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Abstract

Laboratory experiments are vital to provide input parameters for reservoir simulators that are used to predict the fate of CO_2 in the subsurface. Within ELEGANCY, a new decameter-scale experiment at the Mont Terri URL in Switzerland to enable direct observation of fluid migration along a fault and of its interaction with the surrounding environment. A core-analysis campaign is being designed to provide detailed petrophysical characterization of rock samples collected at the Mont Terri laboratory, both from the damaged fault rocks and from the undisturbed rocks. In this report, we briefly discuss the current plan for the field-test and we present the list of samples that have been selected for the associated laboratory experimental campaign.

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1 INTRODUCTION

Geological storage of carbon dioxide (CO_2) is an essential component of a low-carbon economy based on natural gas reforming for hydrogen (H_2) production. The very large volumes of CO_2 produced imply that the only feasible storage is found in on- or off-shore saline aquifers, or depleted gas fields. Reduced uncertainty in transport and storage of CO_2 is key towards the full-scale deployment of H_2 and CCS. A key challenge here is to ensure both quality and security of storage strata (e.g., ensuring injection rate and containment, and development of effective and robust monitoring tools). Laboratory experiments are vital to provide input parameters for reservoir simulators that are used to predict the fate of CO_2 in the subsurface. Pilot-scale tests are also needed to validate such findings and -most important- to prove the technology at a scale that is small enough to be safe for experimental testing, but large enough to be significant. In this context, recent results from a series of controlled water injection tests conducted at Mont Terri Underground Rock Laboratory (URL) in Switzerland indicate that sub-millimetre slip movements (0.01 – 0.1 mm) can create permeable paths across a fault-zone without producing significant seismic activity (Guglielmi et al. 2017). How such peculiar permeability behaviour may affect the migration of CO_2 remains to be answered. Moreover, while they raise important questions in the evaluation of the integrity of seals above CO_2 sequestration sites, these results also stress the need to understand the mechanisms controlling fluid migration above the same seals when CO_2 reaches the overburden.

Within ELEGANCY, this challenge is addressed by executing a new decameter-scale experiment at the Mont Terri URL in Switzerland. This will enable direct observation of fluid migration along a fault and of its interaction with the surrounding environment, so as to quantify CO_2 mobility in the caprock and in the overburden. To this aim, a core-analysis campaign is being designed to provide detailed petrophysical characterization of rock samples collected at the Mont Terri laboratory, both from the damaged fault rocks and from the undisturbed rocks. In this report, we briefly discuss the current plan for the field-test and we present the list of samples that have been selected for the associated laboratory experimental campaign.

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2 CO_2-CFSI (CAPROCK AND FAULT SEALING INTEGRITY): PRELIMINARY DESIGN OF THE MONT TERRI UGL EXPERIMENT

The design of the CO_2-CFSI experiment is led by the Swiss Competence Center for Energy Research - Supply of Electricity (SCCER-SoE) through its partner institutions, namely ETH Zurich and EPF Lausanne, in collaboration with the Swiss Federal Office of Topography (Swisstopo). The experiment aims at investigating the mechanisms and the physical parameters governing (i) the migration of CO_2-rich brine through a damaged zone within faults; (ii) the interaction of the CO_2 with the neighboring intact rocks (including CO_2 ex-solution from the brine and chemical interactions with the microporous matrix), and (iii) the impact of the injection/migration on the damaged zone and on the intact rocks. In particular, the test seeks to understand the conditions for slip activation to occur (e.g., seismic vs. aseismic slip) and the stability of clay faults, as well as the evolution of the coupling between fault slip, pore pressure, fluid migration and induced “micro” seismicity (if any). To this end, the damaged zone will be stimulated by injecting CO_2-rich brine into the fault core (Opalinus Clay) for a period of about eight months, while monitoring its geo-mechanical response. Additional tracer and transmissivity tests will be conducted at regular time intervals to determine the fluid path evolution of the injected fluid and to infer the potential evolution of CO_2 from the brine. This new test is motivated by observations from a recent study, where a significant increase in permeability of the fault damaged zone (5-6 orders of magnitude (Guglielmi et al. 2017) with resepect to a baseline permeability of about 1×10^{-20} - 1×10^{-19} m^2 of the undisturbed rock (Yu et al. 2017)) was observed upon conduction of a similar test at Mont Terri (albeit not in the presence of CO_2). Numerical simulation work will assist the different phases of the experiment for which laboratory measurements will provide input parameters in terms of baseline rock properties of both the damaged zone and overburden. As described in Section 4, these include estimates of both single- (porosity, permeability, dispersivity) and multi-phase flow properties (capillary pressure, relative permeability and gas trapping characteristic curves). The Opalinus Clay is overlain by the Passwang Formation, consisting of sandy limestones and oolitic marls (Hostetter at al. 2017; Bossart et al. 2017). We plan on conducting experiments on samples from both sedimentary structures, so as to mimic a scenario of fluid migration through the overburden. Because of the very low permeability of these rocks, we anticipate that the samples may need to be artificially disturbed (similar to the procedure adopted for the CO_2-CFSI test). This will enable access to the rock pore space by advection and provide the opportunity to investigate the physical and chemical interactions between the CO_2-rich brine and the porous rock matrix.

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3 FLUID AND ROCK SAMPLES SELECTION

The mineralogy of the Opalinus Clay is reported in *Table 3.1*. In general, the rock is characterised by very high clay content (up to 80 wt% in the shaly facies (Bossart et al. 2017)) with the remaining minerals being quartz (10 – 40 wt%) and carbonates (5 – 60 wt%). From a hydraulic point of view, the Opalinus Clay is characterized by a very low hydraulic conductivity (1×10^{-13} – 1×10^{-12} m/s, corresponding to a permeability of 1×10^{-20} – 1×10^{-19} m^2 or 0.01 – 0.1 microDarcy) and moderate to high porosity (10 – 20%) (Bossart et al. 2017). Reported permeabilities of the (undistrubed) Passwang Formation are similar, although they also show more variability, due to the heterogeneity of the formation (Yu et al. 2017). Interestingly, results from the in-situ fault reactivation test described above have shown a substantial increase in permeability of the rock mass (reaching values in the order of 1×10^{-15} – 1×10^{-14} m^2 or 1-10 mD (Guglielmi et al. 2017)), which would therefore enable advective flow to be established. From a geochemical point of view, the pore water in the Opalinus Clay is of Na–Cl–SO_4 type with a maximum of total dissolved solids (TDS) of 18.3 g/L (Mazurek et al. 2017). This composition will therefore be used for the experiments conducted on core material from the Mont Terri field site.

Table 3.1: Mineralogy of Opalinus Clay. From (Bossart et al. 2017).

Mineralogy	Shaly facies (wt%)	Sandy facies (wt%)	Carbonate-rich sandy facies (wt%)
Clay minerals			
Illite, chlorite, kaolinite	39–80	29–70	8–45
Illite/smectite mixed-layers	5–20	5–15	3–8
Quartz	10–27	22–44	22–36
Carbonates			
Calcite, dolomite, aragonite, ankerite, siderite	4–35	11–25	34–57
Feldspars			
Albite, K-feldspar	0.3–5	0.2–6	3–11
Pyrite	0.9–1.4	1–1.2	0.2–0.5
Organic matter	0.8–1.4	–	–
Accessory minerals			
Apatite, celestine, zircon, monazite	<0.1	<0.1	<0.1

A first appraisal of the available core material from boreholes BPE-1, BPE-2 and BPE-3 was conducted, so as to select samples for petrophysics studies (see layout map in Figure 3.1 for the locations of each boreholes). The two boreholes have been drilled with a diameter of 86 mm, yielding core diameters of about 70 mm. Because of its proximity with the planned location for the CO_2-CFSI test (Niche 8 on the map), two homogeneous sections within BPE-1 were selected for sub-sampling from the shaly and carbonate-rich facies, respectively. Additionally, four sections from BPE-3 were selected to obtain samples that are representative of the more heterogeneous overburden (Passwang Formation). These are associated with characteristic sedimentology structures, such as the presence of horizontal sand lenses, (micro)cracks and bioturbation. A visual representation of the sedimentology structure of the selected regions from BPE-3 is provided in Figure 4.1 and the complete list of samples is summarised in Table 4.1.

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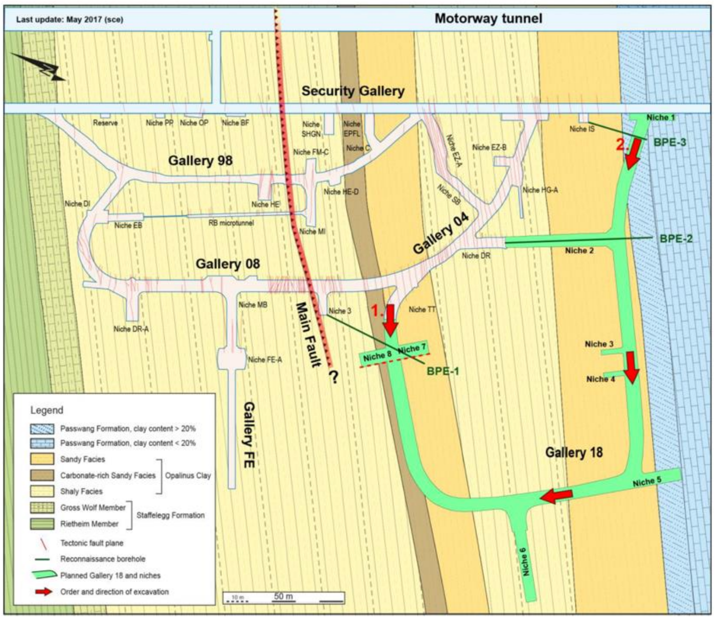

Figure 3.1: Layout map of the Mont Terri UGL. Planned new galleries are colored in green (Niche 8 is foreseen for the CO_2-CFSI test to be conducted within ELEGANCY). Also highlighted are boreholes BPE-1, BPE-2 and BPE-3 from which available cores are considered for laboratory petrophysics tests.

In addition to core-material from the Mont-Terri UGL, experiments will also be conducted using analogue systems showing similar, but more controlled, characteristic sedimentology structures (such as layering), so as to identify their control on the evolution of CO_2 and CO_2-rich brine as they migrate through the rock. These samples may include a selection of clean sandstones and limestones, as well unconsolidated bead packs.

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4 PETROPHYSICS STUDIES FOR SITE CHARACTERISATION

Facilities at Imperial College London (ICL) will be deployed to conduct petrophysics studies on core-material from the Mont Terri UGL, including:

a. Routine core analyses (M2.3.2, month 6)
b. Single-phase injection tests (brine and CO_2-rich brine) (M2.3.3, month 18)
c. Multi-phase injection tests (M2.3.4 and M2.3.5, month 24)

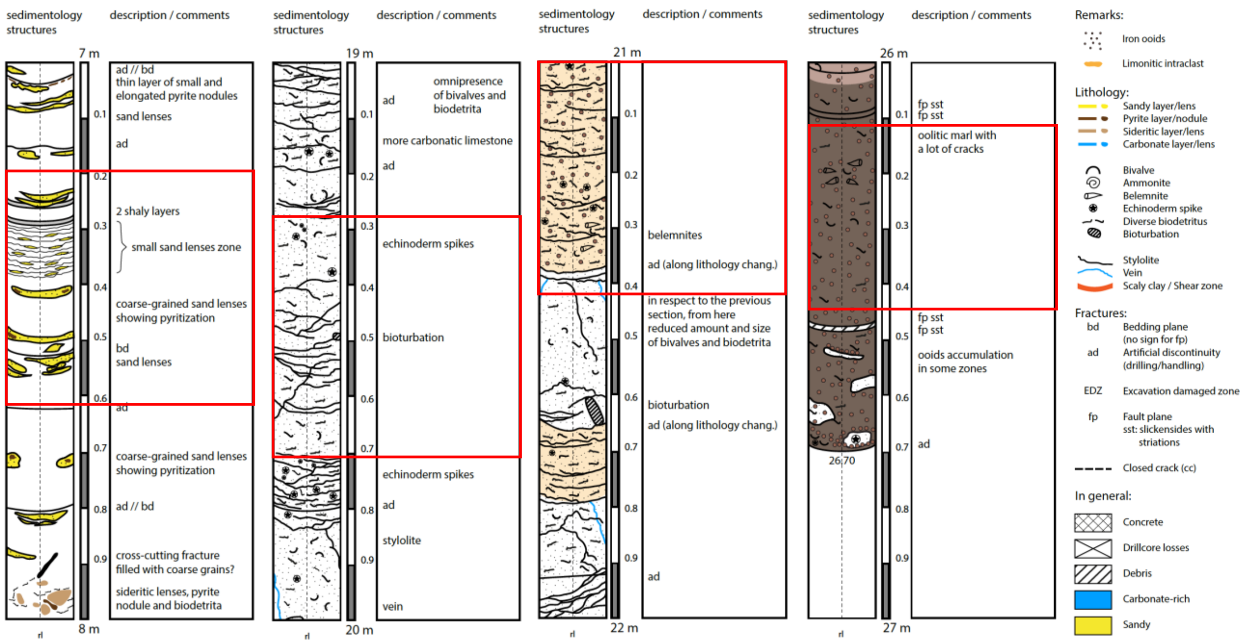

Figure 4.1: Sedimentology description of selected facies within borehole BPE-3 (see Figure 1). Highlighted in red are the regions selected for sub-sampling (details in Table 2). Images: courtesy of Swisstopo.

For measurements under (a), we will deploy an established workflow that entails the physical sub-sampling of mm-size plugs, which will undergo a series of analyses, namely (i) Helium pycnometry (skeletal density), (ii) X-ray micro CT scanning (creating of a digital rock plug and 3D mapping of pore space), (iii) Mercury Intrusion Porosimetry (bulk density, porosity and capillary pressure) (Pini and Madonna 2015; Pini and Benson 2013). Because of the microporous nature of the Opalinus Clay, we anticipate to additionally carry out between (ii) and (iii) physisorption studies for determining (nano)pore-size distribution and surface-area, as well as gas adsorption experiments at subsurface conditions (up to 5 MPa and 40°C) to evaluate the potential of additional CO_2 trapping mechanisms. For experiments under (b) and (c), we will deploy our in-situ, multi-dimensional, multi-scale imaging capabilities, including X-ray Computed Tomography (CT) (Al-Menhali et al. 2015; Reynolds and Krevor 2015, Niu et al.2015) and Positron Emission Tomography (PET) (Pini et al. 2016) to make direct observations of the transport pathways and mechanisms within the rock samples non-invasively. This will provide a unique opportunity to study the structure of Opalinus Clay and the surrounding formations over a wide range of length-scales, from micron to cm.

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Depending on the outcomes from (a), decision will be made regarding the design of the core-flooding tests and on whether the tests will be carried out on intact or fractured samples. Single-phase injection tests will aim at quantifying permeability and the mass transfer mechanisms (mixing and dispersion) with the porous matrix of the Opalinus Clay, which may also involve sorption reactions. Multi-phase injection tests will be conducted using mutually saturated CO_2 and brine phases to provide capillary pressure, relative permeability and residual trapping curves at representative conditions.

Table 4.1: List of proposed samples for petrophysics studies. Two available boreholes are conisdered, namely BPE-1 and BPE-2. OPA: Opalinus Clay; PW: Passwang Formation.

No.	Interval [m]		Core length [cm]	Core diam [in]	Comments	
	From	To				
BPE-1	core diameter 7 cm					
1a	7.1	7.25	15	2 inches	OPA	homogeneous shaly facies
1b	7.25	7.4	15	1.5 inches	OPA	homogeneous shaly facies+pyrite nodules
2a	31.1	31.3	20	2 inches	OPA	carbonate rich facies w/ bioturbation lenses
2b	31.3	31.5	20	1.5 inches	OPA	carbonate rich facies w/ bioturbation lenses
BPE-3	core diameter 7 cm					
3a	7.2	7.4	20	2 inches	OPA	shaly facies with sand lenses
3b	7.4	7.6	20	1.5 inches	OPA	shaly facies with sand lenses
4a	19.3	19.5	20	2 inches	PW	carbonatic limestone w/ bioturbation
4b	19.5	19.7	20	1.5 inches	PW	carbonatic limestone w/ bioturbation
5a	21	21.2	20	2 inches	PW	carbonatic limestone w/ iron oids
5b	21.2	21.4	20	1.5 inches	PW	carbonatic limestone w/ iron oids
6a	26.15	26.3	15	2 inches	PW	oolitic marl w/cracks
6b	26.3	26.45	15	1.5 inches	PW	oolitic marl w/cracks

APPENDIX

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