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The Mont Terri rock laboratory: international research in the Opalinus Clay

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The members of SASEG visited the Mont Terri rock laboratory on 22 June 2015. The excursion is reported by Heinz Bürgisser and is presented in this journal. Here the Mont Terri Project and its rock laboratory are briefly presented. The main emphasis is placed on the organisation of the project, the geology of the rock lab and the ongoing experiment programme.

Aim of the Mont Terri Project

The Mont Terri Project is an international research project for the hydrogeological, geochemical and geotechnical characterisation of a clay formation (Opalinus Clay). Clay formations are being considered in various countries for the deep geological disposal of radioactive waste. Opalinus Clay is the only host rock being proposed in Switzerland for disposal of high-level radioactive waste (Sectoral Plan for Deep Geological Repositories). This is the main reason for the great significance of the Mont Terri rock laboratory in the deep geological disposal program. swisstopo has the task of leading the international Mont Terri research project and operating the rock laboratory. The objective is to carry out the proposed research plans of the Swiss and international partners under optimum conditions. As a neutral and expert federal office, swisstopo is in constant contact with all political, social and corporate stakeholders. The rock laboratory is dedicated solely to research and is never intended for the disposal of radioactive waste.

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Organisation and legal basis of the Mont Terri Project

swisstopo operates the Mont Terri rock laboratory, is responsible for the coordination and implementation of the research programme and applies for annual authorisations (Fig. 1). The research programme is decided democratically among the 16 project partners and covers strategic planning, experimental programmes, financial budgets and selection of contractors. The legal relationship between the operator and the partners is contained in the Agreement 2001, which has been signed by all project partners. The legal relationship between swisstopo and the Republic and Canton of Jura (RCJU) is defined in the Convention 2009. The annual research programme is submitted to the RCJU for authorisation.

Partners of the Mont Terri project

The research programme in the Mont Terri rock laboratory is conducted by sixteen organisations from five European countries and Japan, namely ANDRA (National Radioactive Waste Management Agency, France), BGR (Federal Institute for Geosciences and Natural Resources, Germany), CHEVRON (Chevron's ETC, drilling and completions technology departement), CRIEPI (Central Research Institute of Electric Power Industry, Japan), DOE (US Departement of Energy, Office of Nuclear Energy), ENRESA (National Radioactive Waste Corporation S.A., Spain), ENSI (Swiss Federal Nuclear Safety Inspectorate, Switzerland), FANC (Federal Agency for Nuclear Control), GRS (Gesellschaft für Anlagen- und Reaktorsicherheit mbH, Germany), IRSN (Institut de Radioprotection et de Sûreté Nucléaire, France), JAEA (Japan Atomic Energy

Agency), NAGRA (National Cooperative for the Disposal of Radioactive Waste, Switzerland), NWMO (Nuclear Waste Management Organization, Canada), OBAYASHI (Obayashi Corporation, Japan), SCK•CEN (Belgian Nuclear Research Centre) and swisstopo (Federal Office of Topography, Switzerland). RCJU is the owner of the underground facilities.

The Mont Terri rock laboratory in Opalinus Clay

The rock laboratory is located in and alongside the security gallery of the Mont Terri motorway tunnel in north-western Switzerland. This 3,962 m long tunnel crosses the northernmost anticline of the Jura Mountains, the Mont Terri anticline, which was folded during the Late Miocene to Early Pliocene period, around 10 to 5 My ago. The rock laboratory is situated within the Opalinus Clay (Upper Toarcian and Lower Aalenian), a claystone formation. Presently, the overburden is 300 m thick, and the estimated overburden in the past was at least 1,000 m thick. The security gallery intersects a 245 m long section of the Opalinus Clay, which dips from 35 to 55° towards the southeast and has an apparent thickness of around 160 m. Thrust faulting has led to accumulation of the Opalinus Clay, and thus the true thickness is less than the apparent thickness, around 100 m in the region of St-Ursanne.

Geology of the Opalinus Clay

The Opalinus Clay (Fig. 2) can be grouped into three main facies: a shaly facies, a sandy facies and a carbonate-rich sandy facies. These three facies are the result of different sedimentary environments in a shallow marine basin during the time of deposition. The Opalinus Clay has a complex mineralogy, consisting mainly of sheet silicates, framework silicates and carbonates. X-ray analyses of samples from the shaly and sandy facies were carried out in various laboratories. The qualitative mineralogical composition of the Opalinus Clay is identical in all lithologies that occur at Mont Terri and

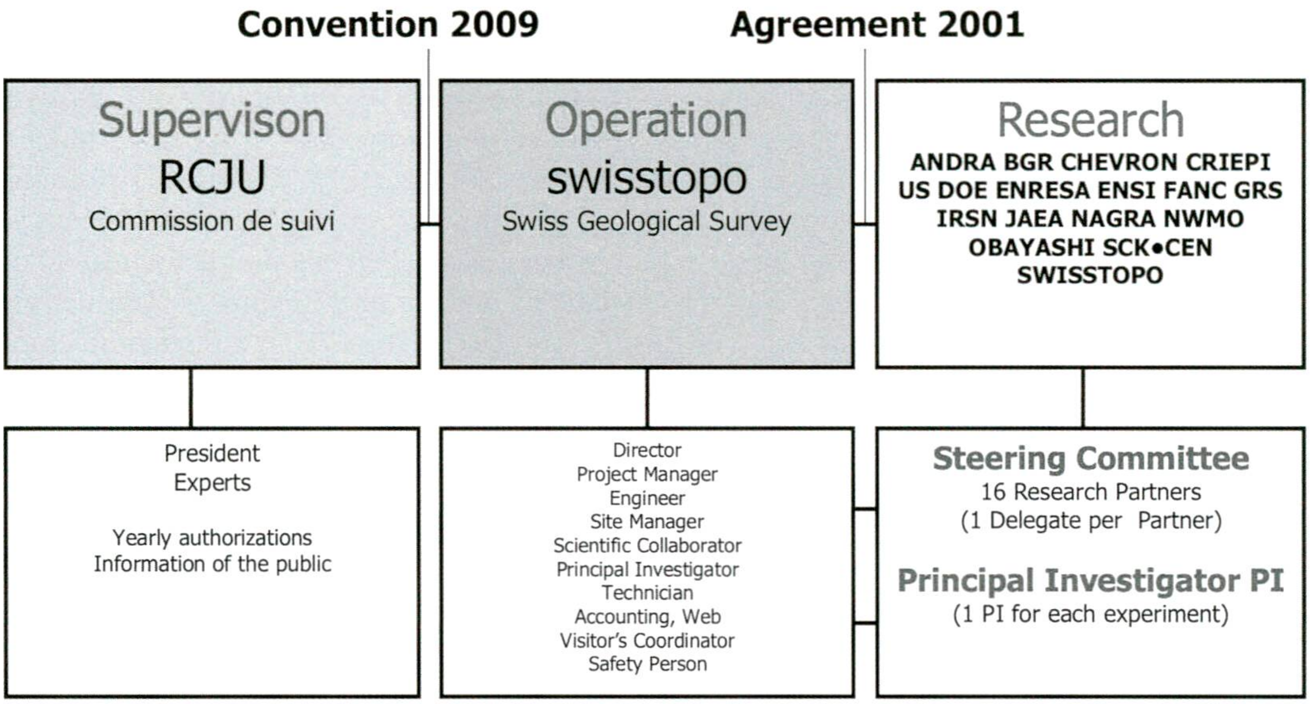

Fig. 1: Organisation of the Mont Terri Project. The different tasks are separated into the following three items: 1] operation of the rock laboratory by the Swiss Confederation, 2] research programme carried out by the 16 national and international experiment partners, and 3] supervision of the facility by the owner, the Canton of Jura.

includes calcite, dolomite, ankerite, siderite, quartz, albite, K-feldspar, muscovite, illite, illite/smectite mixed-layer phases, chlorite, kaolinite, pyrite and organic carbon. Typical values for the shaly facies are the following: 69% clay minerals, 13% calcite, 14% quartz, 2% feldspars, 1.1% pyrite and 0.8% organic carbon. Compared to the shaly facies, the sandy facies contains more quartz (25%) and less clay minerals (50%). Locally, there may be a considerable variability in these mineralogical proportions.

The mapping of fractures on drill cores and outcrops in the Mont Terri rock laboratory has revealed two classes of discontinuities: tectonic and artificial fractures.

Single tectonic faults and thin fault zones with trace lengths of metres to tens of metres have been observed. One major fault zone with a thickness of 1 to 3 m has been identified and is called the «main fault». It is characterised by a large number of fault planes (> 20/m) running sub-parallel to the bedding. Most of these fault planes show slickensides and shear fibres on polished surfaces with a sense of movement that consistently indicates overthrusting. Additionally, the main fault contains highly deformed intervals with folded bedding planes (drag folds). Areas of high tectonic shear strains exhibit loss of cohesion, which results in a fabric similar to that of fault breccia and fault gouge.

The artificial discontinuities are unloading fractures (extension fractures) and shear fractures (mainly reactivation of bedding planes with bedding-parallel slip) found in the so-

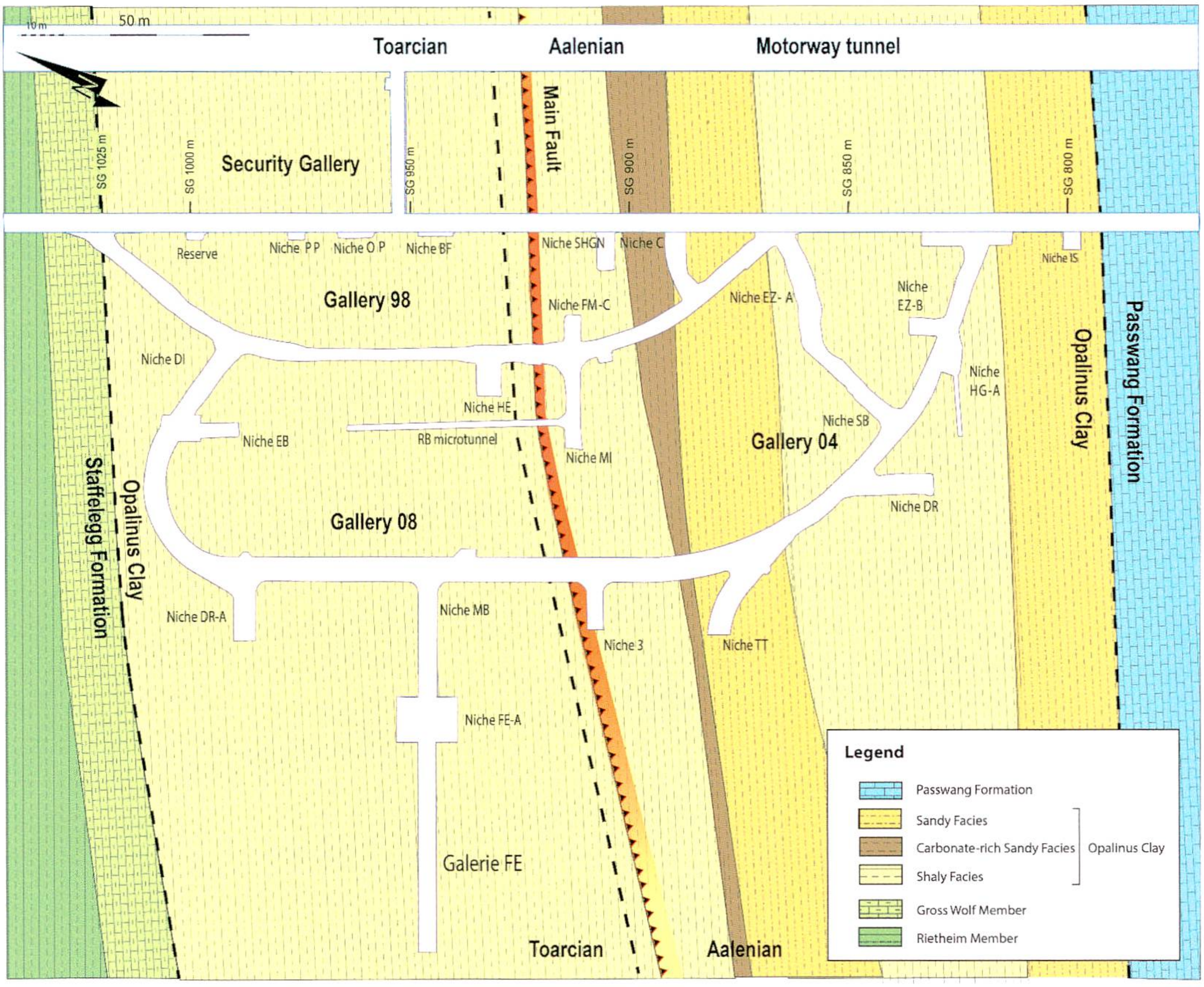

Fig. 2: Geological map of the Mont Terri rock laboratory.

called excavation damaged zone (EDZ). These EDZ fractures were formed by plastic deformation. Analyses of the remote stress field and the redistribution of stresses during the excavation indicate that the tangential stresses in the tunnel walls are higher than the uniaxial compressive strength, leading to the extensile fracturing. The lower compressive strength of bedding planes leads to bedding-parallel slip, which is often observed on the tunnel ceiling and floor. The EDZ fractures form an interconnected network within the first 1 m of the tunnel wall. The geometry of this network is characterised by high fracture frequencies within the first 70 cm of the tunnel wall. The fractures strike parallel to the tunnel axis with sub-vertical dip angles and trace lengths of a few decimetres. Direct observations (e. g. localised gypsum precipitation on fracture surfaces) and measurements (resin injections) indicate that the EDZ fractures are interconnected and connected to the tunnel, and they appear to be filled with air and water vapour instead of being water-saturated.

Hydrogeological setting

The Opalinus Clay can be considered as an aquiclude. Although its pore space is water-saturated, water circulation is almost absent. The Opalinus Clay is overlain by Middle Jurassic karstic aquifers (e. g. Passwang Formation and Hauptrogenstein) and underlain by Liassic marls and limestones of the Staffelegg Formation. The latter are karstic aquifers with advective water flow. The average water content of an Opalinus Clay sample from Mont Terri is around 7% (saturated weight). Around 55% of these water molecules are attached to the surfaces of clay aggregates or are incorporated into the clay minerals. The remaining 45% fill the available pore space, but cannot move freely in this space because the extremely small pore diameters (generally in the range of several to some tens of nanometres) prevent water circulation. Consequently, several porosity types need to be considered. The physical or total porosity is 18%, and the water loss porosity is 16%. The porosity for solutes, sometimes called the effective porosity or the geochemical porosity (volume fraction in which solutes are transported), has to be determined for every solute individually and varies between 5 and 16%. For chloride, the effective porosity is about 9%. Hydrotests carried out on rock samples and in various boreholes show hydraulic conductivities ranging between 2E-14 and 1E-12 m/s, with a mean of 2E-13 m/s. The main conclusion is that the water barely flows – it stagnates in the pores.

The Mont Terri research programme

Different countries have different repository construction and safety concepts under different conditions. Experiments can be planned and conducted by taking into account such concepts and conditions. Particularly important are demonstration experiments, in which the interaction of variously designed engineered barriers systems is assessed in a natural clay barrier environment, such as the Opalinus Clay in the Mont Terri rock laboratory.

Each partner can select the experiments in which he wishes to participate. Each experiment is implemented by an experiment team consisting of the Principal Investigator, the Experiment Delegates and the Project Manager. The experiment costs are shared among the participating partners. The costs of project management, infrastructure and site preparation are added to the experiment costs for each phase and are assigned proportionally to the experiments. Each partner bears all his own costs of participation in the project, such as personnel, administrative and travelling costs. Additionally, a partner may offer his services for specific work as a contractor. The work is carried out by around 100 contracted universities, national research institutes and companies from Europe, Japan and North America.

Since 1996, 80 experiments have been completed and 45 experiments are still on-going

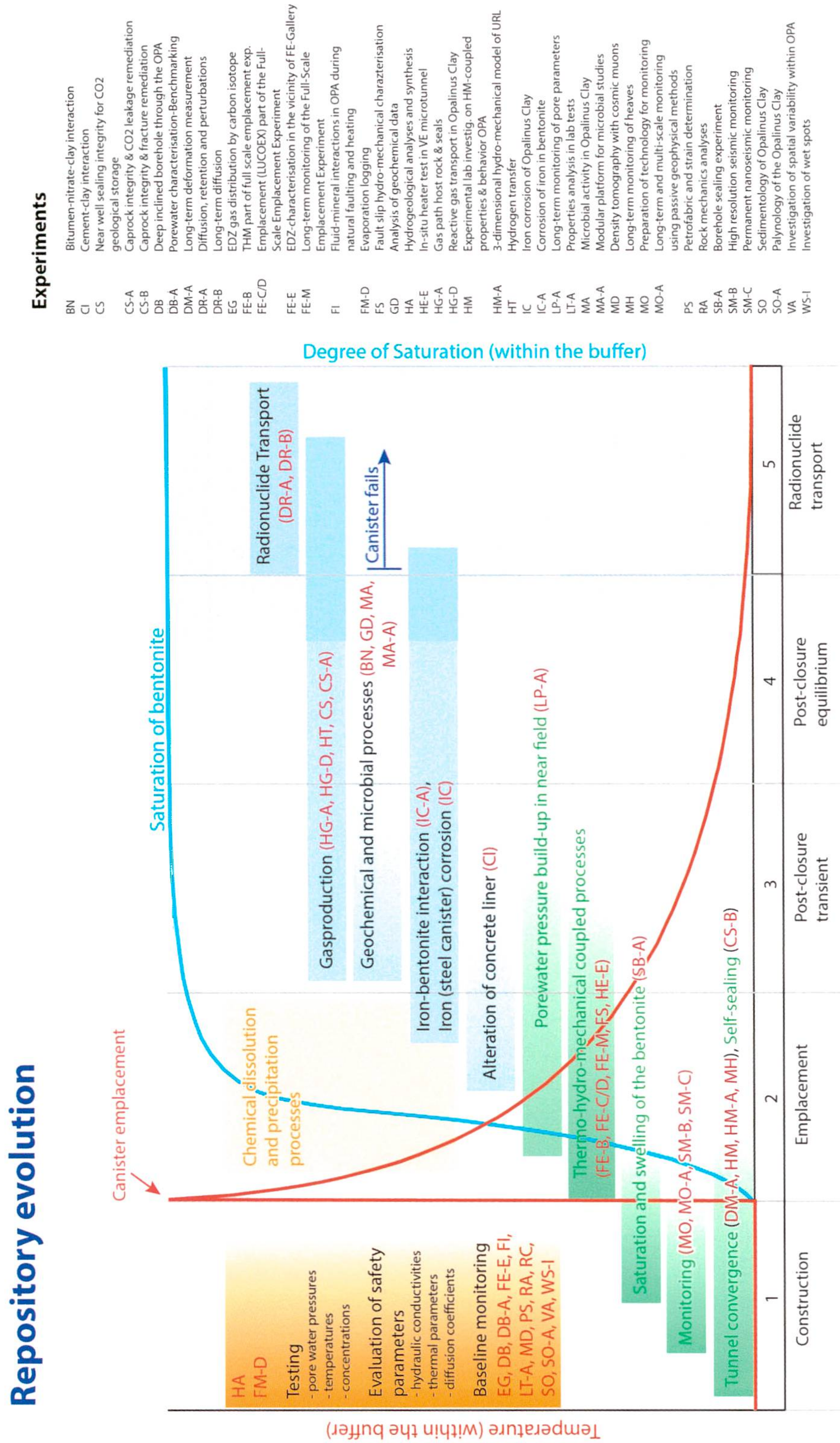

Fig. 3: The affiliation of ongoing experiments to the temporal evolution of a repository. At present there are 45 ongoing experiments.

(Fig. 3). These experiments have focused on the nuclear power programme, meaning that the capability of claystone to safely confine radioactive wastes for the long-term is studied and being proved. Thus, most of the Mont Terri experiments are related to the repository evolution and performance, as outlined in Fig. 3. The 45 ongoing experiments in the Mont Terri rock laboratory are related to the different repository phases, starting from evaluation of safety parameters and ending with the radionuclide release and transport at the end of a repository lifetime. These ongoing experiments can be further subdivided into observation and monitoring experiments over real timescales, such as experiments dealing with the repository construction, mine-by testing, backfilling and sealing. The remaining experiments are designed to investigate long-term processes on timescales that are not directly accessible through conventional laboratory work. Examples are the self-sealing of the excavation damaged zone, anaerobic corrosion or sorption and diffusion. These experiments mostly aim to identify and understand the processes and provide robust parameters, which will then serve as the basis for the long-term safety analyses.

In 2012 swisstopo has decided to open the rock laboratory for the development of carbon sequestration and geothermal energy experiments. The first non-nuclear experiment was dedicated to the geological storage of CO_2. The CS experiment (near well sealing integrity for CO_2 storage) investigates the well integrity evolution under chemical (CO_2), temperature and pressure stresses in Opalinus Clay used as a reference caprock-like formation. This experiment was successfully completed in June 2015 with the overcoring and retrival of the whole well-section. A second experiment, called the CS-A experiment (well leakage simulation and remediation), was launched in spring 2015 with the aim to determine the long-term sealing integrity of well systems. It focuses on potential leakage pathways through the caprock and monitors the boundaries / interfaces between the casing, the cement sheath and the country rock. New experiments related to CO_2 storage and focusing on the caprock and fault sealing integrity are being planned.