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Coupled thermo-hydro-mechanical processes in the near field of a high-level radioactive waste repository in clay formations

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ABSTRACT

The present paper provides an overview of key coupled thermo-hydro-mechanical (THM) processes in clay formations that would result from the development of a high-level radioactive waste repository. Here, in this paper, clay formations include plastic clay such as the Boom Clay of Belgium, as well as more indurated clay such as the Callovo-Oxfordian and Upper Toarcian of France and Opalinus Clay of Switzerland. First, we briefly introduce and describe four major Underground Research Laboratories (URLs) that have been devoted to clay repository research over the last few decades. Much of the research results in this area have been gained through investigations in these URLs and their supporting laboratory and modeling research activities. Then, the basic elements in the development of a waste repository in clays are presented in terms of four distinct stages in repository development. For each of these four stages, key processes and outstanding issues are discussed. A summary of the important areas of research needs and some general remarks then conclude this paper.

1. Introduction

Clay-rich rock, under consideration as host rock for nuclear waste repositories, is a transitional material, with properties intermediate between soils and hard rock. Its properties are sensitive to water content, behaving as brittle rock at low values of water content and as ductile soft material at high values. Clay formations are considered to be well suited for hosting radioactive waste repositories in a number of European countries, because of their very low hydraulic conductivity and potential for self-sealing (of openings or gaps in formations). Clay minerals also provide good sorption capacity for the retardation of radionuclide transport. The features, events, and processes associated with radioactive waste disposal in clays have been cataloged and evaluated [1] under the auspices of the Nuclear Energy Agency. Much progress in the study of clays has been reported in a series of major international meetings in Reims [2], Tours [3], Lille [4], and most recently in Nantes [5].

The present paper provides an overview of key coupled thermo-hydro-mechanical (THM) processes in clay formations associated with the development of a high-level radioactive waste repository and discusses currently open issues. Here, clay formations include plastic clay such as the Boom Clay of Belgium, as well as more indurated clay such as the Callovo-Oxfordian and Upper Toarcian of France and Opalinus Clay of Switzerland. In the next section, four underground research laboratories (URLs) in clay formations that have been in operation over the last few decades are introduced and described. From these URLs, we have obtained extensive research results regarding the behavior and potential evolution of clay repositories. Then, the basic elements for implementing a nuclear waste repository in clays are presented in terms of the different stages in repository development. The following sections discuss the key processes and outstanding issues specific to each stage. A summary of research needs and some general remarks then conclude this paper.

2. A brief overview of major URLs for clay repository research

In this section, we shall briefly introduce four major underground research laboratories (URLs) that have been devoted to clay repository research over the last few decades. Since many of the research results in this area have been gained through these URLs and their supporting laboratory and modeling activities, this brief introduction will facilitate references to these sites when discussing clay processes and behavior in later sections of this paper. Representative properties of the rocks and conditions in the URLs

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are summarized in Table 1. The property values of these sites can be very different from each other, because of their different sedimentology history giving rise to different clay types and contents; different ages giving rise to different chemical consolidation; and different tectonic history and mechanical compaction.

The first is the HADES (High Activity Disposal Experimental Site) URL excavated at 223 m depth in Boom Clay, a tertiary clay formation in Mol, Belgium. Since its construction in 1980, many experimental investigations have been conducted at the site. Fig. 1 shows the construction history of the HADES facility. The main tunnel is about 200 m in length, with an internal diameter averaging about 4 m, from which experiments were conducted in boreholes and side galleries. An extensive summary is provided by Bernier et al. [6].

Of particular interest is the Praclay Gallery constructed in 2007, in which a Seal Test and a Heater Test are initiated in 2010 and 2011, respectively. The layout of the gallery is shown in Fig. 2. The Heater Test involves heating a 30 m long gallery section for 10 years with many monitoring sensors, for the purpose of investigating the thermo-hydro-mechanical (THM) behavior of plastic clay under the most “penalizing” conditions that may occur around a repository [7,8]. In particular, an (almost) impermeable boundary condition will be imposed at the gallery/clay interface during heating. To this aim, the heated section of the gallery will be fully saturated before starting the heating, and a hydraulic seal will be installed to separate the heated from the unheated sections of the gallery. This installation makes up the Seal Test, which was conducted in 2010, and enabled testing of hydraulic seal functionality under heated repository conditions.

The second major URL is the French facility in Bure, at the border between Meuse and Haute-Marne, about 300 km east of Paris. Its construction started in 2000, with a target horizon for the URL between 420 m and 550 m deep in argillaceous rock (Fig. 3). The first experimental facility was completed in 2005 [10]. Key details regarding the work on the Bure URL can be found in Delay et al. [11], Armand et al. [12] and Wileveau et al. [13].

The third major URL is the Mont Terri Facility in northwest Switzerland, located in an argillaceous formation known as Opalinus Clay. This is a generic research facility not located at a potential future repository site. Construction of the facility in conjunction with a motorway tunnel started in 1987, and research activities of the Mont Terri project were initiated in

Table 1
Summary of rock properties and in situ conditions of four URLs located in clays.

Location	Mol (Belgium)	Mont Terri (Switzerland)	Bure (France)	Tournemire (France)
Rock formation	Boom Clay	Opalinus Clay	Callovo-Oxfordian argillite	Toarcian argillite
Age	Rupelian 30 Ma	Aalenian 170 Ma	Callovo-Oxfordian 155 Ma	Upper Toarcian 185 Ma
Water content [%wt, loss at 105°]	22–27	6.6	7	3–4
Porosity [%]	39	16	18	7–8
Clay content [%wt]	23–59	66	55	55
Isotropic hydraulic conductivity [m/s]	2.4×10^{-12}	2×10^{-13}	5×10^{-14}–5×10^{-13}	10^{-15}–10^{-14}
UCS normal to bedding [MPa]	2	15	21 ± 6.8	32
Overburden in the rock lab [m]	233	250–320	495	250

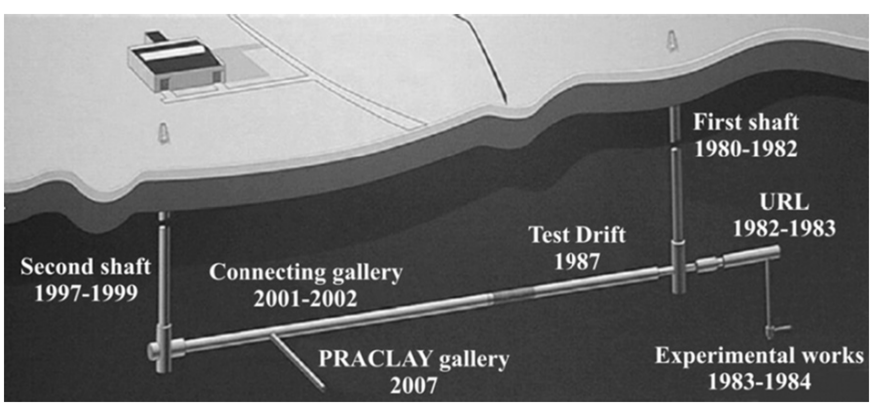

Fig. 1. Construction history of the HADES URL [6].

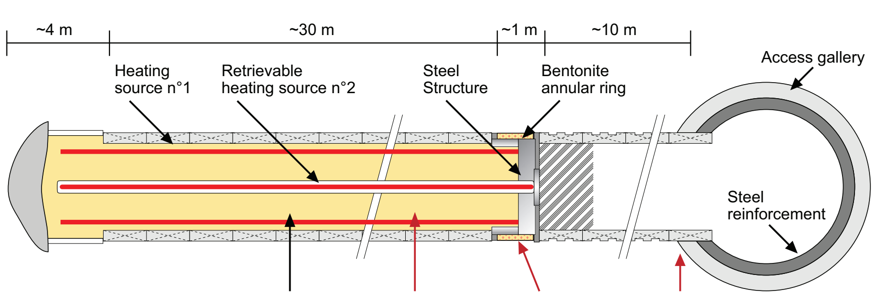

Fig. 2. Layout of the Praclay In-Situ Experiment constituted of the Gallery and Crossing Test, the Seal Test, and the Heater Test [9].

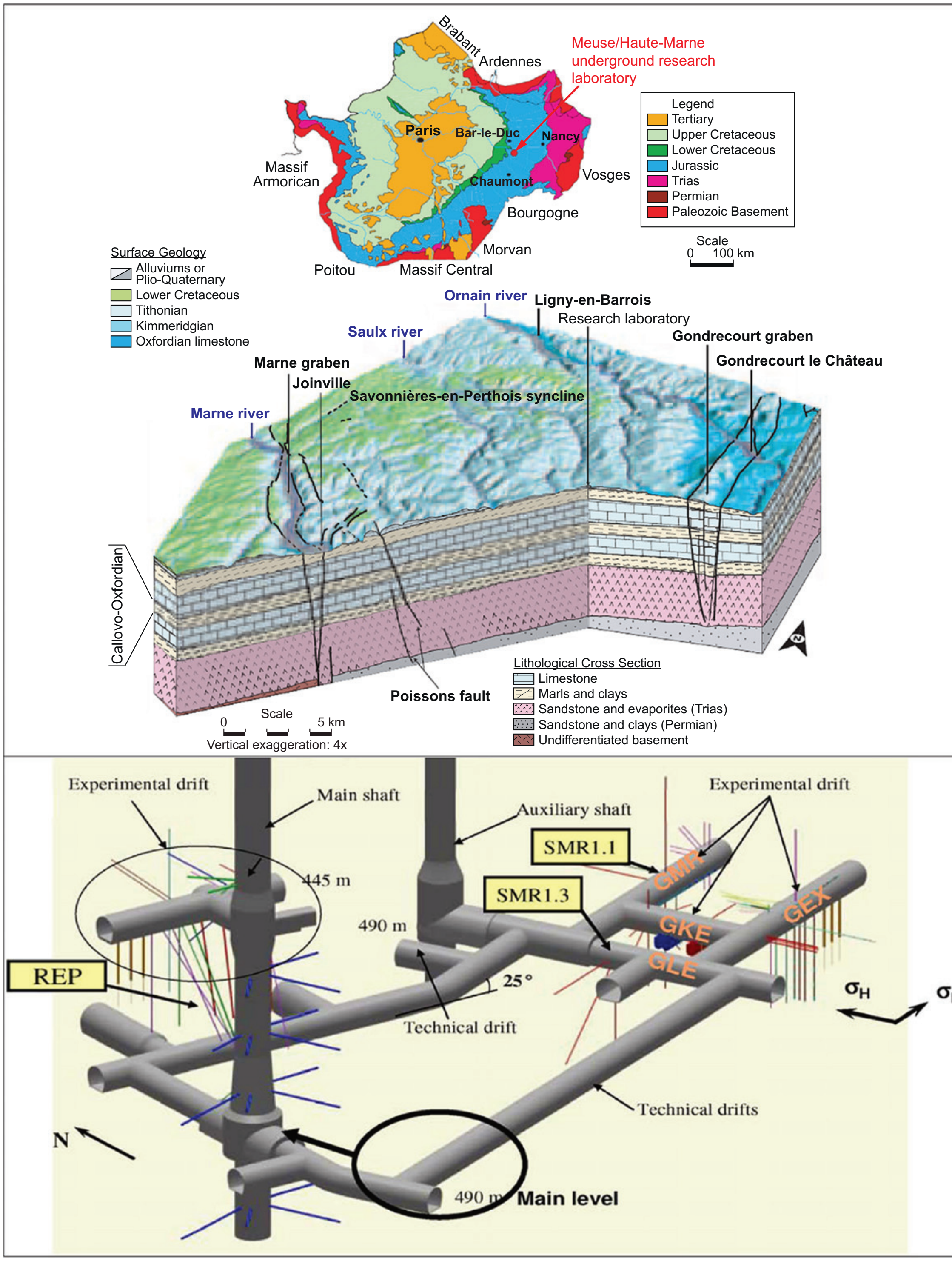

Fig. 3. General view of the Meuse/Haute-Marne URL [22].

1996. Fig. 4 shows the layout of the URL, with different experimental areas known by their initials. A summary of project activities with 78 individual experiments may be found in Bossart and Thury [14].

The fourth URL is the Tournemire Site in the south of France, which is also a generic research facility not located at a future repository site. This URL geological setting is characterized by a 250 m thick subhorizontal indurated argillaceous layer. A railway tunnel, constructed in 1881 through the argillaceous formation, is 1.8 km long, 6 m high and 4.7 m wide, and was excavated using a pneumatic tool. In 1996, two 30 m long, 3.7 m high, and 4 m wide horizontal tunnels were excavated off the main railway tunnel. Then, in 2003, another 40 m long horizontal tunnel was excavated (Fig. 5). Thus, this facility enables study of near-field rock behavior in indurated clay with different time periods of exposure to the atmosphere, namely 129, 14, and 7 years, respectively [15–18]. In 2008, this URL was extended with the excavation of two additional galleries (Fig. 5) to conduct a new series of experiments [19].

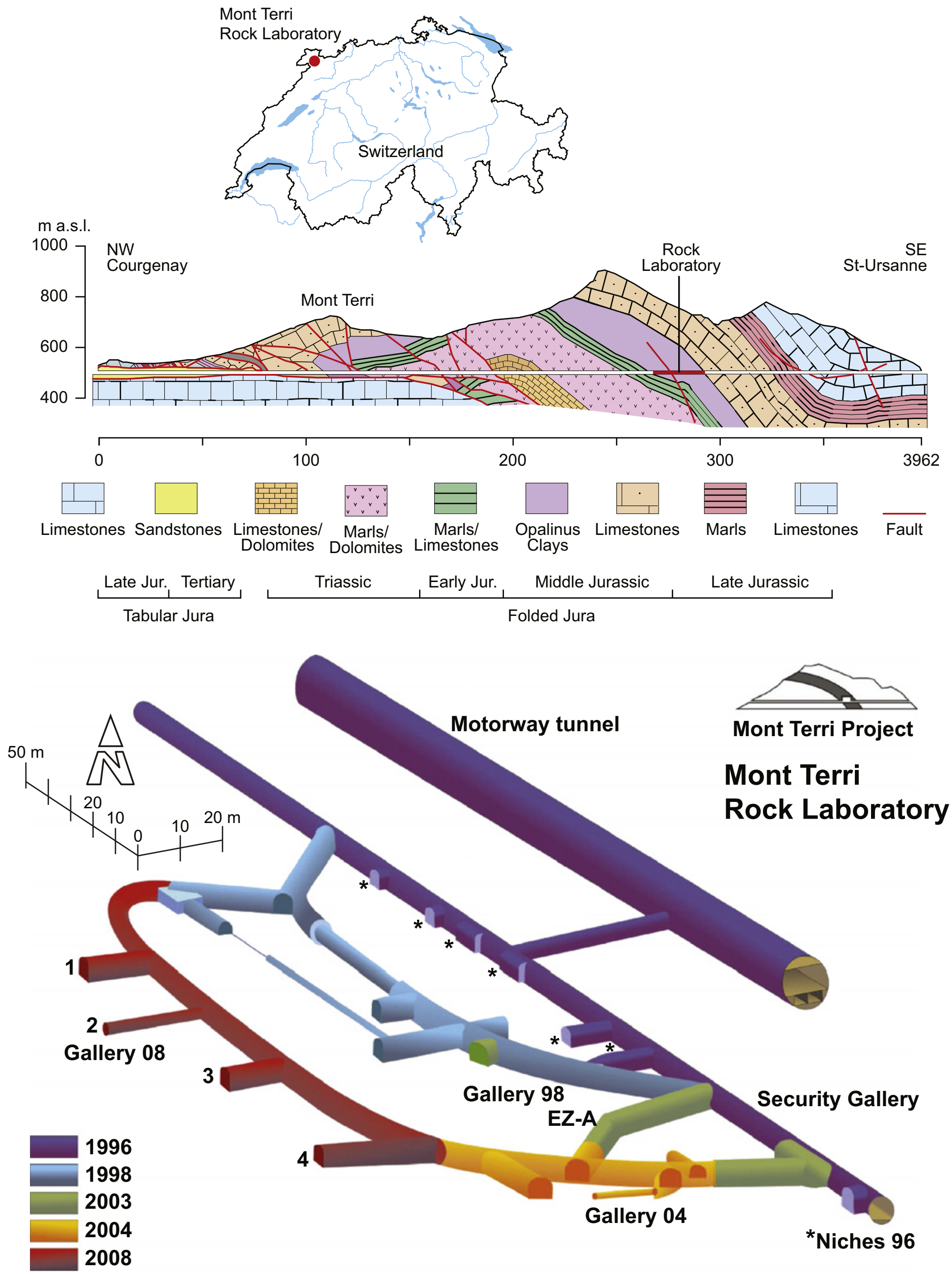

Fig. 4. Geological cross-section (upper) and layout (lower) of the Mont Terri URL.

3. Four stages in the development of a waste repository in a clay formation

The development of a geological repository for radioactive waste can be subdivided into four periods. The first period of repository development may be defined as the disposal tunnel *construction stage*, which extends from tunnel excavation to a few days after lining installation.

The second period, here called the *open drift stage*, lasts from installation of lining and supports to emplacement of waste and buffer materials. Then there is the third period, named here as the *exploitation stage*, which marks the start of the strong perturbation due to the decay heat generated by the radioactive waste—this stage lasts until repository closure. In this third stage, as waste packages are being emplaced in tunnels, deposition holes or chambers, these openings are also backfilled with materials. Both the buffer and backfill materials are partially saturated initially, and then, over time, they become gradually saturated with water from the surrounding rock. Thus, thermal effects must be considered under both unsaturated and saturated conditions. Finally, the fourth period is the *long-term postclosure stage*, which is the basic period of concern for long-term performance and safety assessment. The near-field rock behavior during this stage depends on the processes and effects that occurred during the previous three stages. All stages together influence the long-term characteristics of the rock mass near repository tunnels, which in turn define the transport behavior of radionuclides that will eventually be released from waste canisters.

The key processes and issues defining near-field clay behavior and its evolution during these four stages will be discussed in the following sections. In contrast to hard rock (like granite), clay is significantly perturbed by excavation and humidity changes,

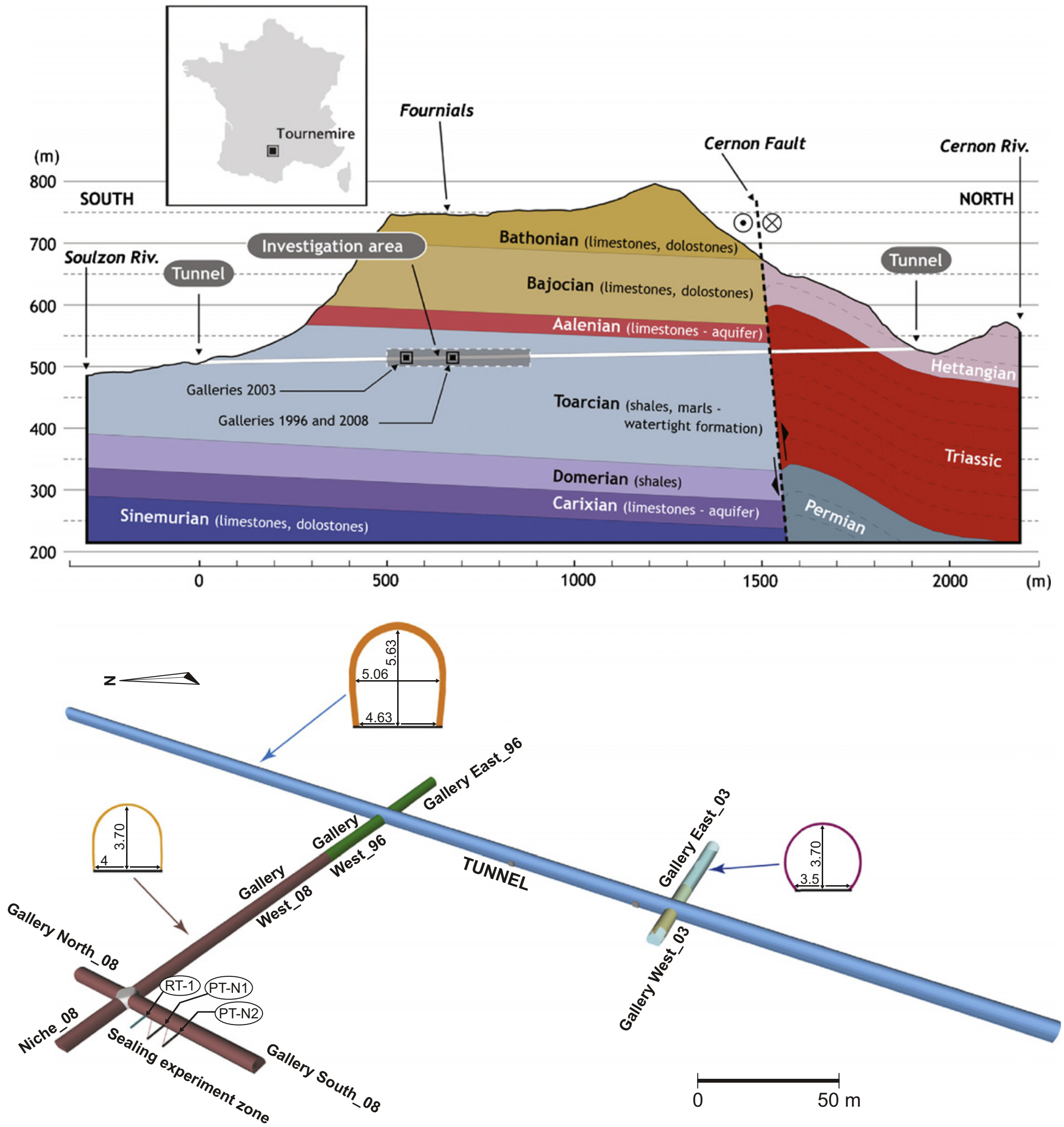

Fig. 5. Geological cross section of the Tournemire URL (top) and locations of the galleries and boreholes (bottom).

so that many processes and issues need to be considered in the early stages. However, the hydrogeological system should be more stable, with fewer issues of concern, at later stages.

In addition to the evolution of near-field clay behavior, open research questions related to radionuclide transport in clay materials still exist, such as the importance of transport in the excavation-damaged zone, the prediction of diffusion behavior in nanoporous materials, and/or the reactive-diffusive transport characteristics. These are not discussed in the present paper.

4. Key processes and outstanding issues during the construction stage

The construction stage represents a major perturbation of the clay formation, with the creation of new openings in the subsurface rock and new hydromechanical boundary conditions. The stress field is redistributed around the tunnel, and the tunnel surface is free to move inward until restrained by tunnel lining and support.

Depending on the strength of the rock mass and on the *in situ* stresses, excavations in clay formations may require timely installation of support and lining, even at comparatively shallow depths. The need for support measures is related to rock-mass strength and stress at the excavation depth. For example, in the weak, high porosity Boom Clay (2 MPa UCS, 39% porosity), specific excavation equipment was required for constructing the Mol URL at a depth of 233 m. As the excavation face moved forward, emplacement of concrete lining followed behind the shield after a short unsupported section that allowed observation of how excavation and stress redistribution affected the rock. Indurated rocks like the Opalinus Clay at Mont Terri can be excavated at a similar depth (280–300 m) with only light support. Here, 10–15 cm thick shotcrete is sufficient to ensure the stability of galleries and niches. Short niches are stable even without any support. In the Tournemire URL, excavation works actually do not require any support. However, in the Callovo Oxfordian argillites at the Bure site, excavation works at 490 m depth require combining several support techniques, including shotcrete, bolting, and steel arches, to control the convergence. The efforts to control convergence during tunnel excavation, the amount of excavation-induced damage, the amount of support work, and the character of the tunnel excavation phase are closely dependent on the depth of excavation and the local rock mass strength.

In general, excavation induces a multiprocess coupled response in the rock around the tunnel. Rock movements resulting from excavation induce a volumetric deformation of the pore space which, when coupled with the low rock hydraulic conductivity, gives rise to strong pore-water pressure variations that will then dissipate slowly. These pore-pressure changes have a significant influence on the effective stress state in the rock and may contribute to failure processes. Such pressure changes have been measured many tunnel diameters away from the tunnel wall, and these changes can last for months. An example of such a case may be found in one recent experiment at Mont Terri (Figs. 6 and 7), where it was found that pore pressures along a predrilled borehole increased with excavation time and then dropped essentially to zero when the tunnel came close to the measurement points [20]. The sharp drops were caused by stress redistribution in the rock from the unloading during mine-by, leading to de-stressing of the rock and the pore space. Similar observations have been reported at the Tournemire URL during excavation of the 2003 gallery [21], and at the Bure URL in the REP and SUG mine-by-tests [22]. Sharp changes in pore pressure were also observed in the Boom Clay following excavation. In that case, dilation caused by unloading (decreased volumetric stress) led to suction and negative pore pressure that could not be recorded by piezometer filters. Then at some point, cracks formed and the measured pressure increased abruptly from zero to atmospheric pressures [6].

During this stage, moreover, the anisotropic nature of the sedimentary rock has a considerable influence on rock behavior and potential failure processes. This anisotropy is a result of mineralogical variability (different proportions of sedimentary constituents) and/or preferred orientation of grain shapes resulting from sedimentation and compaction. Bedding planes may be further weakened by tectonic processes, as in the Mont Terri URL [23]. In short, the entire geological evolution at the site—including sedimentary processes, compaction, cementation during burial, tectonic processes, and unloading during erosion of the overburden—influences the rock-mass properties, including anisotropy. For example, the brittleness of the rock is related to the overconsolidation ratio, which is the ratio of the present overburden to the maximum overburden reached during the geological past.

Creating the underground opening also influences the rock-mass properties. The region adjacent to the tunnel rock may change from water-saturated to unsaturated conditions (or at least suction can develop), which can change rock behavior from plastic to brittle [24]. A suction increase may result in a pseudo-cohesion effect that may enhance rock strength. Generally, the evolution of suction in the near field of a tunnel is an important open research issue.

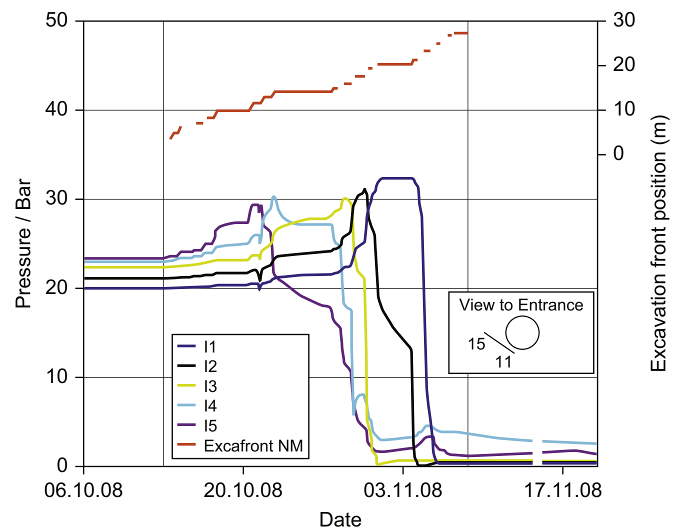

Fig. 7. Pore-water-pressure evolution in the northern sidewall of the MB Tunnel [20].

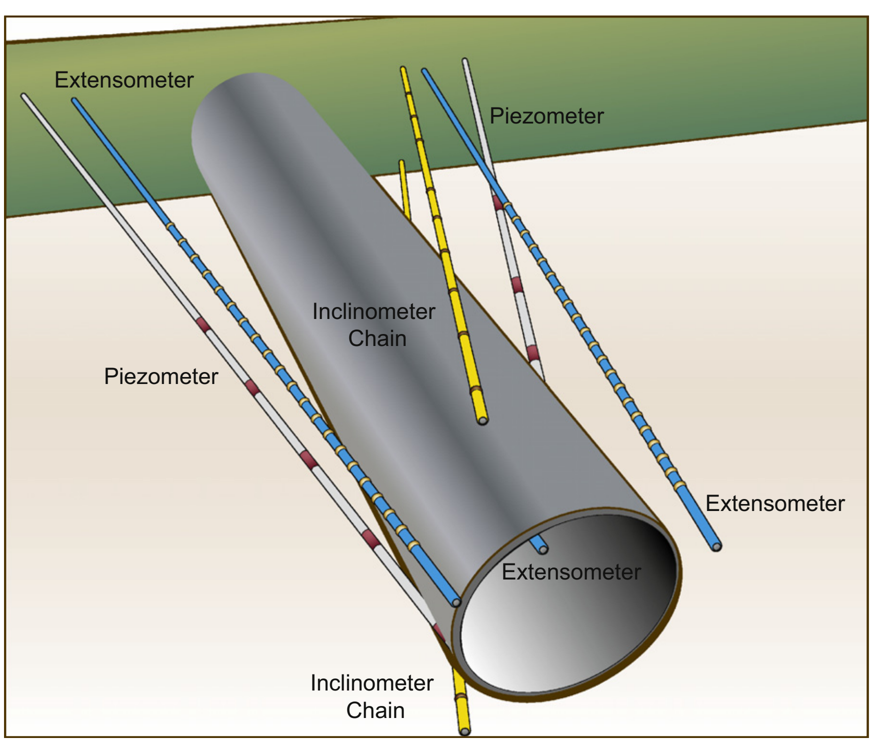

Fig. 6. Sensor array (not all shown) at the Mine-By (MB) Tunnel at Mont Terri URL [20]. The MB tunnel is 4.7 m in diameter and 24 m long.

Of particular interest to long-term repository safety is the potential creation of an excavation damaged zone (EDZ) around the tunnel and how it evolves over time [25,26]. This damaged zone represents a region of enhanced permeability caused by a porosity increase or the creation of tensile or shear fractures [27–36]. An initial increase in permeability of five orders of magnitude has been measured at Mont Terri. A similar magnitude increase was measured at Bure URLs (4–5 orders; see [12]) and Tournemire (5–6 orders around the 1996 and 2003 galleries; see [37]), whereas at Mol a two-orders-of-magnitude increase was observed by the time the first measurements were made. However, this effect decreases over time because of clay swelling and clay creep behavior, especially in cases where swelling refill materials are used to provide a back pressure on the rock [38–40]. Figs. 8–10 show EDZ patterns around tunnels at Mol in Belgium, Bure in France, and Mont Terri in Switzerland, respectively. Fig. 8 shows an inferred herringbone structure of fractures around a tunnel in plastic clay extending 1 m in the radial direction and 6 m axially forward of the tunnel front face. The fracture spacing is about 0.5 m. Some theoretical and numerical models have been developed in an attempt to simulate such a pattern and the processes leading to it. Similar patterns are also found in stiff clay at Bure, as shown in Fig. 9 [22]. At Mont Terri, permeability measurements [23] around the tunnel show many orders-of-magnitude increases (Fig. 10).

The EDZ extent and intensity do not depend simply on whether the clay is plastic or stiff (as at Mol or at Bure, respectively), but on other rock properties, including variability and heterogeneity, the anisotropy of the stress field, the over-consolidation ratio, and the presence of bedding planes [41–48].

To some degree, site-specific design can reduce the extent of the EDZ and can modify the axial connectivity of the fracture network. Such design includes the choice of excavation method, size and shape of tunnels, and the orientation of tunnels relative to stress anisotropy and to the direction of pre-existing planes of weakness (bedding planes). The choice of tunnel support system, considering factors such as its stiffness, thickness, setting time and distance from the excavation front, is also relevant, serving to reduce tunnel convergence and decrease deviatoric stresses at the excavation contour. It is important to control dilatant processes in the rock as much as possible, so as to reduce EDZ formation and to allow resealing of EDZ fractures after backfilling.

Modeling of construction-induced effects in the far field has been shown to be feasible in clay-rich host rock using advanced THM coupled codes [49]. In contrast, the modeling of the excavation process, and the formation and evolution of the EDZ, is very challenging. This is intrinsically a three-dimensional problem involving tunnel orientation, direction of bedding planes, and the anisotropic stress field present at the site. A coupled hydro-mechanical elasto-visco-plastic damage framework may be needed to reproduce the changes in pore-water pressure. Modeling of the EDZ extent depends on the constitutive law used with its choice of the elastic limit and fracturing criteria. Some strain-softening formulation may also be needed to reproduce the progressive change in material strength during excavation, as well as strain localization and shear band occurrences. It is important to ensure that modeling results are not mesh dependent and indeed represent the physics of the involved processes [50].

Open research issues include scale effects in adopting laboratory-measured rock properties to the study of site behavior, methods to limit damage to samples, and changes in sample hydraulic conditions from *in situ* to laboratory environments. At the very least, such damage and such changes should be understood and quantified. Towards this end, some very useful micro-computerized tomography pictures have been produced [51]. Furthermore, measurements of *in situ* anisotropy stress fields at locations of interest remain a challenging problem. There are also significant uncertainties with respect to damage mechanisms: onset of discontinuities in clay and their propagation, interactions with existing discontinuities or bedding planes, bond failure at the microscale, slip and extension along weakness planes, suction-induced fracturing, and creep processes. So far, no single set of consistent or complementary models has been able to reproduce the full hydromechanical behavior of the excavation process, including fracture development, suction effects, sealing processes, and permeability changes.

5. Key processes and outstanding issues during the open drift stage

This stage may be defined as the period between completion of excavation and lining installation and the emplacement of waste and buffer, and may last from a few months to a few years. During this period, the rock wall is in contact with the atmosphere in the

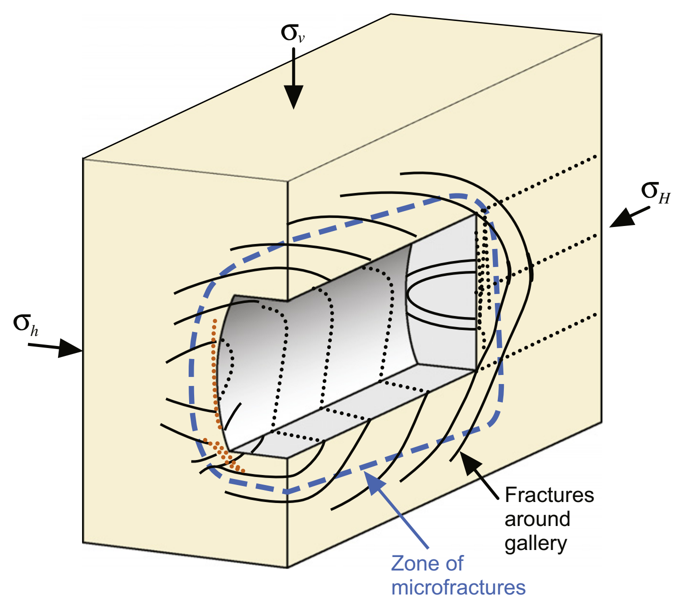

Fig. 9. Herringbone patterns observed at the Bure site in the gallery parallel to σ_H [22].

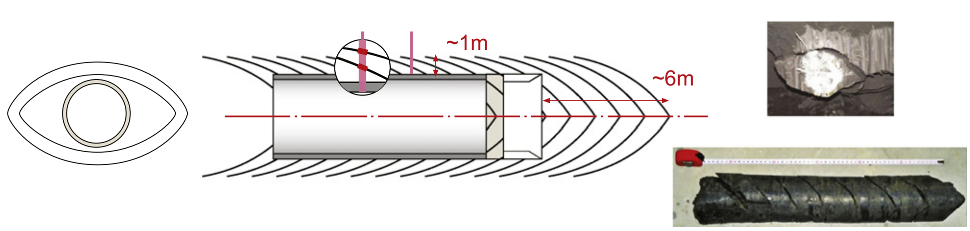

Fig. 8. Fracturation pattern around a gallery: cross section perpendicular with gallery axis (left); and vertical cross section parallel to gallery axis (center), and also around a resin-immobilized borehole (top right) and of a retrieved core (bottom right) (adapted from [6]).

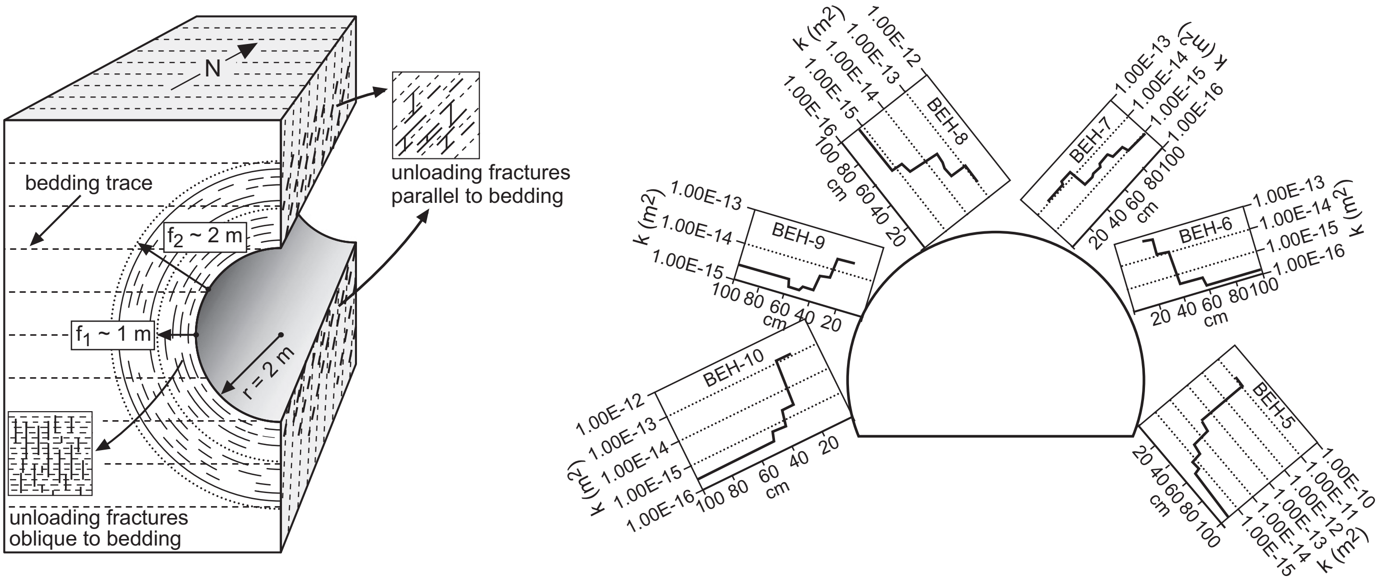

Fig. 10. Conceptual model of the excavation damage zone in Opalinus Clay excavated normal to bedding strike (left); and hydraulic conductivity distribution around the gallery derived from pneumatic testing (right) [23].

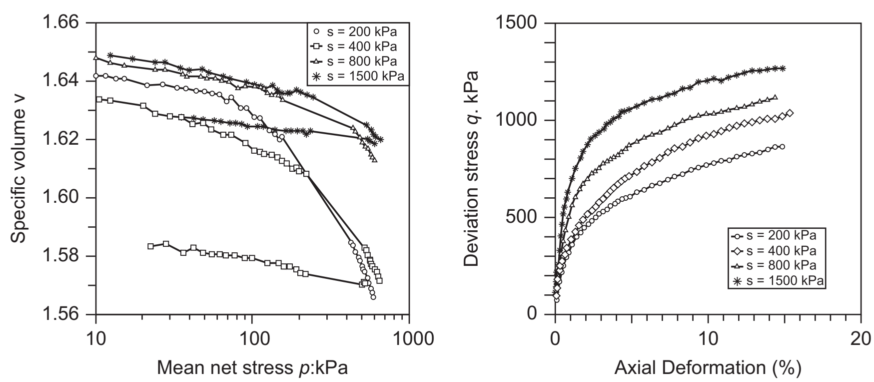

Fig. 11. Suction effects on the volumetric (left) and deviatoric (right) behavior of clayey soil [52], with suction s varying from 200 to 1500 kPa.

tunnel, either directly or through the tunnel lining. The atmosphere, with its (generally lower) humidity, imposes a new hydric condition at the tunnel wall (or the lining, with its own permeability and air entry pressure), changing the local effective stress. Importantly, this condition is not a simple equilibrium between the relative humidity in the air and in the host rock, because the hydric transfer processes depend on several factors such as air velocity and skin behavior. Issues concerning the rock-lining-atmosphere interface remain an open research problem.

Tunnel ventilation and temperature changes may have a strong influence on rock properties, since they may cause desaturation in the near field. Desaturation, in turn, gives rise to capillary forces and hence an increase in rock cohesion and strengthening, while at the same time it increases tensile stress and the potential for bond failure, and furthermore may also change the degree of property anisotropy. One example of suction effects on the volumetric and deviatoric behavior of clayey soil is shown in Fig. 11.

A ventilation experiment (VE) was carried out at the Mont Terri URL, with the objective of understanding and evaluating the desaturation process of the clay tunnel wall subjected to flows of air with different humidity levels [53]. The experiment was conducted in a 10 m section of an unlined horizontal tunnel with a diameter of 1.3 m, and monitored with 86 sensors to measure rock water potential, water content, temperature, and displacement. The injected ventilation air had a humidity of 30% for 2 months, then 1–3% for 5 months, and finally 100% for 3 months. Under these conditions, with a rock permeability of 10^{-20} m^2 (at full saturation), desaturation was found to occur in the clay rock near the tunnel within a thickness of less than 30 cm.

Increases in humidity in the tunnel air can cause clay swelling and rock softening in the rock next to the wall. The former may increase compressive stresses, leading to additional damage to the softened rock. Cyclic seasonal changes in humidity and temperature over a number of years may lead to loss of rock cohesion and generate discontinuities. Fig. 12 shows the results of EDZ characterization at the Tournemire URL, where tunnel sections excavated in 1881, 1996, and 2003 are compared. They display different fracture patterns [15,16] that likely resulted from different mechanisms. Attempts to model such observations were made by Massmann et al. [18] and Rutenberg et al. [54].

Fractures may close and seal, with a recovery of low permeability by clay deformation and moisture-induced swelling. This is an important process for repository safety, because it induces a decrease in EDZ permeability. A number of studies have been conducted to investigate swelling behavior and permeability evolution [38,39,55–58].

Creep occurs especially in plastic clay, but also in indurated clay, possibly leading to long-term tunnel convergence for unsupported tunnel walls and to an increase in the EDZ extent. For walls supported by rigid linings, a large back-pressure may build up on

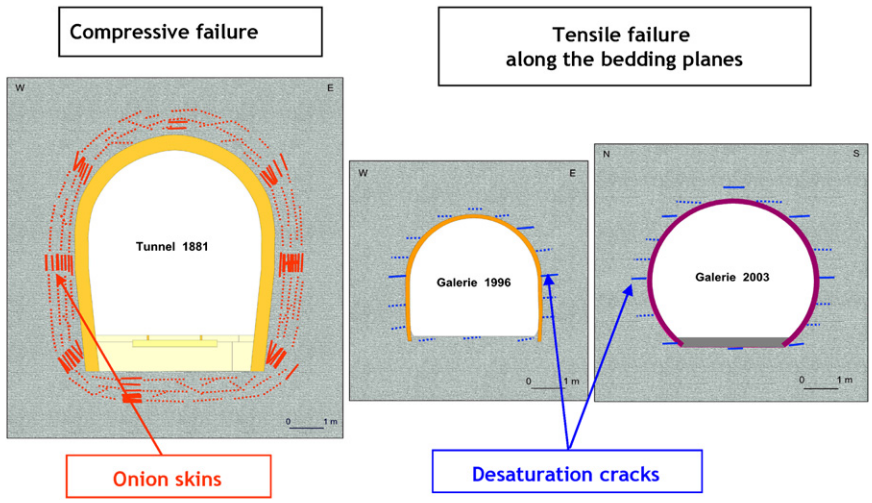

Fig. 12. Types of rock-mass failure around the different drifts at the Tournemire URL (adapted from [16]).

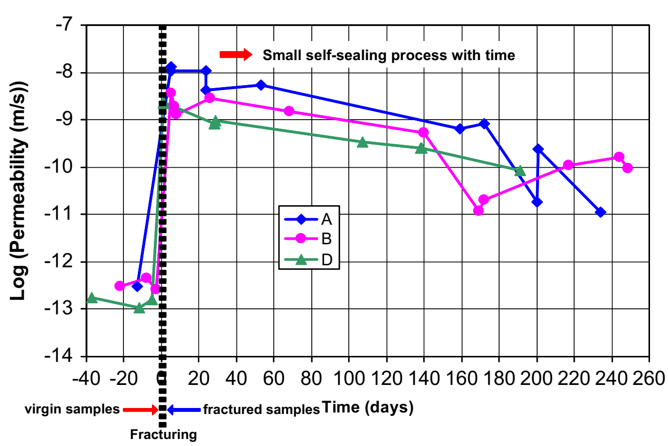

Fig. 13. Evolution of hydraulic conductivity with time in fractured Opalinus Clay samples under confined conditions [60].

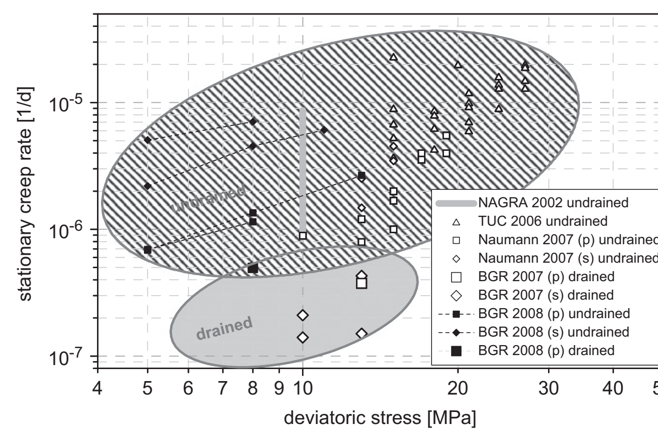

Fig. 14. Comparison of measured creep rates on Opalinus Clay samples [61].

the support, with stress recovery in the rock and a resulting fracture sealing. A number of studies have been conducted to investigate sealing of fractures (e.g., [59,60]). Fig. 13 shows results from a set of laboratory experiments on fractured Opalinus Clay samples from Mont Terri conducted under confined conditions, which correspond to the postclosure stage. After deliberate fracturing, creep-induced fracture closure is shown as a slow reduction of hydraulic conductivity over a period of 200 days. The creep rate of Opalinus Clay from the Mont Terri URL was also measured [61] as a function of deviatoric stress for undrained and drained samples (Fig. 14). Generally, the creep rate can be an order of magnitude larger for undrained than for drained conditions.

Operationally, careful control of air humidity in the tunnel during this period is important for a clay repository. For example, the humidity should perhaps be maintained at a reasonably high percentage value without significant cyclic changes.

Outstanding research issues and challenges include the limitation of laboratory measurements when studying of slow processes such as creep, as well as the need to model complex time-dependent behavior, such as slow pore pressure dissipation and subcritical microfracturing under saturated–unsaturated conditions. Clay–rock mechanical behavior is also sensitive to moisture content, local geochemistry, and temperature. As a consequence, laboratory experiments on these materials require a considerable effort to control temperature, fluid pressure, surface suction, and fluid composition.

6. Key process and outstanding issues during the exploitation stage

At this stage, waste emplacement represents the start of a period of thermal perturbation within the repository environment. Decay heat from radioactive waste has to diffuse away through the buffer and the near-field rock to the far field (though initially before repository closure, the heat release through the open ventilated drifts will be significant). Resaturation is a slow process governed by low rock permeability and buffer characteristics, and will not be uniform over the repository domain. Heating will lead to steam convection in the inner region of the desaturated repository near field. Further, heating will generate transient pore-pressure buildup resulting from differential thermal expansion, leading to changes in effective stress state. Heating may affect some relevant processes discussed in the previous section, e.g., possibly changing creep rate and strength. Studies addressing heating effects using laboratory measurements and field tests include those by Collin et al. [62], Delage et al. [63], Zhang et al. [64], Gens et al. [49], Sultan et al. [65], Tang et al. [66], Cui et al. [67], and Sillen et al. [68].

Fig. 15 shows the layout of the heater experiment HE-D at Mont Terri URL [69,64]. Two heaters with a combined length of 6 m were emplaced in a horizontal borehole of 30 cm in diameter and 14 m in length. The clay rock was heated up to 100 °C, and the temperature, pore-water pressure, gas migration, and deformation in the clay rock were monitored with 110 probes around the heaters. At distances of 0.8–1.4 m from the heaters, pore-water

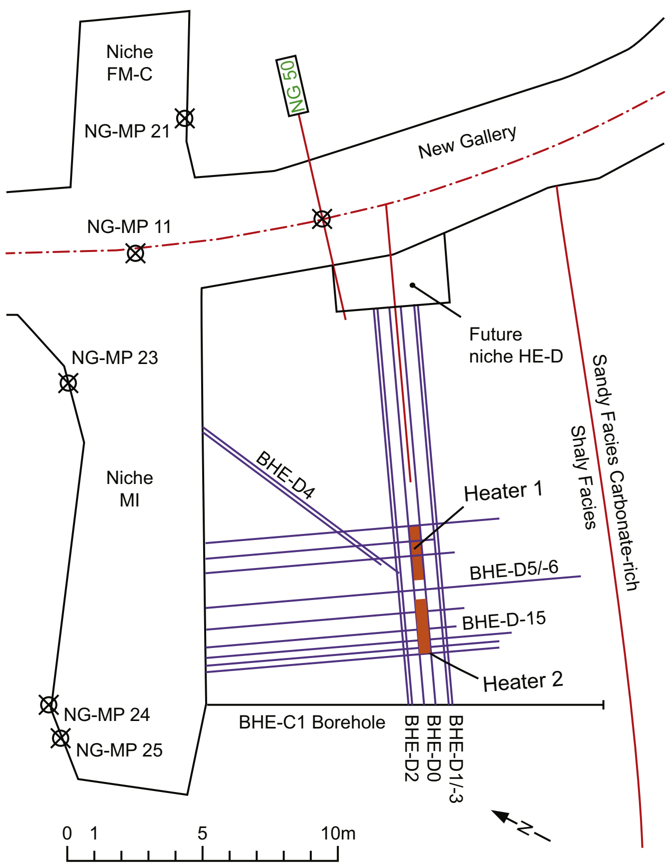

Fig. 15. Layout of HE-D heater experiment at Mont Terri URL [64].

pressure rise of 1–4 MPa was measured and a high gas pressure of 2 MPa was recorded. Thermally induced rock deformation was also monitored, but no macrofractures were generated in the rock.

In this experiment, the very complex THM processes occurring in the clay rock were reasonably reproduced by coupled model calculations. Zhang et al. [69] suggested that there is a need to further investigate (1) the long-term deformation and damage of clay rock under the high-temperature conditions expected around a repository, (2) the swelling behavior (strain–pressure–suction relationship) of heated clay rock caused by rehydration under wet conditions, and (3) the potential self-sealing and healing of thermally damaged clay rock.

Heater tests have also been conducted at the HADES URL in a set of so-called ATLAS Experiments (where ATLAS stands for Admissible Thermal Loading for Argillaceous Storage). The ATLAS III experiment [70] was comprised of a 19 m heater borehole with an 8 m long heating section, together with four monitoring boreholes. The total heating period was one year, followed by a fully monitored natural cooling period. The results showed a large anisotropy in thermal conductivity of the Boom Clay. Further, an instantaneous decrease of pore pressure was recorded by all piezometers in the horizontal plane of the heater, followed by the expected increase in pore pressure due to heating. Modeling studies [71] suggest that these observations probably result from the anisotropic mechanical behavior of the clay. The observed pore pressure variations, including those at large distances during tunnel excavation, also support this hypothesis.

Summarizing, open research issues at this stage include the need to consider anisotropic thermal and mechanical properties, and the need to evaluate the thermal behavior of the complex system created by the waste canister, buffer, lining, and host rock, each with its own thermal properties. In general, the impact of temperature and temperature gradients on clay properties and behavior is still not well known, though there have been many efforts in this direction. Currently at the Mont Terri and HADES URLs, large long-term heater tests, named FE and Praclay, respectively, address many of the open issues.

7. Key processes and outstanding issues during the post-closure stage

Sometime after the closure of a nuclear waste repository in clay, the tunnels will be saturated with water, resulting in swelling of the bentonite-base components of the engineered barrier system (buffer, seals) and a return of pore-water pressure to the original hydrostatic level. Most fractures will probably be sealed owing to clay swelling and enhanced creep processes in the presence of water and heat. Long-term rock deformation behavior is of concern. Czaikowski and Lux [72] and Czaikowski and Wieczorek [73] discuss possible driving mechanisms for coupled hydromechanical time-dependent deformation of clays.

Of importance at this stage may be long-term geochemical processes, with the chemical conditions returning to anaerobic. Degradation and corrosion of canister steel, concrete lining, and/or steel supports have to be considered. Dissolution of chemical species, their transport, and precipitation may occur, creating a potential "geochemical damage zone" (GDZ). The development and evolution of a GDZ are open issues and need to be investigated on a case-by-case basis, since they very much depend on the waste packages and other engineered barrier design choices (e.g., whether they are bentonite buffer, steel-lined microtunnels, or cementitious buffer in a supercontainer). Confirmatory studies with natural analogs may be useful for evaluation of these long-term processes.

Gas production from corrosion and degradation of repository engineering materials and the related pressure buildup and transport are also outstanding issues that have received considerable attention (see e.g., [74–79]). Of particular interest is the international cooperative project named FORGE, which is under way to study this problem [80]. The FORGE project, involving 24 organizations in 12 European countries, is designed to address key research issues related to the generation and movement of repository gases, by means of a series of laboratory and field experiments. These will be accompanied by comprehensive modeling activities, as well as training opportunities.

The FORGE project is strongly linked to *in situ* experiments, among which are the HG-A experiment at Mont Terri and the PGZ1 experiment at Bure. The HG-A is a gas-leak-off test that studies the processes and parameters associated with the migration of gas generated in the repository along tunnels and into the host rock. The experiment consists of a dead-end microtunnel with a large packer that seals off a test region at the tunnel end. After studying the self-sealing of the excavation damage zone in the region of the packer over some years, the experiment is currently conducting gas-injection tests into the test interval. Along with many other parameters, the gas pressure built up in the test section is monitored. The data will be useful for assessing the capacity of the EDZ and the host rock to allow the transport of gas from the microtunnel test interval (Fig. 16).

The ongoing PGZ1 experiment at the Bure URL is dedicated to observing the different gas transfer mechanisms: advection-diffusion of dissolved gas, two-phase flow, dilatancy-controlled flow, and flow in macroscopic tensile fractures [81]. Several test phases are dedicated to characterize a specific mechanism at a time.

Apart from gas transport, the postclosure period is also concerned with radionuclide transport in solution through the clay

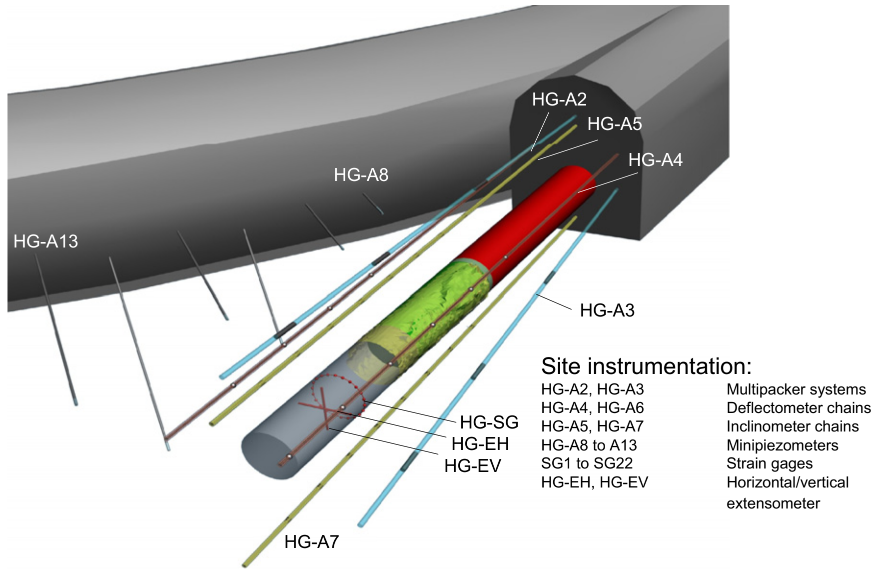

Fig. 16. Setup of the HG-A gas-leak-off test at the Mont Terri URL (packer position in green).

repository. In intact unfractured clays, radionuclide transport will be very slow and dominated by diffusion, because of the low permeability and high retardation capacity of the rock (e.g., [82,83]). As mentioned previously, this paper does not focus on this issue.

8. Summary and concluding remarks

The present paper gives an overview of the key coupled thermo-hydro-mechanical (THM) processes and open research issues related to high-level radioactive waste repositories in clay formations, with particular focus on the characteristics and evolution of the near-field. A substantial reference list of recent publications is provided for further studies.

While much progress has been made over the last ten years or more, a number of open issues remain. These were discussed above for each of the four stages of repository development. Below we shall highlight some of them as major open research areas.

- Short-term constitutive relationships for postfailure behavior of plastic and indurated clays, based on laboratory and analytic studies. This should address issues of elastic limits and fracturing criteria, strain softening for describing progressive change in material strength, and strain localization and shear band occurrence. Host rock material and *in situ* stress anisotropy should not be overlooked. The impact of hydromechanical, thermal, and chemical effects also needs to be considered. For example, a clear relationship between damage and hydraulic conductivity still requires much more work, even though some efforts have been made in this direction [84].
- Long-term (slow) deformation processes such as creep in plastic clays and subcritical crack growth in indurated clays. Particularly for indurated clays, it is an open question whether a creep limit exists and what are the relevant micro-structural mechanisms involved. Related to creep is the question of self-sealing capacity of clay rocks, whose fundamental processes are yet to be fully understood. The effects of moisture changes, temperature gradients and chemical environments need to be studied and formulated. For example, the relevancy of the effective pressure concept in describing pore-pressure effects on rock strength and creep behavior needs further investigation [85]. Further research is also required to include anisotropy and the natural variability of the rock, as well as bedding planes and other planes of weakness.
- Interface problems, including interfaces between canister, buffer, tunnel lining, and steel support, as well as the *in situ* rock. The system behavior at the interfaces under various thermal, mechanical, and hydraulic conditions needs to be studied by laboratory experiments and numerical methods, so that they can be defined and formulated properly. The possible nonequilibrium condition at the rock wall in contact with the tunnel atmosphere, directly or through the tunnel lining, needs to be further understood and characterized.
- Thermo-hydro-mechanical processes in host rock near field. These include damage mechanisms, phase changes, and the interaction of multiple materials (such as those in the engineered barrier system). Considerable progress has been made regarding the TH coupling for small clay deformations. The dependence of key material parameters on T, however, is an area still requiring much work.
- Modeling of excavation procedure and emplacement of waste and buffer. Modeling the creation and evolution of an EDZ is still an open research topic. As pointed out above, so far, no single set of consistent modeling approaches has been able to reproduce all the observations in the URLs. The thermal and geochemical effects on (long term) EDZ evolution need to be considered. The potential occurrence of a geochemical damage zone cannot be ruled out, and its long-term effects must be evaluated.
- Impact of rock-property heterogeneity. There has not been much discussion of spatial variability in hydraulic and mechanical properties in clay formations. Gens et al. [49] compiled data on Opalinus Clay at Mont Terri URL, which show a spread of a factor of 5 for permeability values and a factor of 2–5 for mechanical properties. Lanyon et al. [39] mentioned that data show a moderate spatial variability of one order of magnitude or less for hydraulic conductivity. Impact of spatial heterogeneity needs to be studied. In hydrogeology, spatial heterogeneity is linked to flow channeling phenomenon, and in material mechanics, heterogeneity plays a key role in strain localization and fracturing processes.
- Controls on the *in situ* stress conditions. The stress field may also be spatially varying, depending on local structures and long-term rock-mass strength. The interdependence of stress state and long-term deformation characteristics needs further research.

- Gas transport through very low permeability clays. This can be expected to remain an important issue in the coming years. Indeed, even possible transport modes still remain to be clarified if the corrosion-gas production rate exceeds the capacity of the clay to let it diffuse away in dissolved form through pore water. Significant modeling efforts have been performed in a two-phase flow framework, while most experiments indicate the creation of discrete pathways.

Most of the aforementioned open research issues are related to the coupled HM or THM evolution of the repository near field. Not all of these issues have direct impact on the safety of a waste repository. For example, Blümling et al. [31] show that even extremely increased transmissivities along the tunnels and seal sections do not necessarily degrade the long-term safety of a repository in the Opalinus Clay. Similar studies that relate the open issues to repository safety assessments, under all reasonable conditions and scenarios, are also needed.

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References

[1] Mazurek M, Pearson FJ, Volckaert G, Bock H. Features, Events and Processes evaluation catalogue for Argillaceous Media. Nuclear Energy Agency (NEA), Organisation for Economic Co-Operation And Development OECD; 2003. NEA4437, ISBN, 92-64-02148-5.
[2] Reims 2002. Clays in natural and engineering barriers for radioactive waste confinement. First International Meeting. French National Radioactive Waste Management Agency (ANDRA), Reims, France, December, 2002. (ANDRA Technical report no. 235/2003; Physics and Chemistry of the Earth, vol. 29(1), 2004, Applied Clay Sciences, vol. 26(1–4), 2004).
[3] Tours 2005. Clays in natural and engineering barriers for radioactive waste confinement. First International Meeting. French National Radioactive Waste Management Agency (ANDRA), Tours, France, March 2005. (Physics and Chemistry of the Earth, vol. 32(1–7; 8–14), 2007).
[4] Lille 2007. Clays in natural and engineering barriers for radioactive waste confinement. Third International Meeting. French National Radioactive Waste Management Agency (ANDRA), Lille, France, September 2007. (ANDRA Technical report no. 334, 2007; Physics and Chemistry of the Earth, vol. 33(Suppl 1), 2008).
[5] Nantes 2010. Clays in natural and engineering barriers for radioactive waste confinement. Fourth International Meeting. French National Radioactive Waste Management Agency (ANDRA), Nantes, France, March 2010.
[6] Bernier F, Li XL, Bastiaens W. Twenty-five years' geotechnical observation and testing in the Tertiary Boom Clay formation. Géotechnique 2007;57(2): 229–37.
[7] Li X-L, Bastiaens W, Weetjens E, Sillen X. The THM boundary conditions control in the design of the large scale in situ PRACLAY heater test. In: Proceedings of TIMODAZ/THERESA coupled THMC conference, Luxembourg, September 29–October 1, 2009.
[8] Weetjens E, Sillen X. The source term and the geometry of the PRACLAY heater test. Internal report of EURIDICE, Belgium, 2004.
[9] Van Marcke P, Bastiaens W. Construction of the Praclay experimental gallery at the Hades URF. Clays in natural and engineered barriers for radioactive waste confinement. Fourth International Meeting. March, 2010. Nantes, France.
[10] Andra 2005. Dossier 2005 Argile: evaluation of the feasibility of a geological repository in an argillaceous formation. France: National Agency for Radioactive Waste Management; 2005.
[11] Delay J, Vinsot A, Krieguer JM, Rebours H, Armand G. Making of the underground scientific experimental programme at the Meuse/Haute-Marne underground research laboratory. North Eastern France. J Phys Chem Earth 2006, doi:10.1016/j.pce.2006.04.033.
[12] Armand G, Wileveau Y, Morel J, Cruchaudet M, Rebours H. Excavated damaged zone (EDZ) in the Meuse Haute-Marne underground research laboratory. In: Proceedings of the 11th congress of the ISRM,Lisbon, Portugal, 9–13 July 2007, p. 33–6.
[13] Wileveau Y, Renaud V, Kazmierczak J-B, Armand G. Rheological characterization of a clay formation from drifts excavation: elastic and elastoplastic approach. Proceedings of the Sea to Sky Geotechnique 2006. Vancouver, October 2006.
[14] Bossart P, Thury M, editors. Mont Terri Rock Laboratory – project, programme 1996 to 2007 and results. Reports of the Swiss Geological Survey No. 3, 2008, Wabern. 193 p., 248 p. annex.
[15] Rejeb A. Time-dependent behaviour of Tournemire argillites (France). In: Proceedings of the ISRM 2003 international congress of rock mechanics, September 8–12, 2003, Gauteng, South Africa, p. 955–60.
[16] Rejeb A, Cabrera J. Time-dependent evolution of the excavation damaged zone in the argillaceous Tournemire site (France). In: Proceedings of the "GeoProc 2006," Invited lecture in the second international conference on coupled THMC processes in geosystems and engineering, Nanjing, China, May 22–25, 2006. p. 65–74.
[17] Millard A, Massmann J, Rejeb A, Uehara S. Study of the initiation and propagation of excavation damaged zones around openings in argillaceous rock. Environ Geol 2009;57(6):1325–36.
[18] Massmann J, Uehara S, Rejeb A, Millard A. Investigation of desaturation in an old tunnel and new galleries at an argillaceous site. Environ Geol 2009;57(6): 1337–46.
[19] Barnichon JD, Dick P, Bauer C. The SEALEX in situ experiments: performance test of repository seals. In: Proceedings of the 12th international congress on rock mechanics (ISRM 2011), October 18–21, 2011, Beijing, China, in press.
[20] Vietor T, Armand G, Nyonoya S, Schuster K, Wieczorek K. Excavation induced damage evolution during a mine-by experiment in opalinus clay. Clays in natural and engineered barriers for radioactive waste confinement. Fourth International Meeting. March, 2010. Nantes, France.
[21] Massmann J. Modeling of excavation induced coupled hydraulic-mechanical processes in claystone. Report 77, 2009. Institute of Fluid Mechanics and Environmental Physics in Civil Engineering (ISU), University of Hannover, Hanover, Germany.
[22] Wileveau Y, Bernier F. Similarities in the hydro-mechanical response of Callovo-Oxfordian Clay and Boom Clay during gallery excavation. Phys Chem Earth 2008;33:S343–9.
[23] Bossart P, Meier PM, Moeri A, Trick T, Mayor J-C. Geological and hydraulic characterization of the excavation disturbed zone in the Opalinus Clay of the Mont Terri Rock Laboratory. Eng Geol 2002;66(1–2):19–38.
[24] Delage P, Le TT, Tang AM, Cui YJ, Li XL. Suction effects in deep Boom Clay block samples. Géotechnique 2007;57(1):239–44.
[25] Tsang C-F, Bernier F, Davies C. Geohydromechanical processes in the EDZ in crystalline rock, rock salt, and indurated and plastic clays—in the context of radioactive waste disposal. Int J Rock Mech Mining Sci 2005;42:109–25.
[26] Davies C, Bernier F. Impact of the excavation disturbed or damaged zone (EDZ) on the performance of radioactive waste geological repositories. In: Proceedings of a European commission cluster conference and workshop, Luxembourg, 3–5 November 2003. Published 2005. EUR 21028 EN.
[27] Martin CD, Lanyon GW, Blümling P, Mayor J-C. The excavation disturbed zone around a test tunnel in the Opalinus Clay. In: Proceedings of the fifth North American rock mechanics symposium and 17th tunnelling Association of Canada Conference: NARMS/TAC, 2002, Hammah R, Baden W, Curran J, Telesnicki M, editors. Toronto: University of Toronto Press; p. 1581–8.
[28] Bossart P, Th Trick, Meier PM, Mayor J-C. Structural and hydrogeological characterization of the excavation-disturbed zone in the Opalinus Clay (Mont Terri Project, Switzerland). Appl Clay Sci 2004;26:429–48.
[29] Mertens J, Bastiaens W, Dehandschutter B. Characterisation of induced discontinuities in the Boom Clay around the underground excavations (URF, Mol, Belgium). Appl Clay Sci 2004;26:413–28.
[30] Alheid HJ, Aranyossy JF, Bluming P, Hoteit N, Van Geet M. EDZ development and evolution. State of the art report. European Commission NF-Pro project, 6th EURATOM Framework Programme 2005:141.
[31] Blümling P, Bernier F, Lebon P, Derek Martin C. The excavation-damaged zone in clay formations: time-dependent behaviour and influence on performance assessment. Phys Chem Earth 2007;32:588–99.
[32] Marschall P, Distinguin M, Shao H, Bossart P, Enachescu C, Trick T. Creation and evolution of damage zones around a microtunnel in a claystone formation of the Swiss Jura Mountains. Society of Petroleum Engineers (SPE). International symposium and exhibition on formation damage control, Lafayette (Louisiana), February 15–17, 2006. SPE-98537-PP.
[33] Marschall P, Trick T, Lanyon GW, Delay J, Shao H. Hydro-mechanical evolution of damaged zones around a microtunnel in a claystone formation of the Swiss Jura Mountains. In: Proceedings of the 42rd US rock Mechanics Symposium, San Francisco, 2008. ARMA 08-193.

[34] Corkum AG, Martin CD. Modelling a mine-by test at the Mont Terri rock laboratory. Switzerland. Int J Rock Mech Mining Sci 2007;44:846–59.
[35] Levasseur S, Bésuelle P, Collin F, Chambon R, Charlier R, Viggiani G. EDZ in clayey rocks: which effect on permeability? In: Proceedings of European Commission TIMODAZ-THERESA international conference, September–October 2009. Luxembourg, 2009.
[36] Levasseur S, Collin F, Frieg B, Charlier R. Damage around tunnels in indurated clay: hydro-mechanical modeling aspects. In: Proceedings of European Commission TIMODAZ-THERESA international conference, September–October 2009. Luxembourg, 2009.
[37] Matray JM, Savoye S, Cabrera J. Desaturation and structure relationships around drifts excavated in the well-compacted Tournemire's argillite (Aveyron, France). Eng Geol 2007;90:1–16.
[38] SELFRAC 2007. Fractures and self-healing within the excavation disturbed zone in clays. Final technical report (project FIKW-CT2001-1001-00182). European Commission EUR 22585, 2007.
[39] Lanyon GW, Marschall P, Trick T, de La Vaissière R, Shao H, Leung H. Hydromechanical evolution and self-sealing of damage zones around a microtunnel in a claystone formation of the Swiss Jura Mountains. In: Proceedings of the 43rd US Rock Mechanics Symposium and 4th U.S.–Canada Rock Mechanics Symposium, Asheville, NC, June 28–July 1, 2009 ARMA 09-333.
[40] Levasseur S, Charlier R, Frieg B, Collin B. Hydro mechanical modeling of the excavation damage zone around an underground excavation at Mont Terri Rock Laboratory. Int J Rock Mech Min Sci 2010;47:414–25.
[41] Volckaert G, Bernier F, Sillen X, Van Geet M, Mayor JC, Göbel I, et al. Similarities and differences in the behaviour of plastic and indurated clays. In: Proceedings of Euradwaste'04: Sixth European Commission conference on the management and disposal of radioactive waste, Luxembourg, 2004.
[42] Escoffier S, Homand F, Giraud A, Hoteit N, Su K. Under stress permeability determination of the Meuse/Haute-Marne mudstone. Eng Geol 2005;81(3): 329–40.
[43] Vietor T, Blümling P, Armand G. Failure mechanisms of the Opalinus Clay around underground excavation. In: Van Cotthem, Charlier, Thimus Tshibangu, editors. EUROCK 2006—multiphysics coupling and long term behaviour in rock mechanics, 2006, p. 479–84.
[44] Popp T, Salzer K. Anisotropy of seismic and mechanical properties of Opalinus clay during triaxial deformation in a multi-anvil apparatus. Phys Chem Earth, Parts A/B/C 2007;32(8–14):879–88.
[45] Popp T, Salzer K, Minkley W. Influence of bedding planes to EDZ-evolution and the coupled HM properties of Opalinus clay. Phys Chem Earth 2008;33:S374–87.
[46] Popp T, Salzer K, Minkley W. Hydro-mechanical rock properties of Opalinus clay. In: Proceedings of European Commission TIMODAZ-THERESA international conference, Luxembourg. September–October 2009.
[47] Labiouse V, Vietor T. Laboratory and in situ simulation tests of the fracturing in the EDZ around galleries in Opalinus Clay. In: Proceedings of European Commission TIMODAZ-THERESA international conference, Luxembourg, September–October 2009.
[48] Sillen X, Li XL, Van Marcke P, Chen G, Bastiaens W. On the role of anisotropy in the perturbation of boom clay by a deep disposal repository for high-level wastes. Clays in natural and engineered barriers for radioactive waste confinement. Fourth International Meeting. March 2010. Nantes, France, 2010.
[49] Gens A, Vaunat J, Garitte B, Wileveau Y. In situ behaviour of a stiff layered clay subject to thermal loading: observations and interpretation. Géotechnique 2007;57(2):207–28.
[50] Collin F, Levasseur S, Chambon R. Numerical post failure methods in multi-physical problems – Revue Européenne de Génie Civil 2009;7–8:983–1004.
[51] Viggiani C. An experimental insight into the mechanisms of localized deformation in clay rocks. Rock Mechanics Analysis (RA) Workshop, Mont Terri Project, NAGRA. 3–4 June 2009, Unterägeri, Switzerland.
[52] Cui YJ, Delage P. Yielding and plastic behaviour of an unsaturated compacted silt. Géotechnique 1996;46(2):291–311.
[53] Mayor JC, Velasco M, Garcia-Sineriz JL. Ventilation experiment in the Mont Terri underground laboratory. Phys Chem Earth 2007;32:616–28.
[54] Rutenberg M, Czaikowski O, Lux K-H. Time-dependent deformation of claystone rock mass – numerical simulation and field measurement data. Proceedings of European commission TIMODAZ-THERESA international conference, Luxembourg, September–October 2009.
[55] Meier P, Trick T, Blümling P, Volckaert G. Self-healing of fractures with the EDZ at the Mont Terri Rock Laboratory: results after one year of experiments of work. In: Proceedings of international workshop on geomechanics, hydromechanical and thermohydro-mechanical behaviour of deep argillaceous rocks: theory and experiments, October 11–12, 2000, Paris.
[56] Zhang C-L, Rothfuchs T. Damage and sealing of clay rocks detected by measurements of gas permeability. Phys Chem Earth 2008;33:363–73.
[57] Zhang C-L, Wieczorek K, Xie M-L. Swelling experiments on mudrocks. In: Proceedings of the international symposium on unsaturated soil mechanics and deep geological nuclear waste disposal (UNSAT-WASTE 2009), 24–28 August 2009, Shanghai, China, 2009a.
[58] Bock H, Dehandschutter B, Martin CD, Mazurek M, deHaller A, Skoczylas F, et al. Self-sealing of fractures in argillaceous formations—evidence, mechanisms and implications for performance assessment (An NEA Clay Club Project). Clays in natural and engineered barriers for radioactive waste confinement. Fourth International Meeting. Nantes, France. March 2010.
[59] Naumann M, Hunsche U, Schulze O. Experimental investigations on anisotroply and dilatancy, failure and creep of Opalinus Clay. In: Aranyossy JF, editor. Clays in natural and engineered barriers for radioactive waste confinement. Physics and chemistry of the earth, 2007, p. 889–95.
[60] Labiouse,V, Escoffier S, Gastaldo L and Mathier J-F. Self-sealing of localised cracks in Boom and Opalinus Clay hollow cylinders. In: Proceedings of European Commission TIMODAZ-THERESA International Conference, Luxembourg, September–October 2009.
[61] Gräsle W. Long-term creep behaviour of Opalinus Clay—a new experimental approach involving undrained and drained triaxial creep test. In: Proceedings of European Commission TIMODAZ-THERESA International Conference, Luxembourg, September 29–October 2009.
[62] Collin F, Li XL, Radu JP, Charlier R. Thermo-hydro-mechanical coupling in clay barriers. Eng Geol 2002;64:179–93.
[63] Delage P, Sultan N, Cui YJ, Li XL. Permeability changes of Boom clay with temperature. In: Proceedings of European Commission TIMODAZ-THERESA International Conference, Luxembourg, September 29–October 2009.
[64] Zhang C-L, Wieczorek K, Rothfuchs T, Armand G, Lebon P. Responses of the Opalinus Clay to heating during the HE-D experiment at Mont Terri. In: Proceedings of European Commission TIMODAZ-THERESA international conference, Luxembourg, September–October 2009.
[65] Sultan N, Delage P, Cui YJ. Temperature effects on the volume change behaviour of Boom clay. Eng Geol 2002;64(2–3):135–45.
[66] Tang AM, Cui Y-J, Barnel N. Thermo-mechanical behaviour of compacted swelling clay. Géotechnique 2008;58(1):45–54.
[67] Cui YJ, Le TT, Tang AM, Delage P, Li XL. Investigating the time-dependent behaviour of Boom clay under thermo-mechanical loading. Géotechnique 4, 2009;59:319–29.
[68] Sillen X, Chen GJ, Verstricht J, Li XL. Revisiting a simple in situ heater test: the third life of ATLAS. Clays in natural and engineered barriers for radioactive waste confinement. Fourth International Meeting, Nantes, France, March 2010.
[69] Zhang C-L, Rothfuchs T, Jockwer N, Wieczorek K, Dittrich J, Müller J, et al. Thermal effects on the Opalinus Clay: a joint heating experiment of ANDRA and GRS at the Mont Terri URL (HE-D Project). Final Report—Gesellschaft für Anlagen und Reaktorsicherheit (GRS) mbH, GRS 224, 2007, ISBN 978-3-931995-98-0.
[70] Chen G, Gatabin C, Li XL. Numerical and experimental study of Praclay seal test in URL, Mol. In: Proceedings of European Commission TIMODAZ-THERESA coupled THMC conference, Luxembourg, September 29–October 1, 2009.
[71] Garitte B, Sillen X, Li XL, Armand G, Vaunat J, Gens A. Comparative study of three in-situ heating tests in anisotropic media: the HE-D, TER and ATLAS experiments. In: Proceedings of TIMODAZ/THERESA coupled THMC conference, Luxembourg September 29–October 1, 2009.
[72] Czaikowski O, Lux K-H. Physical modelling and numerical simulation of long-term deformation behaviour of indurated clay with special consideration of anisotropic effects and in situ measurements. EUROCK, Liège, Belgium, May 9–12, 2006.
[73] Czaikowski O, Wieczorek K. Identification of potential driving mechanisms for HM coupled time-dependent deformation of Argillaceous Rocks. Clays in natural and engineered barriers for radioactive waste confinement. Fourth International Meeting. March 2010. Nantes, France.
[74] Marschall P, Horseman S, Simmi T. Characterisation of gas transport properties of the Opalinus Clay, a potential host rock formation for radioactive waste disposal. Oil Gas Sci Technol—Rev IFP 2005;60(1):121–39.
[75] Weetjens E, Sillen X. Gas generation and migration in the near field of a supercontainer-based disposal system for vitrified high-level radioactive waste. In: Proceedings of the 11th international high-level radioactive waste management conference (IHLRWM), Las Vegas, United States, 30 April–4 May 2006/American Nuclear Society (ANS), La Grange Park, Illinois, United States, American Nuclear Society (ANS), 2006, p. 1–8.
[76] Shao H, Schuster K, Delay J, Wang W, Kolditz O. Analysis of dilatancy-controlled gas flow along clay bedding. In: Proceedings of European Commission TIMODAZ-THERESA International Conference, Luxembourg, September–October 2009.
[77] Yu L, Weetjens E. Summary of Gas Generation and Migration: Current State-of-the-Art. Mol, Belgium: SCK•CEN, 2009. 29 p. (External Report of the Belgian Nuclear Research Centre; ER-106; European Commission FP7 FORGE. Fate of Repository Gases). ISSN 1782-2335, 2009.
[78] Hoxha D, Do D-P, Wendling J, Poutrel A. Role of HM coupling mechanisms on the evolution of rock masses around nuclear waste disposals in the context of gas generation. Clays in natural and engineered barriers for radioactive waste confinement. Fourth International Meeting. March 2010. Nantes, France.
[79] Duveau G, Davy CA, Skoczylas F, Shao J-F, Dubois T. Creation of gas pathways through water-saturated argillite: experimental and numerical approaches. Clays in natural and engineered barriers for radioactive waste confinement. Fourth International Meeting. Nantes, France. March 2010.
[80] Shaw R. The FORGE (Fate of Repository Gases) Pan European Project. Clays in natural and engineered barriers for radioactive waste confinement. Fourth International Meeting. Nantes, France. March 2010.
[81] de La Vaissière R, Talandier J, Piedevache M, Lavanchy J-M, Croisé J, Senger R. Gas flow processes in the Callovo-Oxfordian argillite: *in situ* experiment

PGZ1. Clays in natural and engineered barriers for radioactive waste confinement. Fourth International Meeting. Nantes, France. March 2010.
[82] Van Loon LR, Wersin P, Soler JM, Eikenberg J, Gimmi Th, Hernán P, et al. In-situ diffusion of HTO, 22Na+, Cs+ and I- in Opalinus Clay at the Mont Terri underground rock laboratory. Radiochim Acta 2004;92:757–63.
[83] Wersin P, Soler JM, Van Loon L, Eikenberg J, Baeyens B, Grolimund D, et al. Diffusion of HTO, Br-, I-, Cs+, Sr-85(2+) and Co-60(2+) in a clay formation: results and modelling from an in situ experiment in Opalinus Clay. Appl Geochem 2008;23:678–91, doi:10.1016/j.apgeochem.2007.11.004.
[84] Bastiaens W, Bernier F, Li X-L. An overview of long-term HM measurements around HADES URF. In: Proceedings of International Symposium on multi-physics coupling and long-term behaviour in rock mechanics, Liège, p. 15–26.
[85] Cariou S, Dormieux L, Skoczylas F. A constitutive equation for agrgillite. Poro-Mechanics 2009;IV:318–23.