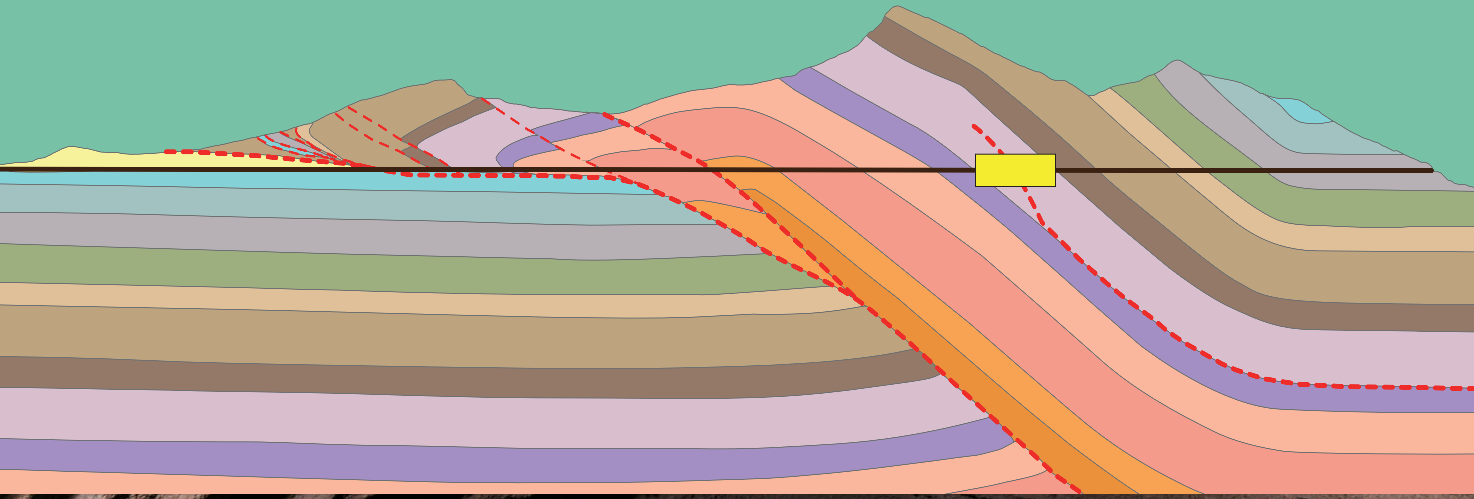
25 YEARS MONT TERRI ROCK LABORATORY



1996 - 2021

Commemorative Publication

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25 ans du Laboratoire Souterrain du Mont Terri

1996 - 2021
Publication commémorative

25 Jahre Felslabor Mont Terri

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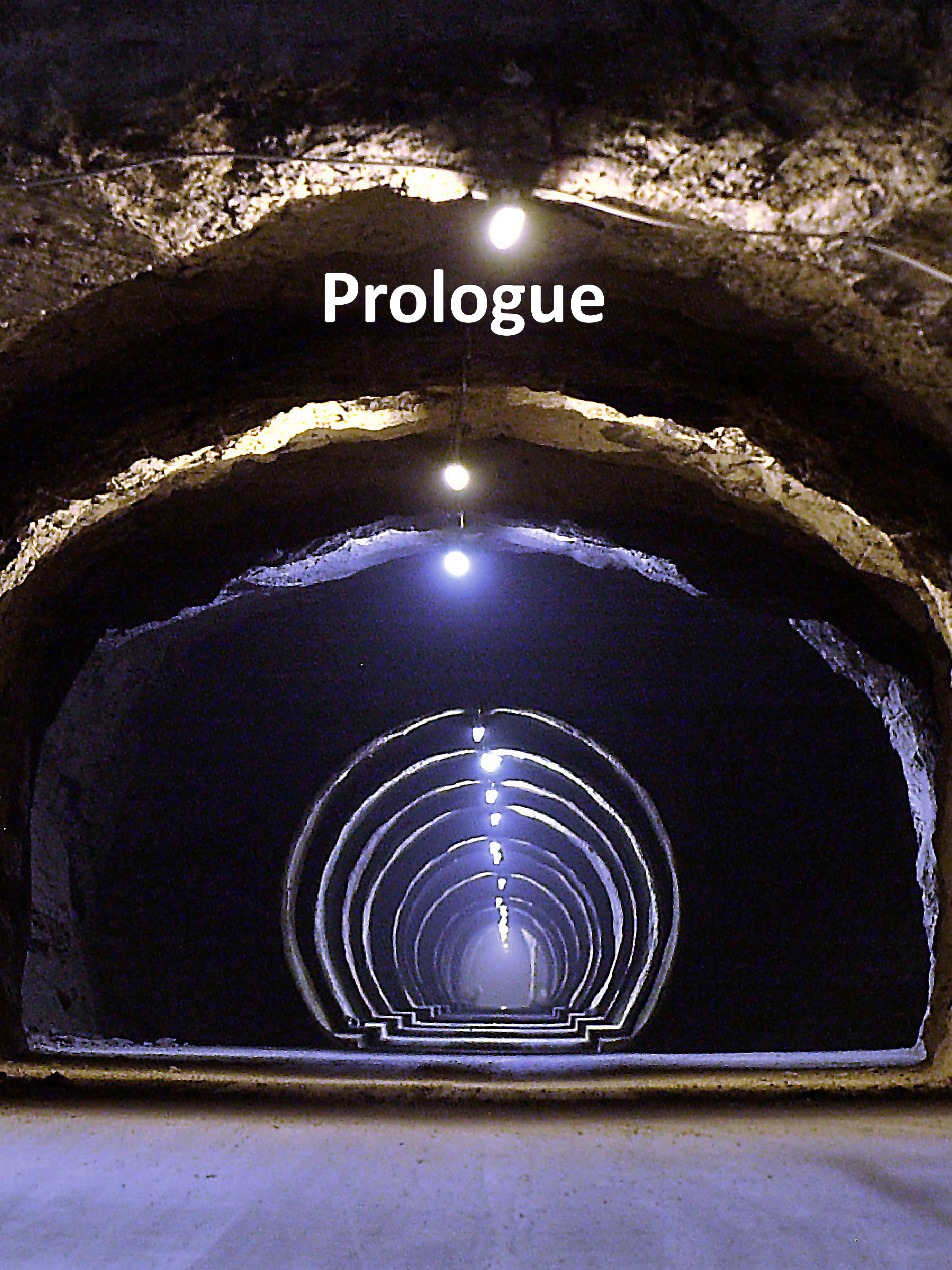
Content

Prologue



The Mont Terri rock laboratory celebrates its 25th birthday in 2021. What began in 1996 as a small research facility in the Opalinus Clay of the Mont Terri motorway tunnel in the Canton of Jura is now an internationally renowned research laboratory. The last 25 years have shown that claystones like the Opalinus Clay can safely contain radioactive waste over very long periods of time. However, claystones and mudstones not only have the function of confinement, but they also prevent gases such as CO_2 from penetrating into the biosphere from deeper layers. This is especially important for a deep repository for CO_2.

We are proud of this milestone birthday and look forward to celebrating it in a distinguished manner. To this end, we have prepared this commemorative publication. It is intended to give an overview of the eventful history of the last 25 years, the development of the Mont Terri rock laboratory, its research results, and also to provide an outlook on future research priorities.

We are very pleased to accept congratulations from the Swiss federal government, the Canton of Jura, and the local community. More than 500 people from our 22 Partner organisations have ultimately contributed to the success of the Mont Terri Project and the rock laboratory. This commemorative publication is dedicated to these men and women with our special thanks for all their efforts in making this project such a fruitful collaboration.


Messages des autorités
2X
X3

Madame Viola Amherd, Conseillère fédérale, Cheffe du département fédéral de la défense, de la protection de la population et des sports

Il y a 25 ans, presque dans l’anonymat, les premières niches du laboratoire souterrain du Mont Terri étaient excavées dans les argiles à Opalinus. Aujourd‘hui unique par son fonctionnement, le laboratoire est devenu un pôle de recherche de renommée internationale incontournable sur la thématique du stockage géologique. Et ceci grâce, avant tout, au personnel du Laboratoire, à SWISSTOPO, à ses partenaires, aux scientifiques et aux autorités cantonales jurassiennes. Qu‘il s‘agisse de stockage du CO_2 ou des déchets radioactifs, leur travail est une contribution indispensable à des questions essentielles ayant d’importants enjeux sociétaux. Dans ce domaine, la protection de la population reste notre priorité absolue. C’est pour toutes ces raisons que la Confédération va continuer à apporter son soutien à ce projet. Et c’est dans cet esprit de trouver des solutions pour l’avenir que je vous adresse mes meilleurs vœux pour continuer de faire de ce laboratoire un lieu de recherche unique au monde. Les générations futures vous en seront reconnaissantes et vous en remercieront !

Monsieur David Eray, Ministre de la République et Canton du Jura, département de l'environnement

Depuis 1996, grâce à l'imperméabilité et la stabilité des argiles à Opalinus du Mont Terri, le projet international, dont nous fêtons le quart de siècle, constitue un modèle unique de laboratoire souterrain d'analyses géologiques. Proche du cœur de l'anticlinal, ce lieu de recherche est idéalement situé pour observer les roches susceptibles d'héberger les déchets radioactifs ou de stocker du CO_2. A ce jour, 174 expériences ont été réalisées.

Le laboratoire du Mont Terri joue un rôle clé dans la recherche de base pour la sélection de sites de stockage, non seulement pour notre pays, mais également au-delà des frontières. Vingt-deux organisations de neuf pays mènent, partagent et cofinancent des recherches dans le laboratoire du Mont Terri, sous la direction de l'Office fédéral de topographie SWISSTOPO. Il en résulte des gains et profits scientifiques importants pour les partenaires nationaux, internationaux et les organismes de recherche de l'Union Européenne.

Le Canton du Jura continuera d'assumer son rôle de garant d'une recherche au service de la science. Le projet Mont Terri porte fièrement ses 25 ans en 2021, et j'adresse mes plus chaleureuses félicitations à tous les protagonistes qui ont contribué à ce magnifique succès. Nous sommes ravis de célébrer cet anniversaire où la science et la recherche sont à l'honneur.

Monsieur Jean-Paul Lachat, Maire de la Commune Clos du Doubs

Le creusement du laboratoire souterrain du Mont Terri fut une aubaine pour la commune de Clos du Doubs. Ce développement fut d'autant plus apprécié qu'il a été pour nous assez inattendu et a généré très peu de frais en terme d'infrastructures publiques. Mais plus que cela, le développement et les recherches réalisées sur ce site ont permis de faire découvrir notre région au-delà de nos frontières et même à un niveau international.

Notre commune a connu un exode de population et des activités économiques très importants au cours des quarante dernières années. Le Mont Terri Project a donc contribué à limiter cet exode des activités. Nous sommes d'autant plus fiers que celles-ci se conduisent à un haut niveau et sans aucun désagrément pour la commune et notre population. Les travaux scientifiques qui sont conduits à cet endroit ont permis de revaloriser de manière très intéressante un ancien site industriel qui a autrefois beaucoup compté pour Saint-Ursanne. Les forages pour observer le comportement de l'argile à Opalinus dans le laboratoire souterrain du Mont Terri ont remplacé les trous dans la montagne pour en extraire du calcaire. Cette évolution est moins impactante et bien accueilli par la population de Clos du Doubs. Nous tenons encore à relever la bonne collaboration qui s'est installée dès le départ de cette aventure entre les autorités communales, SWISSTOPO et les responsables du Mont Terri Project. Cette fructueuse collaboration permet entre autre à la commune de Clos du Doubs de profiter de l'infrastructure de congrès très moderne qui a été construite sur le site de la gare. Le centre visiteurs du Mont Terri est d'ailleurs devenu le lieu de rencontre officiel des habitants de notre commune puisqu'il accueille régulièrement nos assemblées législatives.

Au nom des autorités communales de Clos du Doubs, nous tenons à remercier le directeur Paul Bossart, son successeur Christophe Nussbaum et tous les collaborateurs du Mont Terri Project, de SWISSTOPO ainsi que les autorités cantonales pour l'agréable et agile collaboration entretenue durant ces 25 ans.
Nous souhaitons à cette entreprise un avenir radieux. Nous continuerons à suivre avec intérêt les futurs développements et à rendre possible une évolution positive de vos activités.

Historical Overview

After the founding of the Republic and Canton of Jura in 1979, the A16/N16 national highway, called Transjurane, was built between the mid-1980s and 2017. It was to become one of the most expensive motorway sections ever built in Switzerland (CHF 6.5 x 10^9). It also included the approximately 4 km-long Mont Terri motorway tunnel near Saint-Ursanne, which was opened in 1998. This tunnel also leads through a 130 m-thick layer of Opalinus Clay. Already at that time, the tunnel's engineers and geologist were struck by the good quality and understandable tectonics of this claystone section that were exposed during the tunnel excavation. The results of the geological tunnel mappings were very positive - no water inflows from Opalinus Clay into the tunnel were recorded, and the clay behaved much better than expected in terms of gallery stability. Together with the horizontal access, all these points made it ideal for a rock laboratory.

In the following, we present an outline of the history of the last 25 years of the Mont Terri Project. This outline is not complete; only important events and strategic decisions are presented (Table 1). A more complete version of the history is in progress, together with the relevant documents. The Mont Terri Project history is divided into 3 periods, each of which has its own characteristics. These are: 1) initiation of the project and construction of the first research gallery, 2) contractual uncertainty and consolidation between the Confederation and the Canton of Jura, and 3) international research in the Mont Terri rock laboratory and operation of a new visitor centre.

1986 – 1999 Initiation of the Mont Terri Project and construction of the first research gallery

The history of the Mont Terri Project actually began in 1986, when the Swiss National Hydrological and Geological Servey (SNHGS) and NAGRA decided to undertake joint projects during the construction of road and railway tunnels. The aim was to explore the hydrogeology of mudstone formations. Both organisations contracted first work in the reconnaissance gallery of the Mont Terri motorway tunnel, comprising excavation of two niches in the Opalinus Clay and detailed geological mapping along the reconnaissance gallery. At that time, there was no talk of a deep repository in clays. NAGRA was convinced that granite was the best repository host rock. The whole paradigm shift from granite to clay came later.

NAGRA and the SNHGS submitted an initial research programme to the authorities of the Canton of Jura, which was approved in 1995. The Mont Terri Project was born: the French ANDRA, the Swiss NAGRA and SNHGS, the Japanese PNC, now JAEA, and the Belgian SCK.CEN assured funding (the Mont Terri Project Partners are shown in Figure 1). As a legal form, these partners founded the "Mont Terri Consortium". All future partners can easily join this consortium. In early 1996, the Mont Terri rock laboratory began its operation with the excavation of eight niches in the reconnaissance gallery of the Mont Terri motorway tunnel (see Figure 2). In these niches, hydraulic and mechanical experiments to characterise the Opalinus Clay were carried out in the framework of a project limited to 2 years. The results were very promising: the Opalinus Clay was mechanically more stable than expected and the permeability was negligible; the clay was hydraulically very tight. New partners soon joined, first the German BGR and the Spanish ENRESA, and a little bit later also the French IRSN and the Japanese OBAYASHI (Figure 1). A first research gallery, the so-called Gallery 1998, was realised, in part since the motorway was opened in 1998 and the reconnaissance gallery could now be used as a Security Gallery for the Mont Terri motorway tunel.

By the end of 1999, the research results of the Gallery 1998 were so promising that a re-evaluation gradually took place in Switzerland. The geologists at NAGRA, HSK (now ENSI), LHG and

Year	Action & Event
1986-1994	Construction of the Mont Terri motorway tunnel. The Opalinus Clay appears to have interesting properties as a host rock for deep geological disposal. Joint geological mapping project in the Mont Terri reconnaissance gallery, carried out by the Swiss National Hydrological and Geological Service SNHGS (now Swiss Geological Survey at SWISSTOPO) and NAGRA.
1995	The Canton of Jura (RCJU, République et Canton du Jura) authorises the first research program in the reconnaissance gallery of the Mont Terri motorway tunnel.
1995-1996	Start of the Mont Terri research project with five partners (ANDRA, SNHGS, PNC (now JAEA), NAGRA and SCK.CEN). SNHGS has the patronage of the project. Construction of eight niches in the Security Gallery. Later in the year, ENRESA joins the Mont Terri Project.
1997-1998	Construction of the first research tunnel “Gallery 1998” and its inauguration. Opening of the Mont Terri motorway tunnel. The organisations of BGR, IPSN (now IRSN) join the project and become Mont Terri Project Partners.
1999	OBAYASHI joins the Mont Terri Project.
2001	Agreement between the Swiss Confederation and the Project Partners, including management rules for EC/SERI co-financed experiments.
2001-2003	GRS joins the Mont Terri Project in 2001, CRIEPI in 2002 and HSK (now ENSI) in 2003. Decision for the first extension of rock laboratory: the Gallery 2004.
2004	Construction of the research tunnel “Gallery 04”.
2005	Convention between the Confederation and the Canton of Jura. All rights and obligations are negotiated and agreed in this "Convention 2005". The Federal Office of Geology (FOWG) becomes rock laboratory operator. - By end of 2005 FOWG is suspended.
2006	SWISSTOPO takes over the role of the former FOWG and becomes operator of the facility as well as Project Partner. Celebration of 10 years of the Mont Terri rock laboratory. Decision of a further rock laboratory extension.
2007-2008	Construction of the research tunnel “Gallery 2008”. NWMO joins the Mont Terri Project in 2008.
2009	Approval of Convention 2009 (adaption of Convention 2005) between Confederation (SWISSTOPO and Federal Office of Roads) and Canton of Jura. Regulation of laboratory operation and its access. CHEVRON joins the Mont Terri Project in 2009.
2010-2011	Construction and inauguration of the Mont Terri visitor’s centre with the aim of providing up to 6000 people per year with research information.
2011-2014	Launch of the Full-Scale Emplacement experiment (FE), excavation of the FE-Gallery, canister installations and bentonite backfill, start of heating in 2014.
2013	The Lawrence Berkely National Laboratory of the US Department of Energy DOE joins the project.
2015	The Belgium safety organisation FANC joins the Mont Terri Project. Start of the first experiments involving CO_2 sequestration.
2016	Celebration of 20 years of the Mont Terri rock laboratory. From a total of 138 experiments, 93 have been completed and 45 are still in progress.
2018	Three organisations join the Mont Terri Project: the French company TOTAL, the German HELMHOLTZ (research centres UFZ, GFZ, FZJ, HZPR und KIT), and the English RWM are Project Partners.
2018-2019	Main extension of the rock laboratory: excavation of the Gallery 2018 in the sandy facies.
2019	Two organisations join the Mont Terri Project: the German BASE and the Swiss ETH (SSS, EAWAG, PSI, Engineering Geology).
2020	The German BGE joins the Mont Terri Project. By end of 2020, 22 Project Partners are participating in the Mont Terri Project. Due to the COVID-19 pandemic, the visitor centre has to be closed; however, research can be maintained on a limited basis.
2021	The pandemic seems to loose intensity. Reopening of the Visitor Centre. Celebration of the 25th anniversary of the Mont Terri Project.

Table 1: Historical timeline

the federal commissions slowly became convinced that claystones were a better alternative than crystalline rocks for a deep repository of radioactive waste. This was the basis for the continuation and expansion of the Mont Terri rock laboratory over the coming years of the new millennium.

There are many persons who played a key role in shaping the project during this period. They are presented in Table 2. Special mention should be made of Marc Thury from NAGRA, who was the driving force in this period and who is considered as the founder of the Clay Club and of the Mont Terri Project. Together with him, other persons were also involved in the founding phase. These were Minister Pierre Kohler, Jacques Babey, André Voutat, and Alain Waldmeyer from the Canton of Jura, as well as Charles Emmenegger and Jean-Pierre Tripet from the SNHGS, and Andreas Gautschi from NAGRA.

2000 – 2005 Contractual uncertainty and consolidation between the Confederation and the Canton of Jura

On the scientific level, the success was there in the year 2000: nine national and international Project Partners who financed and operated a rock laboratory, and the Opalinus Clay with better properties for deep geological disposal than expected. And already in this early 2000s period, the first demonstration experiments started: on the initiative of the Spanish partner ENRESA, a heater test and a 1:1 engineered barrier experiment with granular bentonite were launched.

On the other hand, the contractual side was lacking. There were mainly gentlemen‘s agreements and no legal contracts between the partners, the federal government and the Canton of Jura. In 2001 a first contract between the Federal Office of Water and Geology (FOWG) as representative of the Swiss federal government and the Project Partners was elaborated, that defined the rights and obligations, the so-called “Agreement 2001.” The core points of this agreement are still valid today. A first convention between the FOWG and the Canton of Jura was also drawn up in 2001. What was missing in this convention, however, was a responsible Swiss rock laboratory operator who was liable to the Canton of Jura and who was responsible for the safety underground. The Canton of Jura requested a federal organisation, whereas the FOWG only wanted to continue its patronage as before, but not the role of a rock laboratory operator. The paradigm shift from granite to clay as repository host rock also meant that NAGRA took up the banner of the Mont Terri rock laboratory, their proof of disposal (Entsorgungsnachweis 2002) was based primarily on results from the Mont Terri rock laboratory. However, the Canton of Jura did not want an implementer organisation such as NAGRA as rock laboratory operator on its territory, but rather that the federal government take responsibility. The federal government, on the other hand, wanted to hand over the Mont Terri rock laboratory to NAGRA for legal reasons. It was like a snake that bit its own tail. This mixing of science and politics led to a conflict between the Swiss stakeholders. Even the “Commission de suivi”, the cantonal monitoring commission of the rock laboratory set up by the Canton of Jura in 2001, failed to reach a consensus. Too many particular interests between the Mont Terri Project direction and the cantonal monitoring commission and too little willingness to compromise prevented a consensual solution.

In the following years 2002-2004, there were several changes in the project direction of the rock laboratory. The investments of the research partners also decreased massively. This was the reason that we were strategically fighting on two fronts: on the one hand, the planning and initiation of a long-term research project to bind the Project Partners, and on the other hand, finding an operating organisation of the Swiss Confederation that would establish legal contracts and enjoy the trust of all stakeholders.

Country	Mont Terri Project Partner	Entry
Switzerland	SWISSTOPO Federal Office of Topography	2006
	ENSI Swiss Federal Nuclear Safety Inspectorate	2003
	NAGRA National Cooperative for the Disposal of Radioactive Waste	1995
	ETHZ Swiss Federal Institue of Technology, Zurich	2019
Belgium	SCK•CEN Belgian Nuclear Research Centre	1995
	FANC Federal Agency for Nuclear Control	2015
France	ANDRA National Radioactive Waste Management Agency	1995
	IRSN Institut de Radioprotection et de Sûreté Nucléaire	1998
	TOTALENERGIES TotalEnergies S.A.	2018
Germany	BASE Federal Office for the Safety of Nuclear Waste Management	2019
	BGE Bundesgesellschaft für Endlagerung	2020
	BGR Federal Institute for Geosciences and Natural Resources	1997
	GRS Gesellschaft für Anlagen- und Reaktorsicherheit GmbH	2001
	HELMHOLTZ Forschungszentren UFZ, GFZ, FZJ, HZPR, KIT	2018
Japan	OBAYASHI Obayashi Corporation	1999
	JAEA Japan Atomic Energy Agency	1995
	CRIEPI Central Research Institut of Electric Power Industry	2002
Spain	ENRESA National Radioactive Waste Corporation S.A.	1996
Canada	NWMO Nuclear Waste Management Organization	2008
United Kingdom	RWM Radioactive Waste Management	2018
USA	CHEVRON Chevron Energy Technology Company	2009
	U.S. Department of Energy Lawrence Berkeley National Laboratory	2013

Figure 1: Twenty-two Project Partners from nine countries are involved in the Mont Terri research programme and the rock laboratory. The year of project entry is present in the last column. These partners plan, carry out, and finance the experimental programme. In addition, there are implementer organisations such as ANDRA, NAGRA and NWMO, and also safety organisations like ENSI, FANC and IRSN. Most of the Project Partners are under public law, but there are also private-sector organisations like CHEVRON and OBAYASHI.

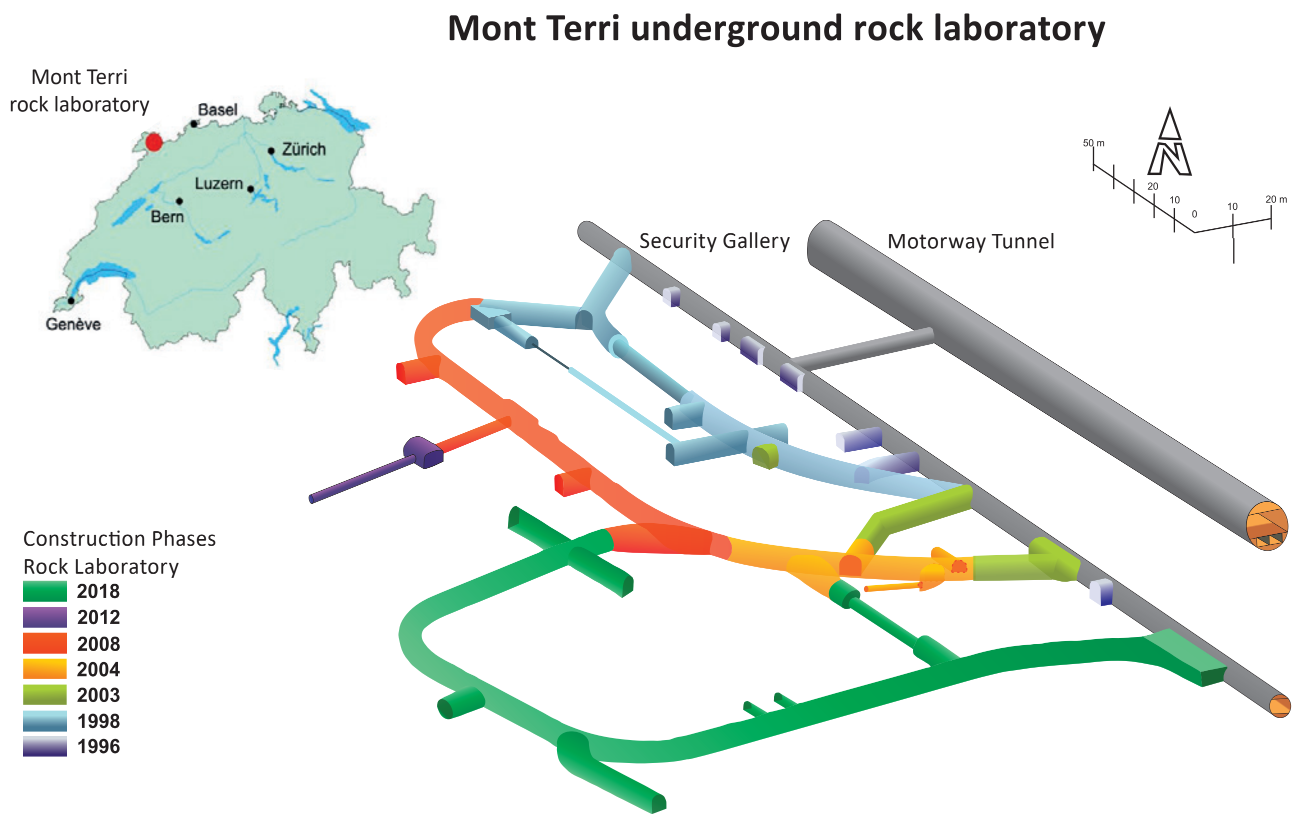


Figure 2: Perspective view of the Mont Terri rock laboratory, status 2020: it started in 1996 in small niches, then continuously expanded in 1998, 2004, 2008 and 2012, with the last major expansion in 2018-19 doubling the size of the laboratory. The total length of the rock laboratory is 1280 m.

The first point was easier to achieve than the second. As early as in June 2002, the Swiss partners discussed the future of the Mont Terri Project as new partners entered the project (CRIEPI, GRS and HSK – now ENSI). A research programme for the next 5 to 10 years and an extension of the rock laboratory was proposed. In the following, the Project Partners submitted a total of 60 experiment proposals and guaranteed funding. The extension of the rock laboratory with Gallery 2004 and its research project were born and realised, and thus the project saved – at least from the scientific research side. The second point, finding a rock laboratory operator and having the legal basis, was more difficult. Finally, in 2004, the Swiss stakeholders (representatives of the Swiss Project Partners FOWG, NAGRA, HSK (now ENSI), and the Canton of Jura) sat down at one table and negotiated a new convention under the leadership of the Federal Office of Water and Geology, FOWG. The negotiations were lengthy, as everyone came to the table with maximum expectations. Slowly, trust grew and everyone was open to compromise. This was the basis for saving the project, which was really hanging by a thread in those years.

Here also, there are several persons who played key roles during this period. Many of them are presented in Table 2. Special mention should be made of Federal Councillor Moritz Leuenberger, Ministers Pierre Kohler and Laurent Schafter from the RCJU; in the end, they supported the solution of an operator affiliated with the Swiss Confederation. The negotiating team for a new convention between the Canton of Jura and the Swiss Confederation consisted of the following persons: Christian Furrer, director of the

FOWG, Marcos Buser and Pascal Mertenat (cantonal monitoring commission), Markus Fritschi (NAGRA), Erik Frank (HSK, now ENSI), and Paul Bossart (Geotechnical Institute, GI AG).

2005 – 2021 International research in the Mont Terri rock laboratory and creation of the visitor centre.

Negotiations for a new legal basis for the Mont Terri rock laboratory between the Canton of Jura and the Swiss federal government were successfully concluded in 2005 and resulted in the "Convention 2005", which defines all rights and obligations, including the remuneration of the experts of the cantonal monitoring commission. The operation of the rock laboratory was delegated to the Federal Office of Water and Geology, FOWG. The contract was designed in such a way that future changes could also be easily integrated. This was the case in 2009, for example, when the question of access, as well as the ownership, were clarified and are now regulated in the Convention 2009.

So, in 2005, everything seemed to be in order and everyone should be happy and have more time for research again. Should…! The major disturbance was that the FOWG was dissolved at the end of 2005, a decision made by the Swiss Federal Council. The question was thus back on the table: who will operate the Mont Terri rock laboratory? This time we went proactively in search of an operator. Finally, the Swiss Geological Survey at SWISSTOPO made itself available and took over all contracts (Agreement 2001 and Convention 2005) at the beginning of 2006. This brought back peace and order. Since 1996, the rock laboratory has been operationally managed by the staff of the Geotechnical Institute AG. With the newly constituted rock laboratory operator, the staff were transferred to SWISSTOPO. This transfer was completed in 2008.

In 2006, the 10th anniversary of the Mont Terri Project was celebrated. At a scientific meeting in Saint-Ursanne, researchers from the 12 Project Partners and the participating universities and research institutes reported on the various experiments and the very valuable results and findings obtained. For this we organised a dignified dinner in the great hall of the Fabrique de Chaux. A torrential rain poured down during the dinner, water splashed through the leaking roof and the tables had to be moved! It was not a catastrophe for the guests; on the contrary, there was a spirit of optimism, a new research programme with a laboratory expansion was launched. In 2008, this resulted in the largest expansion of the Mont Terri rock laboratory for new experiments to date. The aim was to create enough space in the rock laboratory for the Project Partners to carry out new and larger experiments under the best possible conditions. The so-called Gallery 2008 was excavated with around 300 m of tunnels and niches. Co-financing was provided by the Swiss partners (HSK now ENSI), SWISSTOPO and NAGRA), the French ANDRA, the German BGR and GRS and the Japanese CRIEPI. The rock laboratory had then a total length of 815 m and could by then rightly be considered a major international research facility in a claystone, the Opalinus Clay. During 2008, the Canadian Implementer NWMO joined the project. This partner also helped to co-finance Gallery 2008.

With Gallery 2008, new geochemical and microbiological experiments began. The presence of microorganisms and their role in the degradation of corrosive gases like hydrogen suddenly become important (Figure 3). But also, thermo-hydraulic-mechanical coupled processes were increasingly addressed, especially in the near field of the rock laboratory. The artificial barriers and their behaviour with regard to long-term safety began to play an important role. These experiments were and still are sometimes very time-consuming and it can take 10 to 20 years before reliable results are available. In summary, we can say that from the methodology and characterisation of the Opalinus Clay in the late 1990 and early 2000 years, we were moving

Figure 3: A technician checks the tightness of sampling containers at the site of the "Hydrogen Transfer" experiment.

more towards demonstration experiments. This involved the inclusion of the technical barriers such as canisters and bentonite materials and their interaction with the clay.

The need to visit the Mont Terri Rock Laboratory has increased considerably in recent years. In 2000, there were only about 200 visitors, but from 2005 onwards the number of visitors rose steadily and increased tenfold to 2000 in 2009. Demand was particularly high from the future deep geological repository siting areas in Switzerland. To meet this demand, the Swiss partners SWISSTOPO, NAGRA and ENSI founded the "Consortium Centre Visiteurs" with the aim of receiving up to 6000 people a year to be informed about research in the Mont Terri rock laboratory and about the results of site selection for deep geological repositories for radioactive waste in Switzerland (Figure 4). A preliminary project submitted by SWISSTOPO for the construction of a pavilion, a bypass road, and a storage model in the rock laboratory was approved by the Jura government in autumn 2009, and the corresponding construction project was submitted in February 2010. The Canton of Jura granted the building permit in May 2010. On 5 September 2011, Federal Councillor Ueli Maurer ceremoniously inaugurated the visitor centre with around 100 invited guests from Switzerland and abroad. During this time, we were also able to welcome foreign politicians to the rock laboratory who were committed to the topic of radioactive waste disposal. Worth mentioning are Lower Saxony's Environment Minister Hans-Heinrich Sander, who, together with a delegation from Gorleben, informed himself about the Opalinus Clay and the Swiss disposal concept in the Mont Terri rock laboratory in autumn 2010. Then in November 2011, the head of the Baden-Württemberg Ministry for the Environment, Climate and Energy, Franz

Figure 4: Visitors can learn about the experiments in the Mont Terri rock laboratory and make up their own minds about deep geological repositories.

Untersteller (Bündnis 90/Die Grünen), visited the rock laboratory and wanted to learn more about the Swiss program for radwaste disposal. His statement was remarkable. He said, “We consider the final repository search process in Switzerland to be exemplary and are striving for a similar approach for Germany“. Less than 10 years later, the process started in Germany with full energy.

During a steering meeting of the Mont Terri Project Partners at the JAEA rock laboratory in Horonobe Japan in 2010, the delegates of the partners decided to award a prize to persons who had shown exceptional commitment to the Mont Terri Project. It is the “Mont Terri watch award“: a high-quality mechanical watch produced in the Canton of Jura in an edition of 100 pieces and donated to deserving people in the coming years (Figure 6). All 14 Partner Delegates joined in and agreed to finance this award. The watch was manufactured by the Swiss company ETA SA. The initial recipients can be seen in a photo of Figure 15 c.

In 2011, the so-called Full-Scale Emplacement Experiment under the lead of NAGRA was launched near the Gallery 2008. This is a thermo-hydraulic-mechanical experiment on a 1:1 scale with a duration of at least 15 years (Figure 5). The aim is to simulate the processes after the emplacement of high-level radioactive waste. However, no radioactive waste is used; heating elements simulate the waste heat. A 50 m-long tunnel was built, the heating canisters were emplaced and the cavity filled with bentonite granulate, and the heaters were turned on 2014. The experiment is still running 10 years later and the majority of sensors produce valuable data.

In 2011, the French Geological Survey BRGM contracted the Mont Terri Project direction to carry out the first CO_2 experiment in the Mont Terri rock laboratory. Thanks to EC funding through BGRM we were able to start with carbon capture and storage (CCS) experiments in the rock laboratory. This was then also officially constitutionalised: in 2012, the operator SWISSTOPO decided to open the laboratory to other “energy“ experiments. Thus, not only experiments for the deep geological disposal of radioactive waste in the Opalinus Clay will be carried out, but also experiments on CO_2 sequestration are now possible. In CO_2 sequestration, clay layers act as a protective and sealing layer so that the gas from the deeper permeable aquifers cannot penetrate into the biosphere. The weak points in the Opalinus Clay are being investigated, e.g., how the gas can escape upwards along fault zones or along old boreholes. A whole range of experiments have been launched to test the tightness of the clay. Looking back, we can say that the CCS experiments have been strongly developed thanks to the Geological Surveys (SWISSTOPO as catalyst, the French BRGM, and later also the German BGR) together with LBNL of the U.S. Department of Energy (DOE), the Swiss Federal Institute of Technology (ETH and EPFL), and also the oil industry (CHEVRON, TOTAL and SHELL).

The year 2013 was a rather quiet. There were no political obstacles, research was also in full swing, including the new experiments like the full-scale emplacement demonstration experiment. It is worth mentioning that the Lawrence Berkeley National Laboratory (LBNL) of the U.S. DOE joined the project as a new partner. But then, already in 2014, an acute lack of space for new experiments was becoming apparent. The lack of space is well visible in Figure 10, which corresponds to a snapshot in 2016. An extension was lively discussed with the partners during the steering meetings and a strategy paper for a comprehensive research project was developed. No one wanted to pay for new galleries in advance. However, good experiments where underground space was still needed (so-called consumables for experiments) met with interest. Finally, the 16 Mont Terri Project Partners, including the Belgium FANC who joined the project in 2015, gave their green light for an extension of the laboratory in order to continue clarifying the

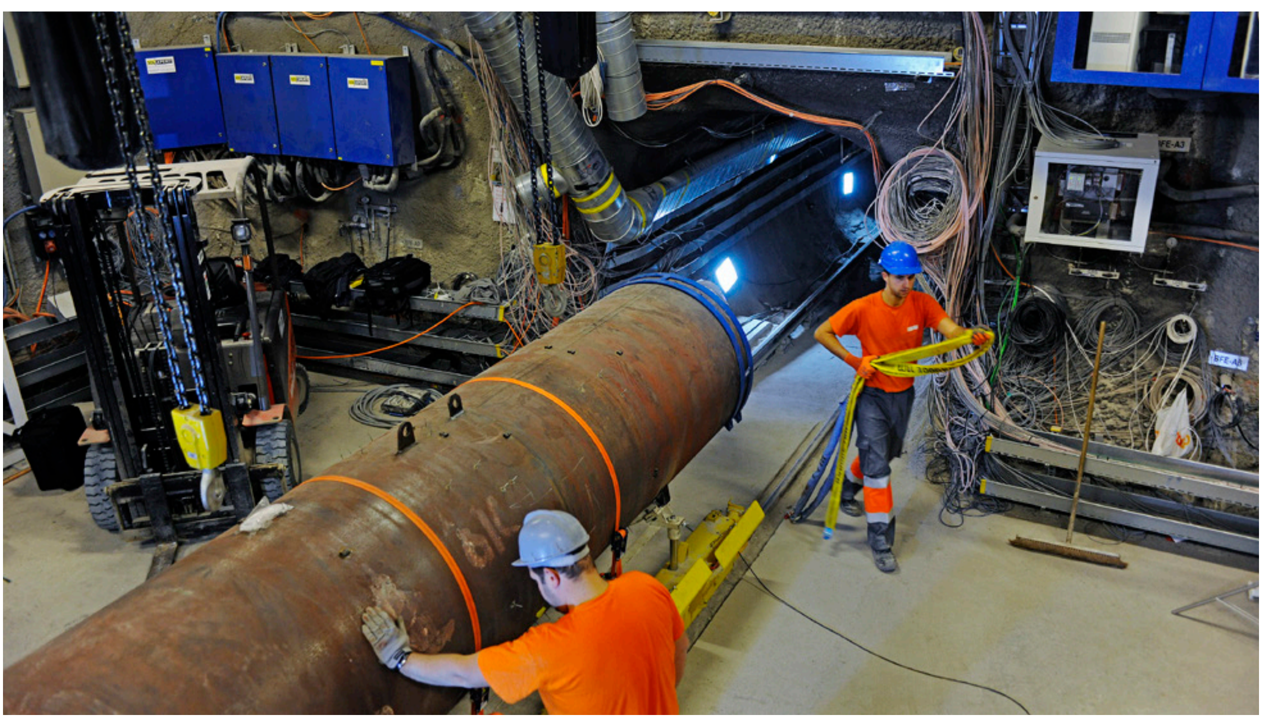


Figure 5: Installation of a canister in the “Full-Scale Emplacement Experiment“ on a scale of 1:1, under the lead of NAGRA. Instead of radioactive waste, the canister contains a heating element to simulate waste heat.

Figure 6: The Mont Terri Watch Award. Design of a mechanical watch produced by the Jurassic company ETA SA in an edition of 100 pieces.

outstanding questions in the coming years. A good opportunity to motivate the Project Partners to financially contribute to this extension was at the 20th anniversary of the Mont Terri rock laboratory: the Swiss Federal Councillor Guy Parmelin ceremoniously opened the anniversary in September 2016, looked back on what had been achieved and expressed optimism about the future. This also helped to secure the financial commitments of the partners. Finally, all the Project Partners were ready to financially cover this expansion. The Mont Terri team developed the preliminary project and received the green light from the Canton of Jura in October 2016; the definitive construction project was submitted to the Canton of Jura after the financing and procurement rules had been clarified. An important goal was to make the extension in the sandy facies. In this type of clayrock, which is mainly located in the upper part of the Opalinus Clay, only limited experiments had been carried out so far. Gallery 2018 with a total length of 465 m took around 2 years and was completed at the end of 2019.

The experiments already started in Gallery 2018 are shown in Figure 11. One lighthouse experiment is the "sealing of tunnels and shafts" project, the Sandwich experiment. Two shafts of 10 and 12 m depth were drilled and backfilled using a new sealing technique. Also, a complex injection experiment in a tectonic fault was initiated. This is especially intended to explore possible flow paths in fault zones and the associated seismic risks. An important aspect of this applied research is to discuss and document the results with our Partners and to plan new experiments. For this purpose, we established Technical Meetings at the beginning of the project in 1996. Once a year, all scientists, technicians, principal investigators and delegates but also students involved in our experiments meet at this workshop-like Technical Meeting. This exchange is important because it allows us to maintain personal and friendly contacts. The number of participants has increased almost tenfold in the last few years: while at the end of the nineties there were 25 to 30 people, in 2018 there were over 200. A good meeting place is the old Jesuit church in Porrentruy. Not only are good lectures and poster presentations possible there, but also organ concerts.

Between 2018 and 2020, a total of six additional organisations joined the Mont Terri Project. These are TOTAL, HELMHOLTZ, BASE, RWM, BGE and ETH Zurich (Swiss Seismological Service, Engineering Geology, EAWAG and PSI). Details of all the organisations and year of joining are shown in Figure 1. At the end of 2020, 22 Project Partners are represented in the Mont Terri Project. With the German HELMHOLTZ organisation and the Swiss ETH, we have the universities on board. We consider this a milestone, especially for the long-term radioactive waste disposal and CO_2 sequestration projects. New research methods developed at the universities can not only verify the results obtained and improve the overall safety, but they also can identify possible future risks and propose appropriate amelioration measures. This makes it possible for young scientists to contribute to socially relevant projects. It is also important to mention that oil companies such as CHEVRON and TOTAL are involved. These companies have a great deal of know-how in clay rocks and are also involved in the CO_2 sequestration experiments. All in all, the domestic and foreign Project Partners bring together a wealth of knowledge. This increases the feasibility and safety of deep geological disposal in clay rocks, whether in the Opalinus Clay or in any other clay formation worldwide. The idea of a national drillcore storage facility was also taken up in 2018. SWISSTOPO negotiated a long-term use of the old lime factory in Saint Ursanne with the Canton of Jura. Together with the Federal Office for Buildings and Logistics, a preliminary project for such a drillcore facility was drawn up and submitted to the Canton of Jura in 2020. If all goes well, it will be opened in 2025.

Just as we were about to get started with new experiments and projects in spring 2020, the COVID-19 pandemic hit. With a heavy heart, we had to cancel all visits and temporarily close the visitor centre. The planned inauguration of Gallery 2018 in April 2020 also could not take place. However, international research continued with restrictions, in compliance with the relevant safety guidelines. Fortunately, we have had no COVID-19 cases to date.

At the end of 2020, Paul Bossart retired. He had been actively involved in the project since 1995. Christophe Nussbaum was elected as his successor and has been the new director of the Mont Terri Project since the beginning of 2021. Christophe has been successful in acquiring carbon storage experiments and has built up a scientifically active network among the Partners.

There are many important key persons and organisations presented in Tables 2 and 3 who played a key role in shaping the project during this period. Not mentioned in this table are people who helped us to find a new operator and supported us in the elaboration of the legal contracts. These are Minister Philippe Receveur from the Canton of Jura, as well as Jean-Philippe Amstein (former director) and Christoph Beer (former head of Swiss Geological Survey) from SWISSTOPO. Mention should also be made of Markus Fritschi of NAGRA, who can be regarded as the driving force behind the Mont Terri visitor centre. And last but not least, we would like to mention Jacques Delay from ANDRA. He had the idea of the Mont Terri Project award and skilfully motivated the Partner delegates to participate.

The Mont Terri Research Project

What is it?

The Mont Terri Research Project is an international research platform where experiments can be conducted under realistic conditions in an argillaceous formation, be it for a deep geological repository for radioactive waste or for the storage of CO_2 deep underground. The Mont Terri Project has three main objectives: 1) to research and develop new methods that can be applied in claystones such as the Opalinus Clay, but which are also transferrable to other argillaceous formations worldwide, 2) to characterise the Opalinus Clay, that means, to acquiring knowledge of the physical, chemical and biological properties of this clay formation, and 3) to carry out demonstration experiments. The latter primarily serve to demonstrate the long-term behaviour and the construction feasibility of a disposal system. The main question we have to answer is always the same, be it for radioactive waste or CO_2 storage: is a deep repository system safe in the sense that it does not pose a threat to the operators on the short-term and to the geosphere and the biosphere on the long-term?

The Mont Terri rock laboratory, which is the essential part of the Mont Terri Project, allows us to make detailed scientific measurements of the mechanical, hydrogeological, chemical and microbial characteristics of the Opalinus Clay that are not possible using classical methods such as measurements on drillcores or along boreholes. In general, data from Mont Terri can be obtained at larger and more realistic scales and are thus more relevant to the scale of an actual disposal system. The collected body of scientific information obtained in the Mont Terri rock laboratory provides added confidence about the safety and engineering feasibility of a disposal system in claystones.

During the last 30 years, especially European countries, USA, Canada and Japan have worked together combining their research potential and facilities (e.g., the HADES rock laboratory of SCK.CEN in Belgium or the Meuse Haute Marne Underground Facility of ANDRA in France). Scientists, engineers, technicians and operators from many countries are involved in the experiments. Under the aegis of international instances (Nuclear Energy Agency NEA of the OECD in Paris, International Atomic Energy Agency IAEA in Vienna), extensive knowledge and experience have been accumulated and quality and controlling standards have been developed. The rock laboratories are thus privileged sites of learning for countries that do not have yet such facilities and intend to develop them in the future. In this spirit, the Mont Terri rock laboratory has provided technical supervision to many interns from foreign organisations. One example are the scientists from China who, before the pandemic, were regular scientific fellows to the rock laboratory.

The Mont Terri rock laboratory is also an essential element for the information and communication policy of implementers, safety authorities, and regulators. Citizens can come into contact with scientists. And here the Mont Terri visitor centre comes into play. SWISSTOPO, ENSI and NAGRA run this centre where visitors can ask detailed questions about disposal concepts and technical issues, and also about phenomena and time scales that cannot easily be understood. During such visits, people can build their opinion about geological disposal in an informative manner. It is our task to provide information that is as neutral and factual as possible; without propaganda, but with honest discussion of the advantages and disadvantages of the concepts. We welcome critics of deep geological disposal as well. Finally, we are convinced that this way of informing the public and this kind of communication will increase the acceptance of deep geological disposal among the population. The national referendum in 2031 on the siting areas in the Opalinus Clay in Northern Switzerland will show this.

The organisation of the Mont Terri Research Project

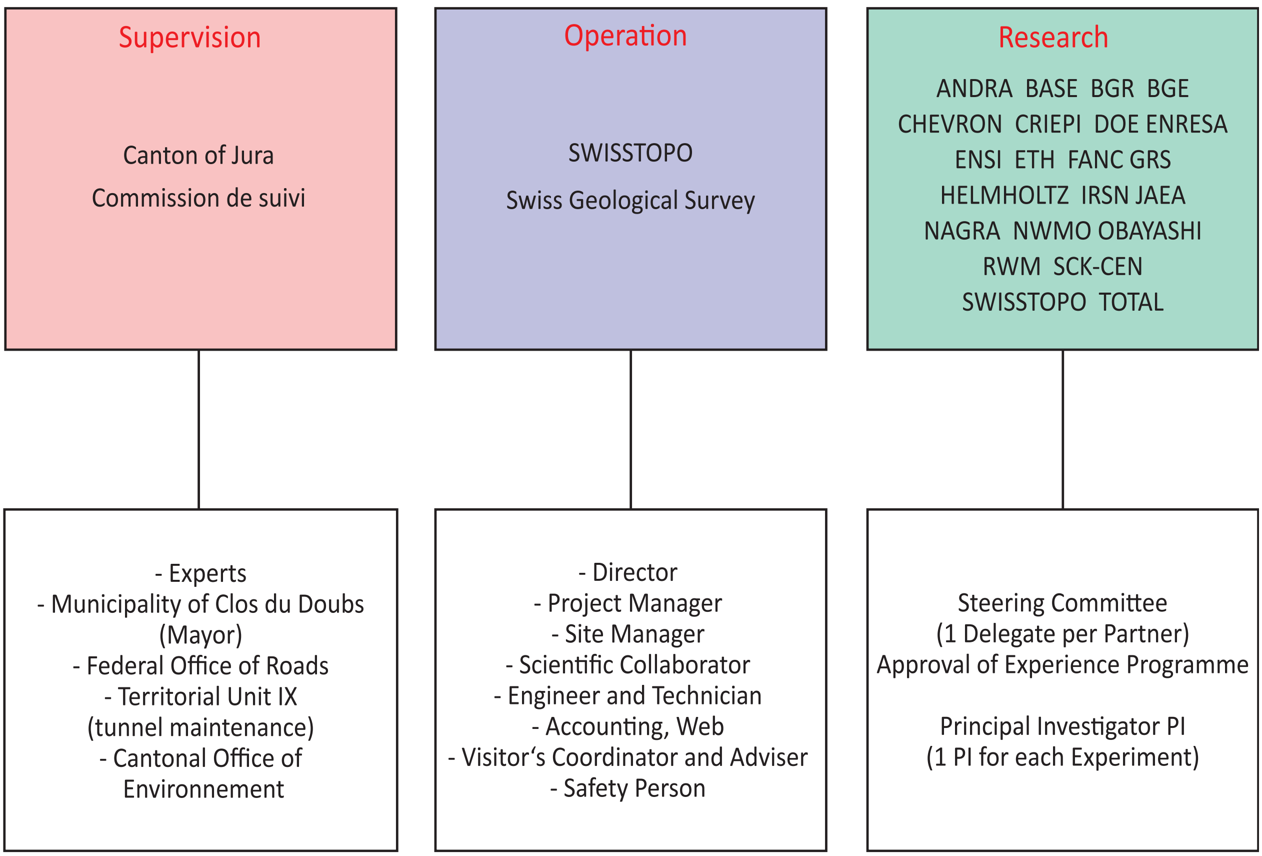


Figure 7: The organisation of the Mont Terri Research Project can be divided into three units with different tasks and functions (supervision, operation, research). From left to right: supervision carried out by the “Commission de suivi” of the Canton of Jura, which prepares the yearly authorisations for the cantonal government and informs the public in the canton. Several experts are working in this commission. SWISSTOPO is responsible for the operation of the rock laboratory. The staff comprise ten collaborators, seven of them are involved in the Mont Terri research programme, and three in the operation of the visitor centre. The 22 Project Partners are responsible for the research projects. There is a steering committee where one delegate represents each partner. For every experiment there is one principal investigator (PI), who is responsible for the scientific management. There is a legal base between the three units, consisting of the “Convention 2009” between the operator and the supervisor, and the “Agreement 2001” between the operator and the Project Partners.

How are we organised and what is the legal basis?

The Mont Terri Project is unconventionally structured and organised in a way that is unique in the world. Other rock laboratories are usually run by a single organisation that manages, operates and finances the facility on its own, according to its needs. The Mont Terri Project, on the other hand, is democratically organised, all partners have equal rights and obligations, and the research project is jointly financed by the Project Partners.

The organisation and interaction of the different organisations is explained in Figure 7. The legal basis between the research partners and the operator is the “Agreement 2001,” which defines the rights and obligations of the Project Partners. Between the Canton of Jura and the operator SWISSTOPO there is the “Convention 2009,” which regulates all matters. Both agreements are short documents and can be downloaded from mont-terri.ch. What we have seen time and again is that even good contracts are useless if there is a lack of trust. And we have been able to steadily improve this in recent years with all stakeholders.

SWISSTOPO operates the Mont Terri rock laboratory

The Federal Office of Topography SWISSTOPO is the geo-information centre of the Swiss Confederation. It is responsible for national surveying and coordinates the federal government‘s activities in the field of geodata and geoservices. This office is also the federal authority responsible for the supervision of cadastral surveying and houses the Swiss Geological Survey. To this end, SWISSTOPO has established a branch in Saint-Ursanne in the old lime factory. Ten employees are responsible for running the rock laboratory and the visitor centre (Figure 8).

Since 2006, SWISSTOPO has managed the Mont Terri Project and operates the Mont Terri rock laboratory. SWISSTOPO concluded contracts with the Canton of Jura as owner of the facility and with the research partners. Since 2010, SWISSTOPO has been running the Mont Terri Visitor Centre together with NAGRA and ENSI.

The Canton of Jura as owner authorises the research

The Canton of Jura, represented by the Department of the Environment and Equipment and its services, is the owner of the Opalinus Clay in the Mont Terri rock laboratory. As the owner of the facility, the Canton of Jura supervises the operator SWISSTOPO and grants it annual authorisation to carry out the experiments. Thus, the Canton of Jura has implemented a monitoring commission, the so-called Commission de suivi, which coordinates the various tasks of the services concerned. The Federal Office of Roads and the mayor of Saint-Ursanne are also represented in this commission. Furthermore, this commission ensures that the safety requirements underground are met by the operator and the research partners.

The Project Partners carry out the research

Currently 22 Project Partners are involved in the Mont Terri Research Project and these are shown in Figure 1. In the last 10 years, the number of partners has roughly doubled. So far, not a single partner has dropped out.

It is easy to see that the Project Partners are mainly implementing organisations, i.e., organisations that are responsible for a national disposal programme (in Switzerland this is NAGRA, in France ANDRA, in Germany BGE, in the United Kingdom RWM, and in Canada NWMO). On the other hand, also represented are safety organisations that monitor the implementers (in Switzerland these are ENSI, in France IRSN, in Germany BASE and in Belgium FANC). It is important to note that these safety organisations carry out their own experiments in the rock laboratory and do not usually collaborate with the implementers. Other organisations are national geological services (Swiss Geological

Figure 8: The SWISSTOPO rock laboratory operator team from left to right: David Jaeggi, Thierry Theurillat, Romain Nicol, Michèle Pretalli, Nathalie Artho-Bovard, Chloé Nicaty, Paul Bossart, Senecio Schefer, Christophe Nussbaum and Marilyn Rohrer.
Photo taken in December 2020; archive SWISSTOPO.

Survey at SWISSTOPO, BGR in Germany), but also petroleum organisations, such as TOTAL in France and CHEVRON in the USA. Their know-how is considerable and everyone can benefit from their participation.

Behind all the partners are individual men and women: scientists, technicians, engineers and managers. We have listed in Table 2 and on the back cover of this commemorative publication all the names of the key persons, principal investigators and experiment delegates who have been involved in one or more experiments over the past 25 years. If we also would include the contractors, the total is more than 500 people. Incredible.

What are the investments so far?

To date around 180 experiments have been performed in the rock laboratory. Of these, 75% have been completed, i.e., the data have been analysed and published in reports and research journals. Currently around 45 experiments are running.

The investments since 1996 are shown in Figure 9. In total, the Project Partners have invested 102.5 million CHF in the research programme up to mid-2021. The European Community has contributed around 10% of this. This corresponds to an average annual budget of 4.1 million CHF. These costs do not include the annual maintenance and operating costs of SWISSTOPO, which amount to around 0.8 million CHF per year. The salary costs of the Project Partners' staff are also not included. If these were included in a full cost calculation, the costs of 102.5 million CHF would be approximately doubled. Around 20% of these invested funds remain in the Canton of Jura, mainly via contracts with private industry. The money spent in the hotel and catering industry would have to be included separately. The population around Saint-Ursanne benefits from this.

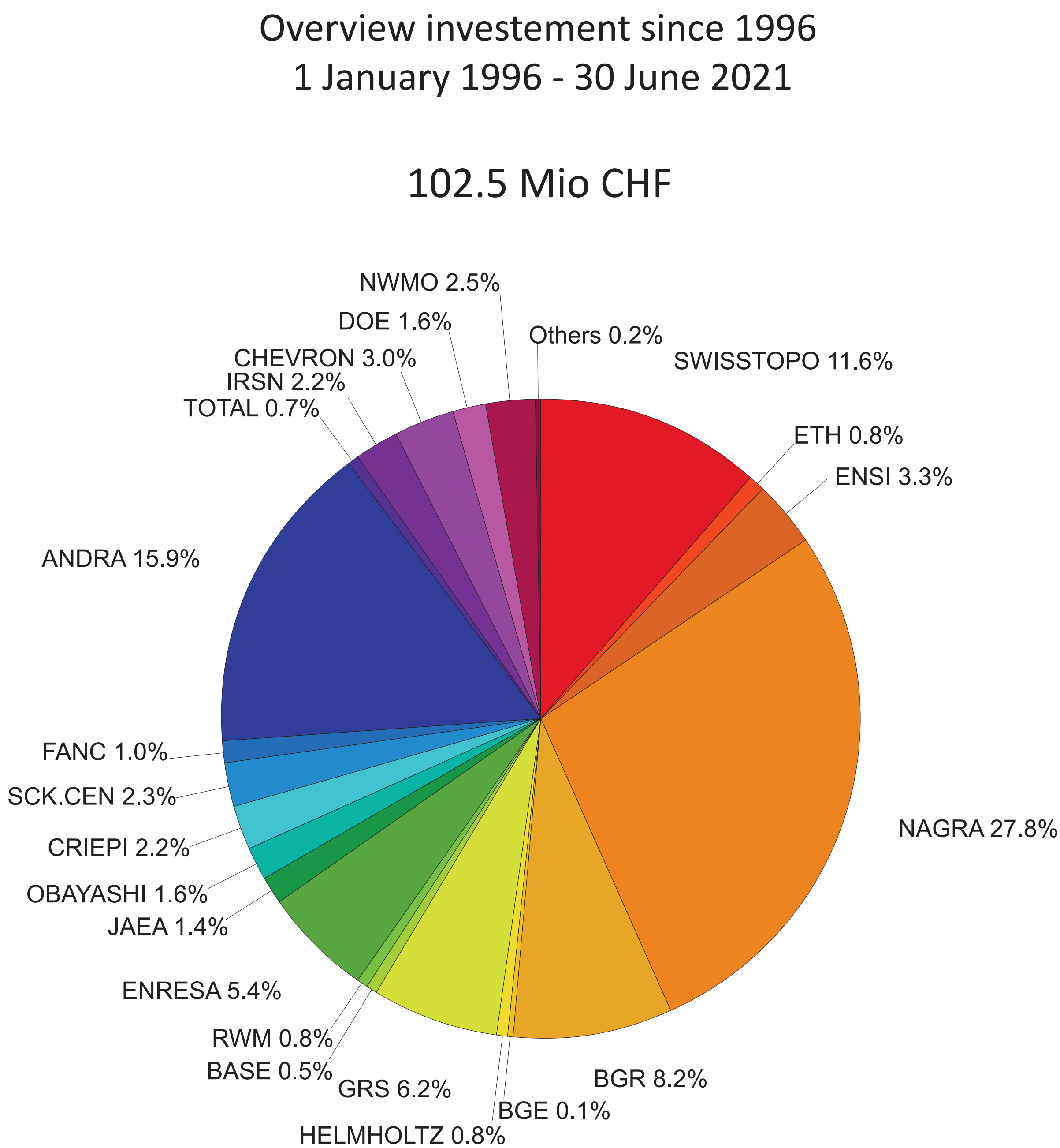


Figure 9: Since 1996, 102.5 million Swiss francs have been invested in the Mont Terri Project for research. This corresponds to an average annual budget of 4.1 million Swiss francs. Approximately 20% of this amount remains in the Canton of Jura for local contractors.

Key Results

In the last 25 years, researchers from the partners have gained a tremendous amount of knowledge about deep geological disposal in claystones. A cumulative body of knowledge has come together. More specifically, the Mont Terri rock laboratory has made a significant contribution to the definitive selection of Opalinus Clay as a host rock for radioactive waste in Switzerland. But Opalinus Clay is also indispensable for CO_2 sequestration. We have been conducting experiments in this area over the last several years. If CO_2 is ever stored deep underground in Switzerland, the Opalinus Clay is indispensable as a barrier rock.

The results and evaluations of the last 25 years have been documented in more than 2000 technical notes and reports, as well as scientific papers in international peer-reviewed journals. It must be said that every disposal concept and every geologic host rock has advantages and disadvantages. The “egg-laying milk-giving wool-pig“ does not exist! In the following, we briefly list these strenghs and weaknesses below. Both weaknesses can be reduced with adequate measures, such as ensuring enough distance between emplacement galleries to avoid overheating, and engineered lining measures that guarantee short term stability of the access galleries.

Strengths and weaknesses of Opalinus Clay as host rock for radioactive waste disposal

Strengths:

1. Claystone formations as the Opalinus Clay exhibit extensive retention potential for sorbing radionuclides due to the large reactive surface areas of clay minerals. The majority of radionuclides remain stuck and will be sorbed onto clay mineral surfaces.
2. Non- or weakly-sorbing radionuclides are transported through Opalinus Clay by molecular diffusion, which is a slow process. By the time these radionuclides reach the biosphere, they have decayed to the point where they no longer pose a threat to the environment.
3. Opalinus Clay reveals distinct self-sealing properties due its smectite-illite mixed-layer clay minerals. Interconnected fracture networks, which are formed in the excavation-damaged zone during repository construction or possibly generated in the future by earthquakes, will self-seal in relatively short time spans. Thus, rapid radionuclide transport along preferential flow paths out of the repository into the biosphere is unlikely.

Weaknesses:

1. Heat conductivity of Opalinus Clay is rather small when compared to other host rocks. Heating of Opalinus Clay over 100 degrees Celsius in a high-level waste repository might create a thermally induced damaged zone and/or reduce the sorption capacity.
2. Construction of a repository at greater depths (e.g., at 800 m depth) could result in a more extended EDZ (excavation damaged zone) and high tunnel convergence. This is a challenge in terms of stability for the engineers. A deep repository in Opalinus Clay will also be quite expensive.

Opalinus Clay as caprock for the CO_2 storage

The Opalinus Clay also plays an important role in CO_2 storage in the deep underground. However, its function is different from that of radioactive waste: in CO_2 storage, claystones act as a protective and sealing layer so that the CO_2 gas from the deeper permeable aquifers cannot penetrate into the biosphere. A whole series of experiments have been launched to test this impermeability. The following three sets of questions are crucial. (1) Is the Opalinus Clay permeable at all, and if so, how long does it take for the CO_2 to traverse the clay formation? Are there chemical reactions in the clay in which the CO_2 is converted into solid minerals and thus becomes bound? (2) In geology there are no homogeneous materials, Opalinus Clay is not the same everywhere; there are different types (clayey, sandy, calcareous), and above all, there are tectonic fault zones. The question is whether such fault zones represent preferential flow paths for CO_2. Also, could gas-flow along fractures trigger earthquakes that pose a danger to the population? (3) The last set of questions concerns old exploration wells that penetrate the Opalinus Clay. Could gas penetrate and escape through these wells into the biosphere, e.g., into drinking water aquifers, and pollute them? The issue here is again to understand the process: is CO_2 converted into solid minerals in old boreholes and thus gets bound there? And if not, can such old boreholes be sealed with smart sealants?

These investigations and the corresponding experiments are ongoing. But what we can already say is that the clay barrier to CO_2 is quite robust and major contamination with CO_2 in the biosphere is unlikely. The Opalinus Clay's function as a caprock seems to be working. It still needs to be investigated whether storage rocks exist at depth below the Opalinus Clay that could absorb the future injected CO_2 at all.

Disposal concepts in clays in other countries

All the countries where our Project Partners come from are developing disposal concepts. Radioactive waste repositories to be constructed in argillaceous formations have been proposed already in Belgium and decided in France and Switzerland. In Belgium this is SCK.CEN who is running the HADES rock laboratory, and in France it is ANDRA with their Meuse Haute Marne Underground Research Laboratory, and IRSN with their own rock laboratory in Southern France. All of these underground facilities are in argillaceous formations, having different ages and geological compositions, and thus also different characteristics. What is the same, however, are the processes such as radionuclide retention, slow migration of radionuclides by molecular diffusion, self-healing and sealing of fractures. Other countries are also considering storing radioactive waste in clay rocks, for example in Germany, Spain, and Canada. Our Project Partner countries also have somewhat different repository concepts, be it the technical barriers, the way of waste emplacement, and potential waste recovery in the future. Here, too, a lively discussion and exchange of experience between implementers and safety authorities is underway. This will make deep disposal safer for all.

Public acceptance

The Mont Terri rock laboratory is also an essential element in the dissemination of information and communication policy among implementers, safety authorities, and regulators. People visiting these facilities get an impression of the underground works and the different types of scientific and engineering experiments. Especially important are open days allowing stakeholders to contact scientist and engineers, ask detailed questions about repository concepts and technical issues, and also to discuss phenomena and time scales that cannot easily be comprehended. During such visits, people can build an educated opinion about geological disposal in a neutral and informed manner. As in all of the communications from Mont Terri rock laboratory, we express what has been learnt and the conceptual domains within which these apply in an understandable, neutral, and scientific fashion.

Since 2011, SWISSTOPO, NAGRA, and ENSI have been operating the Mont Terri Visitor Centre. About 4000–5000 persons visit the Mont Terri rock laboratory each year (except in the pandemic year 2020 and 2021, where the visiting services had to be suspended). These visits contribute essentially to the acceptance and credibility of the research in the context of deep geological disposal of radioactive waste and sequestration of CO_2. Critics and supporters of deep geological disposal will be informed about the national and international developments of deep geological disposal and they can exchange their ideas and opinions.

In conclusion, we are proud to say that the methodologies developed, experience gained, and experimental results achieved in the Mont Terri rock laboratory have increased the general knowledge of the complex behaviour of argillaceous formations in response to coupled hydrogeological, mechanical, thermal, chemical, and biological processes. The research we have carried out at Mont Terri over the last 25 years has considerably contributed to the safety and technical feasibility of deep geological disposal, be it for the storage of radioactive waste or sequestration.

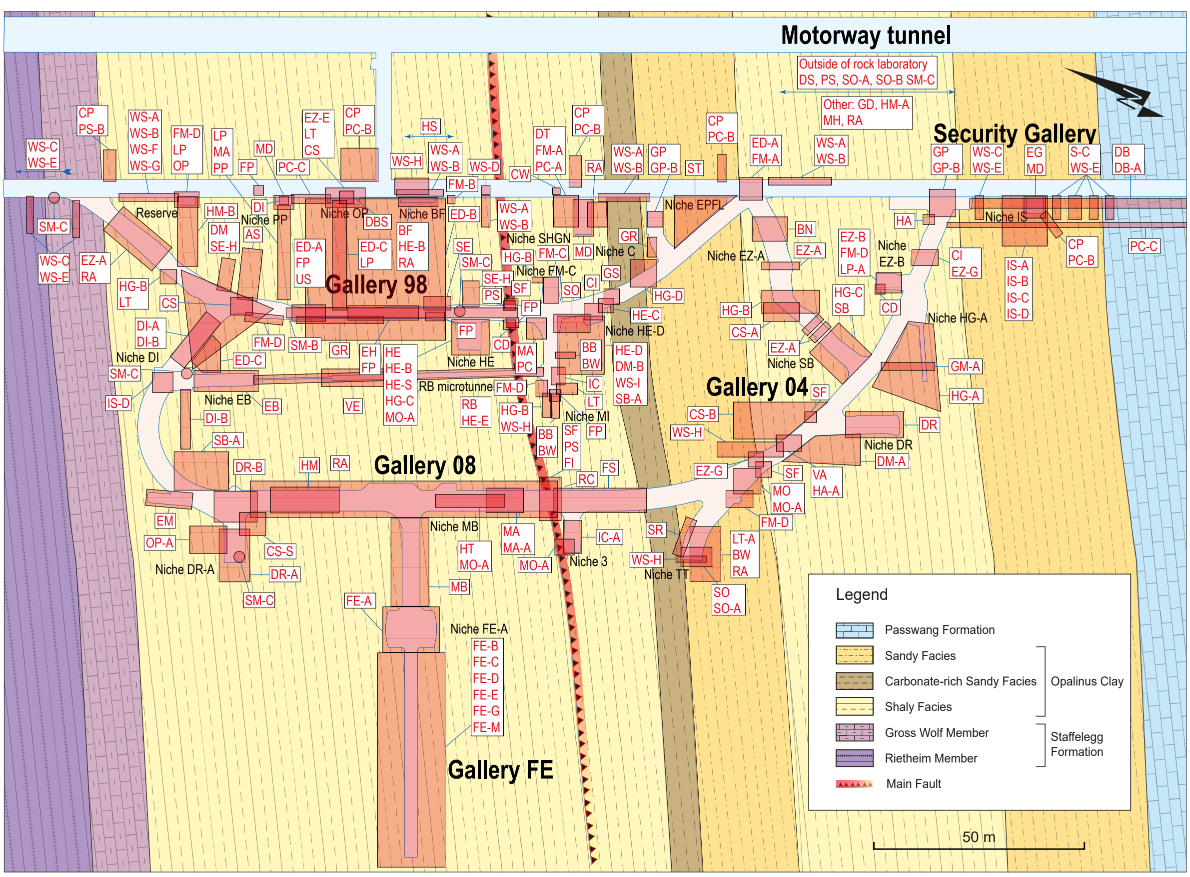
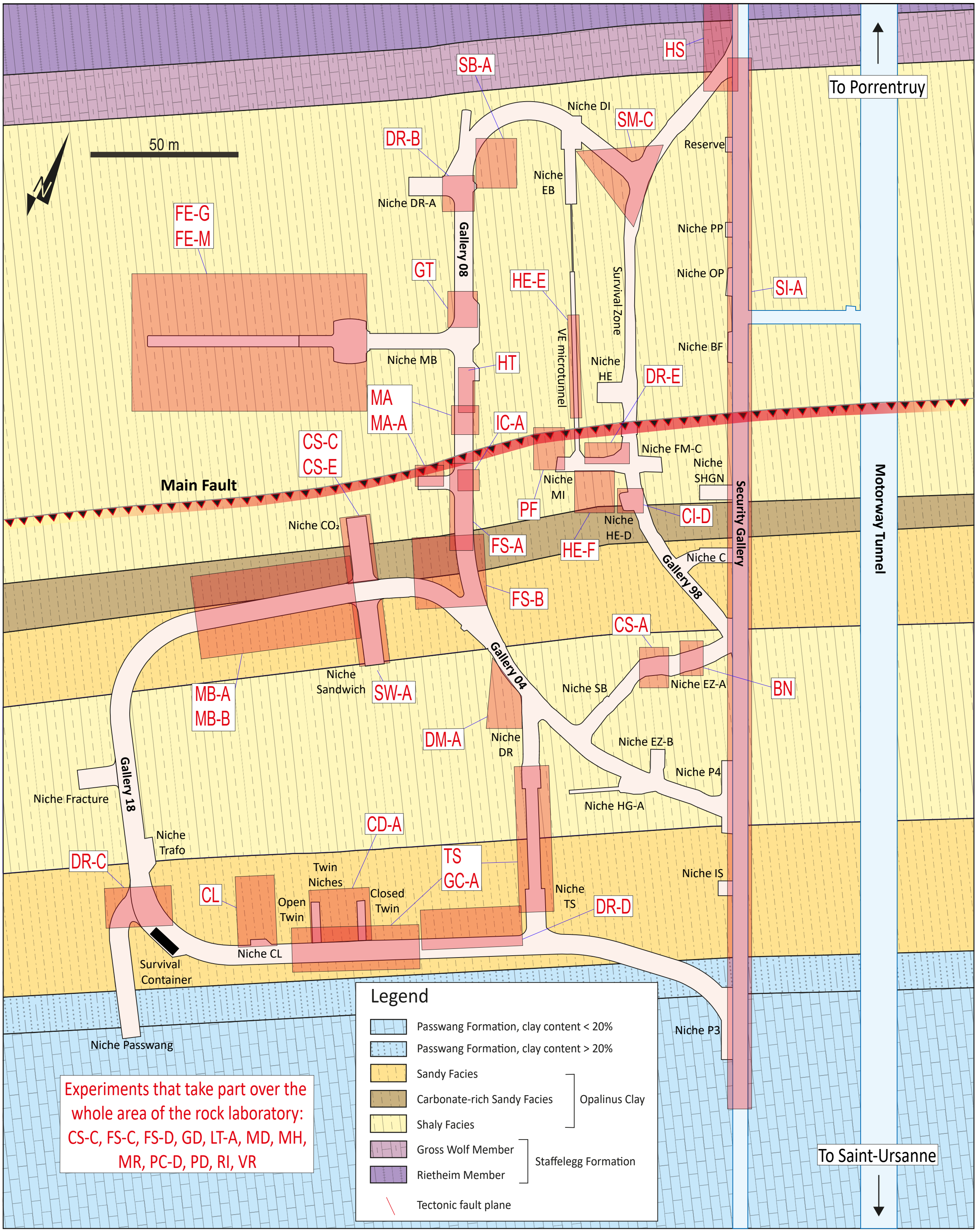


Figure 10: This map of the rock laboratory is a snapshot from 2016. It contains all experiments since the start of the Rock Laboratory in 1996. In total, 138 experiments have been carried out in these 20 years, 45 of which were still running in 2016. The abbreviations of the experiments are shown on the map. The majority of the experiments are concentrated on the shaly facies of the Opalinus Clay. It is clearly visible that there is practically no more space available for new experiments.

Geological map of the Mont Terri rock laboratory and ongoing experiments



List of ongoing experiments: abbreviations and short titles

BN:	Bitumen-nitrate-clay interaction.
CD-A:	Influence of humidity on cyclic and long-term deformations.
CI:	Cement-clay interaction.
CI-D:	Diffusion across a 10-year old concrete/claystone interface.
CL:	CO_2 long-term periodic injection.
CS-A:	Well leakage simulation and remediation.
CS-C:	Experimental assessment of shale properties for safe geological CO_2 storage.
CS-E:	Mini-fracturing and sealing.
DM-A:	Long-term deformation measurements.
DR-B:	Long-term diffusion experiment.
DR-C:	Diffusion in a thermal gradient.
DR-D:	Heterogeneity of sandy facies by geophysical characterisation and diffusion studies.
DR-E:	Long-term diffusion experiment in fault zones.
FE-M:	Long-term monitoring of the full-scale emplacement experiment.
FE-G:	Monitoring the gas composition within the full-scale emplacement experiment.
FS-A:	Friction properties of Opalinus Clay.
FS-B:	Imaging the long-term loss of faulted host rock integrity.
FS-C:	Understanding fault slip and subsequent sealing processes in Opalinus Clay.
FS-D:	Laboratory characterisation of fault slip by acoustic imaging and hydromechanical tests.
GC-A:	Geo-mechanical in-situ characterisation of Opalinus Clay.
GD:	Analyses of geochemical data.
GT:	Gas transport models and the behaviour of Opalinus Clay to gas pressure.
HE-E:	In-situ heater test in VE microtunnel.
HE-F:	Gases and water-soluble organics in Opalinus Clay at elevated temperatures and pressures.
HS:	Hydrogeological survey of aquifers around the Opalinus Clay.
HS-A:	Geochemical characterisation of the Staffelegg Formation.
HT:	Hydrogen transfer in Opalinus Clay.
IC-A:	Corrosion of iron in bentonite.
LT-A:	Analysis of properties and physical processes of claystones by laboratory tests.
MA:	Microbial activity in Opalinus Clay.
MA-A:	Modular platform for microbial studies.
MB-A:	Mine-by test in sandy facies.
MB-B:	Simulation of the mine-by test in Gallery 2018.
MD:	Cosmic muon density tomography.
MH:	Long-term monitoring of heaves.
MR:	Moisture detection using magnetic resonance.
PC-D:	Porewater gas-characterisation methods, reactive and noble gases.
PD:	Effect of physical deformation of isotopic signatures of clay minerals.
PF:	Progressive evolution of structurally controlled overbreaks.
RI:	Response investigation of Gallery 2018.
SB-A:	Borehole sealing experiment.
SI-A:	Seismic imaging ahead of and around underground infrastructure.
SM-C:	Permanent nano-seismic monitoring.
SW-A:	Large-scale sandwich seal experiment.
TS:	Testing different tunnelling support in sandy facies.
VR:	Virtual URL (underground research laboratory) combining experiments and models.

Figure 11: This map of the rock laboratory shows the current laboratory including its extension, the Gallery 2018. The Gallery 2018 is located in the upper part of the Opalinus Clay, mostly in the sandy facies. A total of 46 experiments are underway, and already the Gallery 2018 is occupied with new projects. The abbreviations of the experiments are included in the map and the titles are given above.


a)
1 cm

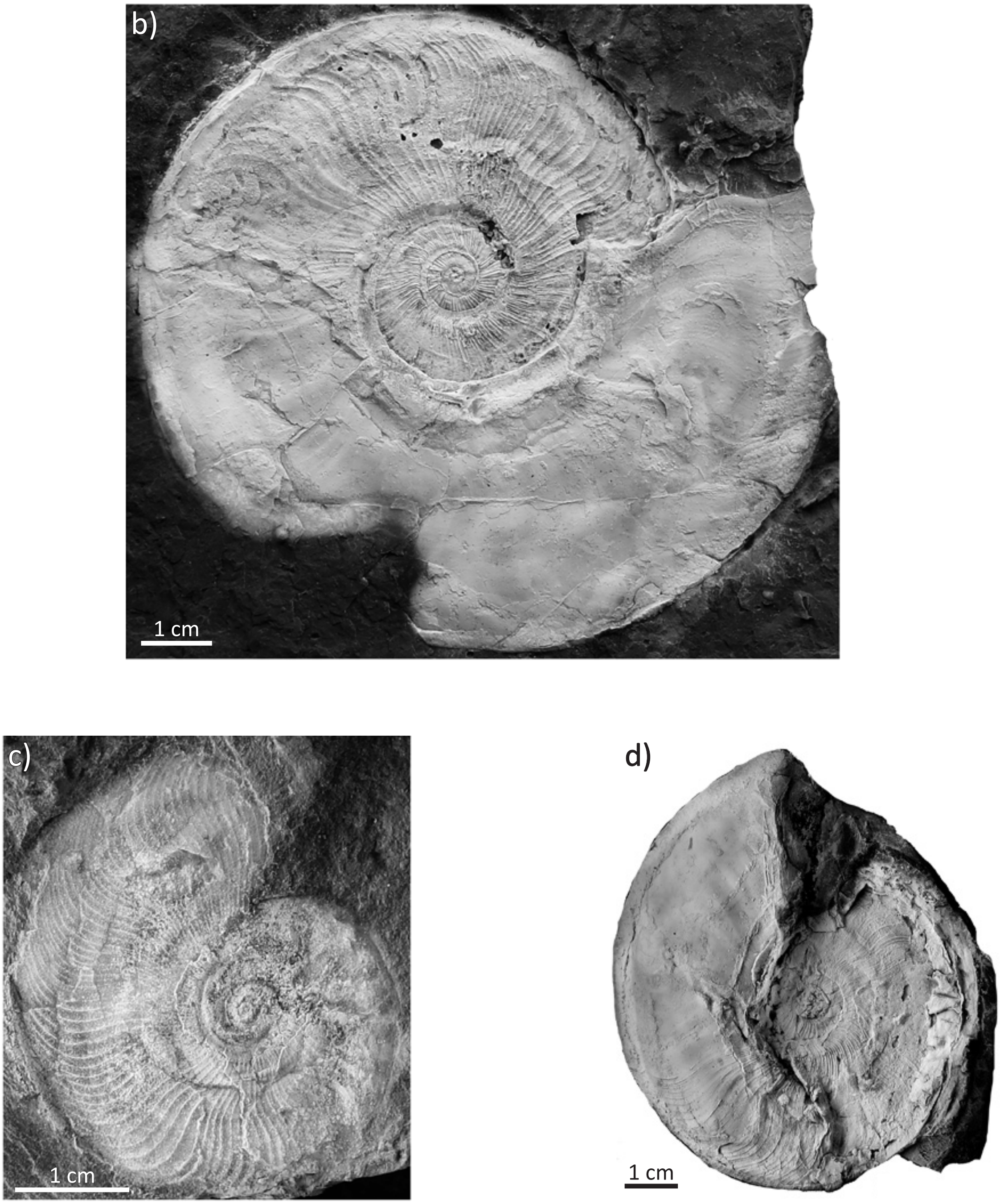


Figure 12: We found many ammonites in the excavated rock material. These have great scientific value, as they can be used to determine the sedimentation age of 174 ± 0.5 million years of the Opalinus Clay a) Leioceras opalinum (Reinecke, 1818), b) Leioceras ex gr. opalinum, c and d) Leioceras subglabrum. The Leioceras opalinum gave the name to this unique geological claystone formation: Opalinus Clay in English, "argiles à Opalinus" in French, and "Opalinuston" in German.

These ammonites were collected in the Mont Terri rock laboratory, prepared, determined and preserved by Bernhard Hostettler and Ursula Menkveld, Naturhistorisches Museum, Bern.

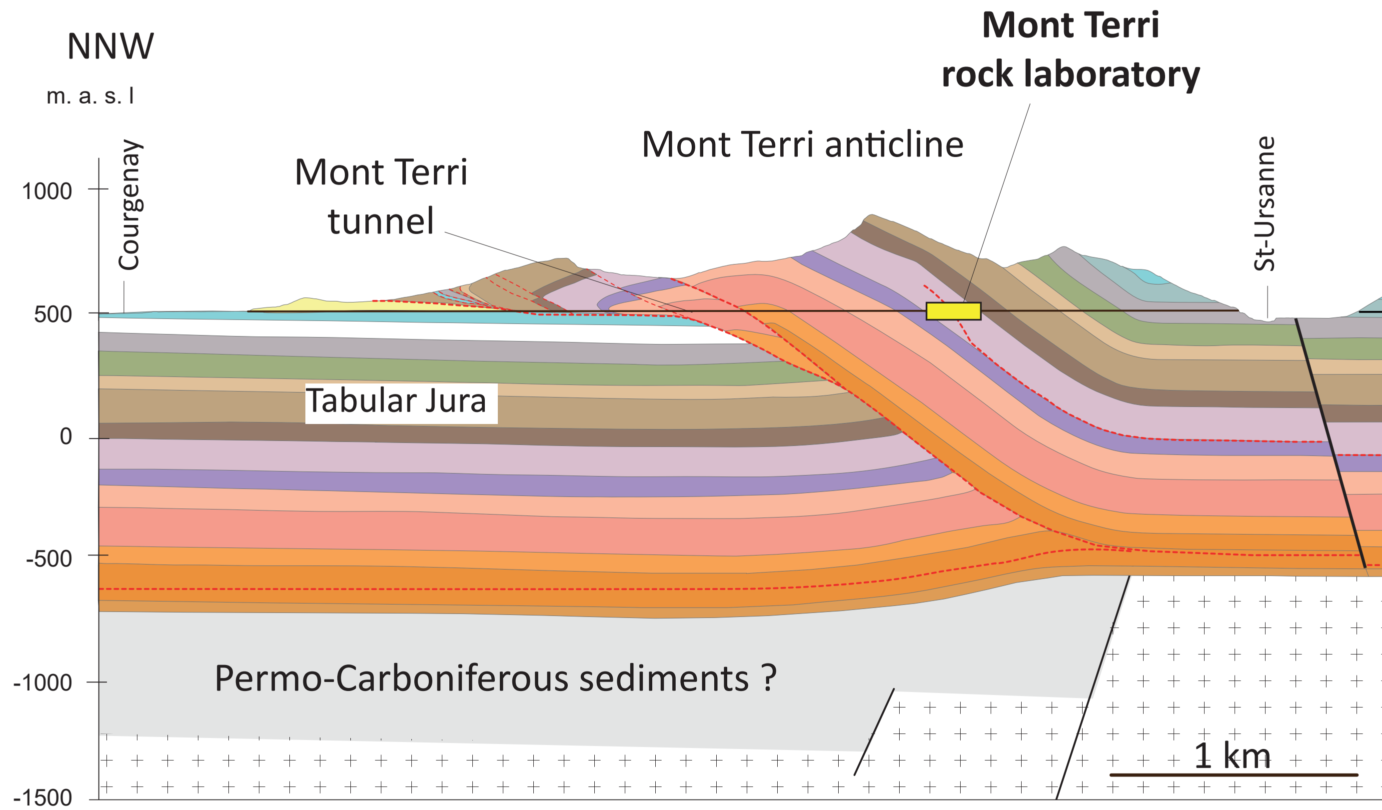
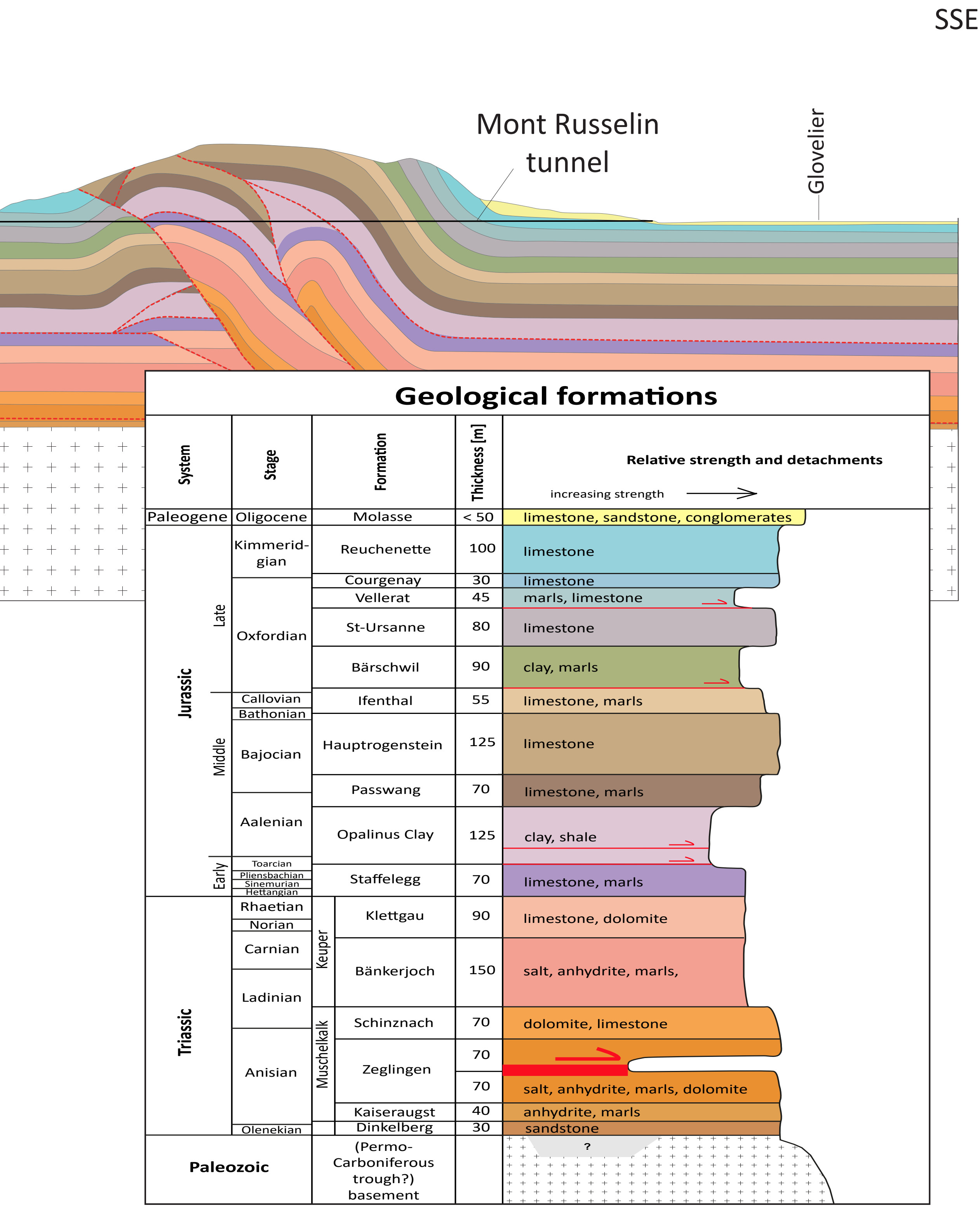


Figure 13: The geological profile along the Mont Terri highway tunnel. The Mont Terri anticline was formed during the Jurassic folding about 10 million years ago. During this process, the sediments were pushed northwards over the horizontal layers of the Tabular Jura. The rock laboratory is located in the southern limb of this anticline, and is easily accessible via the Mont Terri motorway tunnel. The different rock formations are shown in Figure 14.

What is Opalinus Clay?

The Opalinus Clay is an argillaceous rock, a claystone that was formed some 175 million years ago in a shallow sea during the Jurassic period. The name of the formation comes from the opalescent shine of fossil shells of the ammonite “Leioceras opalinum” that are found in the clay (Figure 12). The Opalinus Clay consists largely of clay minerals. In Mont Terri, the layer of Opalinus Clay is about 130 m thick. The younger sediments deposited on top of the Opalinus Clay pressed a large part of the water out of the original clay mud with their weight. This created an increasingly hardened rock. The Opalinus Clay is almost completely impermeable to water and the remaining pore water of marine origin still contained in the pores hardly moves. Opalinus Clay has excellent properties with regard to the retention of radionuclides, and can also function as a sealing rock for CO_2 storage.

Figure 13 shows a profile along the Mont Terri tunnel. This is a large domal fold, the so-called Mont Terri anticline, which was thrust northwards onto the Tabular Jura. The rock laboratory is located in the southern limb of this anticline. Figure 14 shows the geological formations that occur in the profile of Figure 13. In addition to the claystones, there are also limestones, dolomites, marls and various evaporites, such as rock salt and anhydrite.



Geological formations

System		Stage		Formation	Thickness [m]	Relative strength and detachments (increasing strength →)
Paleogene		Oligocene		Molasse	< 50	limestone, sandstone, conglomerates
Jurassic	Late	Kimmeridgian		Reuchenette	100	limestone
		Oxfordian		Courgenay	30	limestone
				Vellerat	45	marls, limestone
				St-Ursanne	80	limestone
				Bärschwil	90	clay, marls
	Middle	Callovian		Ifenthal	55	limestone, marls
		Bathonian, Bajocian		Hauptrogenstein	125	limestone
				Passwang	70	limestone, marls
		Aalenian		Opalinus Clay	125	clay, shale
	Early	Toarcian, Pliensbachian, Sinemurian, Hettangian		Staffelegg	70	limestone, marls
Triassic		Rhaetian, Norian	Keuper	Klettgau	90	limestone, dolomite
		Carnian		Bänkerjoch	150	salt, anhydrite, marls,
		Ladinian	Muschelkalk	Schinznach	70	dolomite, limestone
		Anisian		Zeglingen	70	
					70	salt, anhydrite, marls, dolomite
				Kaiseraugst	40	anhydrite, marls
		Olenekian		Dinkelberg	30	sandstone
Paleozoic				(Permo-Carboniferous trough?) basement		?

Figure 14: The geological formations in the Mont Terri anticline, together with the thicknesses and the names of the stratigraphical stages. The colours of the formations correspond to those in the profile of Figure 13.

Presentation of Key Persons

It is simply impossible to present all the people who have been involved in the Mont Terri Project and who helped to shape it. These are the scientists (especially geologists, geophysicists, geochemists, mechanical and construction engineers, social scientists), technicians of various disciplines, project managers, principal investigators, experiment delegates, delegates of partners, general managers, bosses, accountants, controllers, directors and politicians, etc., all over the period of the last 25 years. It would certainly be around a thousand people.

We have tried to do this in Table 2, in which we show above all the people having been directly involved or who are still involved in a 25-year histogram. Among them are also the operation team of the rock laboratory and the visitor centre, the Project Delegates of the partner organisations, and people from the cantonal monitoring commission. On the back side of this commemorative publication, we have printed the names of the principal investigators, the experiment delegates and the engineers, who have worked in one or more experiments over the last 25 years. The list of contracted services is very long. We have tried to list in Table 3 not the person‘s names, but the most important universities and research institutions that have received and carried out research contracts, or are still actively involved in the research. This listing is certainly not complete and we apologise to all we may have inadvertently forgotten.

Figures 15 to 18 give a few impressions. Historical pictures of the start of the project, steering meetings and first installations but also the first people to receive the Mont Terri watch award. Furthermore, we show impressions about the excavation of the rock laboratory, but also the handwork of the geologist in mapping the Opalinus Clay. Not to be forgotten are the visitors, who can inform themselves about the experiments and form an opinion about deep geological disposal in the Opalinus Clay. And all this in the charming surroundings of the small Jurassic town of Saint-Ursanne.

It remains for us to sincerely thank all the people and organisations for their commitment. Twenty-five years is a long time. And it will be another long time before the first deep geological repositories in claystones are operational. But it has been worth it: we know much more today than we did at the turn of the millennium. Clay rocks such as Opalinus Clay are robust repository rocks.

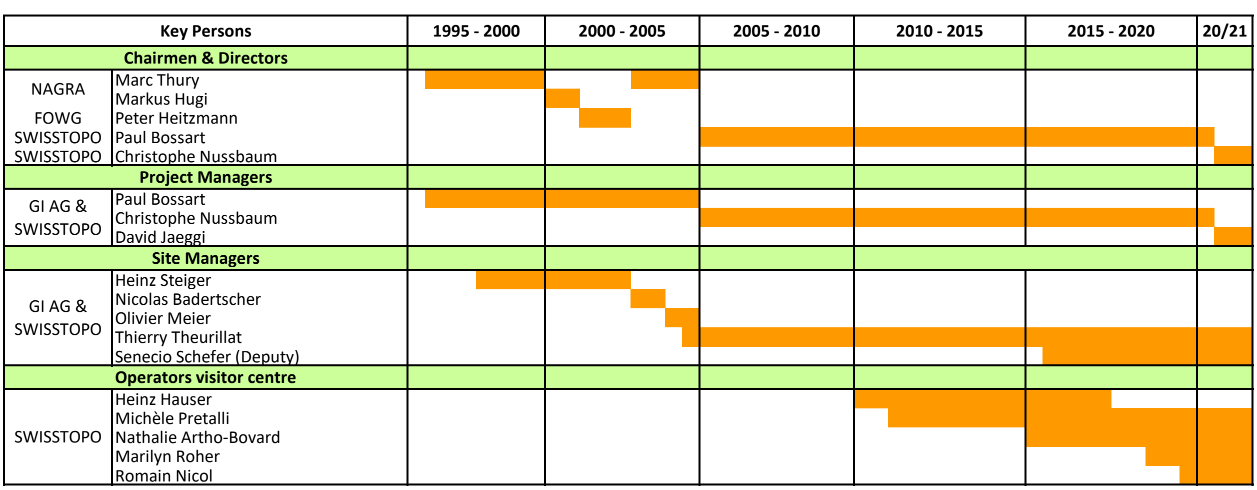


Table 2: Presentation of key persons

Key Persons		1995 - 2000	2000 - 2005	2005 - 2010	2010 - 2015	2015 - 2020	20/21
Delegates of the Partners							
SNHGS/ FOWG/ SWISSTOPO	Jean-Pierre Tripet						
	Marc Thury						
	Peter Hayoz						
	Paul Bossart						
	Andreas Möri						
ANDRA	Bertrand Vignal						
	Jacques Delay						
	Sarah Dewonck						
	Emilia Huret						
BASE	Axel Liebscher						
	Christoph Borkel						
BGE	Marc Wengler						
BGR	Rolf Lüdeling						
	Hans-Joachim Alheid						
	Kristof Schuster						
	Dorothee Rebscher						
CHEVRON	Peter Connolly						
	Russel Ewy						
	Dean Thornton						
CRIEPI	Kenzo Kiho						
	Takahiro Oyama						
	Shingo Yokoyama						
U.S.DOE	Jens Birkholzer / Prasad Nair						
ENRESA	Julio Astudillo						
	Juan-Carlos Mayor						
ETH Zurich	Rolf Kipfer						
FANC	Frédéric Bernier						
GRS	Tilmann Rothfuchs						
	Klaus Wieczorek						
HELMHOLTZ	Michael Kühn						
HSK	Erik Frank						
ENSI	Martin Herfort						
IRSN	Jean-Yves Boisson						
	Jean-Michel Matray						
PNC / JNC / JAEA	Kunio Ota						
	Seietsu Takeda						
	Kaz Aoki						
	Naotaka Shigeta						
	Kenji Tanai						
	Yutaka Sugita						
NAGRA	Marc Thury						
	Andreas Gautschi						
	Philip Birkhäuser						
	Keith Kennedy						
	Markus Hugi						
	Peter Blümling						
	Tim Vietor						
	Olivier Leupin						
NWMO	Ben Belfadel						
	Mark Jensen						
	Laura Kennell-Morrison						
Obayashi	Hideki Kawamura						
	Masaaki Fukaya						
	Tomoyuki Shimura						
RWM Ltd	Sally Thompson						
SCK.CEN	Bernard Neerdael						
	Gert Volckaert						
	Frank Druyts						
	Christophe Bruggeman						
TOTAL	Anne Brisset						
Commission de Suivi RCJU							
	Marcos Buser, president						
	Pascal Mertenat, president						
	Marzio Giamboni, president a.i.						
	Thierry Beuchat, president a.i.						
	Jacques Babey, JU-OEPN						
	Albert Piquerez, maire St-Ursanne						
	Jean-Paul Lachat, maire St-Ursanne						
	Jean Fernex, JU-ENV						
	Thomas Flüeler, ZH-AWEL, expert						
	Erik Frank, HSK/ENSI						
	Marzio Giamboni, expert						
	André Herrmann, expert						
	Pascal Mertenat, JU-SIN, expert						
	Philippe Poffet, FEDRO						
	Claude Ramseier, JU-cant. Chemistry						
	Christophe Riat, JU-SIN						
	Daniel Stadelmann, JU-SIN						

Table 2, continued: Presentation of key persons

Switzerland

- EAWAG, Swiss Federal Institute of Aquatic Science and Technology, Dübendorf
- EMPA, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf
- EPFL, Ecole polytechnique fédérale de Lausanne
- ETHZ, Swiss Federal Institue of Technology, Zürich
- HSR, UMTEC, Institut für Umwelt-und Verfahrenstechnik, Rapperswil
- ISSKA, Institut Suisse de Spéléologie et de Karstologie, La Chaux-de-Fonds
- PSI, Paul Scherrer Institute, Würenlingen
- Universität Basel
- Universität Bern
- Université de Fribourg
- Université de Genève
- Université de Neuchâtel, CHYN
- ZHAW, Zürcher Hochschule Für Angewandte Wissenschaften, Winterthur
- FHNW Muttenz

Germany

- BGR, Federal Institute for Geosciences and Natural Resources, Hannover
- EIFER, European Institute for Energy Research
- GRS, Gesellschaft für Anlagen- und Reaktorsichereit mbH, Braunschweig
- GSF, Gesellschaft für Strahlenschutz und Umweltforschung, München
- KIT, Karlsruhe Institute of Technology
- LUBW, Landesanstalt für Umwelt, Karlsruhe
- Ruhr-Universität Bochum
- Technische Universität Darmstadt
- TU Berlin, Institut für Aufbereitung und Deponietechnik, Clausthal-Zellerfeld
- TU Clausthal, Clausthal-Zellerfeld
- TU Darmstadt, Thermische Verfahrenstechnik, Darmstadt
- Universität Aachen
- Universität Freiburg
- Universität Heidelberg
- Universität Karlsruhe
- Universität Stuttgart

France

- ASGA, Association Scientifique pour la Géologie et ses Applications, Vandoeuvre-les Nancy
- BRGM, Bureau de Recherches Géologiques et Minières, Orléans
- CEA, Commissariat à l'Énergie atomique et aux Énergies alternatives, Gif-sur-Yvette
- CNRS, Centre National de recherche Scientifique, Paris
- DAMRI, Département des Applications et de la Métrologie des Rayonnements Ionisants, Nuclear Research Centre, Grenoble
- École nationale des ponts et chaussées ParisTech, Marne-la-Vallée
- ENSG, Ecole Nat. Supérieure de Géologie, Laborat. De Géomécanique, Nancy
- G2R, Faculté de Sciences, Vandoeuvre-les-Nancy
- GeoAzur, Nice
- IFP Energies nouvelles, Rueil-Malmaison
- IMFT, Institut de mécanique des fluides de Toulouse
- INERIS, Inst. Nat. de l'Environnement Industriel et des Risques, Verneuil-en-Halatte
- Institut de Physique du Globe de Paris
- IPG, Institut de Physique du Globe, Université de Paris 6
- LAEGO, Laboratoire Environnement Géomécanique et Ouvrages, Vandoeuvre-les-Nancy
- Université de Bordeaux I & II
- Université de Cergy-Pontoise
- Université de Lille
- Université de Montpellier
- Université de Nancy
- Université de P. & M. Curie, Paris
- Université de Paris Sud
- Université de Pau
- Université de Strasbourg
- Université de Rennes
- Université Jospeh Fourier, Grenoble

Spain

- AITEMIN, Asociación para la Investigación y Desarrollo Industrial de los Recursos Naturales, Madrid
- CEDEX, Centro de Estudios y Experimentación de Obras Publicas, Madrid
- CIEMAT, Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas, Madrid
- CSIC, Instituto de Ciencias de la Tierra Jaume Almera, Barcelona
- IDAEA Institute of Environmental Assessment and Water Research, Barcelona
- Universidad da Coruña
- UPC, CIMNE Universidad Politécnica de Cataluña, Barcelona
- UPV, Universidad Politécnica de Valencia

Table 3: Overview of national and international research organisations, universities and private organisations carrying out research in the Mont Terri rock laboratory.

Australia

- CSIRO Petroleum, Australian Resources Research Centre, Kensington

Belgium

- SCK • CEN, Studiecentrum voor Kernenergie • Centre d'Étude de l'énergie Nucléaire, Mol

Canada

- MIRARCO, Mining Innovation, Rehabilitation, University, Sudbury
- Queen's University, Kingston
- University of Alberta, Edmonton
- University of British Columbia, Vancouver
- University of New Brunswick and Fredericton
- University of Ottawa

Chile

- Universidad de Santiago

Czech Republic

- CTU, Czech Technical University, Prague

Finland

- University of Helsinki

Japan

- Okayama University
- Saitama University
- Kyoto University
- OYO Corporation, Tokyo, Japan

Netherlands

- Universiteit Utrecht

Norway

- CIPR, Center for Integrated Petroleum Research, Bergen
- NGU, Geological Survey of Norway, Trondheim
- SINTEF Petroleum Research, Trondheim

Ungary

- Budapest University of Technology and Economics

United Kingdom

- AEA Technology Environment, Oxfordshire
- BGS, British Geological Survey, Nottingham
- Heriot-Watt University, Edinburgh
- NNL, National Nuclear Laboratory, Warrington
- University of Reading
- University of Newcastle
- University of Nottingham

USA

- Lawrence Berkeley National Laboratory, University of California, Berkeley
- Los Alamos National Laboratory, US Department of Energy, Los Alamos
- MIT, Massachusetts Institute of Technology, Cambridge
- Montana State University, Bozeman
- Princeton University
- University of Illinois, Urbana

Key Contractors

- AITEMIN, Madrid, Spain (now AMBERG Infraestructuras, Madrid)
- COFOR, Maisse, France
- COREIS, Maisse, France
- GeoSonic France, Jardin, France
- Gerätebau Wiedtal Schützeichel GmbH & CO.KG, Neustadt, Germany
- GGT Groupe Grands Travaux, Delémont, Switzerland
- Inelectro SA, Porrentruy, Switzerland
- Rothpletz, Lienhard + Cie AG, Aarau, Switzerland
- Sixense Monitoring, Nanterre, France
- SolData, Nanterre, France
- Solexperts AG, Mönchaltdorf, Switzerland
- Stump-BTE AG, Solothurn, Switzerland

Table 3, continued: Overview of national and international research organisations, universities and private organisations carrying out research in the Mont Terri rock laboratory.

a)

b)

Figure 15: This is a selection of historical photos of the Mont Terri Project.
a) The excavation of the first niches in the reconnaissance gallery, in early 1996, with the pioneers of the time. These are, from right to left: Bernard Neerdael (SCK.CEN), Marc Thury (NAGRA), Alain Waldmeyer (Ponts et Chaussées, JU), Jean-Pierre Tripet (SNHGN), Bertrand Vignal (ANDRA), Kunio Ota (PNC, now JAEA), and Paul Bossart (GI AG, now SWISSTOPO).
b) The Partner Delegates during a Steering Meeting in 2001, picture taken in the Gallery 1998. From left to right: Julio Astudillo (ENRESA), Jacques Delay (ANDRA), Peter Heitzmann (FOWG), Seiji Takeda (JAEA), Jean-Yves Boisson (IRSN), Markus Hugi (NAGRA), Hans-Joachim Alheid (BGR), Jean-Pierre Tripet (FOWG), and Paul Bossart (GI AG, now SWISSTOPO).

Figure 15, continued:
c) Paul Bossart (left) hands over the first Mont Terri Watch Award in 2012 to (from right to left) Marc Thury, Charles Emmenegger, Jean-Pierre Tripet, Pierre Kohler and Laurent Schaffter, for their meritorious contribution to the success of the project.

d) Here is the excavation team which came through first at the breakthrough of the Gallery 2018 on 27 May 2019, and handed over the statue of St Barbara. From right to left: Domenika Stutz (ROTHPLETZ AG), Senecio Schefer (SWISSTOPO), Thomas Styner, Daniel Lanz and Helio Albino Nunes (all ROTHPLETZ AG).

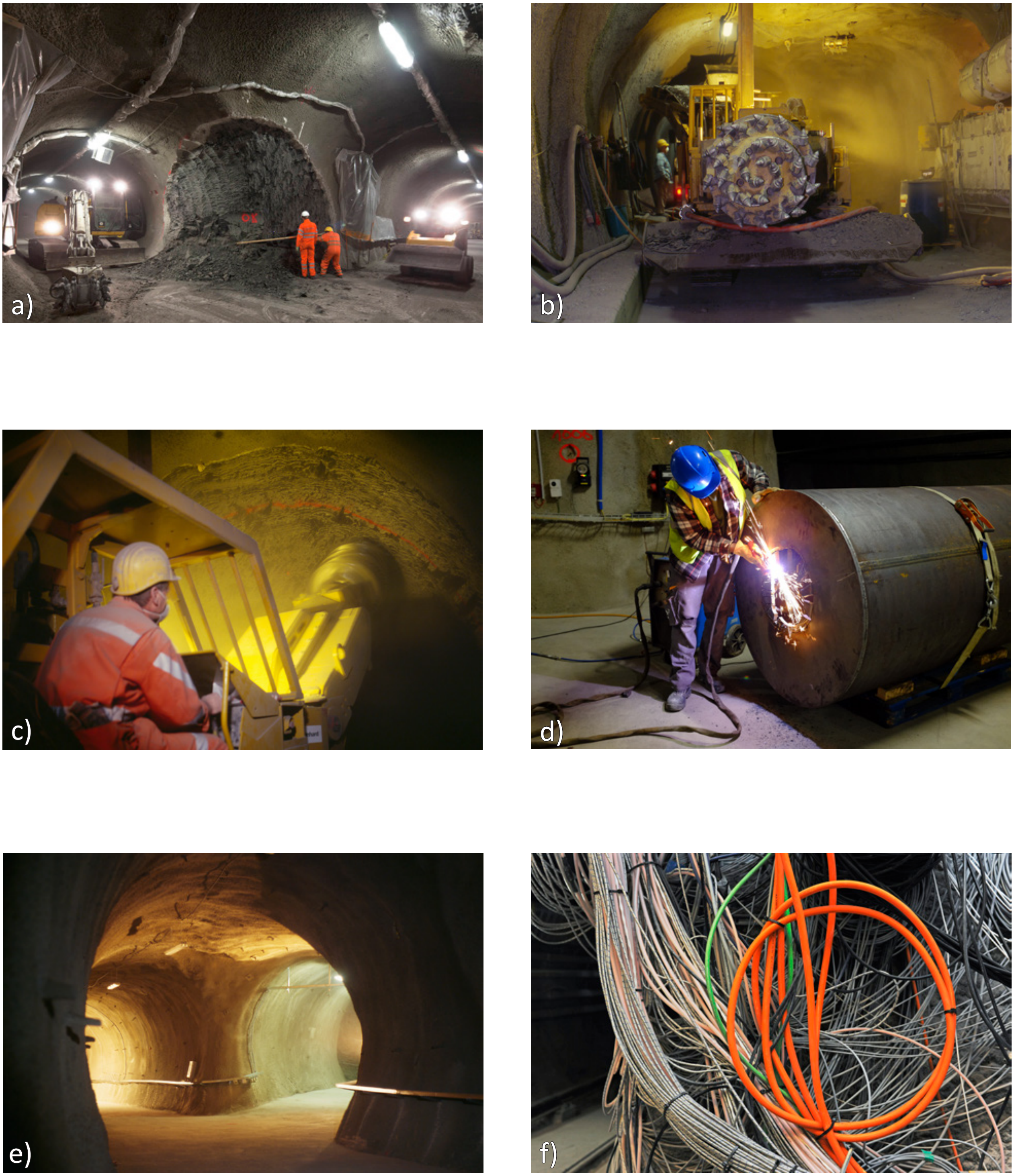


Figure 16: Excavation impressions, a) construction site in the Opalinus Clay, b) road header excavation machine, c) operator of road header, d) welding work, e) newly excavated and empty tunnel section, f) soon the newly excavated tunnel space is used for experiments and covered by installations.

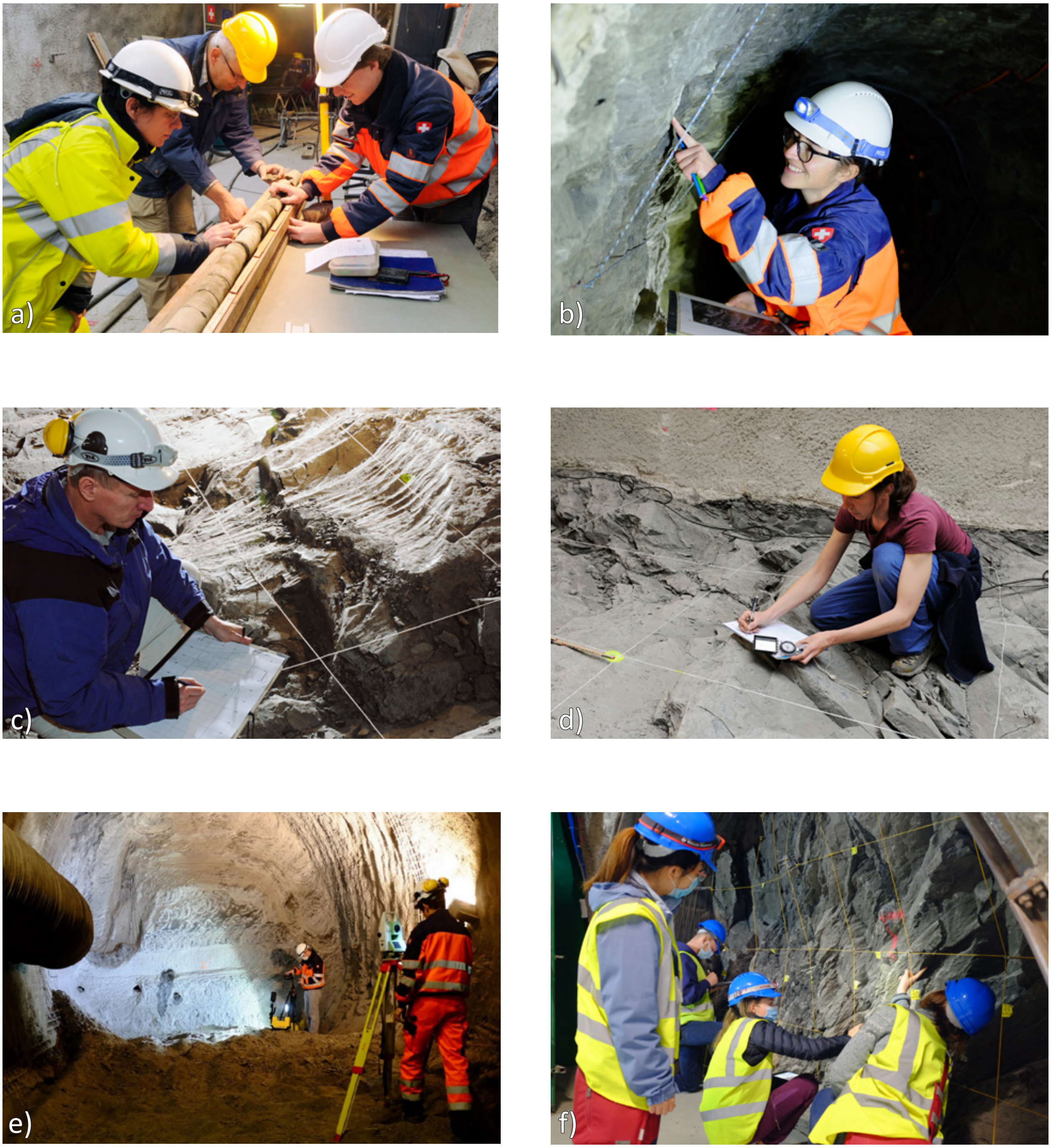


Figure 17: Impressions of daily geological work, a) drillcore mapping, b) geological mapping of tunnel wall, c) micro structural mapping of newly excavated surfaces, d) orienation mesurements of tectonic faults, e) application of photogrammetry techniques to document geological structures, f) students apply new mapping methods they have learned in theory.

Figure 18: The Mont Terri visitor centre, a) the reception pavilion, b) entrance to the Mont Terri rock laboratory, c) safety inspection and d) safety exercise, e) introduction to Opalinus Clay geology, f) explanation of the different experiments.

Interviews

Fridolin Wicki
Director of SWISSTOPO, Switzerland

Why does SWISSTOPO, as the Swiss Federal Office of Topography, operate the Mont Terri rock laboratory?

According to Swiss law, the administration and management of the subsurface is in the sovereignty of the cantons. The Canton of Jura, as the canton where the Mont Terri rock laboratory is located, explicitly wanted a neutral operator at the time of the laboratory's foundation. This operator was found in the Swiss Geological Survey, which today is a division of the Federal Office of Topography, SWISSTOPO.

Keyword "Energy strategy 2050 of the Swiss Confederation": can the research in the Mont Terri rock laboratory make a contribution here?

Geothermal energy is one of the key technologies for a sustainable, CO_2-free, energy production. The Mont Terri rock laboratory will be able to make a significant scientific contribution to this research in the future.

How do you see the future of the Mont Terri rock laboratory?

In addition to the energy strategy, the Federal Council has also decided that by 2050 Switzerland should not emit more greenhouse gases than natural and technical reservoirs can absorb ("net zero emissions"). One means of achieving this goal is by CO_2 sequestration, i.e., the separation of carbon dioxide from combustion exhaust gases and its storage in deep underground rock layers. The Mont Terri rock laboratory is predestined to contribute to the research of these technologies due to its location and the knowhow of its staff.

Matthias Braun
CEO of NAGRA, Switzerland

Where was, and is, the Mont Terri Project able to make a significant contribution to Switzerland's national radioactive waste management programme?

The Mont Terri rock laboratory is a worldwide one-of-a-kind science hub for clay rock research. The body of knowledge accumulated over the years is very impressive and is well recognised beyond the "radwaste" community.

It also offers a platform for scientific exchange to all the engineers and scientists involved, allowing for international networking. This exchange among peers is an important means for promoting advances in science.

Within Switzerland, the Mont Terri Project has become an important platform for communication and training. If a lesson is to be learned from decades of planning deep geological repositories, then it is that society needs to be considered as an important stakeholder in the process from the very beginning.

Can the technical and scientific findings from the rock laboratory be transferred directly to the siting regions in Northern Switzerland?

NAGRA has profited hugely from decades of scientific and practical work in the Mont Terri rock laboratory, resulting in a flawless and highly efficient deep borehole campaign in Northern Switzerland for site characterisation with a view to the general licence application for a repository.

Process aspects such as transport properties (diffusion of radionuclides or gas) can be transferred to the siting regions without too many modifications. Other processes such as those related to geomechanics need to be reassessed on-site.

Will NAGRA continue to be involved in the Mont Terri rock laboratory after obtaining the general licence for a radioactive waste repository in Switzerland?

NAGRA relies on the Mont Terri Project as a centre of competence and will continue with long-term experiments, although the focus will shift to the characterisation of the selected sites as foreseen in the different licensing steps.

Dorothee Rebscher
Senior Scientist and Delegate of Project Partner BGR, Germany

What are the benefits of the Mont Terri rock laboratory for the German Partners and how does the rock laboratory benefit from the German Partners?

Argillaceous rocks with their property of being almost impermeable and evidencing self-sealing behaviour are of high relevance for almost all uses of the subsurface. Not the least, it is of special interest as host rock for the disposal of nuclear waste. In this broad context, working in the world-renowned Mont Terri rock laboratory is particularly advantageous. Here, the remarkable benefit is based on a transferable geological situation, the established scientific partnerships realised by an active community of experts, a comprehensive database, and the established infrastructure. This unique combination has already played a significant role in the research of argillaceous rocks as one of three host rocks in the German site selection process and will continue to do so. This view is supported by the fact that there are now five German Partners participating in the international Mont Terri Consortium. Furthermore, as the subsurface is gaining prominence, the topics of faults and caprocks, of containment and integrity, are receiving more attention by stakeholders of science, industry, politic, and the public. Accordingly, it is obvious that the Mont Terri rock laboratory will remain an important research site for its contribution to transparent repository explorations and will attract investigations on other subsurface uses such as geothermal energy or storage of carbon dioxide.

The five German Mont Terri Partners comprise a regulator (BASE), implementer (BGE), geoscientific authority (BGR), technical support organisation (GRS), and an Association of Research Centres (Helmholtz). Each of them is participating in numerous of the almost 50 ongoing on-site experiments, employing their specific strong scientific background and technical knowhow in various fields of expertise. Among their contributions are innovative characterisation and monitoring methods, progressive numerical modelling, as well as analytical laboratory work. Their diverse foci and long-term engagement in the joint interdisciplinary research project is to the benefit of all Mont Terri Partners. Evidently, the underlying concept of the inter-disciplinary and international cooperation has been proven successful for over more than 25 years. The German Partners are thankful to SWISSTOPO and all other partners from Europe, Canada, Japan, and USA for their commitment; we are looking forward to prolong this excellent and exemplary partnership in the future.

Where do you see the research priorities for the coming years for BGR in the rock laboratory research field?

As BGR is the central geoscientific authority providing unbiased advice to the German Federal Government, we gather, produce, and evaluate scientific and technical knowledge on all topics related to the subsurface. This task encompasses aspects regarding safe nuclear waste repositories as well as other uses of the subsurface, such as storage or extraction of fluids and energy. Hence, BGR‘s key aspects of research in Mont Terri for the last two decades comprise characterisation of clay-rock, investigations of geotechnical barriers, and optimisation of technical barriers. Furthermore, BGR participates in demonstration projects and long-term in-situ experiments. Noteworthy is the extensive in-kind work performed by my BGR colleagues. This includes certified drilling, development of novel experimental methods, as well as complimentary numerical efforts and advanced studies in analytical laboratories. We intend to enhance this competence for the mutual benefit within the whole consortium, as we are convinced that the challenges associated with safe and sustainable uses of the subsurface are best faced in close international cooperation. Therefore, BGR is looking forward to remaining an active partner in the scientifically very productive, international research at the Mont Terri rock laboratory.

A somewhat subjective question: in your view what do you think is going well at the rock laboratory, and what could be improved?

Ok, a subjective answer. I am really happy and grateful to be part of the vivid Mont Terri community. This is not only due to the extensive opportunities provided by the Mont Terri Project, i.e., the fascinating and challenging interdisciplinary approaches, comprising innovative fundamental research to advance the understanding of scientific puzzles on very small scales in time and space and to further applied science with its relevance for the societies of today – and potentially those in 10,000 years or more! It is due to each of the individuals I have had the fortune to encounter, to learn from, to discuss, and to work with. Each of them has had a special impact, e.g., by shaping a multi-partner experiment, by improving a complex method, or by just optimising a single cable connection. All contribute with their ideas and their commitment, jointly creating a friendly atmosphere of mutual respect, not in an ivory tower but in a maze-like, mostly grey tunnel. Moreover, these scientific, collaborative, and friendship-promoting conditions are in my opinion of crucial importance for the lasting success of a rock laboratory. It is my impression that this is going really well here in Saint-Ursanne. We all should continue to facilitate and to pursue this tried-and-tested environment in the future. Especially when we face new challenges or tackle recurrent problems while continuing to work on established research topics or initiating new ones, we should follow the important lessons from Mont Terri and ensure that our results are accessible and understandable for the public. All this together is what makes Mont Terri such a special place.

Alfred Eul
Drilling Master of the German Company SCHÜTZEICHEL KG

Why is a German drilling company involved in the Mont Terri rock laboratory?

By chance we were referred to the laboratory by a friend in 2005, and with the first order we started a good cooperation that continues today. We are a drilling company with our own mechanical engineering and diamond tool manufacture, so we are able to adapt to every situation individually in order to achieve the common goal, which we have achieved so far.

What are the particular challenges of drilling in the Opalinus Clay?

The challenge with the Opalinus Clay is that it has to be drilled dry, while the exact directional accuracy must be strictly adhered to in order to overcore and recover the tests afterwards. The cored drilling work is carried out in a wide variety of diameters from 46 mm to 1200 mm with single, double and triple core tubes at 360° in all directions and depths of up to 70 m.

Tell us about an event that went particularly well and one that failed. What did you learn?

So far, nothing has failed because we have always found a solution together with our on-site knowledge. The greatest challenge was the Sandwich Seal (SW-A) experiment in 2020. A 1200 mm cored hole to a depth of 13 m with a core length of approximately 1,50 m and a core weight of plus/minus 4 tons.

Jacques Delay
Senior Scientist, Project Partner ANDRA, France

You initiated the Mont Terri Watch Award, which is very popular today. What was the idea behind it?

When I joined the Mont Terri Steering Meeting in 1999, I was impressed by the fantastic collaboration between scientific teams coming from various horizons. Ten years later, following the 10th anniversary and many very successful technical meetings, I realized that beyond scientific production, the Mont Terri Project should acknowledge the outstanding contribution of the people that have participated in the adventure. Therefore, I submitted the idea of an "Award" in an informal discussion during a coffee break at a Steering Meeting. Immediately, all the other delegates supported this idea. Then we had to find an object that would represent the commitment of all the participants to the project. Very quickly we agreed upon an object that could be of use for all of us, manufactured locally in the Canton of Jura, that represents quality, accuracy and a long history of scientific and technical developments. It became obvious that it would be a watch! Then, the Mont Terri team took care of the final design and production of the watch. Finally, the delegates agreed upon the conditions to receive it. The Mont Terri Watch Award was born!

How could and can ANDRA benefit from the generic Mont Terri rock laboratory?

ANDRA's activities in the Bure Underground Research Laboratory (URL) are now mainly oriented towards the technical development and optimization of technical concepts for disposal. However, the Bure URL will remain for a long period a scientific tool to support research to increase the long-term and operational safety of disposal solutions. In order to keep the research at its highest level of excellence, the scientists need to be challenged by peers and to remain open to the best and latest developments of scientific and technological in their domains. As long as the Mont Terri Project will remain an incubator of ideas, a forum for pooling intelligence, and a place where ideas could be transformed in experiments and scientific achievements, ANDRA will benefit from participating with the Mont Terri rock laboratory research projects.

ANDRA is already very far along in the planning of the definitive deep geological repository in clay rocks (CIGEO Project, France). What do you think, should generic rock laboratories like the one of Mont Terri continue to operate after final repositories are built, or should they simply be closed?

ANDRA has already achieved major steps in implementing a disposal facility for high and intermediate level long-lived radioactive waste. ANDRA is now close to the licensing submission, but the path to actual operation of a facility is still far away! For ANDRA, continuous research and development (R&D) will be required throughout the stepwise development process of a disposal facility construction to be able to improve and optimise systems with respect to decreasing uncertainties and increasing safety margins. As part of the R&D program to be carried out all along the operational phase of a facility, the challenge to maintain competences and transfer knowledge amongst generations of engineers and scientists should be addressed. Although large parts of underpinning scientific and technical knowledge are site specific, I am convinced that working together in a generic laboratory, without the pressure of an industrial and operational Nuclear Basic Installation, and with practical cutting-edge scientific projects, is a key to progress and to build confidence amongst scientists and beyond, to all the public.

Michèle Pretalli
Rock Laboratory Visitor's Coordinator, Mont Terri Visitor Centre, SWISSTOPO

The Covid-19 pandemic has reduced the original 5000 annual visitors to almost zero. How will you attract this number of visitors again?
In 2020, due to the Covid-19 pandemic, the number of visitors dropped to around 1000. At the beginning of 2021, the Visitor Centre has been closed due to health measures related to the pandemic. We are still receiving weekly requests for temporary visits, which we will organise as soon as the authorisations are given and the Visitor Centre opens again. The interest and desire to visit the underground laboratory are still there. In order to increase this attraction, we have decided to professionalise our communication and develop our presence in social networks, and have created Instagram, Facebook, and Twitter accounts. The main objectives are to expand the community on social networks and to strengthen our reputation by arousing the interest of young people in particular and to promote visits and increase the number of visits and visitors.

The visitors can form an opinion about deep geological disposal. Does the rock laboratory really contribute to the acceptance of radioactive waste and carbon dioxide storage?
Given the number of visitors that take part in our guided tours of the laboratory (approximately 4500 in normal times), these tours definitely contribute to the formation of public opinion. The feedback forms we collect clearly show that visitors have a better understanding of the issues at stake in the research laboratory and have a more precise opinion on the subject after a guided tour. A research project has been launched to analyse the impact of the laboratory on public acceptance. The evaluation is ongoing.

As a visit coordinator, you have daily contact with visitors. Can you say what concerns the visitors, what they want to know? What do they like and where are they more critical?
First, the visitors appreciate the free and transparent nature of the guided tours. The quality of the welcome is particularly touching. They are also surprised by the size of the laboratory, as they have no idea that so many experiments were and are taking place in the Mont Terri rock laboratory. And above all, the visitors become aware of the need to store radioactive waste and sequestering CO_2 underground in Switzerland.

It is very difficult for visitors to imagine that a future repository must be safe for a million years. This time scale is difficult for humans to perceive. They are also concerned about the reliability of extrapolating the results obtained at Mont Terri to the future repository site.

Sometimes some visitors regret that there are not more active scientists in the laboratory to better understand how they do their research.

Marzio Giamboni
Member of the "Commission de suivi", Supervisory commission of RCJU

Why does the Mont Terri rock laboratory need cantonal supervision? Is the federal administration not sufficiently trustworthy as operator of the rock laboratory?

As in any other laboratory, the operator of the Mont Terri rock laboratory is responsible for the safety of people and the environment. Since some experiments can involve risks for people and the environment (explosion, fire, water pollution, etc.), special safety precautions must be taken by the operator (SWISSTOPO) in accordance with the Swiss environmental law. According to the law, the assessment of the risks and the implementation of the measures must be supervised by the Canton. In the case of the Mont Terri rock laboratory, this is done by the Commission appointed for this purpose.

Where does the Canton of Jura benefit and where may it also face some drawbacks?

I cannot speak on behalf of the Canton of Jura. From my point of view, the Canton of Jura makes an important contribution to research by providing the location for this worldwide unique laboratory and, where possible, supporting the operator in its goals. The research activities in the Mont Terri rock laboratory are associated with the search for a location for deep geological repositories (Deep Geological Repositories Sectoral Plan). This requires good communication on the part of the Canton of Jura and the operator so that the difference between basic research for the location search in the laboratory and the proper location search by the Sectoral Plan is clearly understood by the population. For the Commission, this also means that research in the laboratory continues to be carried out at a high scientific level and remains as independent as possible.

What has the Commission de suivi achieved over the last years, and what does it still want to achieve?

A lot has changed since the constitution of the Commission: today it can be said that the level of safety in the laboratory corresponds to the state of the art and that safety has its due place in the operational processes. Thanks to an active exchange between the Commission and the operator, we have achieved a common understanding of the security issues. This is to be pursued in the coming years. With the emergence of new research topics outside just nuclear waste management, the Commission must familiarize itself with new issues so that it can perform its supervisory function competently.

Christophe Nussbaum
Director of the Mont Terri Project, SWISSTOPO

What are the advantages and disadvantages of the Opalinus Clay for the storage of radioactive waste?

The Opalinus Clay has been selected to be the host rock for the geological disposal of radioactive waste in Switzerland for its remarkable long-term confining properties. Claystones offer a robust and natural barrier whose effectiveness is mainly provided by its very low permeability, self-sealing of fractures, retention of radionuclides (strong sorption on clay minerals), and very slow diffusion-controlled transport in the rock matrix. Opalinus Clay was deposited over a very broad palaeogeographical region with a large lateral and vertical homogeneity. Side effects of high clay content in the natural barrier are the limited strength, pronounced anisotropy, limited thermal conductivity, low gas permeability and the complex coupling of physical, chemical and microbiological processes.

Why are claystones such as Opalinus Clay essential for the underground storage of CO_2?

An essential perquisite for a safe geological sequestration of carbon dioxide is that the storage reservoir, composed of highly permeable rock formations, must be overlain by one or multiple impermeable formations (caprock) to prevent upward migration of CO_2. Faults are one of the major risks for the storage of CO_2 since they could potentially serve as upward migration pathways and then lead to contamination of groundwater. Nevertheless, fault zones in claystone are known to be as tight as in the non-fractured rock. In addition to its role as safe host rock for the geological storage of radioactive waste, the Opalinus Clay is also considered as a tight caprock for the storage of CO_2. In Switzerland, potential locations for CO_2 storage are located in the Molasse basin. At least three potential reservoirs are located below the Opalinus Clay with the most promising one in the Upper Muschelkalk. Most of the remarkable confining properties of the Opalinus Clay that are positive for the storage of radioactive waste are also valuable for the safe storage of CO_2.

Which important characterisation and demonstration experiments are planned for the next 5 to 10 years?

The most important demonstration experiment that will run for the next 10 years is currently the large-scale Sandwich Seal (SW-A) experiment in the context of the radwaste programme. The SW-A experiment consists of highly conductive equipotential layers emplaced in alternation with sealing layers to obtain a more homogeneous re-saturation of the seal. This experiment is important for demonstrating the efficient sealing of a repository once it is closed. Future planned characterisation experiments will focus on diffusion properties in the sandy facies and in fault zones intersecting the Opalinus Clay. Much data are still available on previous diffusion experiments, but all were conducted in the shaly facies and in the non-fractured rock. Hydrogeological characterisation of the surrounding (bounding) aquifers is also of prime importance for the safety of a repository. Two experiments have been initiated on the overlying Passwang Formation and underlying Staffelegg Formation aquifers. In the context of CO_2 storage, caprock integrity will be investigated with repeated CO_2 injections during at least 10 years. This experiment will be a key demonstration to test the ability of undisturbed and non-fractured claystone (e.g., Opalinus Clay) to serve as tight caprock.

Future Development

The Mont Terri rock laboratory is a so-called generic rock laboratory. This means that it is used exclusively for research and there will never be a deep geological repository here. This is in contrast to a site-specific rock laboratory that is built at the chosen location for the storage of radioactive waste. But there is still a long way to go until a site for deep radioactive waste disposal is chosen in Switzerland, about 10 years at the earliest (details are contained in the Swiss sectoral plan procedure for radioactive waste). Until then, the Mont Terri rock laboratory will still exist, and possibly even longer.

An important feature of the Mont Terri rock laboratory is that the Project Partners are free to choose their research priorities. In this way, unconventional projects are also given a chance. One is also allowed to make mistakes and commit errors. We have gained many interesting insights only after an experiment has “failed.” Other special points are that innovative projects usually have a good chance of being realised, individual experimental partners share the costs, and the operators do not interfere, they only ensure adherence to the contracts and conditions of the owner, the Canton of Jura.

So, what needs to be researched in the next 15 to 20 years? Research into all aspects of a repository for the deep storage of radioactive waste in clay rocks will continue to be the main theme. But increasingly, the rock laboratory will also make an important contribution to the federal government‘s Energy Strategy 2050. CO_2 experiments have already begun and will continue. Experiments on geothermal energy could also be included in the future.

In the following, we present some research priorities that might be tackled in the coming years, provided that the Project Partners will agree upon them. In the field of radioactive waste, there is still a whole series of questions to be clarified that could well be carried out in a generic rock laboratory like the one at Mont Terri. Some of the future potential research topics are listed below (the list is not complete):

- A fundamental set of questions are: does a repository for high-level radioactive waste in a claystone really work as predicted (i.e. as the models say)? Do we understand all the processes and do they run in a staggered manner? Answers to these questions require long-term demonstration experiments in the range of 50 years and more. This would mean that long-term experiments would be inherited by the next generation. And the next generations could then better judge on the long-term safety of a deep geological repository, and also make the decision when a repository has to be closed.

- Experiments in the sandy facies of the Opalinus Clay: in the last 25 years, we have focussed on the clayey type (shaly facies) of the Opalinus Clay, thoroughly investigating all its aspects. But we kept away from investigating the sandy type. Research has showed, however, that the sandy facies may have advantages that we previously overlooked. The new Gallery 2018 was built in the sandy facies and has been ready for experiments since the beginning of 2020. Experiments following this theme have already been launched and are continuing. Other key research targets are new diffusion experiments where radionuclides diffuse into the clay in a thermal field. In addition, a large sealing experiment, the so-called Sandwich Experiment was started. It is investigating which materials can be used to completely seal shafts and galleries and to saturate them as homogeneously as possible.

- Experiments to optimise the technical barriers of a repository in Opalinus Clay by using materials other than steel; many deep geological repository concepts in clay facies use steel containers to confine the highly radioactive waste. Steel is a proven material with many advantages, but it has also disadvantages. A significant one is anaerobic corrosion, whereby hydrogen is formed. A whole range of chemical-microbiological processes take place in the long-term of such a repository. These are further coupled with thermo-hydraulic-mechanical processes, making the whole a complex system. The question here is whether steel could be replaced by other materials. Ceramics are already being researched, but have never been tested in-situ in the Mont Terri rock laboratory until now. Certainly, the repository system and some processes could be simplified with such alternative containments.

- To what extent can we minimise the area of a repository in the Opalinus Clay? The spatial footprint of a deep repository will range from a few to some tens of square km, depending on how much high-level heat-producing waste has to be disposed. The question here is whether one can accept increased temperatures in the near field without losing positive properties such as retention and self-sealing of the claystone. A smaller repository area would massively reduce costs of a repository.

- All questions regarding a realistic retrieval of radioactive waste: these should be demonstrated now, and not in 20 years at a site-specific laboratory. Such a realistic retrieval concept will certainly have an impact on the repository concept. Here we can also learn from our Project Partner ANDRA, who has already demonstrated their retrieval concept.

Related to the federal government's Energy Strategy 2050 program, priority is being focussed on underground CO_2 storage. Here, some borehole and fault-integrity experiments in the Mont Terri rock laboratory have already been started and new ones will be launched soon. There is also potential for hydrothermal experiments in the surroundings of the rock laboratory. However, hydrothermal projects are, as all experiments in the Mont Terri rock laboratory, subject to the approval of the Canton of Jura. We know that the population is rather critical on geothermal exploration; that is why such experiments have not been a top priority, until now.

Below is a list of possible future experiments and projects; again, the list is not exhaustive.

- Fault-integrity experiments have already been initiated in the main fault of the Mont Terri rock laboratory. This tectonic fault structure was hydraulically stimulated and a well-defined flow field was created. It appears that the permeability decreases over time. New experiments will show whether repeated injections reactivate old flow paths and/or create new ones. The question is: are self-sealing and self-healing processes responsible for these permeability changes? If these processes can be shown to be indeed responsible and generally active, then the risk of rapid CO_2 transport through the caprock is very minimal.

- In a neighbouring site, CO_2 was injected into the fault zone and extracted again in an adjacent borehole. Here, too, there is some evidence that self-sealing and self-healing processes are taking place. We have already created initial models for this process. Again, in this case, hydraulic-mechanical-chemical simulations also play an important role. In the future, attempts will be made to inject more CO_2 under higher pressures. The aim here is also to understand the reactive CO_2 mass transport and to determine the new solid mineral phases. The challenge here lies not only in the scientific results, but also in the occupational safety of the scientists and technicians who work with CO_2 in the rock laboratory.

- Long-term periodic injection of CO_2 into the undeformed Opalinus Clay without fault zones will start soon. Such experiments investigate thermal, hydraulic, mechanical, and chemical effects of CO_2 migration under in-situ conditions over a time period of more than a decade. The aim is to enhance the understanding of caprock behaviour and its integrity. Here, insight on geochemical reactions is important due to their influence on argillaceous composition and rock properties, mainly hydro-mechanical ones. Experimental data on reaction rates and barrier properties with adequate accuracy are needed to perform reliable reactive transport simulations as a base for CO_2-storage-site characterisation and risk assessment of long-term storage safety. However, as of yet, only data from lab scale (scale of a few cm) and computer simulations are available. We therefore expect more realistic and robust results from this long-term injection in the metre to decametre scale.

- A pilot test with the emplacement of supercritical CO_2 in an aquifer below the Opalinus Clay may be started, provided that the project is financially feasible and that the Canton of Jura gives its approval. Such a pilot test can demonstrate the performance and feasibility of the reservoir and the Opalinus Clay-caprock in a CO_2 repository. However, such a project requires a preliminary seismic campaign and borehole drilling to a depth of about 1 km in order to identify a permeable reservoir. A first step will be to develop a reliable hydrogeological predictive model of the aquifers beneath the Opalinus Clay. For this purpose, it is planned to drill a shorter borehole from the rock laboratory through the Liassic formations into the upper Keuper. Hydrotests will then be used to characterize the aquifers and determine the hydrogeological parameters of the model.

- Hydrothermal experiments in aquifers below the Opalinus Clay may be launched to increase our understanding of flow, transport, and heat exchange in heterogeneous carbonate aquifers. Aquifers in carbonate formations are important geothermal plays below the Swiss molasse basin. Heterogeneity plays a dominant role in the reservoir behaviour, however, and many details are insufficiently understood. Lateral facies variations and tectonic deformation control the natural permeability of the reservoir. Such a reservoir is also found in the upper permeable formations below the Opalinus Clay in the Mont Terri anticline. A better understanding of such heterogeneous flow partitioning is important to optimise the performance and energy gain of geothermal reservoirs.

Closing Words

Over the last 25 years, the Mont Terri rock laboratory has developed enormously. The scientific results from the experiments clearly show that clay rocks in the right geological context are safe candidates for radioactive waste disposal. But they also play an important role in CO_2 sequestration as sealing rocks.

These findings are thanks to the 22 national and international Project Partners. They have financed the experiments and contributed to the results thanks to their technical and scientific skills. Many people who stand for this are shown on the back cover of this commemorative publication. Without their commitment and giving of their time in long hours in the rock lab, we would not be where we are today. We thank all those most sincerely for what they have achieved and also motivate them to continue on the long road of deep geological disposal.

We would also like to sincerely thank the Canton of Jura for allowing us to research in its underground, but also for the constructive cooperation with the Commission de suivi in recent years. Last but not least, we would like to thank SWISSTOPO for its willingness and consistency to operate the rock laboratory for over 15 years.

Photo Bibliography

We received the photos of the portraits on pages 7, 8, 9, 49, 50, 52, 53, 54 and 55 directly from the persons addressed.

- Bundesanstalt für Geowissenschaften und Rohstoffe, BGR Hannover, A. Weitze (photo on page 4)

- Comet Photoshopping GmbH, Dieter Enz (photo cover page, photos on pages 22, 28, Figures 5, 15b, 16b, 16c, 16e, 16f, 17a, 17c, 17d)

- Galliker, B., Nagra (Figure 18e)

- Kleger, M., Photography (photo on page 48, Figures 4, 18f)

- Naturhistorisches Museum Bern, Bernhard Hostettler and Ursula Menkveld (Figures 12a – d)

- Rütschi, M. (Figure 16a)

- SWISSTOPO, Béatrice Devènes (photo on page 10, Figure 18b), Senecio Schefer (photo back page, photo on page 38, Figures 3, 8, 16d, 17b, 17e, 17f, 18a, 18c, 18d), Paul Bossart (Figures 15c, 15d).

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