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Mont Terri rock laboratory, 20 years of research: introduction, site characteristics and overview of experiments

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Abstract Geologic repositories for radioactive waste are designed as multi-barrier disposal systems that perform a number of functions including the long-term isolation and containment of waste from the human environment, and the attenuation of radionuclides released to the subsurface. The rock laboratory at Mont Terri (canton Jura, Switzerland) in the Opalinus Clay plays an important role in the development of such repositories. The experimental results gained in the last 20 years are used to study the possible evolution of a repository and investigate processes closely related to the safety functions of a repository hosted in a clay rock. At the same time, these experiments have increased our general knowledge of the complex behaviour of argillaceous formations in response to coupled hydrological, mechanical, thermal, chemical, and biological processes. After presenting the geological setting in and around the Mont Terri rock laboratory and an overview of the mineralogy and key properties of the Opalinus Clay, we give a brief overview of the key experiments that are described in more detail in the following research papers to this Special Issue of the Swiss Journal of Geosciences. These experiments aim to characterise the Opalinus Clay and estimate safety-relevant parameters, test procedures, and technologies for repository construction and waste emplacement. Other aspects covered are: bentonite buffer emplacement, high-pH concrete-clay interaction experiments, anaerobic steel corrosion with hydrogen formation, depletion of hydrogen by microbial activity, and finally, release of radionuclides

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This is the introductory paper (including a list of abbreviations and acronyms) to accompany the 20 research papers (papers 1–20) included in the Special Issue.

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into the bentonite buffer and the Opalinus Clay barrier. In the case of a spent fuel/high-level waste repository, the time considered in performance assessment for repository evolution is generally 1 million years, starting with a transient phase over the first 10,000 years and followed by an equilibrium phase. Experiments dealing with initial conditions, construction, and waste emplacement do not require the extrapolation of their results over such long timescales. However, experiments like radionuclide transport in the clay barrier have to rely on understanding long-term mechanistic processes together with estimating safety-relevant parameters. The research at Mont Terri carried out in the last 20 years provides valuable information on repository evolution and strong arguments for a sound safety case for a repository in argillaceous formations.

Keywords Underground research laboratory (URL) · International research programme · Nuclear waste disposal · Repository evolution · In situ experiments · THMC processes · Switzerland

1 Introduction

1.1 Objectives of underground rock laboratories

An underground rock laboratory (URL) is a research facility in which site characterisation and testing activities are carried out, along with technology development and demonstration activities in support of the development of deep geological repositories for disposal of radioactive waste (OECD 2013). Therefore, the prime objectives of investigation programs in rock laboratories are to acquire data that will provide in-depth understanding of long-term performance of repository components in a geological environment, and to obtain data that will be used as a starting-point for development and testing of safety assessment models. A further objective is to demonstrate and optimise key components of the engineered barrier system (e.g. testing of canister and backfilling materials and its interaction with the host rock). An important contribution of a rock laboratory is to investigate the selected geological environment and to test models at more appropriate scales and conditions than can be achieved at the surface. A final objective is the evaluation of transferability of individual parameters, investigation techniques, data evaluation methods, process understanding, and conceptual models to reach high-level conclusions (e.g. engineering feasibility, safety aspects) relevant to a safety case[1] for a future repository program (Mazurek et al. 2008; Blechschmidt and Vomvoris 2010; Delay et al. 2014; Alexander et al. 2015).

There are two types of URL: generic and site-specific. Generic URLs are independent of final disposal sites and comprise facilities that are developed for research and testing purposes at a site that will not be used for waste disposal. Site-specific URLs are located in the host rock in an area that is considered as a potential future repository. They include facilities that are developed for specific investigations at the given site and may, indeed, be a forerunner to the development of a repository at that site. During the last 40 years, about 30 generic and site-specific URLs have been constructed and about half of them are still in operation (Blechschmidt and Vomvoris 2010). Many of these URLs were constructed in granitic (40%) but the majority (60%) in sedimentary rocks, such as bedded salt and salt domes, clays, tuffs, limestones, and diatomite. There are three major URLs in claystones: (1) the site-specific Meuse/Haute Marne URL, located in the Paris basin in France at a depth of 490 m in the stiff Callovian-Oxfordian clay formation, and operated by ANDRA; (2) the site-specific Hades URL at a depth of 225 m in the plastic Boom Clay in Belgium at a depth of 225 m, operated by SCK.CEN; and (3) the generic Mont Terri rock laboratory, located in the canton Jura in Switzerland at a depth of 280 m in the stiff Opalinus Clay, operated by the Swiss Geological Survey at swisstopo (Swiss Federal Office of Topography). This Special Issue of the Swiss Journal of Geosciences presents 20 papers describing the key experiments that have been carried out during the last 20 years of applied research at the generic Mont Terri rock laboratory. In this introductory paper, we give an overview of the papers comprising this Special Issue and placing them within a conceptual scheme of repository evolution.

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[1] A safety case is a structured argument, supported by evidence, intended to justify that a system is acceptably safe. According to the IAEA (2012), it is "…the collection of scientific, technical, administrative and managerial arguments and evidence in support of the safety of a disposal facility, covering the suitability of the site and the design, construction and operation of the facility, the assessment of radiation risks and assurance of the adequacy and quality of all of the safety related work associated with the disposal facility".

1.2 Research in the Mont Terri rock laboratory

The Mont Terri rock laboratory lies north of the town of St-Ursanne in the canton of Jura. The research facilities are located at a depth of 280 m below the surface and are accessed through the security gallery of the Mont Terri tunnel of the A16-Transjura highway, which passes through the Jura mountain range. The research galleries in the Opalinus Clay layer have a total length of ca. 700 m.

The major aims of the international Mont Terri research project are to investigate and analyse the hydrogeological, geochemical, and rock mechanical properties of argillaceous formations. The Mont Terri rock laboratory offers a scientific and technical platform for international collaboration in the field of deep geological disposal. In the Mont Terri rock laboratory, experiments are dedicated to investigate the properties of a pristine claystone, the Opalinus Clay, its perturbation when an underground opening is constructed, the early and late time interplay of engineered barriers and the natural claystone barrier, and ultimately the understanding of the migration of radionuclides at varied length (near and far-field) and timescales. The latter experiments lead to an increase in confidence in estimating radionuclide mass transport through engineered and natural barriers and improving the reliability of the predictive numerical tools. Understanding mass transport processes is central to a repository safety case.

The Swiss Geological Survey at swisstopo is responsible for operation of the facility and directs the international Mont Terri project. Sixteen organisations from Belgium, Canada, France, Germany, Japan, Spain, Switzerland, and the USA, all of which are considering clay formations as potential host rocks for deep geological disposal of radioactive waste, are involved in the underground (in situ) experiments.

The Opalinus Clay has been selected in Switzerland as the preferred host rock for disposal of high-level waste (HLW) and is among the possible host rocks for low- and intermediate-level radioactive waste (LLW, ILW). A sectoral plan process, led by the Swiss Federal Office of Energy (SFOE), is now underway with the objective of selecting sites for deep geological repositories (SFOE 2008). However, the Mont Terri rock laboratory is first and foremost a research facility for international implementers and safety organisations to conduct collaborative international science and research projects in a low-permeability, smectite-rich claystone with self-sealing (swelling) properties. In this sense, the Mont Terri rock laboratory can be considered as a generic underground rock laboratory. Disposal of radioactive waste will not be considered here. However, some of the experiments at the Mont Terri rock lab should be seen in the context of a potential repository in Opalinus Clay at other locations in northern Switzerland (Nagra 2002, 2010). These include experiments dealing with the horizontal emplacement of waste canisters and demonstration of selected aspects of the Swiss multi-barrier concept.

This introductory paper gives an overview of the geology in and around the Mont Terri rock laboratory (Sect. 2). In Sect. 3, we outline all the experiments that have been carried out over the last 20 years, and give an overview of the papers in this Special Issue and correlate them with the evolution of a potential repository in the Opalinus Clay. In Appendix, we list abbreviations and acronyms which are used throughout the Special Issue with their explanations. For a glossary of technical terms, we refer to Alexander et al. (2015), and to the IAEA-website: http://www-pub.iaea.org/books/IAEABooks/6682/Radioactive-Waste-Management-Glossary.

In the Electronic Supplementary Material attached as Online Resources 1–9 to the present paper, we give additional information about the Mont Terri research project for consultation online (Online Resource 1: explanatory text. Online Resources 2–9: figures and tables). There, we present the partner organisations that are involved in the research project together with their key persons, a retrospective historical overview over the last 30 years, the financial investments, and the project organisation between research partners, operator and owner of the facility. Furthermore, we present a complete list of performed and ongoing experiments since 1996, together with a map of the rock laboratory showing where these experiments are localised.

2 Site characteristics

The canton of Jura, where the Mont Terri rock laboratory is located, lies within the Jura mountain belt (Fig. 1). Stratigraphically, this mountain belt encompasses the period from Late Palaeozoic to Quaternary, but the majority of the rocks belong to the "Jurassic" time period. Tectonically, it can be divided into the Folded Jura, an arcuate fold-and-thrust belt located to the northwest of the Alpine arc and its foreland basin, extending from Lake Annecy in eastern France to the Zurich area in northern Switzerland and further into southern Germany, and the more external Tabular Jura with undeformed Mesozoic sediments (Fig. 1). The fold-and-thrust belt of the Folded Jura is surrounded by Tertiary basins of different types, to the north the Rhine Graben, to the west the Bresse Graben, and to the southeast the Swiss Molasse Basin. The Rhine and Bresse Grabens are associated with the Oligocene West-European rift system, whereas the Molasse Basin corresponds to an Oligo-Miocene foreland basin, which developed in front of the Alpine orogeny (Sommaruga 1999).

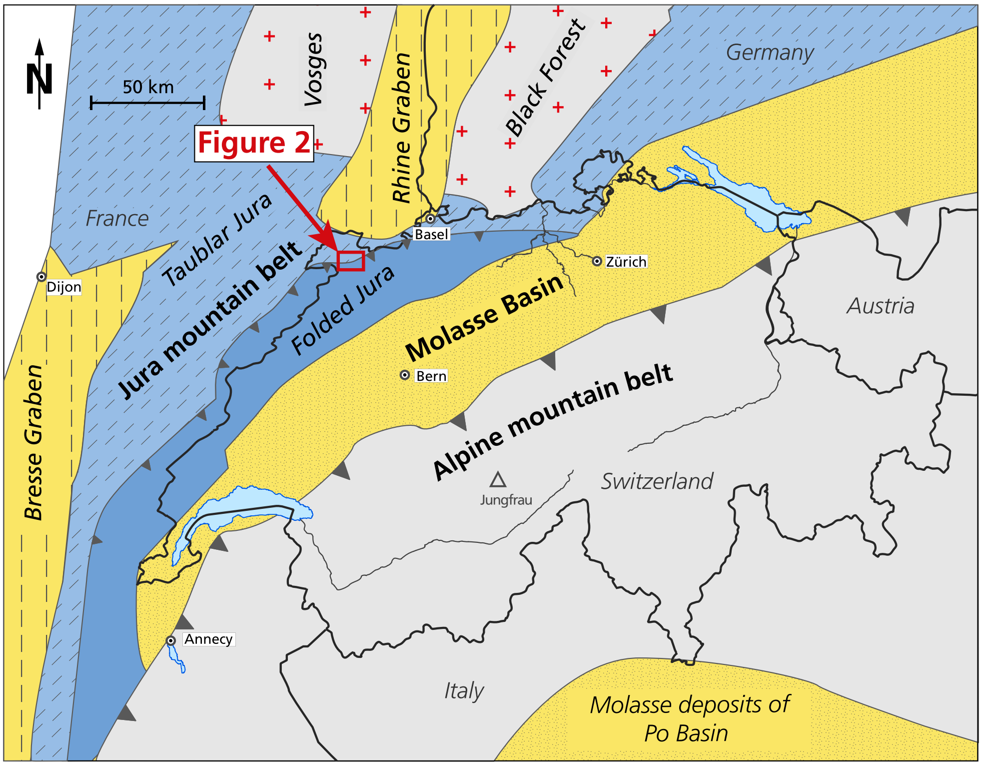

Fig. 1 Sketch map of tectonic units in Switzerland and neighbouring States. The Mont Terri rock laboratory is located in the Canton of Jura besides the Mont Terri motorway tunnel along the A16 Transjurane, in the Folded Jura. The *inset* refers to the geologic map of Fig. 2

Fig. 2 Geologic map of the folded and tabular Jura in the region of ▶ St-Ursanne, Canton of Jura. The A16 tunnels of Mont Russelin and Mont Terri are projected onto the map and provide the profile trace for Fig. 3. The Mont Terri rock laboratory is located in the southern limb of the Mont Terri anticline. In this large anticlinal fold, two deep *boreholes* (*numbers 1–2*) and 3 important surface outcrops (*numbers 3–5*) are indicated. Surface outcrops of Opalinus Clay are rare and altered due to weathering. The traces of the axial planes of the Mont Terri, Caquerelle, and Clairemont anticlines and the sinistral strike-slip faults are shown as the key tectonic structures of this map. The Paleogene and Neogene deposits comprise the following formations: Porrentury conglomerates, Terres jaunes, Meeresand, Septarienton, Alsace Molasse, Upper Marine Molasse (red marls and gompholites), and Upper Freshwater Molasse (Formation du Bois de Raube, Vogesenschotter). Further details are given in the legend. This map is based on the Geological Atlas of Switzerland 1:25,000, map No. 40 "St-Ursanne," (Laubscher 1963), available through swisstopo online under https://map.geo.admin.ch

The region of St-Ursanne, where the Mont Terri rock laboratory is located, lies within the Folded Jura, and comprises sedimentary rocks ranging in age from Carboniferous to Quaternary (Fig. 2). The Late Palaeozoic clastic sediments are unconformable overlain by almost 1600 m of Mesozoic limestones, marls and shales, around 400 m of Tertiary Molasse, and, locally, Quaternary fluvio-glacial sediments. Of special interest are the Liassic–Dogger units, which comprise several shallowing-upward regressive cycles, starting with the Opalinus Clay and ending with shallow-water carbonates (Blaesi 1987). The Opalinus Clay[2] consists of a monotonous sequence of dark grey, silty, micaceous clays and sandy shales, deposited around 174 Ma ago. This age is based on a new stratigraphic investigation in a deep borehole cutting the Opalinus Clay and adjacent formations near the rock laboratory (Hostettler et al. 2017). The Opalinus Clay is overlain by the Passwang Formation of sandy limestones, shales and oolitic ironstones, and underlain by the Staffelegg Formation consisting of limestones, marls, and shaly intercalations (see geologic map of Fig. 2 and vertical profile of Fig. 3). At Mont Terri and adjacent areas, the Opalinus Clay is barely exposed at the surface. One of the first lithological descriptions of the Opalinus Clay was given by Schmidt et al. (1924) from a borehole near Buix, located about 20 km to the NW of Mont Terri, where a total

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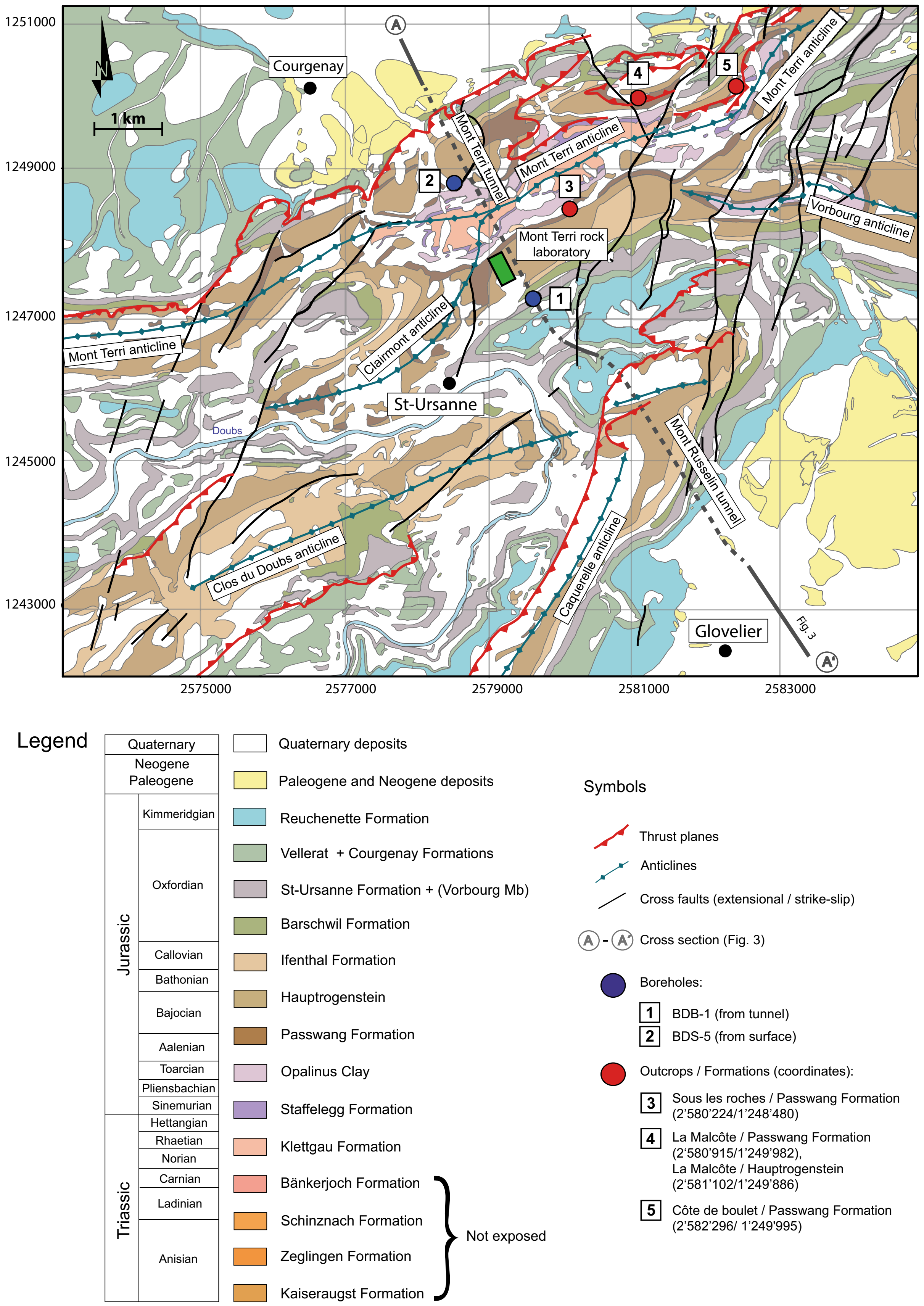
[2] Definition and usage of the term "Opalinus Clay": it is regarded in this and following papers as a lithostratigraphic formation, the latter defined as a rock of similar mineralogical and petrophysical properties, which is clearly discernible and mappable as a distinct rock unit in the field. Unweathered, fresh Opalinus Clay is a monotonous succession of dark grey, mica bearing clay and silty marl, with carbonate and sandy lenses that become more abundant towards the top (http://www.strati.ch). According to Wetzel and Alia (2003) the thickness of this formation varies between 60 and 150 m. Its age is of late Toarcian to early Aalenian (~174 Ma). An update of its litho- and biostratigraphy is given in Hostettler et al. (2017).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Mont Terri tunnel
Mont Russelin tunnel
Mont Terri rock laboratory
Mont Terri anticline
Clairmont anticline
Clos du Doubs anticline
Caquerelle anticline
Vorbourg anticline
Fig. 3
1
2
3
4
5
Legend
Quaternary
Neogene Paleogene
Jurassic
Kimmeridgian
Oxfordian
Callovian
Bathonian
Bajocian
Aalenian
Toarcian
Pliensbachian
Sinemurian
Triassic
Hettangian
Rhaetian
Norian
Carnian
Ladinian
Anisian
Quaternary deposits
Paleogene and Neogene deposits
Reuchenette Formation
Vellerat + Courgenay Formations
St-Ursanne Formation + (Vorbourg Mb)
Barschwil Formation
Ifenthal Formation
Hauptrogenstein
Passwang Formation
Opalinus Clay
Staffelegg Formation
Klettgau Formation
Bänkerjoch Formation
Schinznach Formation
Zeglingen Formation
Kaiseraugst Formation
Not exposed
Symbols
Thrust planes
Anticlines
Cross faults (extensional / strike-slip)
A - A' Cross section (Fig. 3)
Boreholes:
1 BDB-1 (from tunnel)
2 BDS-5 (from surface)
Outcrops / Formations (coordinates):
3 Sous les roches / Passwang Formation (2'580'224/1'248'480)
4 La Malcôte / Passwang Formation (2'580'915/1'249'982), La Malcôte / Hauptrogenstein (2'581'102/1'249'886)
5 Côte de boulet / Passwang Formation (2'582'296/ 1'249'995)

thickness of 157.5 m was encountered. The present thickness of the Opalinus Clay in the Mont Terri rock laboratory has been estimated to be 131 m. This corresponds to a sedimentary thickness of about 120 m when corrected for tectonic overthrusting (Hostettler et al. 2017). The Opalinus Clay at Mont Terri is an overconsolidated claystone. The maximum burial is estimated to have been 1350 m. This results in an overconsolidation ratio of almost 5, assuming a present-day mean overburden of 280 m.

2.1 Regional tectonic setting

Nussbaum et al. (2011) describe the regional geologic–tectonic setting in detail, which we summarise here. Pre-existing fault systems together with Permo–Carboniferous grabens and the Rhine–Bresse transfer zone (where the region of St-Ursanne is located) have largely influenced the thrust-and-fold-belt geometry of the Jura Mountains, resulting in complex interference structures such as cross-folds and strike-slip fault zones. Cross-folds occur with different trends, for example, the Caquerelle and Mont Terri anticlines and the divergence of the Mont Terri anticline at its western margin (Figs. 1, 2). During the Jura thrusting phase, inherited transcurrent faults from the European Cenozoic intra-continental rifting phase triggered development of both frontal and oblique ramps, depending on fault orientation with respect to transport direction. Consequently, the Mont Terri anticline can be considered as a non-cylindrical domal anticline. Its north-eastern border is cut by inherited sinistral strike-slip faults, and its southwestern end is interpreted as the result of cross folding. The detailed kinematic evolution of this structure is described in Nussbaum et al. (2017).

2.2 Local geology of the Mont Terri rock laboratory

2.2.1 *Lithofacies*

During construction of the Mont Terri tunnel system in the late 1980s, the reconnaissance gallery of the Mont Terri highway tunnel revealed fresh and high-quality exposures of Opalinus Clay. This led to more detailed lithostratigraphic, hydrogeological, and geochemical descriptions of this formation (Schaeren and Norbert 1989; Tripet et al. 1990; Blaesi et al. 1991, 1996; Gautschi et al. 1993; Hostettler et al. 2017). Not only the discovery of the Opalinus Clay at this locality, but also the simple geometry (limited thrust zones and imbricates) and the possibility of horizontal access, led to establishing the Mont Terri rock laboratory. The laboratory is located entirely in the Opalinus Clay, which can be subdivided into five units and comprises three lithofacies types (Fig. 4). At the bottom there is a shaly facies consisting of mica-bearing marly shales with nodular zones or mm-thick layers of quartz in the silt fraction. Above this there is a sharp transition to a thin carbonate-rich sandy facies, which is characterised by quartz-bearing calcareous biodetritic layers up to 10 cm thick. Then a sandy facies follows with calcareous silty claystones, and above this a dark-grey, mica-bearing, and slightly silty claystone, which is attributed to the shaly facies. The uppermost unit of the Opalinus Clay consists again of sandy facies, a light-grey silty claystone with lenses of laminated silt and lenses of bioclastic material. Schaeren and Norbert (1989) and Blaesi et al. (1991) defined the base of the Opalinus Clay as a lithological transition of argillaceous sediments to more marly sediments. The latter have been identified as the Gross Wolf

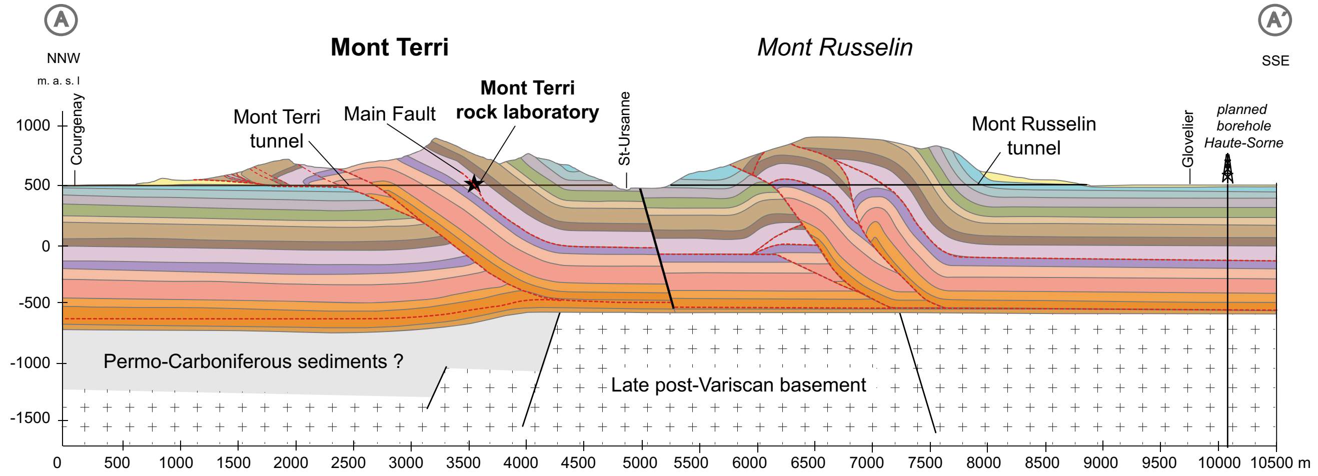


Fig. 3 Balanced geological profile along the Mont Russelin and Mont Terri tunnels. The profile trace is indicated in Fig. 2. These profiles are based on Schaeren and Norbert (1989), Freivogel and Huggenberger (2003), Caër et al. (2015), and Nussbaum et al. (2017). The latter reference gives the kinematic evolution of this cross-section. Note the simple geometry of the Opalinus Clay in the Mont Terri rock laboratory compared to the Opalinus Clay of the other tunnel outcrops (i.e. Mont Russelin)

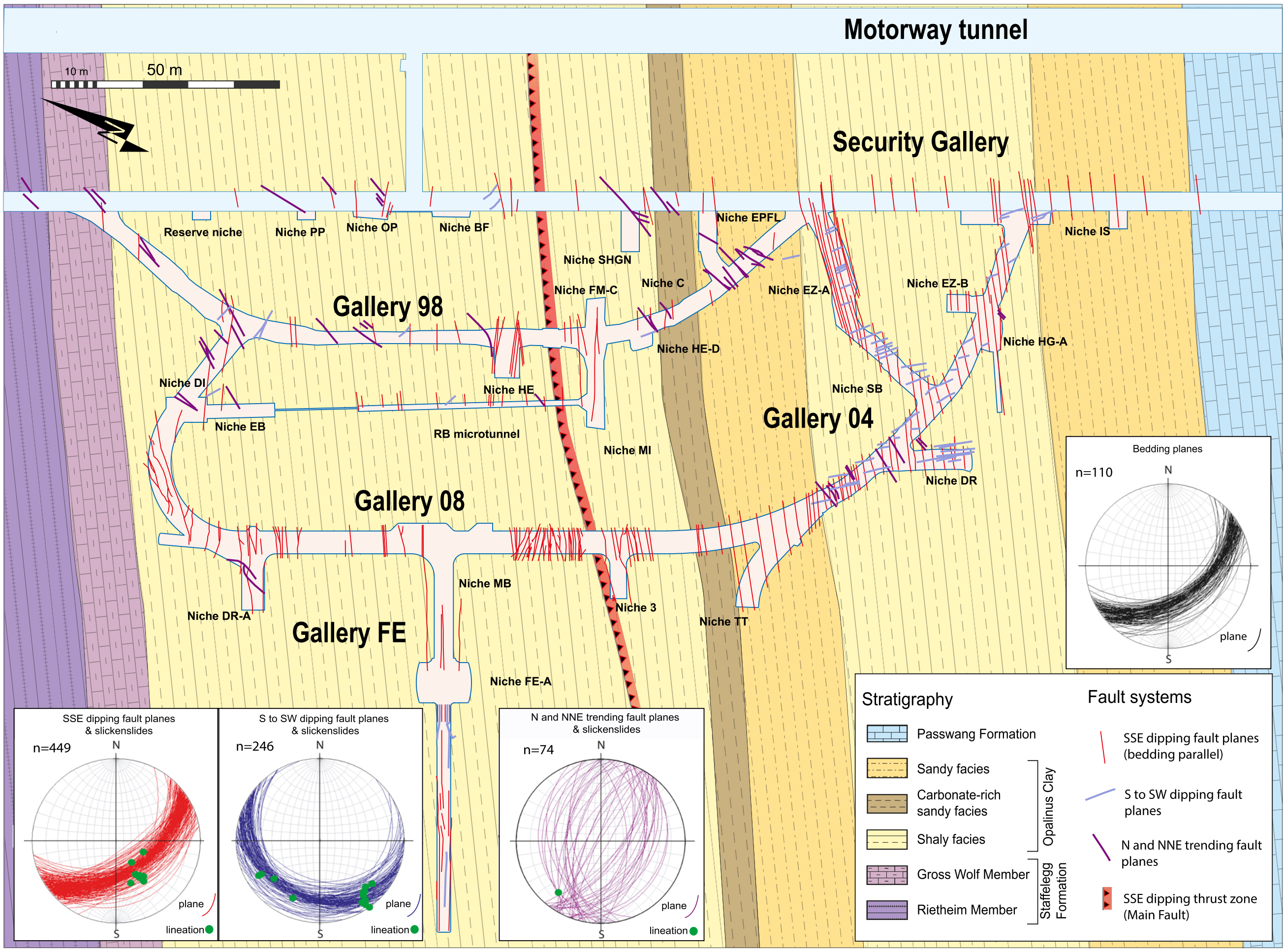


Fig. 4 Geologic–tectonic map of the Mont Terri rock laboratory. The Opalinus Clay is sandwiched between the Staffelegg Formation (*base*) and the Passwang Formation (*top*). There are three different facies of Opalinus Clay: shaly, carbonate-rich sandy, and sandy facies. The mapped tectonic faults can be assigned to one of three fault systems as shown on the stereoplots (*bottom left*, lower hemisphere Wulff projections). The rock laboratory is intersected by a major fault, called the "Main Fault"

Member of the Staffelegg Formation (Reisdorf et al. 2011; Hostettler et al. 2017). The upper boundary of the Opalinus Clay is defined by a distinct hardground of chamositic crusts (Blaesi et al. 1991) and iron oolites.

2.2.2 *Structural relations*

A prominent tectonic overprint of the Opalinus Clay in sections of the Mont Terri and Mont Russelin is confirmed by numerous studies on structural data conducted during the evolution of the rock laboratory (e.g. Nussbaum et al. 2011). The Mont Terri rock laboratory is located in the southern limb of the Mont Terri anticline (Figs. 2, 3). The present overburden varies between 250 and 320 m and the strata dip with an angle between 30° and 50° towards SSE in the northern and southern part of the Mont Terri rock laboratory, respectively. The Mont Terri anticline developed between 10 and 2 Ma ago at the junction of the frontal part of the Jura thrust-and-fold belt and the Rhine–Bresse transfer zone. The geometry is an imbricate fault-bend fold with a component of trishear (Nussbaum et al. 2017). In the Mont Terri rock laboratory, three different fault systems are identified that correlate with regional-scale tectonic structures. The three fault systems are shown in the stereoplots of Fig. 4. They comprise (1) N to NNE-striking steeply inclined normal faults of the Rhine–Bresse graben system reactivated in sinistral strike-slip mode during the Late Miocene Jura thrusting phase, (2) SSE-dipping faults subparallel to bedding initiated during the late stage of reverse faulting and anticline folding by flexural slip, and (3) SW-dipping, sub-horizontal faults resulting from lateral extension during thrusting of the Mont Terri anticline above the frontal ramp. The largest tectonic feature in the rock laboratory is the so-called Main

Fault, a thrust fault zone, which at the rock lab level dips on average about 15° steeper than bedding planes and exhibits a similar strike direction (Figs. 2, 3).

2.3 Mineralogy of Opalinus Clay

The mineral composition of the Opalinus Clay has been analysed by various groups (e.g. Mazurek 1999). In general, the shaly and sandy lithofacies display a qualitatively similar mineral composition. The shaly facies contains more clay minerals and less quartz compared to the sandy facies. The carbonate-rich sandy facies contains more calcite and quartz, but less clay minerals. Observed minerals are quartz, illite and mixed-layer illite–smectites, kaolinite, chlorite, biotite and muscovite, calcite, aragonite, siderite, dolomite and/or ankerite, albite and/or plagioclase, K-feldspar, pyrite, organic matter, and other accessory minerals such as apatite, celestine, zircon, and monazite. The total dry wt% of illite, chlorite and kaolinite varies between 8 and 80%, and the mixed-layer illite–smectites varies between 3 and 20% (Table 1). A best estimate of the total clay content is 66%, with mixed-layer illite-smectites of 10%. Quartz varies between 10 and 44%, with a best estimate of 14% and carbonate minerals vary between 4 and 57% with a best estimate of 13%. The best estimate for pyrite is 1.1% and that for organic carbon is 0.8%. Some secondary minerals have also been detected but not quantified, including celestine and barite in veins, and elemental sulphur. Other phases, namely gypsum and traces of jarosite, have been detected only in material that has been altered by oxidation. The bulk of organic material in the Opalinus Clay is kerogen or other uncharacterised material of terrestrial detrital origin. Organic geochemical indices and biomarkers show that the Opalinus Clay in the Mont Terri section is thermally immature, having experienced maximum burial temperatures of about 80 °C during Cretaceous burial (Mazurek et al. 2006), and shows low hydrocarbon source-rock potential.

2.4 Other key properties of Opalinus Clay

The Opalinus Clay is an anisotropic material with different properties perpendicular and parallel to bedding. Properties for the shaly and sandy facies are given in Table 2, taking into account parameter values perpendicular and parallel to bedding. These properties were derived from Opalinus Clay at the level of the rock laboratory (280 m below surface).

From a hydraulic point of view, the Opalinus Clay is characterized by a very low hydraulic conductivity of 2×10^{-13} m s^{-1}. Solute transport is, therefore, mainly controlled by molecular diffusion. This is also confirmed by measured natural chloride and helium (^{4}He) concentrations in the pore-water (Pearson et al. 2003). Chloride and helium concentrations in the pore-waters of Opalinus Clay and its bounding aquifer formations show smooth, regular profiles with depth, with some profiles being more symmetric than the others. When modelling these profiles taking into account the local erosion pattern, it was assumed that the upper aquifer in the Passwang formation was activated first, followed by the lower aquifer in the Staffelegg formation. The best interpretation, which includes this concentration pattern, is the process of molecular diffusion whereby solutes in the Opalinus Clay have diffused into the bounding aquifers (Mazurek and de Haller 2017). Also migration experiments with artificial non- to low-sorbing radionuclides in the Mont Terri rock laboratory confirm solute transport by molecular diffusion,

Table 1 Mineralogy of Opalinus Clay

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

The mineral compositions are presented for the shaly, sandy, and the carbonate-rich sandy facies. Values are given in wt%

Table 2 Selected in-situ and laboratory-derived key parameters for the Opalinus Clay in and around the Mont Terri rock laboratory (after Jaeggi and Bossart 2014)

Parameter	**Shaly facies** [a]		**Sandy facies**	
	Range	**Best estimate**	**Range**	**Best estimate**
Density (humid) [g/cm^3]	2.40-2.53 [a] (239)	2.45	2.42-2.63 [d] (65)	2.52
Total (physical) porosity [Vol %]	14-25 [a] (17)	18	5.3-17.7 [d] (17)	11.1
Water loss porosity [Vol %]	13-21 [a]	16	4.9-17.5 [d] (19)	10.5
Water content [weight %]	5.0-8.9 [a] (22)	6.6	2-6 [e] (112)	4
Seismic P-wave velocity Vp (N) [m/s]	2220-3020 [a] (48)	2620	1470-4610 [e] (61)	3280
Seismic P-wave velocity Vp (P) [m/s]	3170-3650 [a] (111)	3410	2870-5940 [e] (112)	3860
Hydraulic conductivity (N) [m/s]	2E-14 - 1E-12 [a] (57)	2E-13	1E-13-5E-12 [f] (10)	1E-12
Specific storage [m^{-1}]	1E-7 - 1E-4 [a] (6)	2E-6	1E-6 - 1E-5 [g] (4)	7E-6
Effective diffusion coefficient (P) - Tritiated water HTO [m^2/s] - Iodine [m^2/s]	4.0E-11 – 6.8E-11 [b] (5) 1.0E-11 – 3.0E-11 [b] (5)	5.4E-11 2.0E-11	-	-
Effective diffusion coefficient (N) - Tritiated water HTO [m^2/s] - Iodine [m^2/s]	7.1E-12 – 1.1E-11 [b] (2) 2.3E-12 – 4.2E-12 [b] (2)	1.0E-11 3.0E-12	-	-
Effective porosity - Tritiated water HTO [%] - Iodine [%]	12.0 – 16.4 [b] (5) 5.0 – 12.5 [b] (2)	15.0 8.5	-	-
Uniaxial compressive strength, UCS (N) [MPa]	5-10 [c] (19)	7	6-37 [e] (51)	16
Uniaxial compressive strength, UCS (P) [MPa]	4-17 [a] (22)	10.5	4-37 [e] (60)	18.0
Elastic module, E-module (N) [GPa]	2.1-3.5 [a] (34)	2.8	0.4-19.0 [e] (51)	6.0
Elastic module, E-module (P) [GPa]	6.3-8.1 [a] (39)	7.2	2.0-36.7 [e] (60)	13.8
Poisson ratio (N) [-]	0.28-0.38 [a] (73)	0.33	0.06-0.42 [e] (51)	0.22
Poisson ratio (P) [-]	0.16-0.32 [a] (73)	0.24	0.13-1.23 [e] (59)	0.44
Thermal conductivity (N) [$Wm^{-1}K^{-1}$]	1.0-3.1 [a] (9)	1.2	-	-
Thermal conductivity (P) [$Wm^{-1}K^{-1}$]		2.1	-	-
Heat capacity [$JKg^{-1}K^{-1}$]	-	1000 [h]	-	-
Porewater composition	Na-Cl-SO_4 pore water with TDS of 18.3 g/l [i]			
Total cation exchange capacity CEC (Co-Hexamin, Ni-en in bold) [meq/100 g rock]	**9.4-13.4** [a] **(24)** -	**11.1** 16 (24)	7.3-21.9 [j] (13)	14.4
Gas entry pressure [MPa]	1.2-3.2 [k] (11)	1.8-2.5	-	-

The table is ordered into petrophysical (orange), hydraulic (blue), rock-mechanical (grey), thermal (red), and geochemical parameters (yellow, green). Parameters are provided for the ranges and best estimates for the shaly and sandy facies. The number of parameter values, if available, are indicated in parenthesis. Note that currently not all parameters are available for both facies types, e.g. molecular diffusion and thermal parameters are only available for the shaly facies.

Parameters are distinguished for anisotropy by (N) samples normal to bedding, and (P) samples parallel to bedding. The petrophysical and rock-mechanical parameters originate mainly from drillcore measurements in the laboratory. Parameter values for the shaly facies are partly derived from [a] Bossart et al. (2008). The effective diffusion coefficients and effective porosities of the shaly facies are derived in situ and come from [b] Leupin et al. (2017a). The uniaxial compressive strength (UCS) values of the shaly facies normal to bedding come from [c] Amann et al. (2011a, b). The petrophysical and rock-mechanical parameters of the sandy facies come from [d] Peters et al. (2011) and [e] Gschwind (2013). In-situ derived hydraulic conductivities of the sandy facies come from [f] Lavanchy and Mettier (2012). The specific storage for the sandy facies are derived from [g] Yu et al. (2017). The heat capacity for the shaly facies come from [h] Garitte et al. (2014). Pore-water compositions with total dissolved solids originate from [i] Pearson et al. (2003). The total cation exchange capacity for the sandy facies has been derived by [j] Lerouge et al. (2011). The in-situ derived gas-entry pressure of the shaly facies originates from [k] Miehe et al. (2010). The seismic P-wave velocity values in this table were derived from drillcore measurements in the laboratory; in-situ derived P-wave velocities are provided by Schuster et al. (2017)

providing diffusion parameters such as diffusion coefficients parallel and normal to bedding, effective porosities, and retardation parameters for sorbing radionuclides (Leupin et al. 2017a). As indicated in Table 2, these diffusion parameters can vary considerably and have to be evaluated separately for every species. This can be illustrated when comparing the parameters of non-sorbing tritiated water (HTO) and iodine: the effective diffusion coefficient of HTO parallel to bedding is 5.4×10^{-11} m^2 s^{-1}, with an effective porosity of 15%, which is about equal to the water loss porosity of 16%. The effective diffusion coefficient of iodide parallel to bedding is 2.0×10^{-11} m^2 s^{-1} (less than half of that of HTO), with an effective porosity of only 8.5%, which is about half of the water-loss porosity. One reason for these different parameter values lies in the pore-space geometry of Opalinus Clay. The mean pore diameter is 40 nanometres, and the rather large iodine ions can access only about half of the total pore-space, whereas the rather small HTO molecules can access almost the whole pore-space.

From a rock-mechanical point of view, the Opalinus Clay can be considered as a transverse isotropic material (Bock 2009) with a best estimate of uniaxial compressive strength (UCS) for the shaly facies, parallel to bedding of 10.5 MPa, Poisson ratio of 0.24, and Young's modulus of 7.2 GPa. These mechanical parameters show rather different values in the sandy facies (Table 2). Generally, Opalinus Clay exhibits a quite complex rheological behaviour, which includes anisotropy, plasticity, and damage (Parisio 2016).

Thermal parameters were estimated only for the shaly facies. With a relatively low mean thermal conductivity of 1.8 W m^{-1} K^{-1} and a heat capacity of 1000 J kg^{-1} K^{-1} (Garitte et al. 2014), increased geothermal gradients are observed between bottom and top of the Opalinus Clay.

From a geochemical point of view, the pore-water is of $Na–Cl–SO_4$ type with a maximum of total dissolved solids (TDS) of 18.3 g l^{-1}, exhibiting a sea-water signature on the Cl^-/Br^- plot and a cation exchange capacity CEC) (Ni-en) of 11.1 meq/100 g rock (Table 2). The age of this marine pore-water in the region of the Mont Terri anticline is much younger than the sedimentation age of Opalinus Clay (174 Ma). Researchers applied two approaches to date pore-waters: Clauer et al. (2017) interpreted strontium isotope ratios of calcite from the matrix, veins, and fault gouges of the Opalinus Clay to yield an upper Eocene age of 38–36 Ma; Mazurek and de Haller (2017) analysed data on the geochemical evolution of pore-waters in and around Mont Terri giving a slightly younger age, close to the Oligocene/Miocene boundary at ca. 23 Ma. Both teams interpret these findings as marine incursions into the region of the future folded Jura of upper Eocene and Oligocene/Miocene ages, respectively.

Opalinus Clay also has the property of self-sealing, which means that cracks and fissures of the excavation damaged zone (EDZ) close when moisture is provided. Fractures in the EDZ, stress or anisotropy-induced, have the potential to act as preferential flow paths for radionuclides from the repository site to the biosphere. Thus, sealing of these fractures, especially when exhibiting an interconnected fracture network, is essential in order to reduce transmissivity of the EDZ network and thus to prevent any advective flow from the repository to the biosphere. This self-sealing propriety is mainly due to the mixed-layer illite-smectite clay minerals, which are present in both the shaly and sandy facies, and which swell when moisture is provided. This might be not true for the carbonate-rich sandy facies, where mixed-layer illite-smectite contents are small (Table 1). More detailed information about the parameters of the Opalinus Clay is given in Bossart and Thury (2008).

3 Thematic overview of experiments

3.1 Research topics focussed from 1996 to 2016

The Mont Terri research programme between 1996 and 2016 consists of 138 individual experiments; 93 experiments were successfully completed by mid-2016, and 45 experiments are still in progress (a compilation of these 138 experiments is presented in Online Resources 8 and 9). The three basic aims of these 138 experiments were and are: (1) understanding the characteristics, processes and mechanisms in undisturbed claystones, (2) understanding the repository-induced perturbations, and (3) performing experiments related to the demonstration of repository implementation technology. It is important to note that these experiments provide data and arguments that are relevant for the performance assessment of a repository and its safety case, but the performance of a repository cannot be directly tested in a generic rock laboratory like Mont Terri.

3.1.1 Experiments on characteristics, processes and mechanisms in undisturbed claystones

These experiments include:

- improving drilling and excavation technologies, and testing and sampling methods with the aim of minimising rock perturbations,
- estimating hydrogeological, rock mechanical, and geochemical parameters of the undisturbed Opalinus Clay, including upscaling parameters from laboratory to in situ scale (m to 100 m range),

- identifying geochemistry of pore-water and natural gases; gaining a better understanding of pore-water origin, dating, and its evolution over geological timescales; and assessment of long-term hydraulic transients associated with basin inversion, erosion, and thermal scenarios,
- experimental work associated with understanding diffusive mass transport in the far-field (kilometre scale, timescale of several millions of years), mainly by measuring and interpreting natural tracer profiles in and around the Mont Terri rock laboratory,
- experimental work associated with the evaluation of diffusion and retention parameters for long-lived radionuclides in the near-field (centimetre to decimetre scale, timescale of 1–5 years), by artificially placing radionuclides into boreholes, letting them diffuse into the borehole wall, and then analysing the distribution of radionuclides in the overcores.

The latter two points are crucial to assessing the significance of mass transport and they also provide evidence on the degree to which this is diffusion dominated. A transport regime that is diffusion dominated is preferred for long-term radioactive waste isolation and containment. Our strong evidence that mass transfer in a natural claystone barrier such as the Opalinus Clay is diffusion dominated provides an important argument supporting the safety case of a repository in this lithology.

3.1.2 *Experiments on repository-induced perturbations*

These include:

- hydro-mechanical coupled processes (e.g. stress redistributions and pore pressure evolution during mine-by testing),
- thermo-hydro-mechanical-chemical coupled processes (e.g. heating of bentonite and host rock),
- self-sealing processes in the excavation damaged zone, from small scale to repository scale,
- gas-induced transport of radionuclides in pore-water, gas transport along interfaces in the engineered barrier system,
- influence of cement rock liner on the bentonite backfill, buffering potential of the claystone in the near field, and its geochemical and kinetic processes.

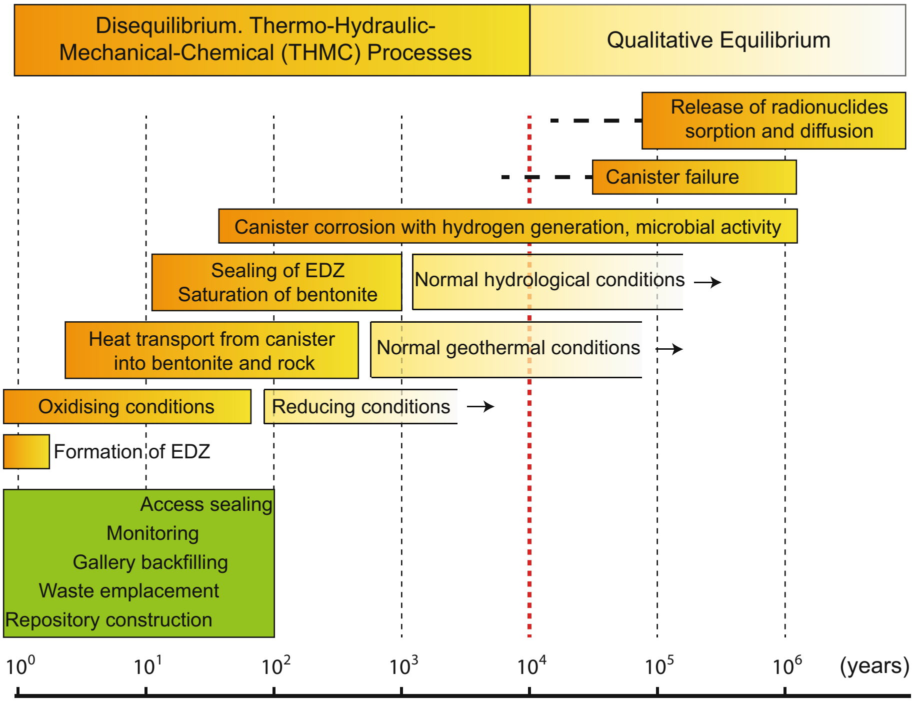
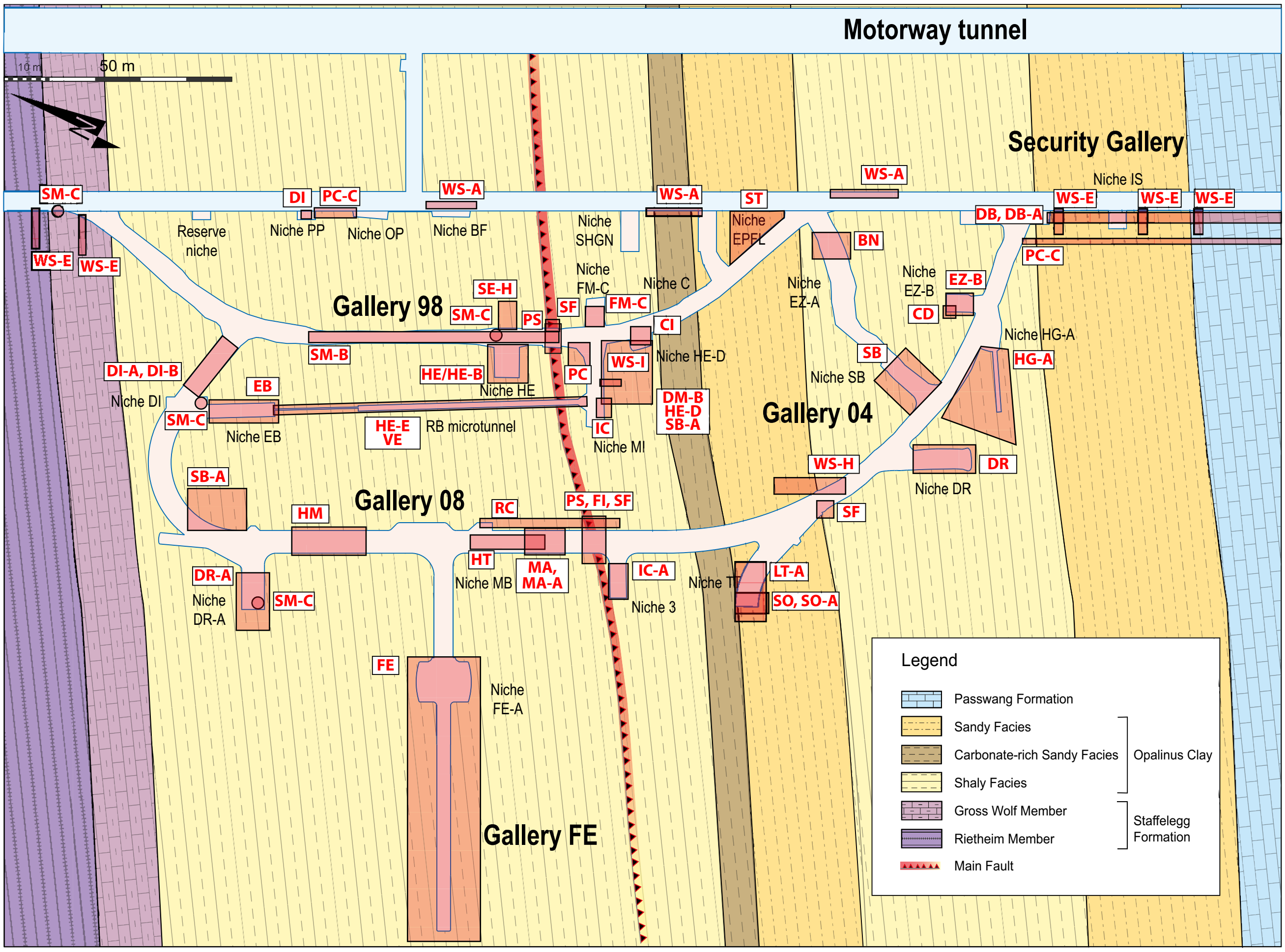


Fig. 5 The possible evolution of a potential high-level waste repository in the Opalinus Clay based on the Swiss disposal concept. Indicated in *green* are the human engineering activities starting with the construction of a repository until its sealing at the end (the time periods are best estimates and may differ considerably, depending on future decisions by the implementer, safety organisation, and authorities). The expected processes during the lifespan of a repository are given in *orange* (disequilibrium) grading to *yellow* (equilibrium), starting with the formation of the excavation damaged zone (EDZ) and ending with the release of radionuclides from breached canisters. Thermo-hydraulic-mechanical and chemical equilibrium is assumed to occur after 10,000 years (see *red line*)



Experiments discussed in Special Issue

BN	Bitumen-nitrate-clay interaction
CD	Cyclic deformations
CI	Cement-clay interaction
DB	Deep inclined borehole through the Opalinus Clay
DB-A	Porewater characterisation-Benchmarking
DI	Diffusion in rock
DI-A	Long-term diffusion
DI-B	Long-term diffusion
DM-B	Long-term deformation measurements
DR	Diffusion and retention experiment
DR-A	Diffusion, retention and perturbations
EB	Engineered barriers
EZ-B	Fracture generation
FE	Full scale emplacement demonstration
FI	Fluid-mineral interactions in Opalinus Clay during natural faulting and heating
FM-C	Flow mechanism (tracer)
HE/HE-B	Heater experiments I and II
HE-D	THM behaviour of host rock (heater test)
HE-E	In-situ heater test in VE microtunnel
HG-A	Gas path host rock & seals
HM	Experimental lab investig. on HM-coupled properties & behavior Opalinus Clay
HT	Hydrogen transfer
IC	Iron corrosion of Opalinus Clay
IC-A	Corrosion of iron in bentonite
LP-A	Long-term monitoring of parameters (porewater pressures)
LT-A	Clay properties, analyses of labtesting
MA	Microbial activity in Opalinus Clay
MA-A	Modular platform for microbial studies
PC	Porewater chemistry
PC-C	Gas porewater equilibrium
PS	Petrofabric and strain determination
RC	Rock mass characterisation
SB	Selfsealing barriers clay - sand mixtures
SB-A	Borehole sealing experiment
SE-H	Self-sealing with heat (Timodaz)
SF	Self-sealing of tectonic faults
SM-B	High resolution seismic monitoring
SM-C	Permanent nanoseismic monitoring
SO	Sedimentology of Opalinus Clay
SO-A	Palynology of the Opalinus Clay
ST	Seismic transmission measurements
VE	Ventilation test
WS-A/E/H/I	Porewater profiles, wet spots

◀**Fig. 6** Compilation of the 43 key experiments in the Mont Terri rock laboratory treated in the following papers of this Special Issue. The sites are shown in the map above and titles and abbreviations of the corresponding experiments are listed below. Only a subset of the Mont Terri experimental portfolio (138 experiments) is shown here. The complete experiment portfolio is presented in the electronic supplementary material (Online Resources 8 and 9)

3.1.3 Experiments related to the demonstration of repository implementation technology

These experiments comprise:

- construction and installation of engineered barriers on a 1:1 scale,
- horizontal emplacement of canisters and bentonite buffer of the space between canister and claystone,
- evaluation of corrosion rate of container materials, resaturation of bentonite buffer under decreasing heat transport from the canister, and long-term geochemical and microbial evolution of engineered barriers,
- sealing of boreholes and repository access tunnels and shafts, and long-term monitoring of the repository.

We emphasise that not all experiments can be strictly assigned to these three research aims. Some experiments come under two or even three of the aims, depending on the experiment objectives and concepts, and also on the temporal evolution of the experiment.

3.2 Overview of research and topics presented in the following papers

3.2.1 Potential repository evolution

Experimental results provide input for assessing different phases of repository evolution and performance. A potential repository evolution with causes and effects is shown in Fig. 5, and this will be used to organise the presentation of papers and experiments in the following section (Sect. 3.2.2). This evolution is based on the Swiss concept for high-level radioactive waste disposal in the Opalinus Clay (cf. Nagra 2002). We would like to emphasise that other countries may develop other repository evolution systems based on their own disposal concepts and construction and safety requirements. In the potential repository evolution shown in Fig. 5, we distinguish a transient disequilibration phase and a qualitative equilibrium phase. Qualitative equilibrium does not mean a thermodynamic equilibrium, but rather an equilibrium that can be compared to the one before the repository was constructed. During construction of a repository (a time period of several years), stress redistribution leads to formation of an excavation damaged zone (EDZ) around the access and emplacement galleries. During the operational phase (waste emplacement, buffer emplacement and backfilling, monitoring and sealing: a time period of up to 100 years, green box in Fig. 5), an unsaturated zone will evolve in the near-field due to ventilation, and redox conditions will become oxidizing. In the first few 100 years after closure, significant changes in the repository will occur, including heat transport from the canisters across the bentonite towards the rock, with canister surface temperatures up to 150 °C, and temperatures reaching ca. 90 °C at the bentonite-rock interface (Nagra 2002). Heat transport into the rock may cause excess pore-water pressures and reduction of effective stresses in the near-field, simply due to the fact that expansion of pore-water is higher than expansion of the rock fabric. As time advances, heat-flow will decrease leading to enhanced saturation in the near-field and swelling of the bentonite buffer. These processes take place concurrently with self-sealing of the EDZ fractures. Both swelling of clay minerals in the EDZ fractures and mechanical fracture closure (swelling bentonite) contribute to self-sealing. Redox conditions in the near-field become clearly reducing and anaerobic corrosion of the steel canisters prevails together with hydrogen production. During this period, microbial activity becomes important: bacteria are involved in redox reactions, degrading hydrogen (pore-water sulphates are reduced to sulphides such as H_2S). A sufficiently dense bentonite backfill is used to protect steel canisters from microbial-assisted corrosion. Finally, release of nuclides from the canisters is not expected to occur before some 10,000 years after emplacement. By this time, equilibrium conditions in the claystone are already re-established and hydraulic and thermal conditions are comparable to those before the repository was constructed. Radionuclide sorption and diffusion into the bentonite and the natural clay barrier is then the final process in the repository evolution, whereby 80% of the nuclides will be immobilized in the immediate vicinity of the canister.

3.2.2 The 20 papers and their relation to repository evolution

The papers in this Special Issue can be linked to the scheme of potential repository evolution shown in Fig. 5 and discussed in the previous section. Altogether, 43 experiments are outlined in the papers, and the location of these is shown in Fig. 6. The results of these experiments are combined and presented in the form of 20 scientific papers according to different themes, often including results from different experiments. The structure of this Special Issue, with the 20 papers organised according to their relevance for different periods of the repository evolution, is shown in Fig. 7. The sequence of the papers as they appear in this issue is given in Table 3, together with their titles and first authors. Figure 6 (location of

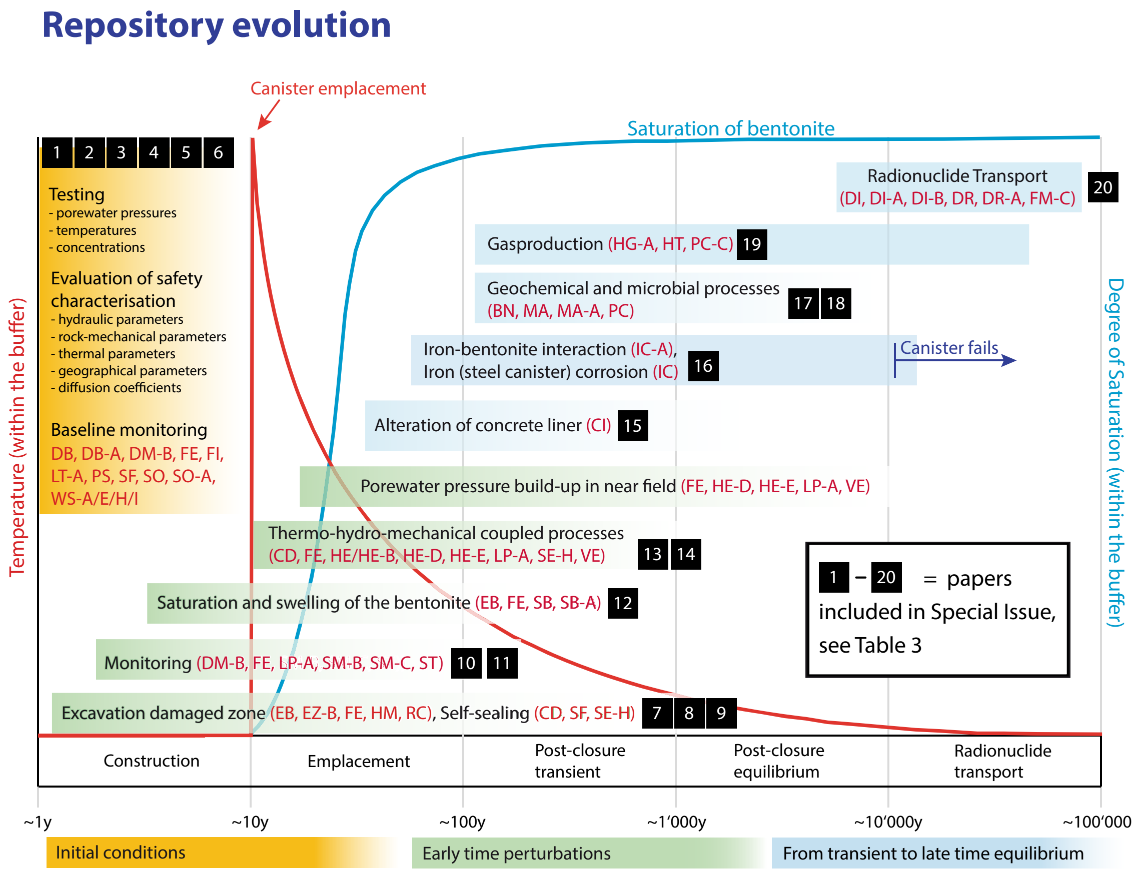


Fig. 7 Repository evolution, key experiments, and related publications in this Special Issue. The repository evolution can be divided into three periods: (1) initial conditions before repository construction (*orange*), (2) early time perturbations during and shortly after construction (*green*), and (3) transient to late time (post-closure) equilibrium (*blue*). The 43 key experiments are indicated as *abbreviations* and refer to Fig. 6, which shows the complete titles of the key experiments together with their sites. The related publications are shown as *black numbers 1–20*. An overview of these publications is given in Table 3. This figure also indicates the temperature (*red curve*) and degree of saturation (*blue curve*) within the buffer

experiments in the rock laboratory) and Fig. 7 (linking corresponding papers to repository evolution) are thus the key figures and, with Table 3 (paper titles, key experiments, and first authors), they provide a guide and continuous thread for the following 20 papers.

From a practical point of view, only a subset of 43 of the total of 138 experiments is considered here and discussed in this Special Issue. However, this subset of 43 key experiments is characteristic for the total 138 completed and ongoing experiments and gives a comprehensive picture of the whole Mont Terri research programme. The other experiments are documented in internal technical notes, technical reports, and publications. For a complete overview, we refer to the electronically provided supplementary material (Online Resources 8 and 9).

As stated above, we chose the following 20 papers to reflect the different stages of the evolution of a potential repository. This compilation is shown in Fig. 7, where the 43 key experiments in the Mont Terri rock laboratory are related to the three repository phases: initial conditions (orange), early time perturbations (green), and the transient to late time equilibrium phase (blue). The papers in this Special Issue are indicated with black boxes with white numbers and are repeated with the titles and authors in Table 3. Figure 7 also shows two features that are important for the repository evolution: (1) temporal temperature variations in the buffer (red curve), indicating the thermal loading of the disposal system by canister emplacement of highly radioactive waste with a temperature peak and its subsequent temperature decrease, and (2) temporal variations in the degree of buffer saturation (blue curve), indicating the continuous saturation of the bentonite buffer until the time when complete saturation of the buffer and Opalinus Clay in and around the emplacement tunnels is reached.

Alternatively, the 43 key experiments shown in Table 3 and Fig. 6 can be divided into observations over relevant timescales and experiments outside the

Table 3 List of scientific papers in this Special Issue and abbreviations of key experiments referred to in each paper, numbered in sequence, as shown in Fig. 7 (the detailed key experiment titles and its locations are given in Fig. 6)

#	Paper title	Key experiments	First author
Initial conditions			
1	Litho- and biostratigraphy of the Opalinus Clay and bounding formations in the Mont Terri rock laboratory (Switzerland)	**SO, SO-A**	Bernhard Hostettler (2017)
2	Tectonic evolution around the Mont Terri rock laboratory, northwestern Swiss Jura: constraints from kinematic forward modelling	**-**	Christophe Nussbaum (2017)
3	Tectonic structure of the “Main Fault” in the Opalinus Clay, Mont Terri rock laboratory (Switzerland)	**PS**	David Jaeggi (2017)
4	Comparative study of methods to estimate hydraulic parameters in the hydraulically undisturbed Opalinus Clay (Switzerland)	**DB, DB-A**	Catherine Yu (2017)
5	Geochemical signature of paleofluids in microstructures from Main Fault in the Opalinus Clay of the Mont Terri rock laboratory, Switzerland	**FI, SF**	Norbert Clauer (2017)
6	Pore-water evolution and solute-transport mechanisms in Opalinus Clay at Mont Terri and Mont Russelin (Canton Jura, Switzerland)	**WS-A/E/H/I, SF**	Martin Mazurek (2017)
Early time perturbations			
7	Geomechanical behaviour of Opalinus Clay at multiple scales: results from Mont Terri rock laboratory (Switzerland)	**EZ-B, HM**	Florian Amann (2017)
8	Hydro-mechanical evolution of the EDZ as transport path for radionuclides and gas: insights from the Mont Terri rock laboratory (Switzerland)	**HG-A, EZ-B, SE-H**	Paul Marschall (2017)
9	Coupled hydraulic-mechanical simulation of seasonally induced processes in the Mont Terri rock laboratory (Switzerland)	**CD, LP-A**	Gesa Ziefle (2017)
10	High-resolution mini-seismic methods applied in the Mont Terri rock laboratory (Switzerland)	**DM-B, EB, EZ-B, HE/HE-B, LT-A, RC, ST**	Kristof Schuster (2017)
11	Seismotectonic analysis around the Mont Terri rock laboratory (Switzerland): a pilot study	**SM-B, SM-C**	Martinus Abednego (2017)
12	In-situ experiments on bentonite-based buffer and sealing materials at the Mont Terri rock laboratory (Switzerland)	**EB, HE-D, HE-E, SB, SB-A**	Klaus Wieczorek (2017)
13	Performance of the Opalinus Clay under thermal loading: experimental results from Mont Terri rock laboratory (Switzerland)	**HE/HE-B, HE-D, HE-E, VE**	Antonio Gens (2017)
14	Implementation of the full-scale emplacement (FE) experiment at the Mont Terri rock laboratory (Switzerland)	**FE**	Herwig Mueller (2017)
From transient to late time equilibrium			
15	5-Year chemico-physical evolution of concrete-claystone interfaces, Mont Terri rock laboratory (Switzerland)	**CI**	Urs Maeder (2017)
16	Corrosion of carbon steel in clay environments relevant to radioactive waste geological disposals, Mont Terri rock laboratory (Switzerland)	**IC, IC-A**	Sophia Necib (2017)
17	Fifteen years of microbiological investigation in Opalinus Clay at the Mont Terri rock laboratory (Switzerland)	**MA, MA-A, PC, PC-**	Olivier X. Leupin (2017)
18	Impact of the electron donor on in situ microbial nitrate reduction in Opalinus Clay: results from the Mont Terri rock laboratory (Switzerland)	**BN**	Nele Bleyen (2017)
19	Natural gas extraction and artificial gas injection experiments in Opalinus Clay Mont Terri rock laboratory (Switzerland)	**HT, PC-C**	Agnès Vinsot (2017)
20	Exploring diffusion and sorption processes at the Mont Terri rock laboratory (Switzerland): lessons learned from 20 years of field research	**DI, DI-A, DI-B, DR, DR-A, FM-C**	Olivier X. Leupin (2017)

The first authors of the corresponding papers are indicated in the last column

observation window. To the first group belong experiments dealing with “initial conditions” such as host-rock characterisation, baseline monitoring, and feasibility experiments, such as construction of emplacement galleries and demonstration of full-scale emplacement. To the second group belong experiments designed to investigate long-term processes on timescales that are not directly accessible through conventional laboratory work. Good examples of this type are diffusion experiments where migration of radionuclides is studied under in situ conditions. The results yield robust transport parameters that are used to calibrate numerical models that simulate mass transport (advective–dispersive–diffusive and reactive transport). Once calibrated, these models can be used to make predictions of radionuclide migration released from a geological repository.

3.2.3 Rock laboratory and performance of geological repository

The question whether a rock laboratory like Mont Terri alone is sufficient to assess the performance of a geological repository at a real site can be clearly answered in the negative. As the geological situation at the proposed sites in northern Switzerland will be different (e.g. flat-lying Opalinus Clay with very few faults, different sub-units, confining rocks, stress situation, burial history etc.), additional site-specific investigations are required for developing a repository safety case. The Mont Terri project can, however, deliver strong arguments for a safety case through confident characterisation of properties governing repository evolution, such as the confirmation of diffusive mass transport as the governing transport mechanism in the

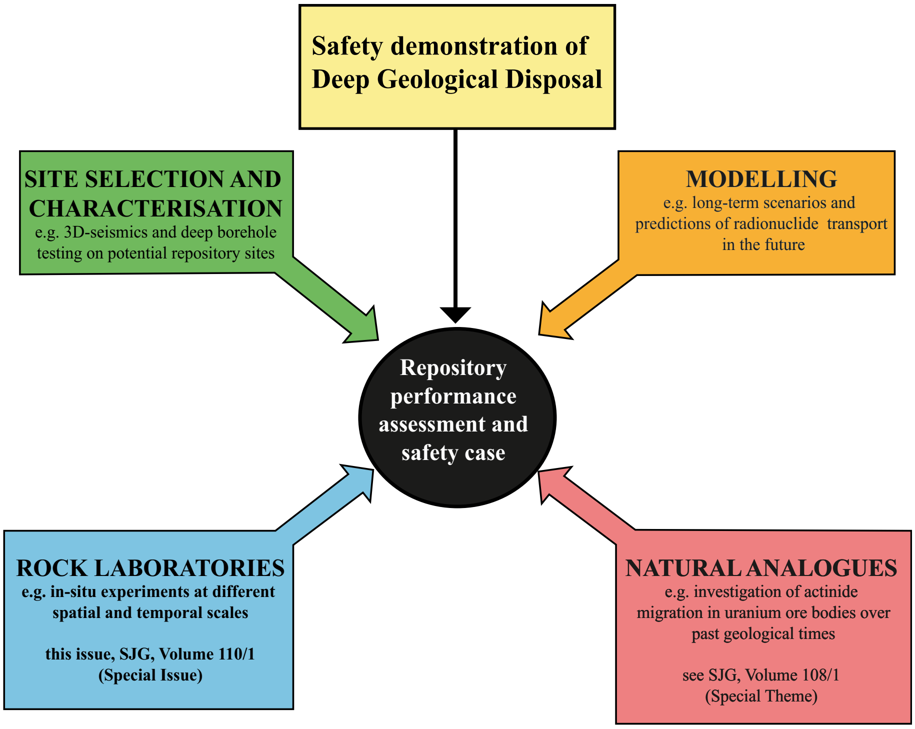


Fig. 8 Diagram showing the four principal contributors to the safety demonstration of a deep geological disposal

Opalinus Clay over different space and time scales. More information and investigations would be needed for an actual safety case, as e.g. the study of natural analogues (e.g. Alexander et al. 2015), testing of specific sites [with the intention of realising a repository, e.g. Nagra (2002, 2008)], and the entire palette of modelling to evaluate long-term scenarios and assess system performance (Fig. 8). Integrating all available information from real and analogue sites, including experimental results obtained from site-specific and generic rock laboratories, is thought to lead to reliable safety demonstrations for deep geological disposal and the development of an appropriate safety case.

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Appendix

Explanation of acronyms and abbreviations, which are used in this Special Issue.

Acronyms and abbreviations	Explanation
A	
ANDRA	Agence Nationale pour la gestion des Déchets Radioactifs, France (French National Radioactive Waste Management Organisation)
APHA	American Public Health Association
API	American Petroleum Index
AWWA	American Water Works Association

Acronyms and abbreviations	Explanation
B	
BDZ	Borehole damaged zone
BdZ	Borehole disturbed zone
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe, Deutschland (Federal Institute for Geosciences and Natural Resources, Germany)
BIB	Broad ion beam
BRGM	Bureau de Recherches Géologiques et Minières, France (French Geological Survey)
C	
CEC	Cation exchange capacity
Chevron	Chevron Corporation, USA
CRIEPI	Central Research Institute of Electric Power Industry, Japan
D	
DAS	Data acquisition system
DECOVALEX	Development of Coupled Models and their Validation against Experiments (project name)
DOE/LBNL	Department of Energy/Lawrence Berkeley National Laboratory, USA
E	
EBS	Engineered barrier system
EDZ	Excavation damaged zone
EdZ	Excavation disturbed zone
EMPA	Eidgenössische Materialprüfungs- und Forschungsanstalt, Schweiz (Swiss Federal Laboratories for Materials Science and Technology)
ENRESA	Empresa Nacional de Residuos Radiactivos S.A., España (Spanish National Radioactive Waste Management Organisation)
ENSI	Eidgenössisches Nuklearsicherheitsinspektorat, Schweiz (Swiss Federal Nuclear Safety Inspectorate, Switzerland)
EPFL	École Polytechnique Fédérale de Lausanne, Suisse (Swiss Federal Institute of Technology, Lausanne, Switzerland)
ESDRED	Engineering Studies and Demonstration of Repository Designs (EC project)
ESM	Electronic Supplementary Material
ETH	Eidgenössische Technische Hochschule in Zürich, Schweiz (Swiss Federal Institute of Technology, Zurich, Switzerland)
EURATOM	European Atomic Energy Community
F	
FANC	Federal Agency for Nuclear Control, Belgium
FEDRO	Federal Roads Office, Switzerland
FIB	Focused ion beam
FORGE	Fate of Repository Gases (EC project)
FOWG	Federal Office for Water and Geology, Switzerland (until 2005)
G	
Ga08	Gallery 2008 (Mont Terri rock laboratory)
Ga98	Gallery 1998 (Mont Terri rock laboratory)
GBM	Granulated Bentonite Mixture, but also Granular Backfill Material
GI Ltd.	Geotechnical Institute Limited, Switzerland
GPa	Gigapascal
GR	Gamma ray
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit gGmbH, Germany
H	
HDO	Hydrodeuteriumoxid
HLW	High level (radioactive) waste
HM	Hydro-mechanical
HSK/ENSI	Hauptabteilung für die Sicherheit der Kernanlagen (until 2008), Eidgenössisches Nuklearsicherheitsinspektorat (Swiss Federal Nuclear Safety Inspectorate, since 2009)
HTO	Tritiated Water
I	
IAEA	International Atomic Energy Agency, Austria
IC	Ion chromatography
ICP-AES	Inductively coupled plasma-atomic emission spectroscopy
ICP-MS	Inductively coupled plasma-mass spectrometry
ICP-OES	Inductively COUPLED PLASMA-OPTICAL EMISSION SPECTROSCOPY
ILW	Intermediate level (radioactive) waste
IRSN	Institut de Radioprotection et de Sûreté Nucléaire, France (French Institute for Radiological Protection and Nuclear Safety)
ISRM	International Society for Rock Mechanics
IVM	Interval velocity measurements
J	
JAEA	Japan Atomic Energy Agency, Japan
JU	Jura (Canton)
JU-cant. chemistry	Laboratoire cantonal jurassien accrédité (Chemical Laboratory of Canton of Jura, Switzerland)
JU-ENV	Office de l'Environnement, Canton du Jura (Office for the Environment, Canton of Jura, Switzerland)
JU-OEPN	Office des Eaux et de la Protection de la Nature, Canton du Jura (Office for Water and Protection of Nature, Canton of Jura, Switzerland)
JU-SIN	Service des Infrastructures, Canton du Jura (Office for Infrastructure, Canton of Jura, Switzerland)
K	
kPa	Kilopascal
L	

Acronyms and abbreviations	Explanation
LLW	Low-Level (radioactive) waste
LUCOEX	Large Underground Concept Experiments (EC project)
M	
Ma	Million years
meq%	Milliequivalent %
MPa	Megapascal
Myr	Million years (duration)
N	
Nagra	Nationale Genossenschaft für die Lagerung radioaktiver Abfälle, Schweiz (National Cooperative for the Disposal of Radioactive Waste, Switzerland)
Ni-en	Nickelethylenediamine solution
NNL	National Nuclear Laboratory, UK
NWMO	Nuclear Waste Management Organisation, Canada
O	
OBI	Optical borehole imager
OECD-NEA	Organisation for Economic Co-operation and Development-Nuclear Energy Agency
OPC	Ordinary Portland cement
P	
PEPS	Long-term performance of the Engineered Barrier Systems (EC project)
Q	
R	
RH	Relative humidity
RWTH-Aachen	Rheinisch-Westfälische Technische Hochschule—Aachen, Deutschland (Technical University, Aachen, Germany)
S	
SCK.CEN	Studiecentrum voor Kernenergie, Belgium (Belgian Nuclear Research Centre)
SEM	Scanning electron microscopy
SF/HLW	Spent Fuel/high level waste
SFOE	Swiss Federal Office of Energy
SGR	Spectral Gamma ray
SGS	Swiss Geological Survey
SJG	Swiss Journal of Geosciences
SNHGS	Service National Hydrologique et Géologique, Suisse (former Swiss Geological Survey, until 2005)
SRB	Sulphate-reducing bacteria
STP	Standard temperature and pressure
swisstopo	Bundesamt für Landestopografie (Federal Office of Topography, Switzerland)
T	
TDR	Time-domain reflectometry
TDS	Total dissolved solids
TEM	Transmission electron microscopy
TH	Thermo-hydraulic
THM	Thermo-hydro-mechanical
THMC	Thermo-hydro-mechanical-chemical
TIC	Total inorganic carbon
TIMODAZ	Thermal Impact on the Damaged Zone (EC project)
TOC	Total organic carbon
U	
URF	Underground Research Facility
URL	Underground Research Laboratory
V	
W	
wt%	Weight percent
X	
XRD	X-ray diffraction
XRF	X-ray fluorescence
Z	
ZH-AWEL	Amt für Abfall, Wasser, Energie und Luft, Kanton Zürich (Office for the Environment, Canton of Zurich, Switzerland)

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