehältern und einem zusätzlichen Gasdurchflussmesser dazwischen geregelt. Auf der Extraktionsseite sind drei Intervalle mit Wasserkreisläufen verbunden, die über Membransysteme mit Gaskreisläufen und einem speziell angefertigten Gasspektrometer, einem sogenannten MiniRuedi, verbunden sind. Für die anfängliche Charakterisierung des Versuchsvolumens und die Basisüberwachungsphase hat sich die MMMS-Anordnung als sehr wertvoll erwiesen. Die Empfindlichkeit und räumliche Auflösung des seismischen Systems, des ERT- und des FO-Sensorsystems erwiesen sich als geeignet für den Umfang des Experiments und die erwarteten Effekte im System während der zukünftigen Injektion. Ein umfangreiches Laboruntersuchungsprogramm an Gesteinsproben wird momentan durchgeführt und erste Datensätze sind verfügbar. Parallel dazu laufen Modellierungsarbeiten mit besonderem Schwerpunkt auf das Systemverständnis von CO_2LPIE. Die CO_2-Injektion über ein Zirkulationssystem, das die Bewertung des diffusiven Austauschs zwischen in Porenwasser gelöstem CO_2 und Porenwasser/Gestein ermöglicht, wird hier zum ersten Mal im CCS-Kontext eingesetzt. Wir erwarten mit diesem neuen Aufbau wesentlich mehr Erkenntnisse über das System und Daten zum geochemischen Austausch als in früheren In-situ-Experimenten. Die hydraulischen Tests werden in Kürze abgeschlossen sein, und letzte Systemchecks sind im Gange. Das Experiment wird im Oktober 2025 betriebsbereit sein, und die CO_2-Injektion kann beginnen. Gemäss dem ersten Zwischenbericht liegen wir im Zeitplan, um das Projekt gemäss der ursprünglichen Antragstellung abzuschliessen. Dies bildet die Grundlage für die Freigabe der restlichen Mittel durch das BFE.

Résumé

L'expérience CL étudie les effets hydrauliques, mécaniques et chimiques (HMC) de l'injection de CO_2 dans des argiles à Opalinus intactes mais hétérogènes à faciès sableux dans des conditions in situ au laboratoire souterrain du Mont Terri. L'objectif est d'améliorer notre compréhension générale du comportement du caprock et de son intégrité, en mettant l'accent sur le CO_2. Le dispositif expérimental innovant se compose de quatre forages d'observation réalisés aux angles d'un carré de 2 x 2 m jusqu'à une profondeur de 17.5 m. Ces quatre forages sont équipés d'un système de mesure multicapteur modulaire (MMMS) nouvellement développé qui permet une tomographie sismique active et passive à haute résolution temporelle et spatiale, une tomographie par résistivité électrique (ERT), une mesure de la déformation longitudinale, une mesure de la température et de la pression interstitielle. Les forages de 14.5 m de profondeur destinés à l'injection et au prélèvement ont été forés dans ce volume d'essai de 24 m^3 à une distance de 1 m entre les axes. Les deux trous de forage sont équipés d'un système hydraulique multipacker quintuple (MPS). En raison d'une défaillance du MPS dans le forage BCL-10 pendant la phase d'équilibrage en mai 2025, un nouveau système identique a été fabriqué et installé dans un forage nouvellement foré, le BCL-11, à une distance réduite de 0.7 m du forage d'injection. Cette réduction de la distance permet de rattraper dans une certaine mesure le temps perdu. L'ancien forage BCL-10 a été abandonné et scellé avec de la résine. Le MPS permet d'utiliser deux profondeurs différentes du forage d'injection pour l'injection d'eau poreuse artificielle enrichie en CO_2. L'injection s'effectue via un système de circulation qui permet un échange diffusif entre la formation et l'eau poreuse dans le circuit/intervalle. La dissolution du CO_2 s'effectue à travers une membrane. Le flux de CO_2 injecté dans le système est régulé par une chute de pression temporelle dans deux réservoirs sous pression reliés entre eux et un débitmètre de gaz supplémentaire situé entre ceux-ci. Du côté extraction, trois intervalles sont reliés à des circuits d'eau qui sont eux-mêmes reliés à des circuits de gaz via des systèmes à membrane et à un spectromètre à gaz spécialement conçu, appelé MiniRuedi. La configuration MMMS s'est avérée très utile pour la caractérisation initiale du volume d'essai et la phase de surveillance de base. La sensibilité et la résolution spatiale du système sismique, du système de capteurs ERT et FO se sont avérées adaptées à l'ampleur de l'expérience et aux effets attendus dans le système lors de l'injection future. Un programme complet d'analyses en laboratoire sur des échantillons de roches est actuellement en cours et les premières données sont disponibles. Parallèlement, des travaux de modélisation sont en cours, avec un accent particulier sur la compréhension du système CO_2LPIE. L'injection de CO_2 via un système de circulation permettant d'évaluer les échanges diffusifs entre le CO_2 dissous dans l'eau interstitielle et l'eau interstitielle/la roche est utilisée ici pour la première fois dans le contexte du CSC. Cette nouvelle configuration devrait nous permettre d'obtenir beaucoup plus d'informations sur le système et de données sur les échanges géochimiques que les expériences in situ précédentes. Les essais hydrauliques seront bientôt terminés et les derniers contrôles du système sont en cours. L'expérience sera opérationnelle en octobre 2025 et l'injection de CO_2 pourra commencer. Selon le premier rapport intermédiaire, nous sommes dans les délais pour mener à bien le projet conformément à la demande initiale. Cela constitue la base pour le déblocage du reste des fonds par l'OFEN.

Contents

List of abbreviations

AE	Acoustic Emission
APW	Artificial Pore Water
BMR	Borehole Magnetic resonance
BOFDA	Brillouin Optical Frequency Domain Analysis
DAS	Data acquisition system
DIL	Dual Induction Log
EDZ	Excavation Damaged Zone
ERT	Electrical Resistivity Tomography
FO	Fibre Optics
MMMS	Modular Multi-Sensor Monitoring System
MPS	Multi Packer System
MT URL	Mont Terri Unterground Rock Laboratory
OBI	Optical Borehole Imager
OPA	Opalinus Clay
SFOE	Swiss Federal Office of Energy
SGR	Spectral Gamma Ray
SysMoG	System for Monitoring Gas
THMC	Thermo-Hydro-Mechanical-Chemical
WP	Work Package

1 Introduction

1.1 Context and motivation

Based on the IPCC's report on global warming, the Swiss Federal Council decided in 2019 that Switzerland will reduce its greenhouse gas emissions to net zero by 2050. This net-zero target lays the foundation for the Climate Strategy 2050, which the Federal Council adopted in 2021 and submitted to the UN Climate Change Secretariat. The aim of this strategy is to reduce the Swiss greenhouse gas emissions by 50% by 2030, compared to 1990, and achieve net zero by 2050. The Energy Perspectives 2050+ show how these targets can be achieved and, in particular, the role of CO_2 avoidance and CO_2 removal. In the CO_2 storage concept, intact caprocks will be prospected.

Strategically, CO_2LPIE is particularly relevant for the federal government and Swiss industry. Switzerland must address the possibility or even necessity of domestic CO_2 storage in order to reduce its dependence on foreign buyers in the future. CO_2LPIE, with its investigations into the safety and monitorability of a caprock and the associated public relations work (acceptance), forms a crucial pillar alongside the parallel projects play fairway analysis (PFA) on possible CO_2 reservoirs in Switzerland and in-situ reservoir characterization, e.g. of the Muschelkalk. In addition, the industry is to be provided with the necessary technical information and instruments to enable it to compete with foreign competitors.

CO_2LPIE is scientifically relevant because of its importance for the reservoir complex, where, in addition to drilling and faults (already being researched at Mont Terri), the processes in the clay rock's effective confinement structure must also be understood and investigated. To date, there has been little data from laboratory experiments (mm-cm scale) (e.g., Makhnenko et al., 2017) or from large-scale experiments (100-1000 m) (e.g., Ketzin, Liebscher et al., 2013), but data from the easily controllable yet realistic rock laboratory scale in the meter range has been completely lacking until now.

Long-term CO_2 exposure tests are necessary to (a) improve understanding of dynamic processes on different time scales, (b) obtain reliable reaction rates for natural clay minerals, (c) determine in-situ rock permeabilities for reactive CO_2 flow and changes due to geochemical rock alterations, and (d) calibrate or improve THMC models. Long-term periodic tests allow the differentiation of experimentally induced signals from the external influence of the rock laboratory, with a better signal-to-noise ratio. These experiments improve the fundamental understanding of the joint inversion of, for example, pressure and deformation data. The latter is ensured by the quasi-continuous monitoring of a comprehensive set of parameters, for which a novel modular multi-sensor system is being developed. Joint inversion is one of the most promising projects for monitoring gas storage facilities and the integrity of the overburden.

The potential and relevance for CO_2LPIE is very high here. CO_2LPIE already combines the laboratory scale via model calculations with the rock laboratory scale, thus covering the entire scale spectrum below large-scale pilot tests. In our view, the project fits very well with the focus areas of application-oriented research, experimental development, and piloting or demonstration of the SFOE energy research concept.

Research into CCS has been conducted at the Mont Terri Rock Laboratory since 2010. In an initial research phase, the focus was on investigating well integrity (Rösli et al., 2022, Goodman et al., 2022, Zhang et al., 2022, Goodman et al., 2023). Are existing oil wells in the caprock sealed in the long term, and what processes occur in the casing, cementation, and rock systems? In a later phase, the experiments focused on fault integrity (e.g., Guglielmi et al., 2022, Zappone et al., 2019). Under what conditions can tectonic faults in claystone be reactivated, and what about the migration of fluids and CO_2 along such discontinuities? These experiments are still ongoing, but a crucial component is missing: rock matrix integrity. The behavior of the actual geological barrier far away from faults and existing boreholes with regard to long-term CO_2 injection has not yet been investigated on a rock laboratory scale in the meter range (e.g., Makhnenko et al., 2017, Rebscher et al., 2018, Sciandra et al., 2022a, b). In addition, systems optimized for clay rocks and CCS are currently lacking for the efficient and cost-effective monitoring of reservoirs. Monitoring/safety will be a key issue in a future pilot project or effective producing reservoir. In addition to the technical feasibility of CCS in Switzerland, the safety of the environment and the population will play an equally important role and have a direct influence on future acceptance by the population.

The partners involved in the Mont Terri project include representatives from the oil and gas industry (Chevron, TotalEnergies, Shell) and research institutes (ETH/Eawag, LBNL, etc.), who are key players in the field of CCS. This expertise can be directly tapped into at Mont Terri and expanded with the present project.

The CO_2 long-term periodic injection experiment (CO_2LPIE, CL) at the MT URL investigates under in-situ conditions hy-draulic, mechanical, and chemical (HMC) effects of CO_2 injection into heterogeneous and anisotropic Opalinus Clay of sandy facies as a proxy for other caprocks. The experiment aims at enhancing our understanding of caprock behaviour and its integrity with a focus on CO_2. Here, the in-sight on geo-chemical reactions is important due to their influence on clay rock composition and hydro-geomechanical rock properties. Experimental data on reaction rates and barrier properties with ade-quate accuracy are required to perform reliable reactive transport simulations as a base for storage site characterization and risk assessment of long-term storage integrity. However, as of yet, only data from small-scale (a few cm) laboratory experiments are used and realistic large scale (above the order of meters) data of the heterogeneous rock matrix and rock mass are not yet available. The CL experiment will close this gap (Ziegler et al. 2024a). Another key aspect of CL is the development and application of a novel monitoring approach, which includes modular multi-sensor systems (MMMS) allowing for robust characterization of the test volume, baseline measurements, and high temporal and spatial res-olution monitoring during the injection phase. The layout and borehole locations of the CL experiment with separate (main) experiment and MMMS pretest sites is shown in Figure 1.1.1.

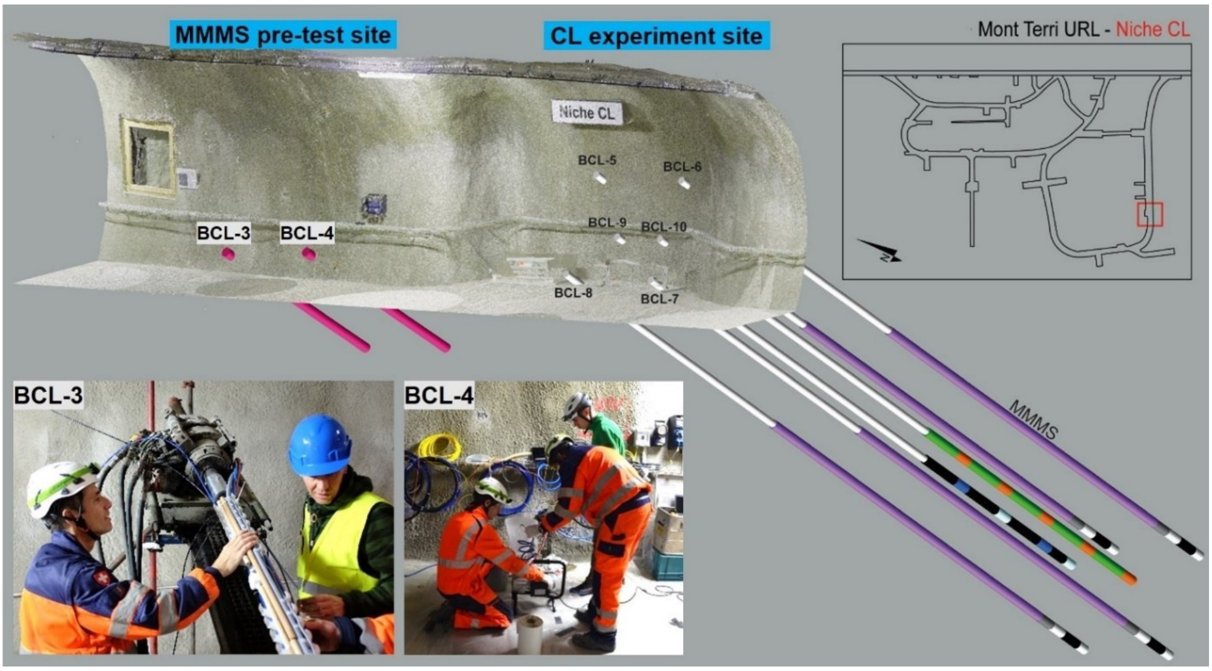

Figure 1.1.1: Locations of the MMMS pretest site with boreholes BCL-3 and BCL-4 and of the CL main experiment. The photos show the installation of an MMMS using a drill rig to push the system into BCL-3 and resin injection at BCL-4. 17.5 m long monitoring boreholes (BCL-5 to -8) surround an injection (BCL-9) and a sampling (BCL-10) borehole, both 14.5 m long at the CL main experiment site.

For rock mass behavior and process understanding, such as explored in experiments conducted at underground rock laboratories or within larger-scale pilot studies, it is crucial to obtain datasets of high spatial and temporal resolution, e.g., when fluid or gas injections and their impact on rock masses should be monitored. Sensor location optimizations, the conditions of sensor to rock mass coupling, and poten-tial disturbances on the target rock mass through the drilling of many monitoring boreholes must be considered. Typically, various boreholes used for different monitoring purposes surround an experimental rock mass volume and, thus, may increase drilling and logging costs, may disturb the target rock mass more compared to a smaller number of boreholes, and rock mass states are rec-orded at different locations that may not always be comparable, e.g., in case of heterogeneous or fractured rock masses. Therefore, combining the monitoring of different state variables (such as tem-perature, pore pressure, strain, seismic and electrical properties) inside a single borehole or smaller array of boreholes may provide benefits but such systems must satisfy requirements of fundamentally different sensor types. The joint development between swisstopo and ZHAW resulted in a thoroughly tested MMMS, which will be very beneficial not only for CO_2LPIE, but in adapted versions as well for industry in the near future.

1.2 Project aims

The subgoals concerning caprock integrity are i) the investigation of the long-term behavior of the Opalinus Clay matrix with respect to the long-term safety of a CO_2 reservoir under realistic and precisely controlled in-situ conditions on a scale of meters to decameters, ii) the investigation of the intermediate scale range (meter range) for upscaling from the laboratory scale to the pilot scale, iii) the direct measurement of the dynamic processes that occur during CO_2 intrusion into the caprock claystone and comparison with the numerical model calculations.

The scientific questions concerning caprock integrity are:
i) what is the long-term behavior of the Opalinus Clay under the influence of CO_2-saturated solutions?
ii) what role do the heterogeneities and anisotropy of the rock play?
iii) how fast and where does the water saturated with CO_2 migrate in the rock?
iv) are the predictions from the model calculations achieved and, consequently, have we understood the relevant processes that control the dynamics of CO_2 underground?
v) how can the laboratory results be scaled up to the rock laboratory or pilot scale?
vi) how does the Opalinus Clay behave with regard to periodically oscillating injection protocols?
vii). at what confining pressure do the transport processes begin to change?
viii) what chemical, mineralogical and physical changes take place in the rock and how fast do they occur?
ix) how do the chemistry of the pore water and the composition of the injected and extracted gas change over time?

Concerning MMMS development the subgoals are i) the development of an innovative, optimized and cost-effective MMMS for clayey rocks, ii) touchless spatial and temporal monitoring of the dynamic processes in high resolution.

The project questions to be solved concerning MMMS are:
i) how does the newly developed MMMS perform in long-term use?
ii) how accurately can the MMMS be used to record the migration of the CO_2 and the changes in the rock over time?
iii) how large are the disruptive effects of the injection and extraction wells on the rock volume to be investigated?

1.3 General status of the experiment

In the first phase of this project, 2023/2024, the MMMS were designed and developed. The systems were thoroughly tested and installed successfully in the four dedicated 17.5 m long monitoring boreholes BCL-5 to BCL-8. The core material was geologically documented and three distinct subfacies types were detected. The geological investigations finally led to a high-resolution geological model of the investigated rock volume. Then a long period of baseline monitoring and rock volume characterization measurements were carried out by means of distributed fibre optical strain and temperature measurements, active and passive seismic monitoring and electrical resistivity tomography. These investigations led to 1 D strain pattern along the four MMMS-boreholes, a 3 D resistivity model and a 3 D velocity model of the investigated rock volume. Besides these in-situ activities the aim, concept and status of the construction of injection and monitoring cabinets was reported.

In the second project phase in 2025 the injection borehole BCL-9 and the extraction or monitoring borehole BCL-10 were drilled to a depth of about 14.5 m each. These boreholes were placed as planned 1 m apart from each other (centre to centre) on a horizontal plane in the middle of the experimental volume. The core material from both boreholes was characterised and samples were taken for numerous lab analysis programmes. Datasets are available for microfacies, lithology, bulk mineralogy, petrophysical properties, pore water chemistry, rock stiffness parameters, CO_2 migration data on core material and rock mass temperature. Not yet available but in analysis/processing phase is data from CT scanning, trough diffusion data, the gas characterization including isotopic signature and partial CO_2 gas pressure, organic geochemistry, THMC frictional properties exposed to CO_2, capillary pressure and pore network geophysical AE characterization and hydraulic rock mass characterization. The boreholes were logged geophysically with OBI, SGR, DIL and BMR and an active seismic survey with moving source in one borehole and monitoring in the other open borehole and all the MMMS seismic receivers was carried out. After that two identical multi-packer-systems (MPS) were installed by the company solexperts and the intervals saturated with artificial pore water (APW). Saturation pressure in the intervals was observed permanently over the solexperts IoT platform.

After a few weeks of operation, two out of five packers in BCL-10 showed weird decreasing pressure signals with some interference to the adjacent intervals and a clear indication of packer leakage. It was decided to build an identical system in the workshop at solexperts and to test the new packer series thoroughly and on a longer term on realistic pressures. In early June the new system was ready and the operation in the rock laboratory was prepared. Retrieval of the existing system was simple, but the quality of BCL-10 borehole was insufficient after reaming and it was decided to abandon this borehole, to seal it with a mixture of resin and gravel and to drill a fresh borehole BCL-11 for the installation of the new MPS. The location of the new borehole BCL-11 is given on Figure 1.3.1 below.

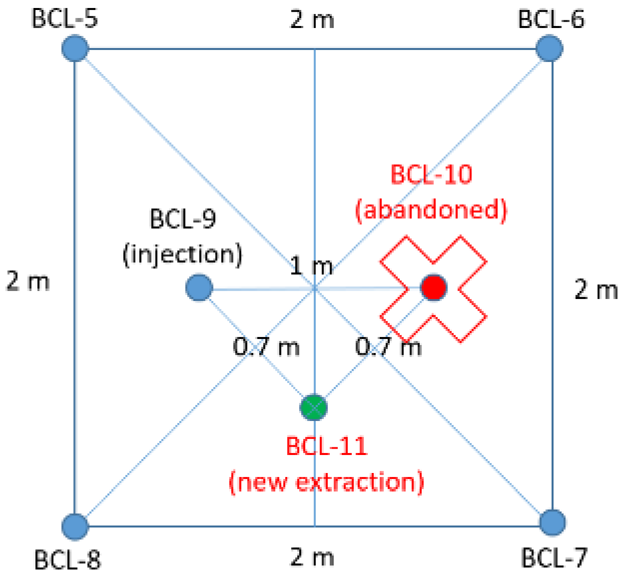

Figure 1.3.1. Plan view of experimental borehole BCL-5 to BCL-11. BCL-5 to BCL-8 are equipped with MMMS. BCL-9 is the injection borehole, BCL-10 the old, abandoned monitoring borehole and BCL-11 the new monitoring borehole.

It was decided to reduce the distance from centre to centre to 0.7 m in order to compensate for the lost time and to set the borehole withing the experimental volume below the injection borehole. The monitoring borehole below the injection borehole allows for the eventual detection of density driven flow while injecting. So far the new system performance is fine and currently hydraulic pulse injection testing and constant head injection testing is being carried out. The surface cabinets to operate the experiment are installed, configured and tested and injection started in November 2025.

In parallel to these onsite and lab investigations the modelling activities led by BGR are ongoing with a focus on further development and validation of modelling approaches, scoping calculations, sensitivity studies and THM or THC long-term calculations. Effects of anisotropy and heterogeneity for CO_2LPIE are modelled and a benchmarking exercise between 5 institutions is ongoing with the main aim of a better understanding of the coupled effects.

1.4 Overall time schedule

With respect to the original time schedule in 2023 submitted for the financial application to SFOE, the injection is delayed by 1 year approximately. The original plan was to inject CO_2 in autumn 2024 and according to the performance of the experimental works and the behaviour of the system components and the rock mass now, the injection will be started in November 2025.

The delay of the experimental steps and the corresponding milestones is due to several reasons:

- Most important reason was the unexpected failure of the MPS in BCL-10 in May 2025 led to another delay – the main reason for the overall project-delay.
- The saturation of the observation intervals (equilibration time) of the four MMMS-boreholes BCL-5 to BCL-8 and as a consequence the baseline monitoring phase took more time than expected originally.
- Design, development and finally the construction of the surface equipment took more time than expected.

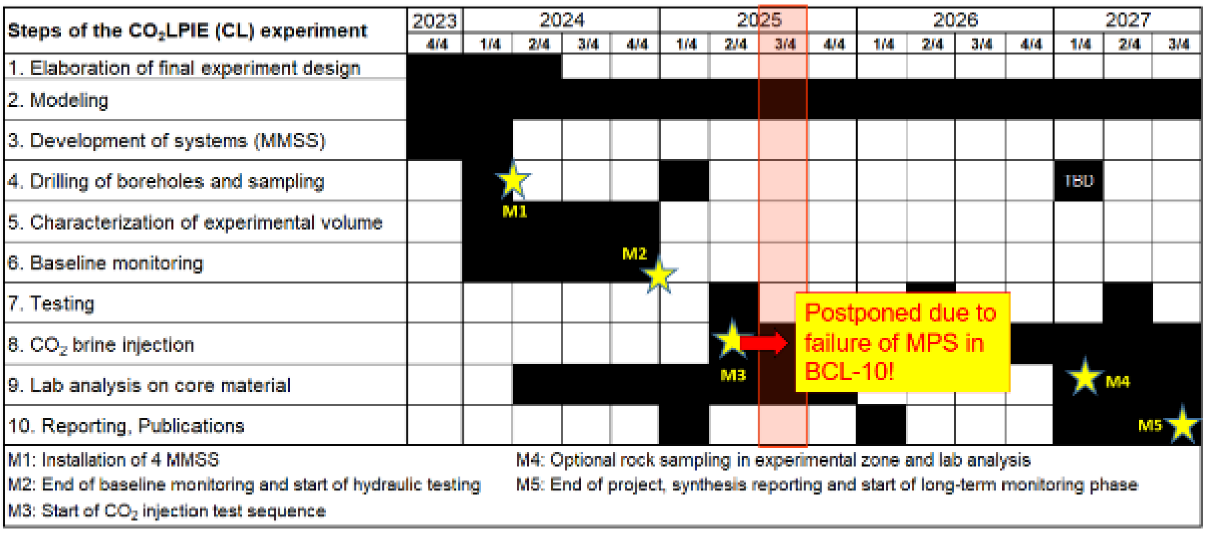

Figure 1.4.1. Time schedule as of early 2025 just before the failure of the MPS in BCL-10.

In order to compensate this overall project-delay, the following operational measure was taken: Distance between injection borehole BCL-9 and extraction/monitoring borehole BCL-11 was shortened from 1 m to 0.7 m from centre to centre and thus the breakthrough of the CO_2-plume or brine will be expected earlier.

2 Approach, method, results and discussion

The CO_2LPIE experiment aims to investigate the behavior of Opalinus Clay in response to periodic CO_2 injections using an in-situ test setup in the Mont Terri rock laboratory. The aim is to determine which processes take place in the rock under the influence of the injected CO_2, how the rock-pore water- CO_2 system behaves in the long term, and how safe the Opalinus Clay will be as a caprock and proxy for clay rocks worldwide for future CO_2 reservoirs. To achieve these goals, CO_2LPIE will also carry out extensive modeling work, laboratory analyses, and the development of a completely new multisensor system for the permanent temporal and spatial monitoring of underground processes. The project is divided into five work packages, whose aims are described below:

WP1: Modelling works (see chapter 2.11)

Modeling at CO_2LPIE is an integral part of the experimental concept, which combines modeling on all scales, analytical laboratory programs, and the in-situ experiment at Mont Terri. Modeling serves to understand the process on an analytical scale, where the injection of CO_2 is studied using 50x100 mm core samples under realistic conditions. Numerical simulations are used to study the coupled dynamic processes relating to thermal, hydraulic, mechanical, and chemical (THMC) behavior.

For the experimental design, predictive modeling is carried out on a rock laboratory scale to determine the ranges of variation caused by CO_2 injection, how the system behaves, and what the propagation speeds and distances are. The results obtained in this way support the determination of the definitive experimental design with regard to type (parameters, sensitivity, measuring range), number and distribution of sensors (sensor density, resolution) and, consequently, the geometry (length, diameter, and location) of the boreholes and measuring intervals. In addition, the simulations on a rock laboratory scale allow the optimal experiment duration and possible sampling times to be determined.

WP2: Development of MMMS (see chapter 2.1)

This work package involves the development of a modular multisensor monitoring system (MMMS). A large number of sensors and systems are required in order to monitor the CO_2LPIE experimental chamber as accurately as possible at depths of 11 to 15 m and with a total volume of 16 m^3. The plan is to characterize and monitor this experimental space after drilling (characterization) and the equilibration phase (baseline). The measurement parameters are deformation in the longitudinal direction (i.e., along boreholes), temperature, pore water pressure, seismic properties, and electrical resistance. For these five parameters, a large number of observation boreholes would normally be necessary, all of which would influence the experimental space. Our goal is to drill only four boreholes at the corners of the experimental space. In order to be able to record the five parameters for each borehole, we have decided to develop an MMMS that optimizes the experimental setup at CO_2LPIE and can also be used for future experiments at Mont Terri and for industrial applications in future CCS reservoirs can be documented. High-resolution spatial monitoring (tomography) of the experimental area also allows the impact of the creation of the injection and extraction boreholes to be documented (drill-by phase). The subsequent equilibration phase (baseline) provides information about the duration and nature of recovery or the return to the original state. This will later allow valuable conclusions to be drawn about the system behavior and the performance of the injection. Spatial monitoring of the migration paths and rock behavior during injection is carried out continuously and in real time using tomographic methods. The system is also designed for long-term monitoring beyond the 4-year project duration.

WP3: Installation of systems, characterization, baseline monitoring (see chapters 2.2 – 2.9)

Work package 3 comprises the installation of the experiment in the Mont Terri rock laboratory, including the six boreholes required for this, core documentation, core analyses, geophysical logging, the installation of the four MMSS, baseline monitoring, functionality tests, hydraulic tests in injection and extraction boreholes, up to the actual CO_2-injection. The CO_2-injection itself is then already an integral part of work package 4.

WP4 System operation and monitoring (see chapters 2.8 and 2.10)

Work package 4 consists of the test sequence, injection, monitoring of the test progress, and geochemical analysis.

After an initial equilibration phase (constant parameter values for pressure, deformation, and temperature), hydraulic tests are carried out to characterize the hydraulic properties of the experimental chamber. After hydraulic characterization and a further equilibration phase, the actual CO_2-injection test is carried out.

Injection follows a precisely defined protocol according to the pressure level and magnitude and length of the planned fluid injection oscillations. The aim is to achieve maximum pressures of 3 MPa, which are well below the fracking pressure of the Opalinus Clay at Mont Terri. The CO_2 will be dissolved in pore water and injected through a diffusive circulation system. It is marked in advance with Kr and δ13C in order to distinguish the injected CO_2 from CO_2 mobilized in the rock. The exact injection protocol is closely based on the results of modeling by CSIC and UniBE and the experience and analytical results of the University of Illinois.

AP5 Final and integral interpretation of the CO_2 injection experiment, final reporting (not yet available)

Work package 5 focuses on the completion of the four-year project. The aim is to use hydraulic characterization to investigate the influence of the two-year CO_2 injection on the rock mass. The analytical work will be carried out at ETH SED, University of Illinois, University of Bern and Eawag.

Depending on the performance of the experiment a sampling campaign might be done in the end by drilling a borehole into the experimental volume. Following this eventual sampling, the experiment will be converted into a long-term monitoring experiment and the stopped injection can be continued and adjusted according to the experience gained.

Final synthesis and final reporting is the main part of this workpackage.

The following paragraphs discuss the status and progess of the different work packages.

2.1 MMMS development, installation and overall performance (WP2)

One of the main aims of CO_2LPIE was the development of an innovative, optimized, and cost-effective monitoring system for touchless spatial and temporal monitoring of dynamic processes in high resolution. At CO_2LPIE, the explicit goal is to use suitable tools to examine the containment-effective rock area as gently as possible with high-resolution methods in terms of time and space and to monitor it in the long term. Appropriate analytical methods and sensors are not commercially available, although new technical manufacturing methods, such as 3D printing, offer opportunities to manufacture the corresponding sensors easily and inexpensively. CO_2LPIE used precisely this technology to manufacture corresponding multisensor systems cost-effectively using additive manufacturing methods. We are convinced that our work in this area will be of commercial interest to industrial partners. With the current MMMS five parameters, such as electrical resistivity, seismic velocity, longitudinal strain, pore water pressure and temperatures can be measured in each of the four boreholes at a very high resolution. The rock mass in the interior of the 2x2 m square is minimally harmed. Optimized this system could be used for large-scale reservoir monitoring.

For solving the scientific questions listed in Chapter 1.2, an MMMS has been developed fulfilling the requirements in the table below (Table 2.1.1).

Table 2.1.1. Requirements of the MMMS.

Item	Requirement
Sensor fixation	- modular system that can hold different sensors as well as electrical, hydraulic and infill lines in boreholes of 101 mm diameter - module length of about 2–3 m and borehole (monitoring) length of 10–20 m - allow for different combinations of electrodes, seismic sensors, and fiber-optic sensor cables - temperature-, humidity- and saltwater stable (resistant to corrosion) - high torsion-resistance but enabling radial and axial deformations and strain transfer from rock formation into the borehole (i.e., system stiffness shall be similar to the stiffness range of the rock formation) - module installation by pushing with drilling rig (possibility of pulling out of hole in worst case) - allow for mounting a hydraulic packer for pore pressure monitoring at lower end - optimization for resin infilling (volume reduction, active cooling to control polymerization temperature)
Sensors	- electrodes for single- and cross-hole electrical resistivity tomography o longitudinal spacing of 5 cm o electrically isolating, stable fixation and bedding (infill) material o in contact with rock formation allowing for low contact resistances - acoustic sensors and receivers for active transmission monitoring and AE recordings o longitudinal spacing of 0.5 to 2 m o fully embedded and stabilized in the filling material o considering acoustic decoupling from fixation system - fiber-optical strain (and temperature) sensor cables o along entire MMMS borehole section o fully embedded and stabilized in the filling material o in contact with rock formation - point temperature sensors - orientation sensor to survey sensor positions upon installation
Gap filling	- synthetic resin with o low viscosity, electrically and hydraulically isolating conditions, chemical stability o long processing time (i.e., delayed polymerization) o no shrinkage / crack development upon polymerization and later mechanical straining o elastic behaviour similar or at least in the same order of Opalinus Clay shale o low or controllable exothermal reaction (resin volume optimization)

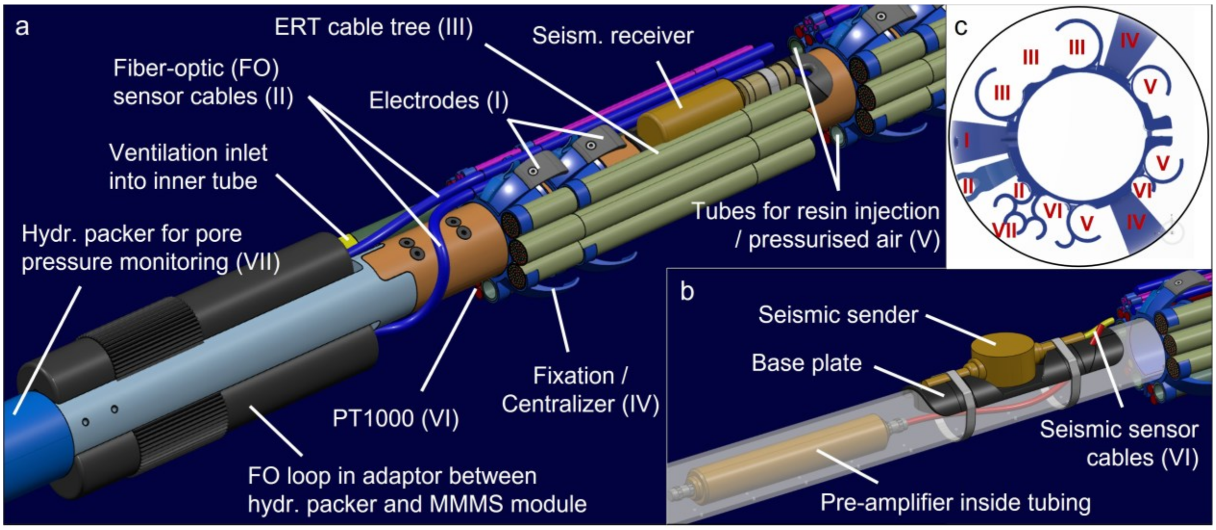

Figure 2.1.1. Major components of the MMMS installed in two short testing boreholes and four long monitoring boreholes of the CL experiment. (a) Section showing a part of the deepest MMMS module with inner rod (orange), fixations/centralizers (blue) and adaptor to the hydraulic packer with location of fiber-optic loops (light blue). (b) Detail of a seismic sender and location of pre-amplifier inside the tubing. (c) Cross-section of a single fixation made of PA (length 50 mm), centralized in 101 mm diameter boreholes (by M. Ziegler, swisstopo).

The MMMS was pre-tested at ZHAW and finally in two short dedicated boreholes BCL-3 and BCL-4 in the Mont Terri rock laboratory. After the testing and some adaptations and improvements of the concept, the installation part in the four monitoring boreholes started. In each of the main CL experiment boreholes three MMMS modules with a total length of about 6 m and with pre-assembled fixations, electrodes and seismic sensors were installed at about 10–16 m depth of the about 17.5 m long boreholes (Figure 2.1.1). Each borehole was completed with one single hydraulic packer, three MMMS modules, five extension rods, and about 80 l of resin. The resin was heated to about 25°C prior to its injection. The borehole completion works took in total 3–4 days per borehole and system. The rotation of the MMMS upon installation was measured with an accelerometer sensor mounted at the loop adaptor, and corrected where necessary, so that the sensors locate at their intended locations. The D=101 mm boreholes were widened to D=104 mm at depth along hole >9 m. Borehole reaming was carried out to reduce friction and ease the installation of the MMMS. We experienced some bending of the last 2–3 extension rods during the push with the drill motor and at one borehole the extension rods had to be guided through an extension tubing outside the hole. Nevertheless, all systems could be installed to their target depth. Resin injections could be carried out smoothly but some leakages into the inner rods were noted at the locations of glued rod connections.

The preheated resin cooled down to about 15–20°C within three hours after injection into the annulus space of the monitoring boreholes, then warmed up over about twelve hours by 1–2°C during the ongoing polymerization reaction, and finally cooled down again to the original background rock temperatures over a few days. During injection, pressurized ambient air ventilation of about 15°C was used to gently cool the exothermal polymerization reaction and avoid potentially higher temperatures.

Lessons learned and first experience with the MMMS:

Installation and testing of the MMMS in two ~ 4 m pretest boreholes enabled refinement of the design and proof of concept. Subsequently, four MMMS units were installed in 17.5 m monitoring boreholes of the CL experiment. Design improvements were informed by early sensor requirement assessments, prior experience, multiple prototype iterations, and the use of flexible additive manufacturing. The system employs a sealed annulus to regulate resin polymerization temperatures via air flushing while minimizing thermally induced disturbances in the rock mass. The initial MMMS installations were successfully completed.

Push-installation of the modules with the drill motor proved effective, with minimal thermal impact during resin polymerization and high-quality monitoring data. The use of electrically isolating, stabilizing resin infill - preventing hydraulic flow along the borehole - is critical for long-term electrical resistivity measurements. The MMMS's modularity, integration of multiple sensor types, and design adaptability through additive manufacturing offer significant benefits for both scientific and industrial applications. For design specifications, manufacturing details, and operational experience see Ziegler and Czerner (2025).

Monitoring results of the MMMS are discussed in chapters 2.4 – 2-6.

2.2 Geological characterization on rock core material (WP3)

The geological documentation of the core material was focused on mapping rock type or subfacies type, sedimentary features and tectonic structures. For the last boreholes BCL-9, BCL-10 and BCL-11, this procedure was done in an entirely digital way with the software Fulcrum™. Cores were scanned with an optical DMT core scanner as a plane scan for BCL-5 to BCL-8 and as a 360° unrolled image for BCL-9, BCL-10 and BCL-11. Approximately every meter a small sample was taken for petrophysical property assessment, such as in-situ water content determination over the buoyancy method and later pycnometry at Uni Bern, density and porosity (Figure 2.2.1). Petrophysical datasets are available but have not been published yet. Rock samples were taken following a predefined sampling plan. The initial extraction borehole BCL-10 was furthermore scanned entirely with the MSCL core scanner from Geotek on XRF, spectral gamma and density. Microstructural analysis was carried out on the optical microscope. Facies identification became an important issue for the sampling strategy and the later interpretation of the geological model. In combination with the geophysical logs (OBI, SGR, DIL and NMR) a model of the subfacies distribution (Figure 2.2.2) could be established in each borehole, which for the modeling teams was collapsed to a generalized synthetic borehole with the subfacies distribution. Currently the data of all 6 boreholes are used to establish a refined 3 D geological model, including faults and fractures.

The monitoring, injection, and extraction boreholes (BCL-5 to BCL-11) were optically and geophysically logged. All boreholes were fully cored, and the cores were lithologically and structurally characterized. At the CL experiment site, the Opalinus Clay corresponds to the upper sandy facies, which is heterogeneous and crosscut by multiple fault sets subjected to structural analysis. The host rock was classified into three subfacies: sandy clay layers, carbonaceous layers, and carbonaceous nodules. Lithological and fracture data guided the placement of CO_2 injection intervals in BCL-9: one in an intact sandy clay layer and another in a sandy, carbonate-rich layered section intersected by tectonic faults (Abdelouhabi et al., 2025).

Outlook.

To date, ~ 370 rock samples have been collected from these boreholes and distributed to various laboratories for structural, mineralogical, petrophysical, hydromechanical, gas, and water analyses. Most analyses are still in progress, and a manuscript detailing the experimental concept and geological model is in preparation.

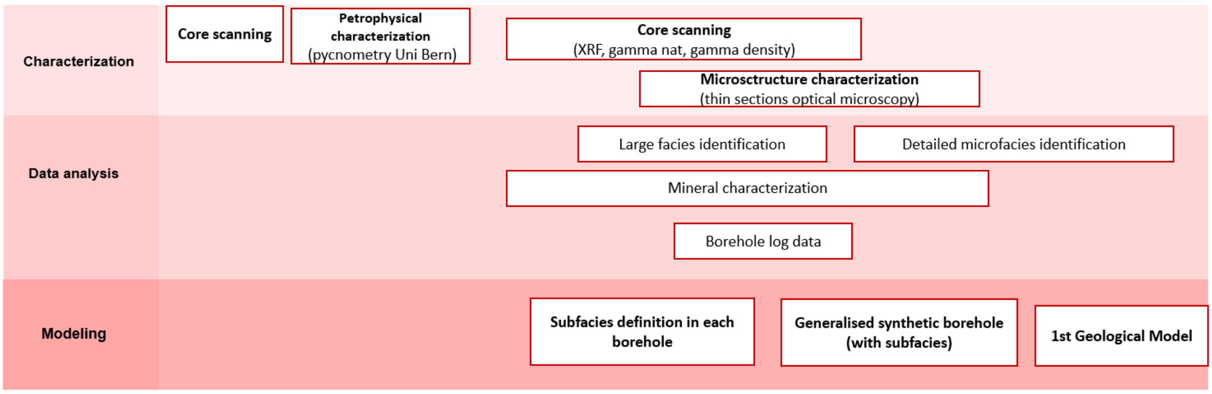

Figure 2.2.1: Concept of geological characterization at CO2LPIE.

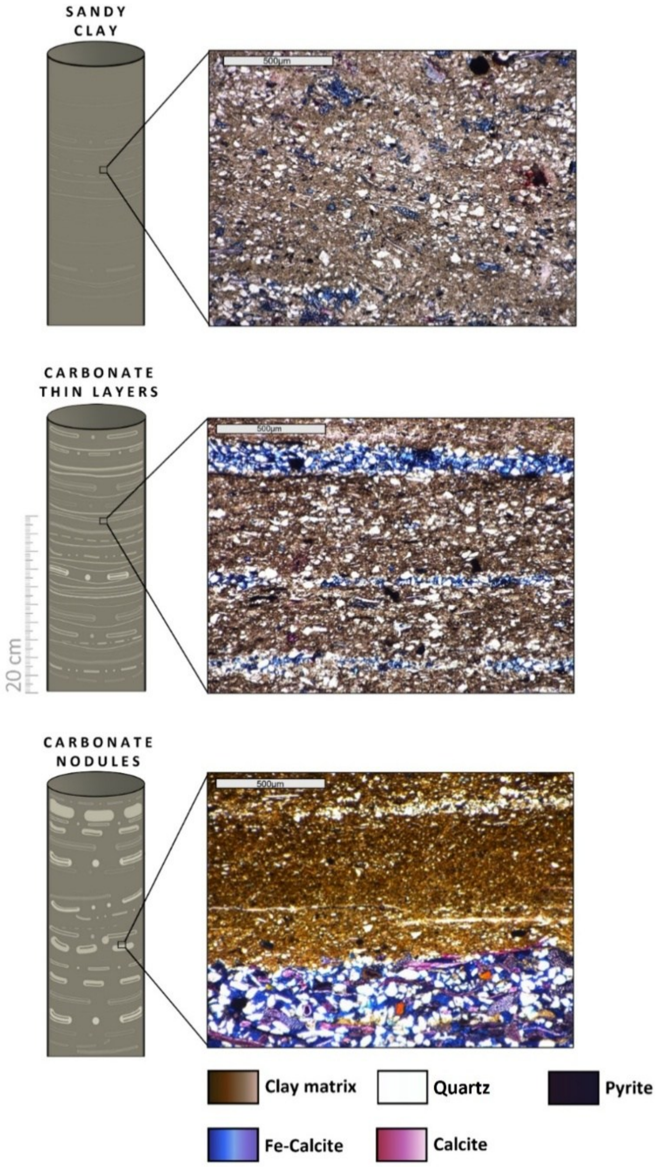

Figure 2.2.2. The three subfacies types identified in the experimental rock volume (upper sandy facies of Opalinus Clay) with the bulk mineralogical composition (by M. Abdelouhabi, swisstopo).

2.3 Seismic borehole characterization (WP3)

Aim of investigation.

To characterize the Opalinus Clay by seismic velocities, an active seismic survey was conducted in January 2025 using crosshole acquisition geometry with a reciprocal setup between BCL-9 and BCL-10.

Current status of measurements and analysis.

In the first configuration, the seismic source was deployed in BCL-10 with the receiver probe in BCL-9; the setup was reversed for the second configuration. Additionally, all GmUG sensors (S1-S13 and R1-R13) in boreholes BCL-3 to BCL-8 were used as receivers to extend coverage of the experiment volume. Signals from R1-R13 were amplified, while S1-S13 were directly recorded. Characterization focused on depths between 8 and 14.4 m. A nominal source spacing of 0.4 m was used, with the receiver probe providing 0.1 m spacing. For the GmUG sensors, additional source points were acquired to achieve an effective source spacing of 0.1 m. The recorded data exhibit a high signal-to-noise ratio, with all GmUG sensors except S1 detecting the seismic signal, including R1 in BCL-3.

Figure 2.3.1. Monitoring activities in niche CL with acquisition units.

Current status of measurements and analysis.

For the characterization, we focused on borehole depth from 8 m to 14.4 m. We chose a nominal source spacing of 0.4 m. Technical specs of the receiver probe result in a nominal receiver spacing of 0.1 m. Additional source points were recorded for the additional GmUG sensors to densify the source spacing to 0.1 m for the GmUG sensors.

Recorded data show a good signal to noise ratio. Except for S1, all GmUG sensors recorded the excited seismic signal, even R1 in BCL-3.

Outlook.

The next step is first-arrival picking to derive apparent velocities for tomographic inversion.

2.4 ERT monitoring (WP3)

Aim of investigation.

The purpose of the ERT (electrical resistivity tomography) measurements or ERT monitoring is to detect and resolve both temporally and spatially possible changes in the electrical conductivity of the rock mass due to the injection of the CO_2 fluid.

Current status of measurements and analysis.

A total of 392 electrodes were installed in boreholes BCL-5 to BCL-8 as part of the new MMMS. Weekly measurements have been conducted since May 2024, with each cycle comprising 10 datasets (4 single-hole and 6 cross-hole), totalling ~18800 individual four-point measurements. The data are processed via inversion algorithms to generate electrical resistivity models between the boreholes.

We received an excellent data quality of the four MMMS regarding electrical resistivity tomography, despite that the sensitivity (coverage) decreased toward the center of the investigated rock mass (Figure 2.4.1a). The tomography about three months after resin injection (end of May 24) show a layered specific resistivity structure between 10 and 16 m depth along hole (Figure 2.4.1b). Isobodies of low specific resistivity (<9 Ωm) and higher specific resistivity (>18 Ωm) highlight the layered structure that is likely a result of alternating clay-rich and carbonate-rich layers of the upper sandy facies of the Opalinus Clay shale (Figure 2.4.1c). Comparisons with borehole dual-induction logs indicate good agreements between the different datasets. Figure 2.4.1d shows the comparison along borehole BCL-5.

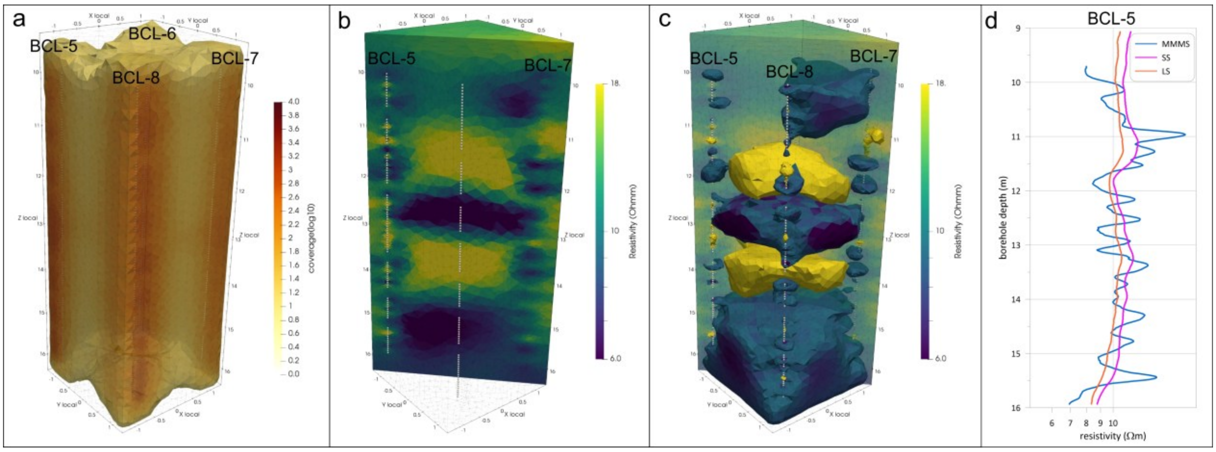

Figure 2.4.1. (a) Coverage (sensitivity) of the electrical resistivity tomography (ERT) between BCL-5 to BCL-8 in May 2024. (b) Tomographic result with cross section between BCL-5 and BCL-7. (c) Same view but with isobodies of low specific resistivity (<9 Ωm) and higher specific resistivity (>18 Ωm). (d) Comparison of BCL-5 single-hole ERT (near-field) with results from a dual-induction conductivity log converted to resistivity (SS: short-spaced; LS: long-spaced) (by M. Furche, BGR).

Outlook.

- Integration of the three injection/observation boreholes (BCL-9–11) into the model grid.
- Development of routines for automated generation of inversion input files, including file aggregation and scaling.
- Testing of time-lapse inversion procedures.

2.5 Fibre optical monitoring (WP3)

Aim of investigation.

Fiber-optic monitoring was conducted during the reporting period in all boreholes (BCL-5-8) using a 'fibrisTerre' interrogator based on Brillouin Optical Frequency Domain Analysis (BOFDA). The system provided distributed strain and temperature measurements along the fibre loop, enabling assessment of long-term trends and characterization of noise in the multi-sensor monitoring system (MMMS).

Current status of measurements and analysis.

Fiber optics monitoring was started in all test boreholes (BCL3 and BCL4) and monitoring boreholes (BCL5, BCL6, BCL7, BCL8) as soon as the modular multi-sensor monitoring system (MMMS) was introduced in each hole. The MMMS includes two multi-fiber cable, one in the central part (measuring the system stiffness) and one in contact with the rock (measuring strain at the borehole wall) once the system is clamped to the borehole. Each fiber optic cables, manufactured by Solifos and referred to as V13, contains three tubes with fibers in metal (FIMT). Two tubes contain a single tight-buffer single mode fiber, and one tube is loose with four fibers in gel (two single mode and two multi-mode). Each cable is terminated at the end of the borehole with a so-called mini-loop. The cables were manufactured so that a single mode, tight-buffer fiber is connected to a loose fiber to create a loop. To measure strain and temperature, we connected a Brillouin interrogator. The Brillouin backscattered light on the fiber is in general sensitive to both temperature and strain. However, the loose fiber will not be easily strained and hence could be used to measure temperature only and to correct the measurement on the tight buffer to obtained absolute strain. The installation and subsequent resin injection in the test and monitoring boreholes represented a perfect test for the monitoring approach with the Brillouin interrogator. The device employed is a fibrisTerre interrogator, that exploits the Brillouin Optical Frequency Domain Analysis (BOFDA) to record strain/temperature at all point along the fiber in a loop.

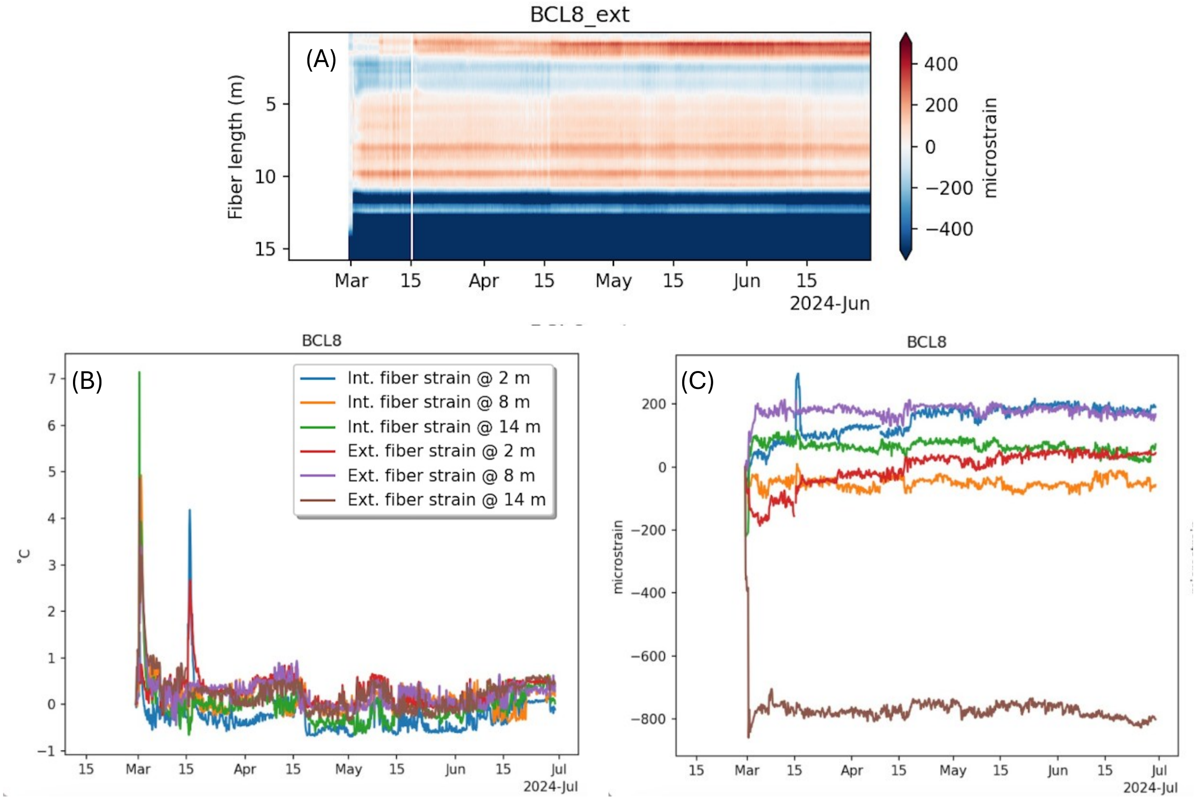

Figure 2.5.1. Monitoring of resin curation at BCL8. (A) Waterfall plot of corrected distributed strain. (B) Temperature changes at various depths for both internal and external fibers. (C) Time evolution of corrected strain at various depths for both internal and external fibers (by A. Rinaldi, ETH).

Figure 2.5.1 shows an example of recording for the temperature changes and subsequent strain during resin curation. Figure 2.5.1A shows the waterfall of the corrected strain, highlighting a strong compression for this borehole in the bottom part (below 11 m). Figure 2.5.1B shows the temperature time series at several points in the boreholes for the two cables, with the two peaks in temperature due to resin injection in two steps. Figure 2.5.1C shows the evolution of the corrected strain at different depths for the two cables, with a relatively stable trend after the initial string deformation due to resin curation.

In July 2024, all fiber optics cable in the four monitoring boreholes were looped to measure all of them simultaneously.

Figure 2.5.2 presents down-sampled, corrected strain data (daily averages) for all boreholes (Jan–Jul 2025). Raw measurements (panels A, C, E, G) are compared with median-filtered data (panels B, D, F, H), the latter effectively suppressing 'common noise' - simultaneous large variations along the entire borehole. The median-filtered records exhibit clearer trends, with strain values generally within the ~ 20 $\mu\varepsilon$ noise threshold, though distinct long-term variations occur at specific depths in all boreholes. Future correlation analyses between strain patterns and geological structures will determine whether these trends reflect genuine physical processes or mechanical settling of the MMMS.

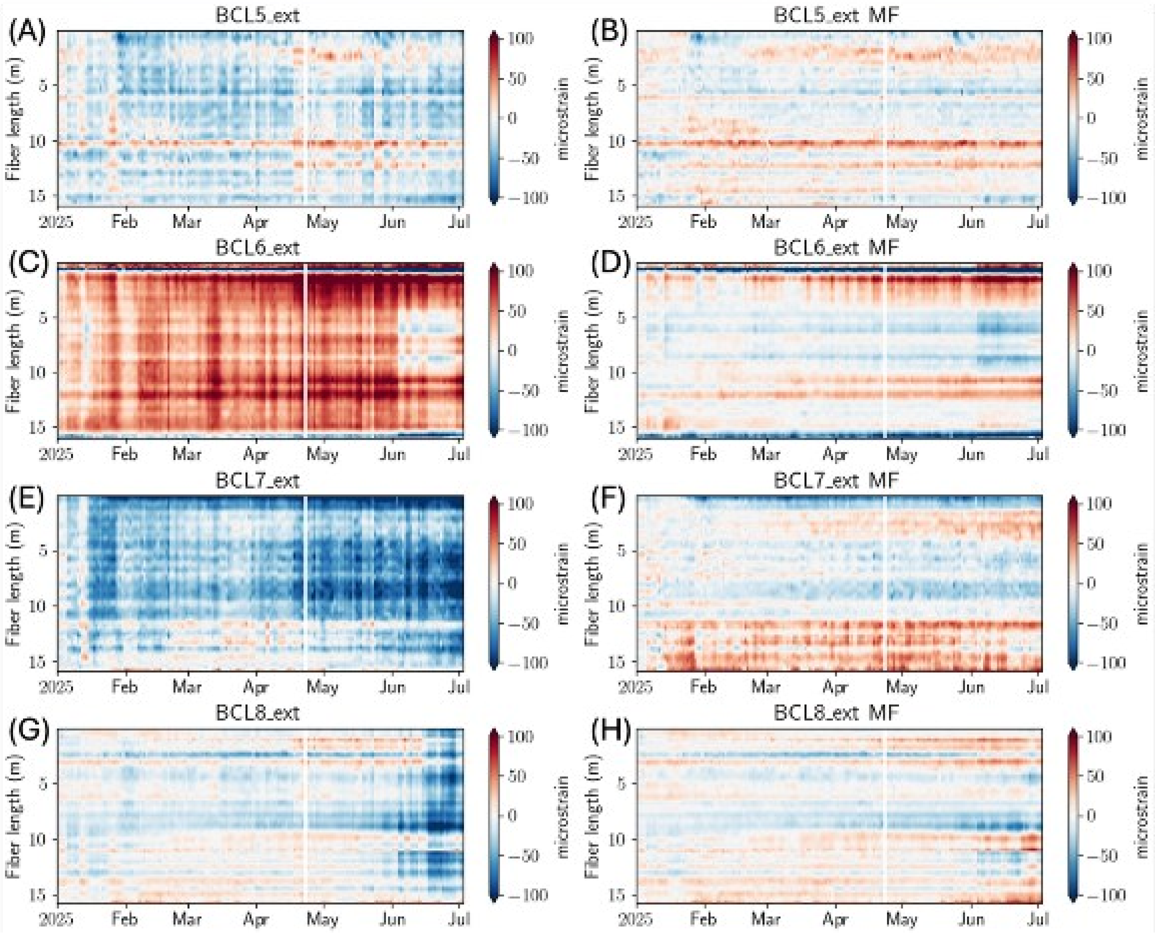

Figure 2.5.2. Background monitoring at external cables of all monitoring boreholes. (A, C, E, G) Waterfall plots of corrected distributed strain, down-sampled to daily measurements. (B, D, F, H) Corresponding plots after median filtering to suppress 'common noise'.

Outlook.

The current measurement accuracy is 15 - 20 $\mu\varepsilon$. To reduce noise levels prior to injection, two measures will be implemented:

- Deployment of a Rayleigh interrogator ('Neuscope NBX 7031, Neubrex'), expected to improve accuracy to 1 - 5 $\mu\varepsilon$.
- Fusion-splicing all boreholes into a continuous loop. The existing loop configuration, formed via fibre-optic couplers, provides acceptable measurements but degrades the signal-to-noise ratio, particularly for boreholes at the loop terminus. Splicing will enhance data quality but will reduce flexibility in the event of a fibre break.

2.6 Seismic monitoring (WP3)

Aim of investigation.

To monitor the integrity and sealing capacity of the faulted Opalinus Clay caprock acoustic transmission data from the CO_2LPIE experiment at the Mont Terri Underground Laboratory were analyzed using coda wave interferometry (CWI). Four monitoring boreholes were equipped with 12 ultrasonic transmitters and 12 acoustic emission receivers.

Current status of measurements and analysis.

For the seismic and acoustic measurements, an array consisting of 12 pairs of seismic transmitters and seismic receivers with preamplifiers is available. The arrangement of the sensors in the four boreholes was optimized so that a high overlap can be achieved in the injection area of the experiment in order to be able to record fluid flow along bedding and also across it.

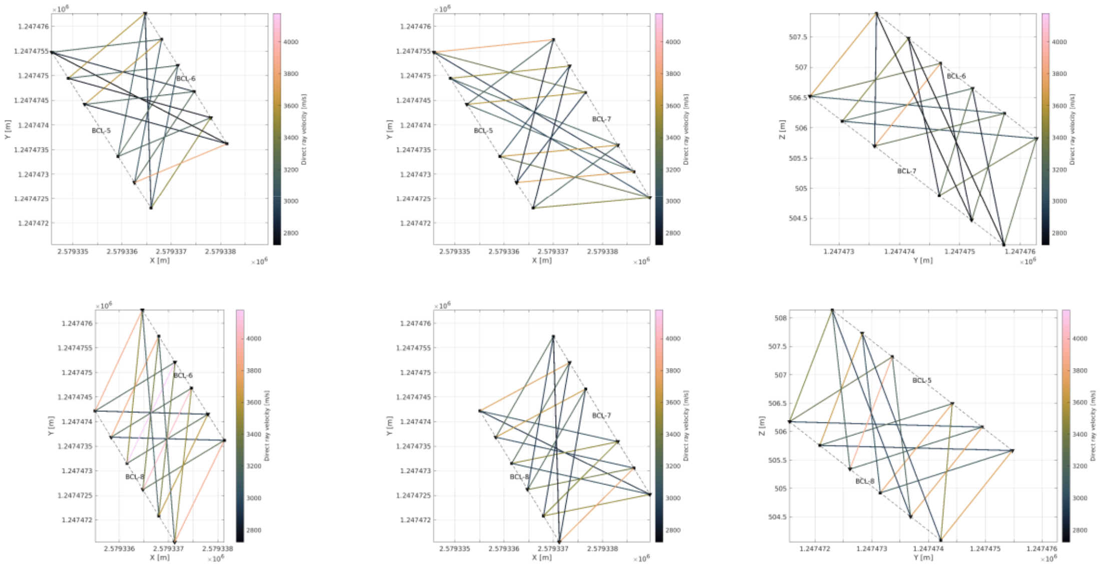

Figure 2.6.1. Direct ray velocity model of CO2LPIE (by J. Junker & A. Obermann, ETH).

Raw data yield high signal-to-noise ratios and indicate that all resin-embedded sensors are well-coupled to the rock formation. A direct ray velocity model is available from picked first arrivals (Figure 2.6.1). The anisotropy of the rock mass is visible, the direct ray velocities orthogonal to boreholes are faster than direct ray velocities that run in a more parallel direction. A glance on the time series during the baseline monitoring phase after MMMS installation generally yields increasing velocities with time. Amplitudes are decreasing with time. Velocity variation and waveform coherency point to temporal effects.

Acoustic emission data. From April to November 2024, after borehole resin filling, daily transmitter shots were recorded at night to maximize signal-to-noise ratio. All 12 transmitters were sequentially activated, and waveforms were acquired at 200 kHz with a maximum source-receiver distance of 4.75 m.
Quantification of velocity and waveform changes. CWI detected subtle changes in the medium, as coda waves densely sample the rock volume. While first-arrival P-waves remained stable, later coda segments of monthly waveforms from selected pairs (e.g., S7-R5, S13-R8) showed gradual phase shifts and slight amplitude reductions.

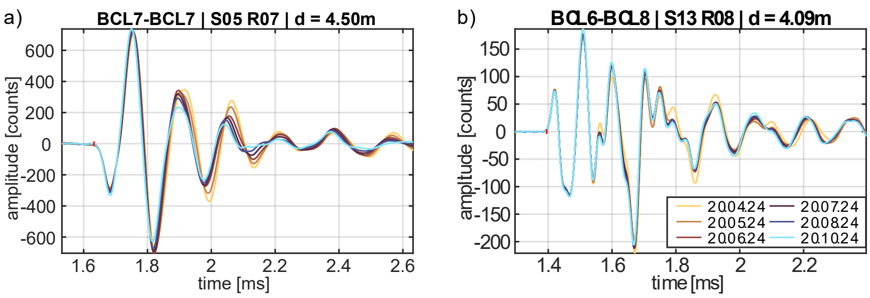

Figure 2.6.2.Visualization of waveforms for two transmitter–receiver pairs on different days of 2024: (a) transmitter 5 to receiver 7 within BCL-7, and (b) transmitter 13 (BCL-6) to receiver 8 (BCL-8). The picked first-break time is marked by a red vertical line.

Relative velocity changes (dv/v) were calculated using the stretching technique (Lobkis & Weaver, 2003; Obermann & Hillers, 2019), by comparing the April 24 reference waveform with subsequent daily records within a time window around the first arrivals. Reflections at ~3.5 ms, linked to borehole operations, were excluded from the analysis.
Seismic velocity variations. Most source-receiver pairs exhibited a gradual dv/v increase during the first month, which steepened between mid-May and September before leveling off in October, with some pairs reaching ~10%. Linear fits for October were applied to illustrate representative long-term trends and corresponding 3D ray paths within the rock volume (Figure 2.6.3.).

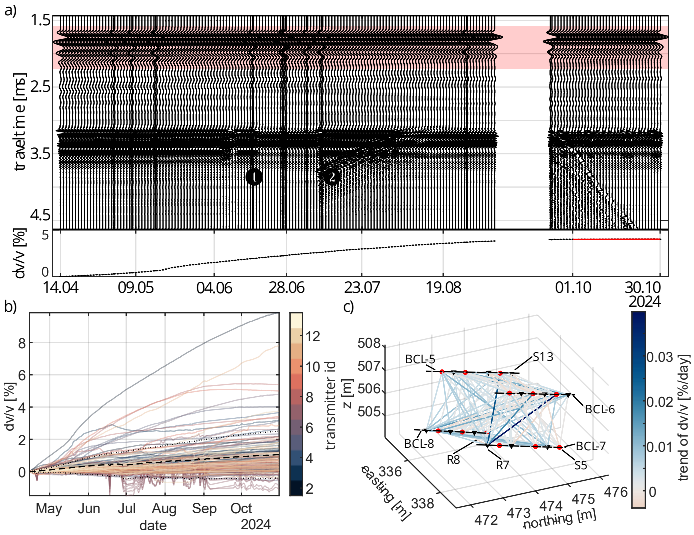

Figure 2.6.3. a) Time series of shots from transmitter S5 to receiver R7. The red shaded area marks the time window used for dv/v calculations. ❶ Wavefield variations around June 21 linked to refilling of BCL-5–BCL-8; ❷ New reflection on July 10 from repressurizing BCL-6 and BCL-7. b) dv/v evolution for all 144 source–receiver pairs; black lines denote mean ± standard deviation. c) dv/v trends in October 2024, red dots represent transmitters, black triangles receivers.

Outlook.

Between April and October 2024, direct P-wave first arrivals remained stable, whereas coda waves revealed ~1% velocity increases, consistent with post-drilling rock settlement. These findings demonstrate the sensitivity of CWI to subtle rock volume changes (Obermann and Ziegler, 2025). Future work will focus on spatially localizing dv/v variations using probabilistic sensitivity kernels (e.g. Pacheco and Snieder, 2005) to map rock property changes and improve caprock monitoring.

2.7 Status main experiment installations (WP3)

In this section the details of the chosen in-situ experimental setup including injection borehole, extraction or monitoring borehole and the surface equipment are described. The installation of the two MPS was carried out in January 2025. The complex surface system was installed in summer 2025.

Both systems (injection- and extraction borehole) are consisting of 5 packers with 88 mm diameter deflated and a length of 875 mm each. The packers are inflated with fresh water over one injection line ss 4/2.3 mm. The intervals are equipped with ss sintered filters 85 mm diameter. Lowermost intervals are single packer systems, all the other intervals are double packer intervals.

Injection borehole (BCL-9)

The more complex system is BCL-9 (Figure 2.7.1. Sketch with dimensions of the two multipackersystems (MPS), BCL-9 at the top and BCL-10 (later BCL-11) at bottom on image. There are 4 lines to intervals 2 and 4, ¼" for pressure and both lines inflow and outflow and bypass control line 4/2.3 mm. The ¼" lines have an inner diameter of ID 4.6 or 5.3 mm. 3 lines are guided to intervals 1, 3 and 5 with ss 4/2.3 mm for pressure, inflow and outflow. There is one inflation line per packer. In total 22 steel lines are to be connected to the cabinet at borehole BCL-9. The two injection intervals are equipped with two 50 µm grade sintered ss filters each, which are connected to each other. In case of clogging problems with the filters, by applying a slight overpressure through an ss 4/2.3 mm control line, a bypass valve can be opened downhole and bypass the two filters. This opening is a one-way procedure, which cannot be closed again. Details of this mechanism will be given in the solexperts installation report about CO_2LPIE, which is expected in Mid-2025. All the other intervals in BCL-9 are equipped with single standard 15 µm grade ss sintered filters and without bypass option.

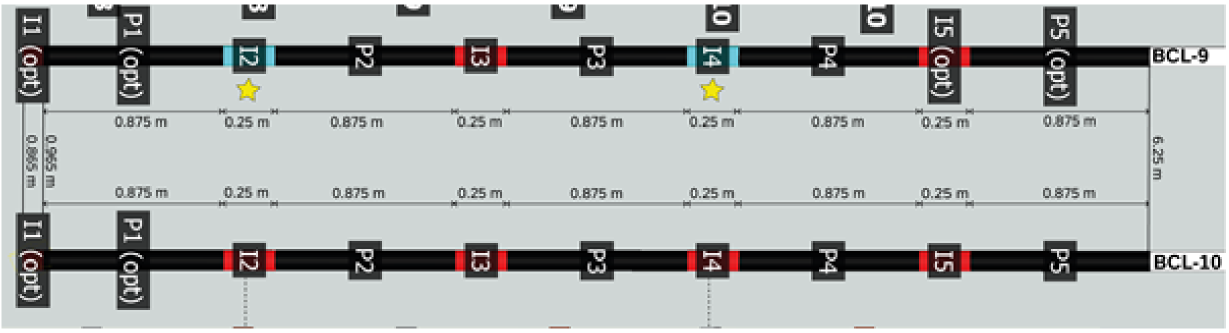

Figure 2.7.1. Sketch with dimensions of the two multipackersystems (MPS), BCL-9 at the top and BCL-10 (later BCL-11) at bottom on image.

Extraction borehole (BCL-10 – later on BCL-11)

In BCL-10 there are 3 ss 4/2.3 mm lines per interval for pressure, inflow and outflow. All the intervals in BCL-10 are equipped with single standard 15 µm grade ss sintered filters. There is one inflation line per packer. In total 20 steel lines are to be connected to the cabinet at borehole BCL-10. The exact positions of the intervals (bottom and top) for both systems are identical. For the double packer systems, the interval filter is considered as fixed. At the lower end of the packers there is the sliding end, which moves depending on exact borehole diameter and inflation pressure 3-4 cm upwards. At the upper end the packer sleeve is fixed and due to inflation of a quite rigid rubber and the bending radius, 4-5 cm are not sealed in the end. The total length of the interval finally is ~ 26 cm.

Surface equipment for injection and extraction boreholes

The chosen experimental concept features two main components:

i) Gas monitoring is achieved over uphole gas membranes, so called SysMoG's developed by solexperts and being tested by Eawag
ii) The injection of the CO_2 dissolved in APW into the formation consists of a diffusive circulation system instead of a direct one-way injection. Both concepts are innovative by their own already, but in combination such installation is novel and innovative for a rock lab scale experiment.

The membrane systems for the separation of the gas phase from the fluid was installed at the surface instead of downhole for several reasons:

- High sensitivity due to accumulation of dissolved gases in top part
- Access to gas chamber for maintenance – clogging with biofilm might be an issue, as experience at CS-D/CS-E experiments has shown.
- Can be used as CO_2 injection device, either for pulse or permanent injection (reversed SysMoG)
- No space limitation for gas
- Monitoring of pH, EC, Eh, etc. feasible

In CO_2LPIE four SysMoG's are installed for gas monitoring in dedicated intervals and one reversed SysMoG will be used for dissolving the CO_2 gas mixture in APW in the injection circuit. For the injection a diffusive circulation system was chosen, since the diffusive exchange of water, gas and added tracers are key for the sound understanding of the near well rock-water-gas interaction processes. The circulation system on the injection side is prepared for adding different kinds of non-radioactive water tracers and for sampling over dedicated vials (constant concentration and pressure) or extraction valve (changing concentration and pressure). If the volume of samples is much smaller than the total volume of the circuit, then both methods are scientifically correct.

There are two solexperts cabinets for DAS (including a Geomonitor-terminal) and a packer control cabinet for the four monitoring boreholes, which have been installed in March 2024 after installation of the MMMS by swisstopo. For the two boreholes BCL-9 (injection) and BCL-10 (extraction) 5 cabinets are needed in total (Figure 2.7.2):

A. Injection cabinet (installation in summer 2025)
B. Monitoring/circulation cabinet (installation in summer 2025)
C. Gas analyses cabinet (installation in summer 2025)
D. Packer control cabinet for borehole BCL-9 (installed in January 2025)
E. Packer control cabinet for borehole BCL-10, later BCL-11 (installed in January 2025)

The most important features/innovations of the deployed injection/extraction system are as follows:

- The injection cabinet contains the injection circuit including the gas mixing part. The CO_2LPIE system features an injection by circulation through the injection interval at controlled variable pressure. Instead of direct one-way injection, the current proposed system allows for the assessment of in-situ diffusion properties by adding conservative tracers, such as I^-, ^{18}O enriched water at low pressure and Br^-, HDO at high pressure into the circuit.
- CO_2 is dissolved in artificial pore water by means of a reversed SysMoG. The saturation process is much better controlled this way and pressure control and gas flowmeter upstream assure full control on the injected volumes.
- Four intervals are monitored permanently. Each individual circuit comprises upstream the SysMoG for the separation of the gas content by a semipermeable membrane, 10 sampling vials of 5 ml volume, an additional sampling valve for non-constant pressure volume extraction, a pulsation free low-pressure circulation pump and a flowmeter. After circulation through the downhole interval, upstream the geochemical on-line sensors for EC, Eh and pH are installed. The four SysMoG's are connected to a custom-made miniRuedi gas mass spectrometer (see below).

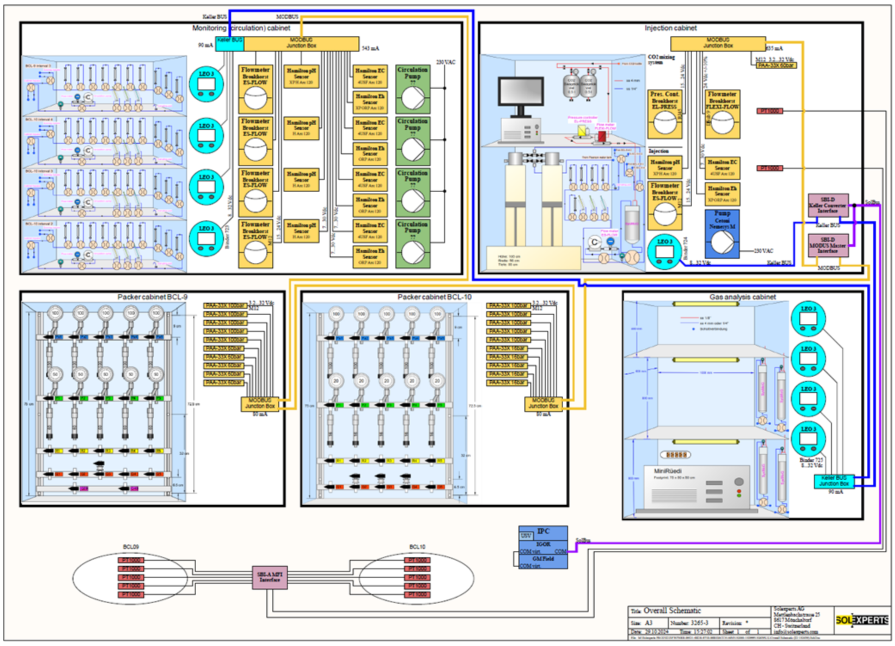

Figure 2.7.2. The five control cabinets for BCL-9 and BCL-10 (later BCL-11). Please note, that the packer control cabinet for BCL-5-8 and the DAS cabinet are not displayed here.

The drilling campaign for BCL-9 and BCL-10 was carried out in January 2025. After drilling both boreholes, geophysical logging with OBI, SGR, DIL and BMR were performed. After that a crosshole seismic survey was carried out by BGR and then the two MPS were installed and saturated by solexperts. The borehole target sections from 10 to 15 m depth were entirely sampled for later analysis.

Current status of system performance, first measurements and analysis.

All 5 cabinets have been manufactured and tested in the solexperts workshop.

The *injection cabinet* contains the injection circuit including the gas mixing part. The CO_2LPIE system features an injection by circulation through the injection interval at controlled variable pressure. Instead of direct one-way injection, the current proposed system allows for the assessment of in-situ diffusion properties by adding conservative tracers, such as I^-, $H_2{}^{18}O$ at low pressure and Br^-, HDO at high pressure into the circuit over a 300 ml tracer vial. Upstream of the circuit, the 50 l Pearson water reservoir is located. Water can be added to the circuit over a double piston syringe pump (Zetoni), which is steered over a dedicated control pc. Each of the two pistons has a volume of 5 ml. The double piston syringe pump allows for controlled oscillations at high pressure and for seamless refill of the pistons, without a need for lowering the pressure for the refilling process. Downstream of the latter, the CO_2 is added to the circuit. CO_2 being labelled with ^{13}C and Kr (Weber et al. 2023) is added to the system over a gas pressure controller, a gas flow meter and a reversed SysMoG.

This *monitoring/circulation cabinet* contains the four monitored water circuits. These circuits are not highly pressurized and generally should measure something like the hydrostatic pressure or bit higher, after a certain operation time. The circuits comprise intervals BCL-9_I3 (guard interval in injection borehole above injector) and intervals BCL-11_I1-3, where I3 is located on the same level, as the injector. Each individual circuit comprises upstream the SysMoG for the separation of the gas content by a semipermeable membrane (note, that these devices are installed in the gas cabinet), 10 sampling vials of 5 ml volume, an additional sampling valve for non-constant pressure volume extraction, a pulsation free low-pressure circulation pump and a flowmeter. After circulation through the downhole interval, upstream the geochemical on-line sensors for EC, Eh and pH are installed.

The *gas cabinet* was prepared by solexperts with the 4 SysMoG's, which are dedicated to the four gas loops (Figure 2.7.3). The gas loops including the 4-port miniRuedi were prepared at Eawag and installed by Eawag and the technical assistance of solexperts in their workshop in Mönchaltorf. Four identical gas circulation units are available. The gas enters the circuit over the SysMoG, which separates the gas phase from the fluid phase over a semipermeable membrane. A gas sampling container can be separated from the loop by a 4-way-valve. The miniRuedi measures not only the gas composition in the four monitored intervals, but also the background concentrations in the air of the rock laboratory. A membrane pump keeps the circulation running and a flow meter measures the gas flow within the circuit.

Two packer control cabinets are dedicated to the multi-packer systems (MPS). The systems are identical concerning number of packers (5 packers) and intervals (5 intervals) however, there are some differences inside. These differences include the interval working pressure, which is up to 3.5 MPa in borehole BCL-9 intervals and hydrostatic or lower (0.8-1.0 MPa) in BCL-11 intervals, thus pressure sensors in BCL-9 are 5x100 bar for packers and 5x60 bar for intervals, all PAA-33x. In BCL-11 pressure sensors are 5x100 bar for packers and 5x16 bar for intervals, all PAA-33x.

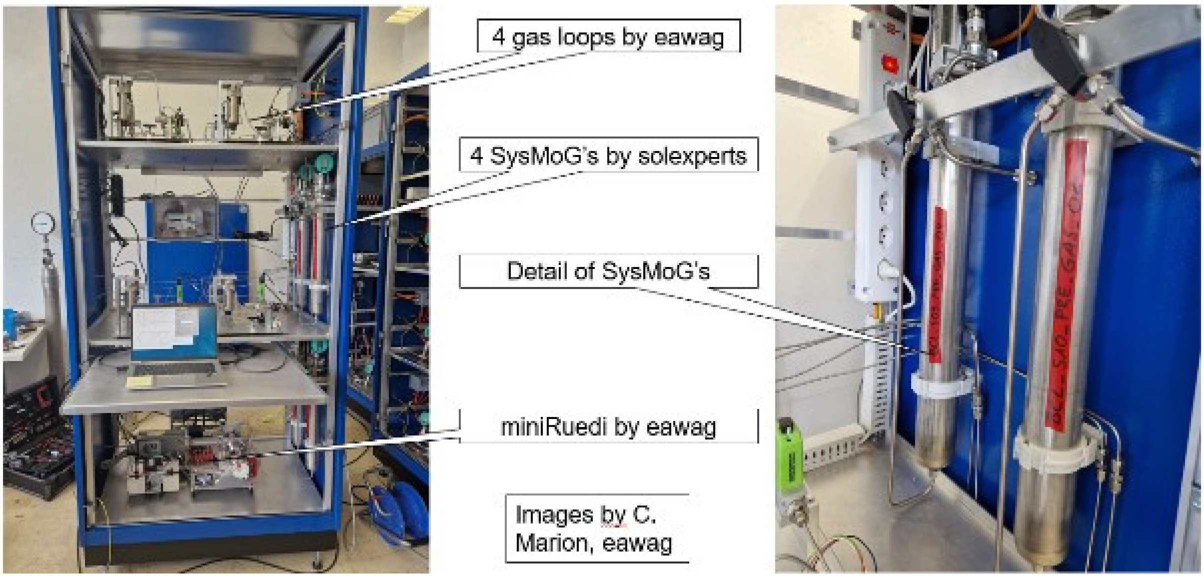

Figure 2.7.3. Detail of gas monitoring cabinet during testing operation in the solexperts workshop.

All these cabinets have been connected to the in situ experiment and the circuits have been saturated with APW in early July before the summer break of the rock laboratory. The hydraulic tests for the hydraulic rock mass characterisation and the tightness and performance testing of the MPS in the injection borehole BCL-9 have been completed. All intervals have been tested with pulse tests and constant head injection tests.

Outlook.

Currently the first diffusion test using tracers I^- and $H_2{}^{18}O$ is running. After this initial monitoring, CO_2-injection together with Br^- and HDO will start most likely in early January 2026.

2.8 Status gas injection module and tracer concept (thesis C. Marion, Eawag, WP3, WP4)

Aim of investigation

This module aims to monitor the geochemical evolution and migration of the injected fluid via continuous, real-time in-situ gas measurements. An on-site gas monitoring station was installed, using 'SysMoG' membrane modules (solexperts) to extract dissolved gases from porewater and a portable mass spectrometer ('miniRuedi') for direct measurement. The system enables daily monitoring of key gases - CO_2, N_2, O_2, CH_4, He, Ar, Ne, and Kr - across four packer-isolated intervals. The gas extraction loop also permits collection of copper tube samples for high-precision laboratory analysis of noble gases.

Current status of measurements and analysis.

The CO_2LPIE project aims to inject dissolved CO_2 with a noble gas tracer to assess the integrity and permeability of Opalinus Clay as a caprock for CO_2 sequestration (Brennwald et al., 2023, Weber et al., 2023). This tracer-based approach separates chemical reactions involving CO_2 from physical processes that affect both CO_2 and the added noble gases. Boreholes have been drilled and instrumented with an MMMS (see above, Ziegler et al., 2025). Additional boreholes for CO_2 injection and extraction have been drilled in early 2025, with gas lines to monitor dissolved gas concentrations being installed shortly thereafter. The exact locations of these 'geochemical' wells BCL-9 and BCL-10/11 were determined based on geophysical data on the geological texture of the targeted rock volume (see before).

In a collaborative effort Eawag, swisstopo and the other project partners designed the injection and extraction lines for the gas injection and monitoring. At the same time, Eawag planned the gas loops, which are currently being constructed at the solexperts factory. The complete system for continuous gas measurements was installed in the rock laboratory in summer 2025.

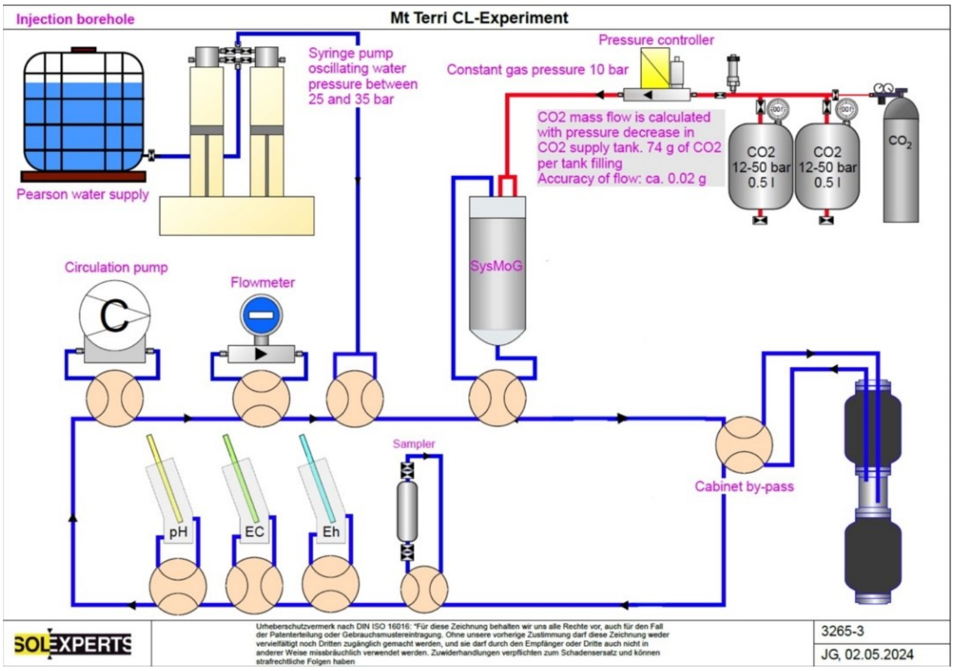

Figure 2.8.1. The final design of the fluid injection system incorporates patented SysMoG membrane modules (SysMoG®, www.solexperts.com/files/downloads/FP_SysMoG_Deepenglisch.pdf) being designed to withstand the high in-situ pressure of the targeted OPA section. These modules enable precise loading of CO2 or other gases, such as noble gases, into the circulating fluid through controlled diffusive exchange across the membranes operating at steady-state. Eawag thoroughly analysed and tested the performance of this innovative technique for injecting specific gas amounts into highly pressurized fluids (Brennwald et al., 2024).

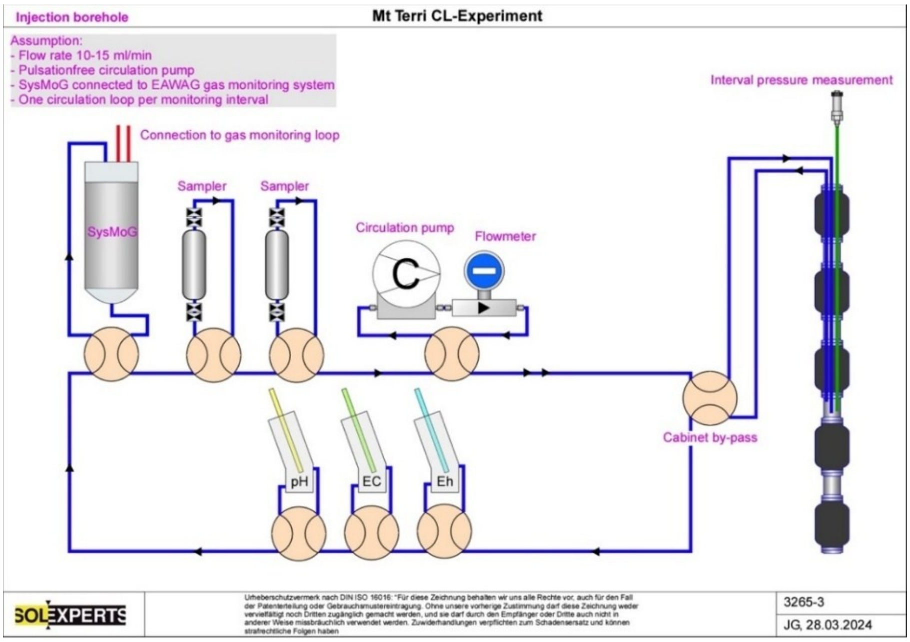

Figure 2.8.2. Porewater injection loop as installed by solexperts.

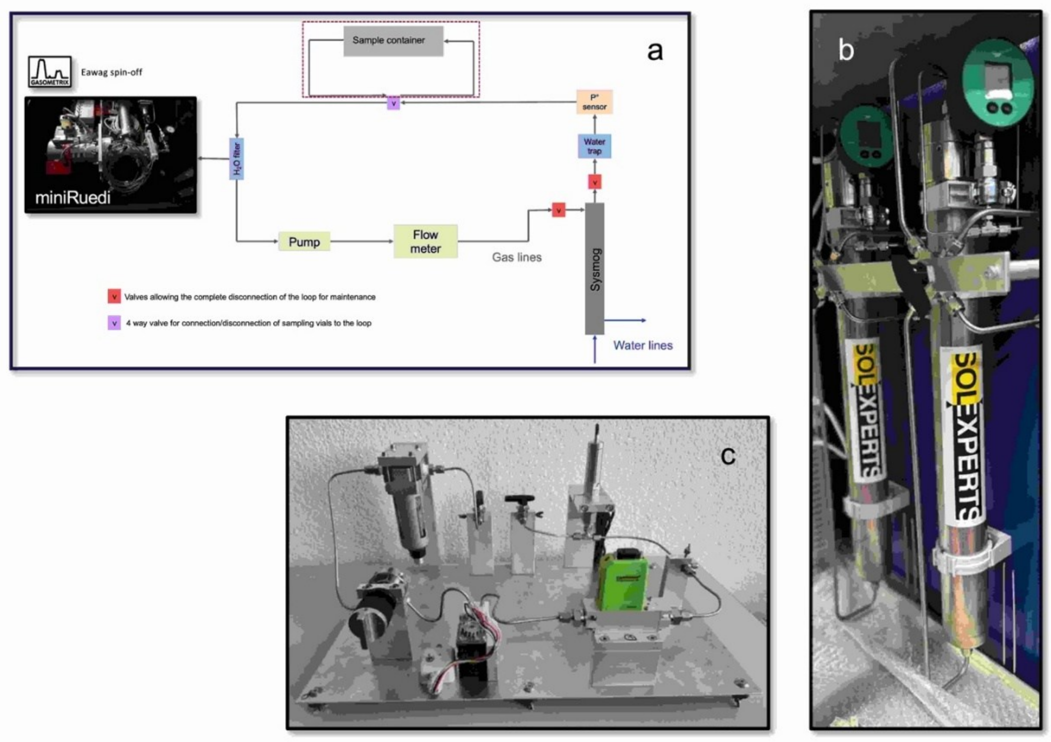

Figure 2.8.3. Concept of the extraction loop which was constructed and installed by Eawag. (a) concept of gas extraction loop (miniRuedi - device for continuous gas measurements (He, Kr, Ar, N_2, O_2, CO_2, CH_4, H_2), (b) SysMoG modules facilitating gas extraction from fluid phase circulating through the packer system installed in the OPA, (c) gas line to feed the extracted gas into the gas detection system (miniRuedi).

Rock samples from borehole BCL 9 have been collected to determine baseline noble gas concentrations in the rock matrix; these samples require several months of equilibration before analysis. The miniRuedi mass spectrometer, custom-built at Eawag for this campaign, features additional inlet valves and enhanced Neon measurement capabilities. The gas extraction and monitoring loops were developed and tested at Eawag prior to integration into the 'Solexperts' instrumentation cabinets (Figure 2.8.4). The complete monitoring system has now been assembled and installed and a successful system-wide test phase was carried out in September and October. On-site gas monitoring has stated in November 2025.

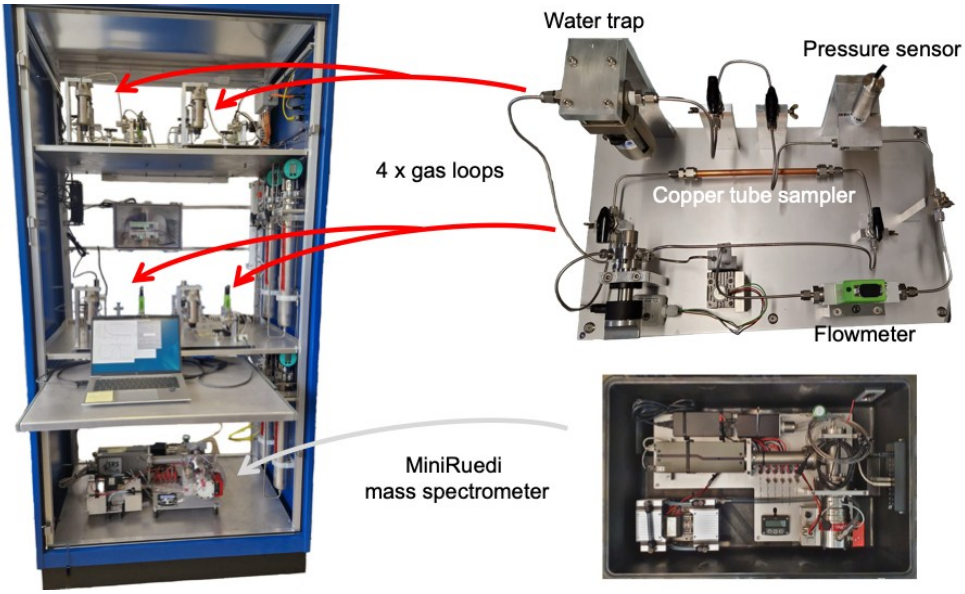

Figure 2.8.4. Gas measurement loops and the mass spectrometer for on-site analysis have been installed. All equipment was developed and tested at Eawag. The gas loops also allow collection of copper tube samples for high-precision analysis of noble gas composition.

Outlook.

The next steps involve continuous measurements to establish the baseline porewater gas composition, which will serve as a reference for detecting changes during fluid injection and subsequent migration.

2.9 Geochemical investigations (Squeezing, Diffusion, WP3)

The overall objective of Uni Bern's contribution is to support CO_2LPIE with geochemical expertise. This includes modelling, laboratory experiments and analytical services.

Aim of investigation.

In this module Uni Bern conducts a series of scoping calculations to support CO_2LPIE experiment planning, including evaluation of injection modes and pressures (2021-2023), assessment of cyclic pressure effects on CO_2 and tracer transport (2024), and analysis of design parameters for short- and long-term tracer tests (2024-2025).

Current status of measurements and analysis.

Artificial porewater, tracer testing, analytical work. For the gas injection experiment the Mont Terri porewater and prepared artificial porewater (APW) were geochemically characterized. This analysis contributed to the design of the tracer tests and will prepare tracers for the short-term diffusion phase (I^- and $H_2{}^{18}O$) and the long-term injection phase (Br^- and HDO). Water samples from the failed borehole BCL-10 have been analyzed and proved a mixing of packer waters with the interval water.

Porewater squeezing: Squeezing experiments were conducted on two drill core samples at the 'CRIEPI' laboratory in Japan. The extracted waters were subsequently analysed at the University Bern. The resulting porewater compositions are consistent with expected values and previously prepared artificial porewater (Figure 2.9.1). Results and interpretation will be documented in a Technical Note.

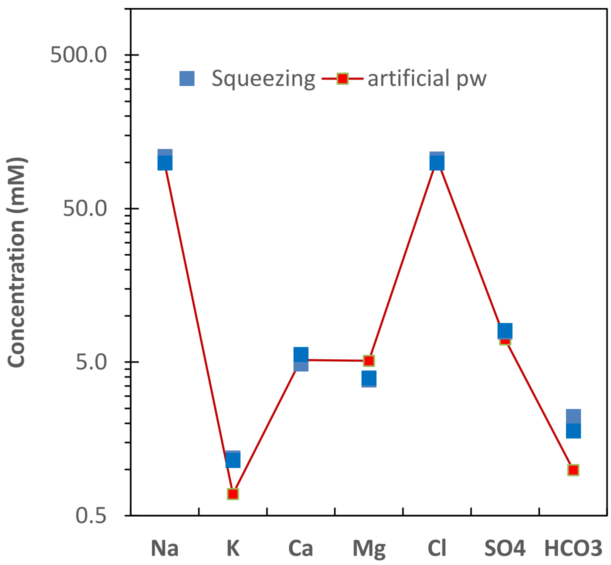

Figure 2.9.1. Schoeller diagram showing the compositions of squeezed porewaters from BCL 7 and BCL 8 (blue squares) compared with the artificial porewater prepared for the CO2LPIE experiment (red squares).

Outlook.

In 2025, three benchmarking modelling exercises addressing diffusion processes (isotropic and anisotropic) and geochemical reactions (e.g. CO_2 dissolution and reaction with calcite and dolomite) will be conducted. The results will form the basis for planning a laboratory batch experiment at BGR.

Soon the diffusive tracer test prior to CO_2-injection to estimate diffusion parameters near the injection borehole will be modelled to simulate the initial phase of the injection experiment.

2.10 Injection concept (WP4)

The injection at CO_2LPIE consists of a diffusion test phase at ambient or hydrostatic pressure and a diffusion test phase combined with the CO_2 injection while rampling up and later oscillation. Due to bad experience with the first packer series installed in borehole BCL-9 and BCL-10 and the later switch to a new borehole BCL-11 with new and thoroughly tested packer series it was decided to switch the injection borehole to BCL-11 and the monitoring borehole to BCL-9. The reason for that is mainly the lower expected pressures on the monitoring side, which will be less risky for additional packer failures in the future.

A diffusion test by adding I- and $H_2{}^{18}O$ via a 300 ml vial to the injection circuit (BCL-9) started on 16 October 2025 at ambient pressure of 0.9 MPa (Figure 2.10.1). After 4 days of circulation in the cabinet, the downhole interval was connected and 2 ml sampling will be continued until 5 December 2025. In week 51 the switch of the injector to BCL-11 and the monitoring borehole to BCL-9 will be done. Subsequent equilibration lasts for 31 days over the X-Mas break. The properties controlling the efficiency of injection together with the rock mechanical behavior (matrix-flow versus fracture dominated flow) will be tested prior to injection by a step pulse tests of 1 day duration. The maximum pressure will be 2.5 MPa. Then the second tracer test with Br- and deuterated water added to the 50 l Pearson water tank starts, together with the CO_2-injection and the subsequent ramping up. The ramping up will be done as a constant-head step injection test (CHSIT) with 7 day steps of 0.2 MPa pressure increase. At 2.6 MPa the pressure will be kept constant over 28 days and then another two steps will increase the pressure to the maximum of 3.0 MPa. The subsequent part will be the periodic injection oscillations with a frequency to be defined.

The cyclic injection pulsation steered by the syringe pump starts at a lowest period of π/2 day (oscillating pressure CO_2 injection phase) and will oscillate between 3 and 2 MPa. Later on, enlarged periods consisting of multiples of π/2 day are foreseen. The cyclic pulse injection ideally should be as close as possible to a sinusoidal signal.

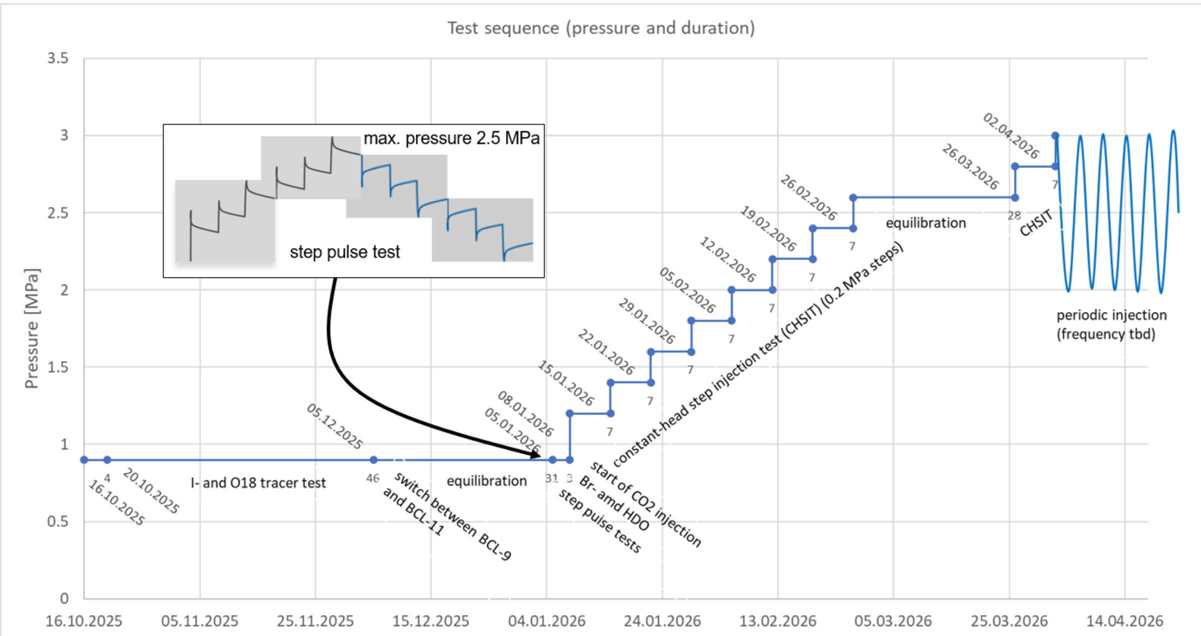

Figure 2.10.1. CO_2LPIE test sequence (status November 2025). After diffusion tests with I- and $H_2{}^{18}O$, injector and monitoring borehole will be switched and equilibrated. Then after the X-Mas break, first a step pulse test will be conducted and then Br- and deuterated water will be added together with CO2 and the ramping up will start (by D. Jaeggi, swisstopo).

2.11 Modeling activities (WP1)

Aim of investigation.

The primary goal of modeling in the CL experiment is to develop and validate approaches for long-term CO_2 injection in the sandy facies of Opalinus Clay, focusing on coupled thermal-hydraulic-mechanical-chemical (THMC) effects. Five institutions - BGR, CSIC, Mines Paris, NTNU, and the University of Berne - employ diverse codes (CodeBright, OpenGeoSys-6, PFLOTRAN, PHREEQC+CHESS) to enable cross-validation. Models are used for scoping calculations, sensitivity studies, and preliminary long-term simulations. Some benchmarks address hydraulic-chemical processes, including transport and reactions (BGR, Mines Paris, University of Berne), while others focus on hydraulic-mechanical effects, such as excavation-induced processes, anisotropic stress, or swelling (BGR, CSIC, NTNU). This coordinated approach validates numerical tools and improves understanding of coupled THMC effects, supporting both model setup and interpretation of results.

Current status of measurements and analysis.

The modeling activities in the CL experiment focus on the further development and validation of modeling approaches for the long-term CO_2 injection in the sandy facies of Opalinus Clay as it is conducted in the CL experiment. The numerical models are used for scoping calculations, sensitivity studies and preliminary long-term calculations considering coupled thermal-hydraulic-mechanical and chemical aspects. In general, a particular focus of the experiment is on investigating the effects of anisotropies and heterogeneities of the host rock. Starting points are simple benchmarks calculations that enable the investigation of parameter sensitivities and the impact of different kinds of model set-up. The defined benchmarks are based on scoping calculations of the experiment that have been performed to optimize the layout and geometric set-up (Sciandra et al. (2022a), Sciandra et al. (2022b), Ma et al. (2024)). Comparisons of the results from these benchmarks, along with discussions of the different modeling approaches - ranging from 2D and rotationally symmetric to fully 3 D models - are currently ongoing. These investigations provide a comprehensive understanding of how model setup affects the results, including the influence of geometry, boundary conditions (such as the geometry of the injection zone and the choice between pressure-controlled or source-term implementation), and the range of modeled processes, including hydraulic-chemical (HC), hydraulic-mechanical (HM), dispersion, and storage effects. The insights gained from these studies are essential for accurately interpreting numerical results and guiding model design. In addition, a complementary laboratory experiment is being conducted to support the modeling work, with the aim of improving the representation of chemical processes in the sandy facies of Opalinus Clay.

Currently, five institutions are involved in CL modelling: BGR, CSCI, MinesParis, NTNU and the University of Bern. These teams use different codes (CodeBright, OpenGeoSys-6, PFLOTRAN, PHREEQC+ CHESS), enabling a comparison and validation of different tools. The modelling focuses on general understanding of the coupled effects: some of the benchmarks are on the hydraulic-chemical aspects, taking into account e.g. transport processes and reactive components (modelled by BGR, MinesParis and UniBern), while others focus on the hydraulic-mechanical aspects like excavation induced processes and the anisotropic stress field amongst others (modelled by BGR, CSIC and NTNU).

Uni Bern has additionally been performing various scoping calculations for the planning of CO_2LPIE experiments, which includes exploring various injection modes and pressures (2021-2023), assessing the impact of cyclic pressure on the transport of CO_2 and tracers (2024), and evaluating design parameters in the short-term and long-term tracer tests (2024). In the near future, Uni Bern will model the diffusive tracer test before the injection of CO_2 to estimate of diffusion parameters near the injection borehole, as well as model the starting of the injection experiment.

Outlook.

By comparing key parameters such as pressure and concentration and validating individual input parameters, a well-validated base model for the CL experiment can be established (publication in preparation). This model provides a foundation for incorporating additional effects, including chemical reactions, kinetics, boundary conditions, heterogeneities, hydraulic and mechanical anisotropy, and anisotropic stress fields across different temporal and spatial scales. These extensions enable investigation of further process variables, such as pH, mineral content, and porosity in HC modeling, and displacements, strains, and stresses in HM modeling.

For example, a 2 D rotationally symmetric setup can be used to compare HC and HM benchmarks in terms of pressure and concentration evolution (Figure 2.11.1). Overall, results from different teams are in good agreement, supporting the validity of the modeling approach and setup. At finer scales, differences reflect varying treatment of poro-elasticity in HM and HC models. Potential chemical effects on solid and liquid densities may also be considered in future studies when comparing pressures.

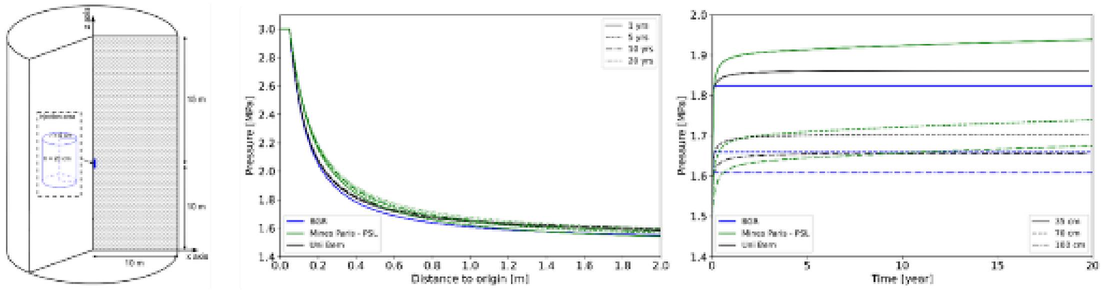

Figure 2.11.1. 2D rotationally symmetric benchmark setup (left) with modeled pressure profile (center) and temporal evolution (right, publication in prep.).

Next steps involve intensifying comparative analyses with the installed measurement systems while integrating geological observations. Model complexity will be progressively increased to identify key influences of anisotropy and heterogeneities. Overall, the modeling efforts in the CL experiment represent a critical step toward developing and validating realistic models for the planned long-term CO_2 injection.

3 Conclusions and outlook

CO_2LPIE is currently approaching the important milestone 3, the injection of CO_2 into the experimental volume. The multidisciplinary and multinational team has made remarkable progress on various fronts. The in-situ installation in the rock laboratory has been completed, marking the end of many years of development and testing work. The systems now in place are fully tailored to the issues addressed by CL and have been optimized to the maximum extent possible using innovative techniques and approaches. The four MMMS have been successfully developed and installed and have now been measuring the baseline in the experiment with high spatial and temporal resolution for more than a year. The technical problems with the MPS in BCL-10 were solved in the best possible way by completely replacing it in a new borehole, BCL-11, with minimal impact on the planned experiment. The characterization of the experiment volume is still ongoing with laboratory tests (diffusion tests, squeezing tests, etc.), but the geological model with high-resolution heterogeneity distribution is already available and has provided indispensable services in the implementation of the two central boreholes. This model will also play a central role in the interpretation of later observations and results. Parallel to all this work, the modeling team has optimized the numerical codes and supported the technical execution of the experiment by means of design and prediction modeling. The relevance of heterogeneity in the experimental space is currently being investigated and the codes are being tested against each other using benchmarking exercises. The originally planned laboratory program has become increasingly extensive due to new additions from interested partners and now covers a very broad spectrum of investigations. For example, with the NTNU, the Norwegians are now also heavily involved in the laboratory program and modeling work. A team from the Montan University Leoben is conducting rock mechanics index tests on samples from CO_2LPIE. Due to the technical problems mentioned above and the longer development and equilibration phase, adjustments had to be made to the schedule. After the current baseline characterization, the start of CO_2 injection is now planned for early January 2026. The hydraulic test program was completed and the in-situ installations have been tested successfully for final tightness. Injection of a first set of conservative tracers has been started in October 2025 as part of the baseline characterization. In 2026, the pressure steps planned in accordance with the injection protocol will be carried out, accompanied by high-resolution monitoring in terms of both time and space.

4 National and international collaboration

At the national level, cemsuisse and VBSA are involved in the CO_2LPIE activities and are regularly informed by the project management about the state of affairs. At the national and international level, CO_2LPIE is integrated as a CL experiment in the Mont Terri Consortium, where a regular exchange takes place at conferences and strategy meetings. In addition to the organizations that have been working on the project for a long time, such as CSIC (Spain) and the University of Illinois (USA), the Smile doctoral network (https://smile-msca-dn.eu/) has recently been added. Within the framework of this network, several modeling related dissertations are dealing with the CO_2LPIE data (Smile project - Multi-diSciplinary and MultIscale approach for assessing coupLed processes induced by geo-Energies, see http://www.seismo.ethz.ch/en/research-and-teaching/projects/smile/). These organizations participate in the modeling meetings organized by BGR in a regular manner. In addition, further collaboration with the University of Leoben (Austria) in the field of rock mechanical tests has arisen within the framework of the project.

5 References

Abdelouhabi M., Ziegler M., Jaeggi D., Kipfer, R., Marion C., Rinaldi, A. P., Obermann, A., Junker, J.,S., Zappone, A. S., Furche, M., Burschil, M., and Wersin. P. (2025) CO2 Long-term Periodic Injection Experiment (Mont Terri URL): Introduction to the in-situ experiment and geological site characterization. Poster presentation at TCCS-13, 16-19 June, Trondheim (Norway) TTC.

Brennwald, M., Schmidt, M., Oser, J., and Kipfer, R. (2016) A Portable and Autonomous Mass Spectrometric System for On-Site Environmental Gas Analysis. doi.org/10.1021/acs.est.6b03669.

Brennwald, M. S., Peel, M., Blanc, T., Tomonaga, Y., Kipfer, R., Brunner, P., Hunkeler, D. (2023) New experimental tools to use noble gases as artificial tracers for groundwater flow. Front. Water, 4, 925294, doi.org/10.3389/frwa.2022.925294.

Brennwald, M. S., Rinaldi, A. P., Gisiger, J., Zappone, A., and Kipfer, R. (2024) Gas equilibrium membrane inlet mass spectrometry (GE-MIMS) for water at high pressure. Geoscientific Instrumentation, Methods and Data Systems, 1, 1-8. doi.org/10.5194/GI-13-1-2024.

Chen, S., Ostertag-Henning, Ch., Kumar, V.,Shao, H., Ziefle, G., and Maßmann, J. (2024) Studying the reactive transport of CO2 in Opalinus Clay with experimental and numerical analyses, Clay Conference 2024, November 24, Hanover, Germany.

Chen, S., and Ziefle, G. (2024) Studying the reactive transport of CO2 in Opalinus Clay with experimental and numerical analyses. Presentation at OGS Community Meeting 2024, Leipzig, Germany.

Goodman, H., Rösli, U., Gisiger, J., Jaeggi, D., Minnig, C., 2022: SEALANT TESTS AT THE MONT TERRI CS-A EXPERIMENT THAT ADDRESS SEEPAGE OF CO2 BEHIND CASING in Carbon Dioxide Capture for Storage in Deep Geological Formations, Volume 5, K. F. Gerdes (Editor), p. 629-668.

Goodman, H., Rösli, U., Gisiger, J., Jaeggi, D., Minnig, C., 2023: CS-A Experiment: Synthesis report of CS-A work activities Sealant test outcomes that address seepage of CO2 behind casing, Mont Terri Technical Report TR2022-02, swisstopo.

Guglielmi, Y., Ajo-Franklin, J., Birkholzer, J., Cappa, F., Cook, P., Hopp, C., Nussbaum, C., Rinaldi, A.P., Robertson, M., Rodriguez-Tribaldos, V., Rutqvist, J., Shadoan, T., Soom, D., Wood, T., Zappone, A. 2022: IMAGING LEAKAGE ASSOCIATED WITH CAPROCK FAULT ACTIVATION: RESULTS FROM THE FAULT SLIP EXPERIMENT IN MT. TERRI OPALINUS CLAY ANALOGUE CAPROCK in Carbon Dioxide Capture for Storage in Deep Geological Formations, Volume 5, K. F. Gerdes (Editor), p. 715-732.

Liebscher, A., Möller, F., Bannach, A., Köhler, S., Wiebach, J., Schmidt-Hattenberger, C., Weiner, M., Pretschner, C., Ebert, K., Zemke, J., 2013: Injection operation and operational pressure–temperature monitoring at the CO2 storage pilot site Ketzin, Germany—Design, results, recommendations, Interna-tional Journal of Greenhouse Gas Control 15 (2013) 163–173.

Lobkis, O., I. and Weaver, R., L. (2003) Coda-wave interferometry in finite solids: Recovery of P-to-S conversion rates in an elastodynamic billiard. Phys. Rev. Lett., 90, 254302. doi.org/10.1103/ PhysRevLett.90.254302.

Ma, J., Alt-Epping, P., and Wersin, P. (2024) Hydro-geochemical scoping calculations for the CO2 Long-term Periodic Injection Experiment (CO2LPIE). In 1st Caprock Integrity & Gas Storage Symposium 2024, p. 108.

Makhnenko, R. Y., Vilarrasa, V., Mylnikov, D., Laloui, L., 2017: Hydromechanical aspects of CO2 breakthrough into clay-rich caprock. Energy Procedia, 114, 3282-3290.

Obermann, A., and Hillers, G. (2019) Seismic time-lapse interferometry across scales. In Advances in Geophysics, 60, 65-143. doi.org/10.1016/bs.agph.2019.06.001.

Obermann, A. and Ziegler, M. (2025) Coda wave interferometry to monitor the evolution of rock mass damage in Opalinus Clay, a study at the Mont Terri Underground Laboratory, to be submitted.

Pacheco, C., and Snieder, R. (2005) Time-lapse travel time change of multiply scattered acoustic waves. The Journal of the Acoustical Society of America, 118, 1300-1310.

Rebscher, D., Vilarrasa, V., Makhnenko, R.Y., Hassanzadegan, A., Schuster, K., May, F., 2018: CO2 long-term periodic injection experiment at Mont Terri (CO2LPIE), Technical Meeting TM-36, 7.–8. Februa-ry 2018, Porrentruy, Switzerland.

Rösli, U., Gisiger, J., Minnig, C. and Goodman, H., 2022: CS-A EXPERIMENT–WELL LEAKAGE AND REMEDIATION EXPERIMENT in Carbon Dioxide Capture for Storage in Deep Geological Formations, Volume 5, K. F. Gerdes (Editor), p. 561-628.

Sciandra, D., Rahimzadeh Kivi, I., Vilarrasa, V., Makhnenko, R., and Rebscher, D. (2022a) Hydromechanical response of Opalinus Clay in the CO2 long-term periodic injection experiment (CO2LPIE) at the Mont Terri rock laboratory. Geomechanics and Geophysics for Geo-Energy and Geo-Resources. 8. doi.org/10.1007/s40948-022-00442-x.

Sciandra, D, Rahimzadeh Kivi, I., Vilarrasa, V., Makhnenko, R., Jaeggi, D., and Rebscher, D. (2022b) 3D Hydro-Mechanical Modeling of Shaly Caprock Response to CO2 Long-Term Periodic Injection Experiment (CO2LPIE). doi.org/10.56952/ARMA-2022-0704.

Weber, U. W., Rinaldi, A. P., Roques, C., Wenning, Q. C., Bernasconi, S. M., Brennwald, M. S., Jaeggi, M., Nussbaum, C., Schefer, S., Mazzotti. M., Wiemer, S., Giardini, D., Zappone, A., Kipfer, R. (2023) In-situ experiment reveals CO2 enriched fluid migration in faulted caprock. Sci. Rep., 13, 17006, doi.org/10.1038/s41598-023-43231-6.

Zappone A, Rinaldi, A.P., Grab, C., Madonna, C., Obermann, A., Wenning, Q., Doonechaly, N.G., Kipfer, R.,, Roques, C., Nussbaum, C., Guglielmi, Y., Mont Terri CS-D experiment: an in-situ experiment to monitor for caprock and fault sealing, Geophysical Research Abstracts, 2019 Jan 1, 21, 2019.

Zhang, W., Eckert, A., Goodman, H., 2022: INTEGRATED INVESTIGATION OF WELLBORE INTEG-RITY OF THE MONT TERRI EXPERIMENTAL CO2 INJECTION WELL in Carbon Dioxide Capture for Storage in Deep Geological Formations, Volume 5, K. F. Gerdes (Editor), p. 669-715.

Ziegler, M.; Jaeggi, D.; Abdelouhabi, M.; Kipfer, R.; Marion, C.; Rinaldi, A. P. et al.: CO2 Long-term Periodic Injection Experiment (Mont Terri URL). Introduction to the in-situ experiment and results of the first phase. In: Clay Conference 2024.

Ziegler M., and Czerner S. (2025) Development and in-situ testing of a modular multi-sensor monitoring system for boreholes. Conference publication at Eurock, 16-20 June, Trondheim (Norway). p. 8.

6 Interne Kontrolle des Projekts (vertraulich)

Sichtweise Mont Terri Projektmanagement:

Alle gesetzten Ziele wurden bis jetzt erreicht. Die Equillibrierungsphase ('einschwingen') hat länger gedauert, als erwartet und auch das finale Design des Injektions- und Extraktionsequippments hat länger gedauert, als geplant. Der Zeitplan wurde entsprechend angepasst. Die Injektion der Wassertracer wurde gestartet und ab Januar 2026 wird das ramping up inkl. CO_2 im Porenwasser erfolgen.

Grosse Budgetposten, wie Bohrarbeiten, Entwicklung der MMMS und die Entwicklung und Installation der Cabinets sind bereits abgeschlossen und liegen in den ursprünglichen Kostenschätzungen. Budgetmässig sind wir trotz der Verzögerungen voll auf Kurs und der Kostenrahmen dürfte eingehalten werden können.

Die Suche nach geeigneten PhD KandidatInnen war auf der Seite der SSS / ETHZ schwierig und wenig zielführend. Entsprechend hat sich der SSS entschlossen, keine Doktorarbeit auszuschreiben und die entsprechenden Arbeiten durch ausgewiesene Institutsangehörige ausführen zu lassen. Durch diese Umschichten der SSS-Arbeiten entstehen keine weiteren Kosten, doch wird garantiert, dass die entsprechenden Untersuchungen mit bestmöglicher Qualität durchgeführt werden.