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April 2010

Abstract

The present paper provides an overview of key processes and outstanding issues related to the development of radioactive waste repositories in clay formations. Here, clay formations include plastic clay such as Boom clay at Mol, Belgium, and indurated clay such as those at Bure, France, and Mont Terri, Switzerland. First, we briefly introduce 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 construction of a waste repository in clays are presented in terms of four stages in repository development. For each of the four stages, key processes and outstanding issues are discussed. A summary of the important areas of research needs and some general remarks conclude this paper.

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1. Introduction

Clays are transitional materials with properties intermediate between soils and hard rocks. Their properties depend sensitively on their water content, behaving as brittle rocks at low values of water content and as ductile soft material at high values. Clay formations are considered to be good candidates for locating 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 the formations. Clay also possesses good sorptive capacity for retardation of radionuclides. The features, events and processes associated with radioactive waste disposal in clays have been catalogued and evaluated under the auspices of the Nuclear Energy Agency (Mazurek et al., 2003). Much progress in the study of clays has been reported in a series of major international meetings: in Reims (2002), in Tours (2005), in Lille (2007), and more recently in Nantes (2010).

The purpose of this paper is to provide a review of key processes and outstanding issues related to the development of radioactive waste repositories in clay formations. Here, clay formations include plastic clay such as Boom clay at Mol, Belgium, and also indurated clay such as those at Bure, France, and Mount Terri, Switzerland. In the next section, four major underground research laboratories (URLs) in clay formations that have been operating over the last few decades are introduced. From these URLs, we have obtained substantial research results on 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 four stages in repository development. The following four sections discuss the key processes and outstanding issues in each of the four stages. A summary of major research needs and some general remarks 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.

The first is HADES (High Activity Disposal Experimental Site) URL excavated at 223 m depth in Boom Clay, a tertiary clay formation in Mol, Belgium. Since construction in 1980, many experimental investigations have been conducted at the site. Figure 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. A good summary is presented by Bernier et al. (2007).

Of particular interest is the Praclay Gallery constructed in 2007, in which a Seal Test and a Heater Test will be initiated in 2010 and 2011 respectively. The layout of the gallery is shown in Figure 2. The Heater Test will involve heating a 30 m 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 (Van Marcke and Bastiaens, 2010; Chen et al., 2009). These include THM behavior of clay under undrained conditions. For this objective, an hydraulic seal will be installed at the intersection between the planned heated and unheated sections of the gallery. This installation makes up the Seal Test, which will be conducted in 2010, and will allow testing the functionality of the hydraulic seal under heated repository conditions.

The second major URL is the French facility in Bure at the boundary between Meuse and Haute-Marne, about 300 km east of Paris. Its construction started in 2000, and the target horizon for the URL is between 420 m and 550 m deep in argillaceous rock (Figure 3). The first experimental facility was completed in 2005 (Andra, 2005). Some details regarding the work on the Bure URL may be found in Armand et al. (2007), Delay et al. (2006) and Wileveau et al. (2006).

The third major URL is the Mont Terri Facility in northwest Switzerland, in an argillaceous formation known as Opalinus Clay. Construction of the facility in conjunction with a motorway tunnel started in 1987, and the Mont Terri research project was initiated in 1996. Figure 4 shows the layout of the URL, with different experimental areas known by their initials. A summary of project activities may be found in Bossart and Thury (2008).

The fourth URL is the Tournemire Site in the south of France. It is characterized by a sub-horizontal indurated argillaceous layer 250 m thick. A railway tunnel, constructed in 1881 through the argillaceous formation, is 2 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 (Figure 5). Thus, this facility allows 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 (Rejeb, 2003; Rejeb and Cabrera, 2006; Millard et al., 2009, and Massmann et al., 2009).

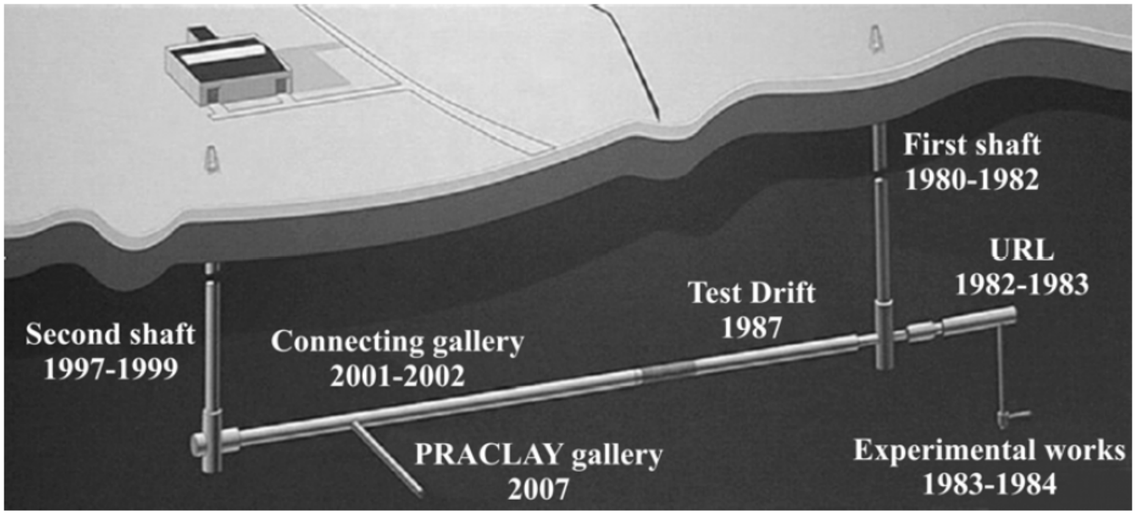

Figure 1: Construction history of the HADES URF (Underground Research Facility) (from Bernier et al., 2007)

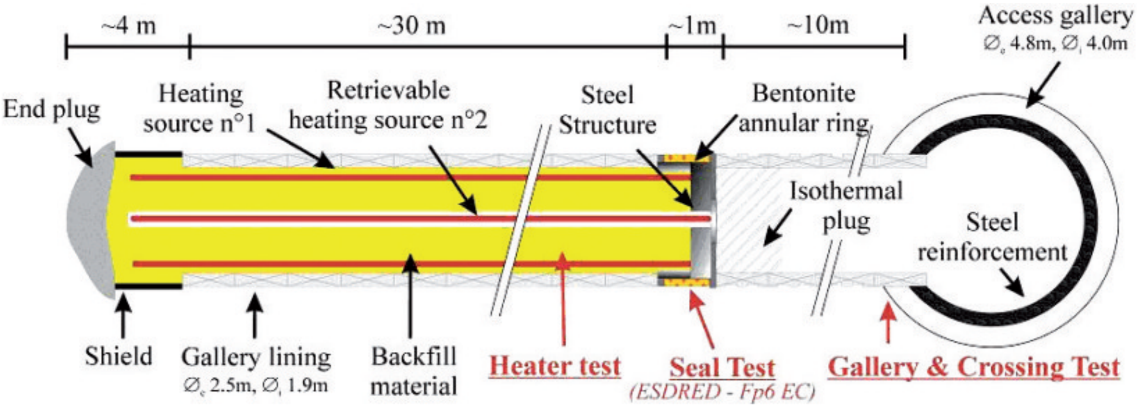

Figure 2: Layout of the Praclay In-Situ Experiment which is constituted of the Gallery and Crossing Test, the Seal Test, and the Heater Test (from Van Marcke and Bastiaens, 2010)

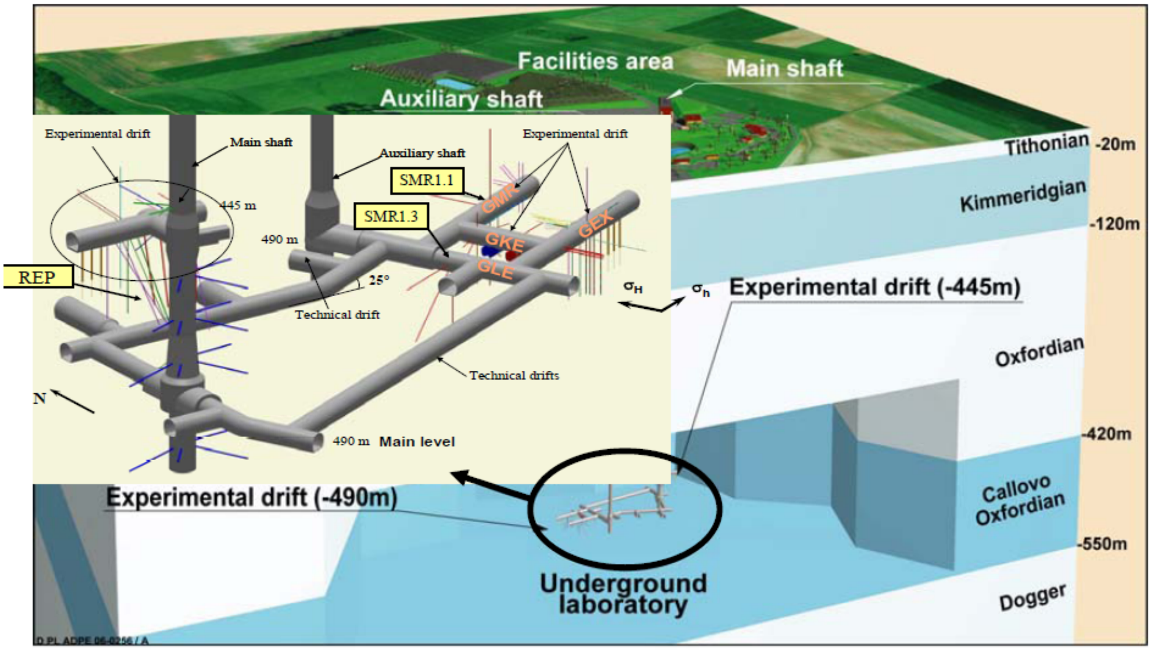

Figure 3: General view of the underground research laboratory at the Meuse/Haute-Marne URL (from Wileveau and Bernier, 2007)

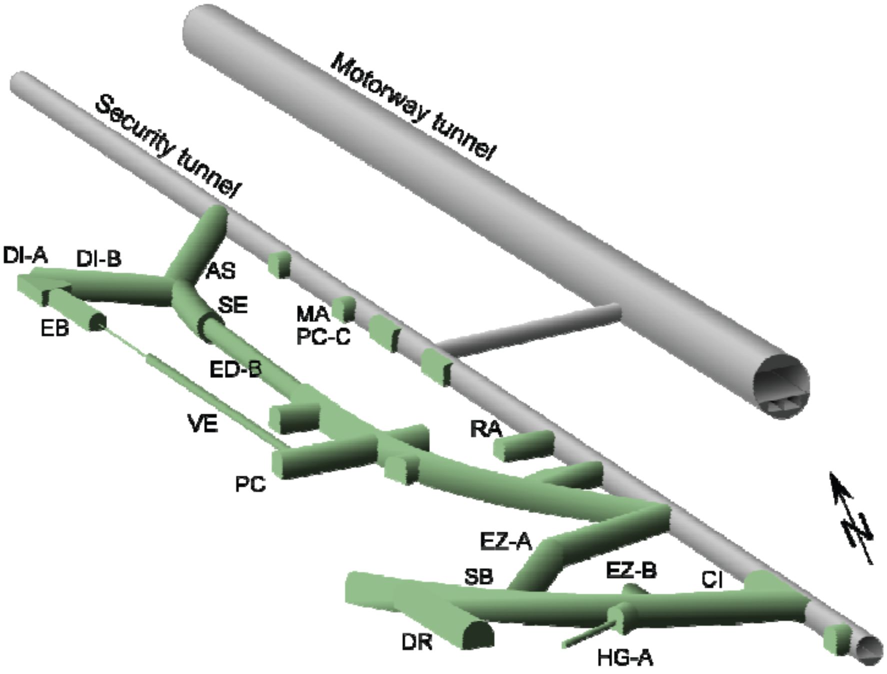

Figure 4: Layout of the Mt Terri Rock Laboratory. The different experimental areas are shown by their initials (from Marschall et al., 2008)

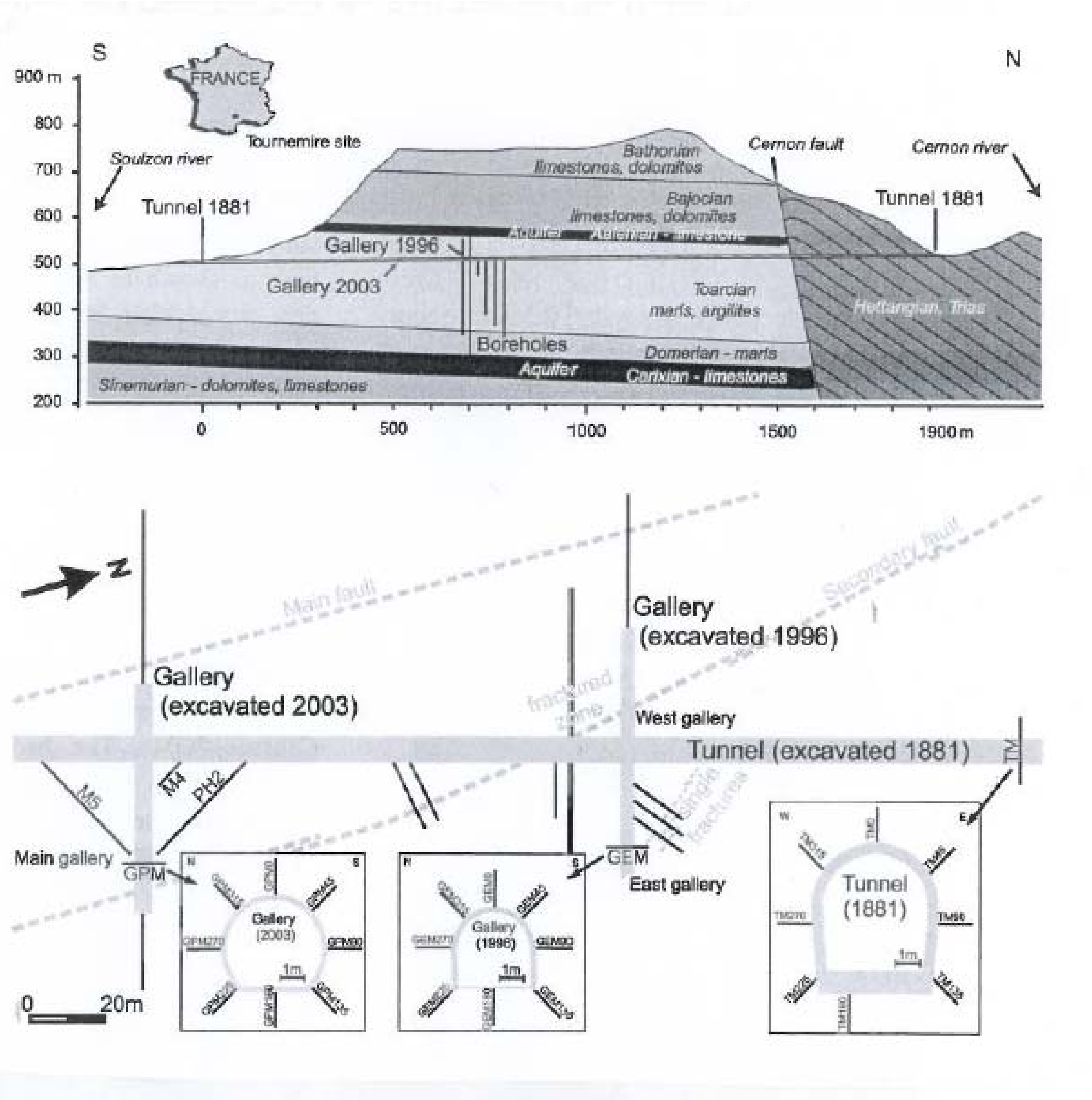

Figure 5: Geological cross-section of the Tournemire site, South France (upper figure) and locations of the galleries and boreholes around each opening for study of near field behavior of clay rock (lower figure) (from Massmann et al., 2009; Rejeb and Cabrera, 2006; Rejeb, 2003)

3. Four Stages in the Development of a Waste Repository in a Clay Formation

Because clay is a soft material, excavation of a tunnel requires timely installation of support and lining. For example, specialized excavation equipment was required for the construction of the URL in Boom clay at Mol, Belgium. As the excavation face moved forward, emplacement of concrete lining and steel supports followed with a small gap that allowed observation of how excavation and stress redistribution affected the rock. The first stage of repository development may be defined as the disposal tunnel construction period, which extends from tunnel excavation to a few days after lining installation.

The second stage may be called the tunnel ventilation period, which lasts from installation of lining and supports to emplacement of waste and buffer materials. Following this is the third stage, which may be strongly affected by the decay heat generated by the radioactive waste—this stage lasts until repository closure. Finally, the fourth stage is the postclosure period, which is the basic period of concern for long-term performance and safety assessment. The near-field rock behavior at this stage depends on the processes and effects of 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 possibly released from waste canisters.

The key processes and outstanding issues defining near-field clay behavior and its evolution during the 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, so that many processes and issues need to be considered in the early stages. 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, there are also open research questions related to radionuclide transport in clay materials, such as the relative importance of advective versus diffusive transport in the excavation-damaged zone, the prediction of diffusion behavior in nanopore materials, and/or the evaluation of sorption characteristics. These are not discussed in the present paper. Issues related to reactive-diffusive transport in clays or bentonite have been reviewed in our recent progress report on reactive transport and coupled THM processes in engineered barrier systems (Steefel et al., 2010).

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. Because of rock movements coupled with low hydraulic conductivity, the rock pore-space deforms and pore-water pressure changes. Such pore-pressure changes have been noticed many tunnel diameters away from the tunnel wall, and the changes can last for months, because the elevated pressures are slow to dissipate. The exception to this is when excavation creates fractures in a region around the tunnel, providing hydraulic connection to the opening, in which case the pore pressure will abruptly drop to atmospheric conditions. An example of such a case may be found in an experiment at Mont Terri (Figures 6 and 7), where it was found that pore pressures along a pre-drilled borehole increased with excavation time, but then dropped to essentially zero when the tunnel came close to the measurement points (Vietor et al., 2010). The sharp drop is possibly explained by the suggestion that these monitoring points became connected to the tunnel through excavation-induced fractures.

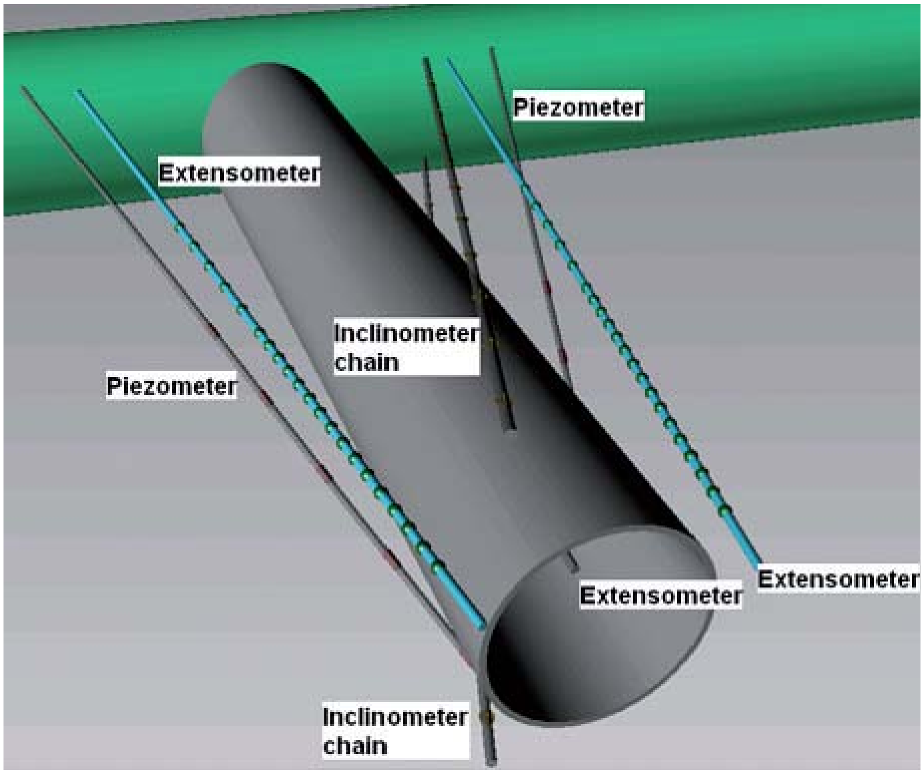

Figure 6: Sensor array (not all shown) at the Mine-By (MB) Tunnel at Mont Terri URL measures 4.7 m in diameter and is 24 m long (from Vietor et al., 2010)

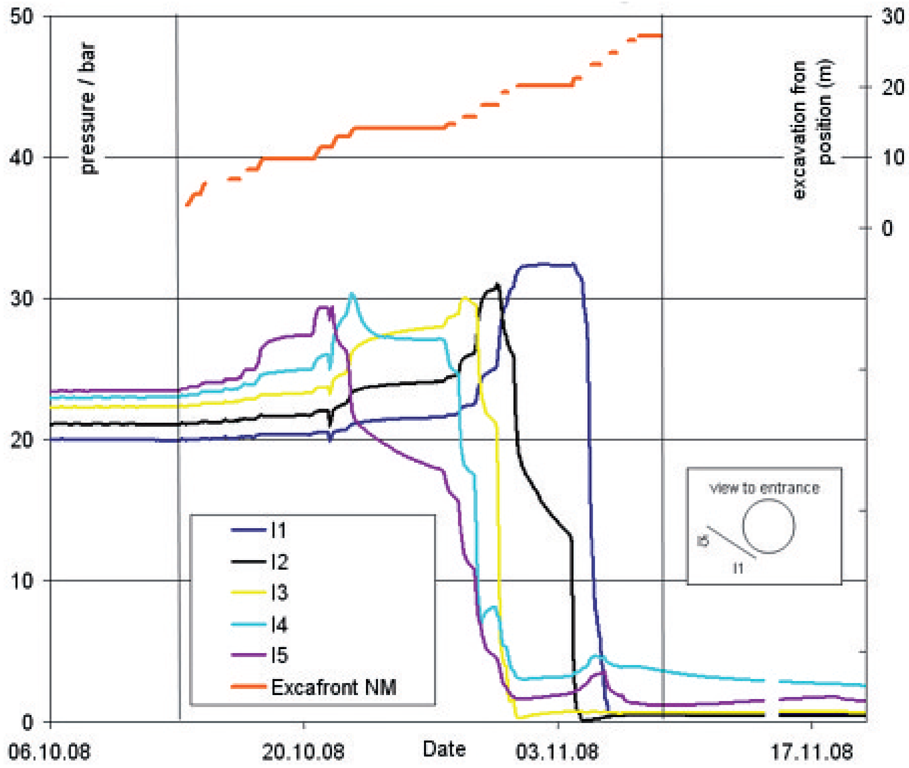

Figure 7: Pore-water-pressure evolution in the northern sidewall of the MB Tunnel (from Vietor et al., 2010)

In general, during excavation, the rock ahead of the excavation front behaves differently from the rock around the tunnel. This can be explained by the fact that the clay rock properties are a function of the confining stresses. The excavation front is basically pushing on the rock, whereas a free surface is created around the tunnel. Other factors that affect the rock behavior include overconsolidation ratio (OCR), gas entry pressure, and rock anisotropy, the last being a function of existing fractures and/or clay bedding planes. As excavation proceeds, the rock around the tunnel may experience an increase followed by a decrease in pore water pressure, depending on the location and distance from the opening.

The region adjacent to the tunnel rock may also change from water-saturated to unsaturated conditions, and this can change rock behavior from plastic to brittle. Unsaturated clay (as well as ventilated clay surfaces) provides water suction (Delage et al., 2007). An increase in suction may result in a pseudocohesion effect and thus may enhance rock strength. The evolution of suction in the near field of a tunnel is an important open research issue.

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 (Tsang et al., 2005; Davies and Bernier 2005). This damaged zone represents a region of enhanced permeability due to porosity increase or creation of tensile or shear fractures (Bossart et al., 2004; Mertens et al., 2004; Alheid et al., 2005; Blümling et al., 2005; Marschall et al., 2006; Corkum and Martin, 2007; Levasseur at al., 2009a, 2009b). An initial increase in permeability of five orders of magnitude has been found. However, this effect decreases over time because of clay swelling and clay creep behavior, especially in cases where steel support and concrete lining provide a back pressure on the rock.

Figures 8, 9, and 10 show EDZ behavior around tunnels at Mol in Belgium, Bure in France, and Mont Terri in Switzerland, respectively. Figure 8 shows an inferred herringbone structure of fractures around a tunnel in plastic clay extending one meter in radial direction and six meters axially forward of the tunnel front face. The fracture spacing is about 0.5 m. Some theoretical and numerical models have been developed to attempt to simulate such a pattern and the processes leading to it. Similar patterns are also found in stiff clay at Bure, France, as shown in Figure 9 (Wileveau and Bernier, 2007). At Mont Terri, Switzerland, permeability measurements around the tunnel (Figure 10) show orders-of-magnitude increases.

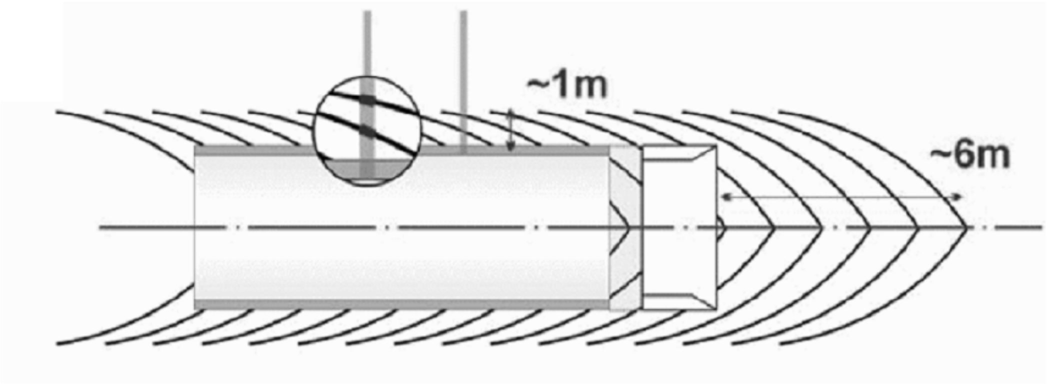

Figure 8: Fractures observed during the construction of the connecting gallery at the URL in Mol—vertical cross section through the gallery showing the fracturing pattern around it, as deduced from the observations (from Alheid et al., 2005)

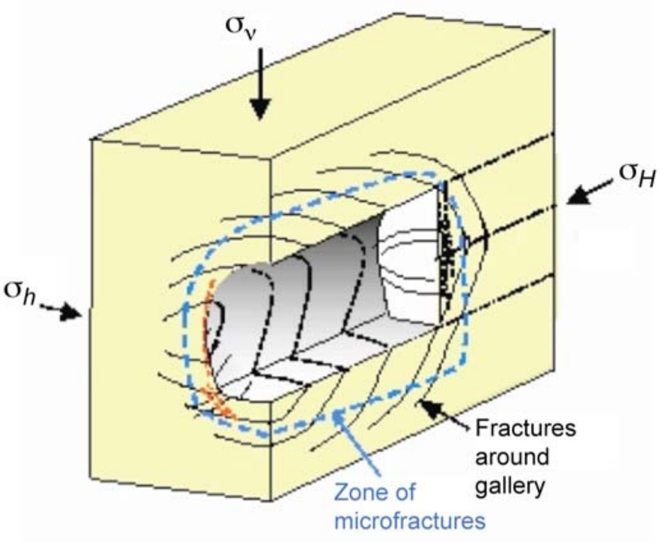

Figure 9: Herringbone patterns observed at the Bure site in the gallery parallel to σ_H (from Wileveau and Bernier, 2007)

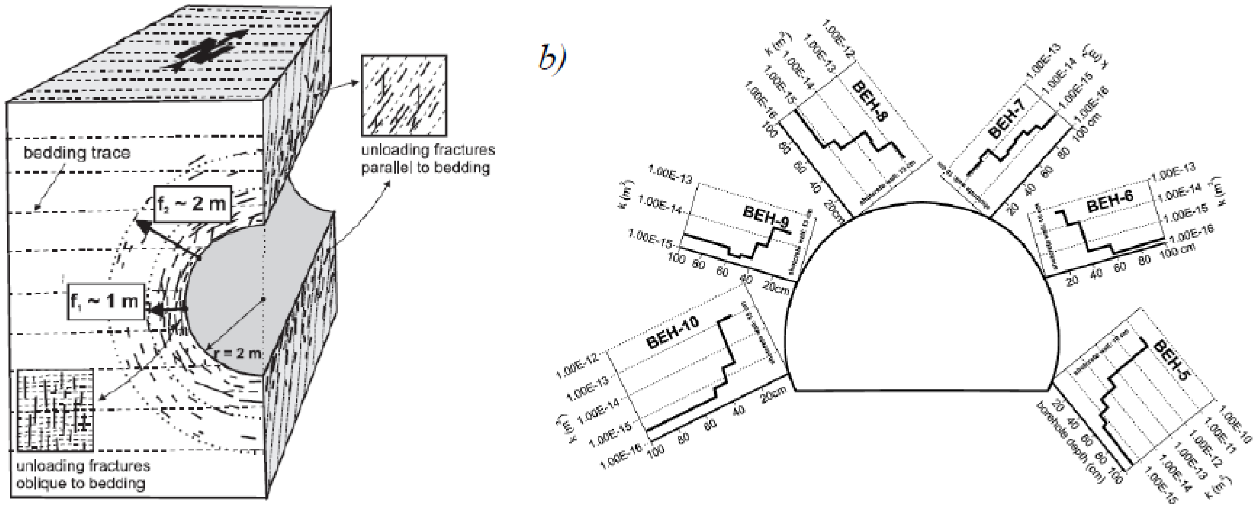

Figure 10: (a) Conceptual model of the excavation damage zone in Opalinus Clay. (b) Permeability distribution around the gallery derived from pneumatic testing (from Bossart et al., 2002).

The EDZ extent and intensity does 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 (Escoffier et al., 2005; Vietor et al., 2006; Popp and Salzer, 2007; Sillen et al., 2010a; Labiouse and Vietor, 2009; Popp et al., 2008, 2009).

Fortunately, to some degree, site-specific design can reduce EDZ extent and intensity. Such design can include 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 the tunnel support system, weighing factors—such as its stiffness, thickness, setting time and distance from the excavation front—is also relevant, serving to provide back pressure to tunnel face convergence and decrease deviatoric stresses. 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 that may have formed.

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. An elastic damage framework is needed to reproduce the changes in pore-water pressure. Modeling of EDZ extent depends on the constitutive law used with its choice of the elastic limit and fracturing criteria. Perhaps a strain softening model is needed to reproduce the progressive change in material strength during excavation, in order to properly reproduce 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 processes involved.

Outstanding 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 changes should be understood and quantified. Further, 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 models has been able to reproduce the full hydromechanical behavior of the excavation process, including fracture development, suction effects, and permeability changes.

5. Key Processes and Outstanding Issues during the Ventilation Stage

This stage may be defined as the period between completion of excavation and lining installation and the emplacement of waste and buffer. This period may last from a few months to several years. During this period, the rock wall is in contact with the atmosphere in the tunnel, either directly or through the tunnel lining. The atmosphere with its (generally lower) humidity imposes suction on the clay surface at the tunnel wall, changing the local effective stress. The interaction between the tunnel atmosphere and the clay rock, especially in the presence of the lining (with its own permeability and air entry pressure), is a complex, outstanding research problem.

Tunnel ventilation and temperature changes may have strong effects on rock properties, since they 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. An example of variation in rock strength and moisture content is shown in Figure 11.

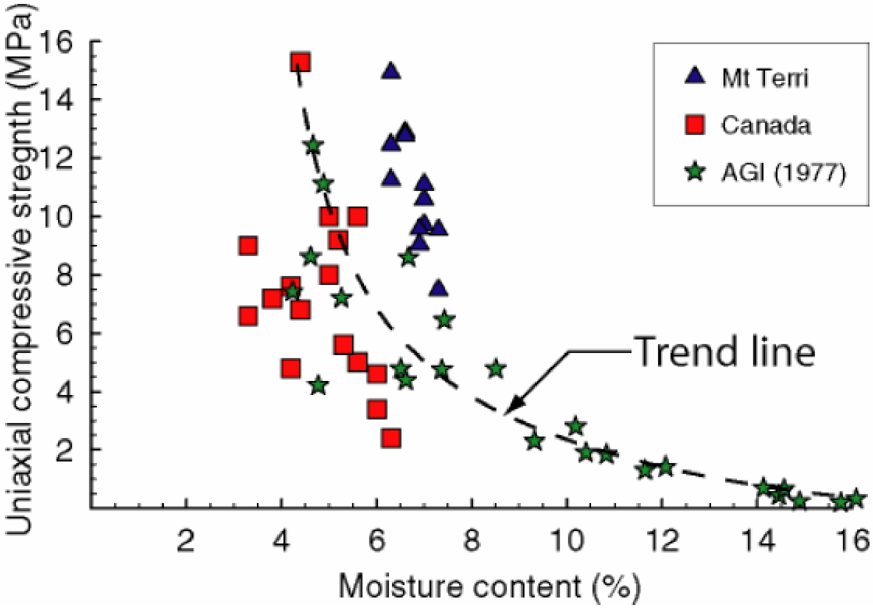

Figure 11: Relationship between uniaxial compressive strength and moisture content for various clay shales (from Martin et al., 2002)

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 flow of air with different humidity levels (Mayor et al., 2007). The experiment was conducted in a 10 m section of a nonlined 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 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 and with a rock permeability of 10^{-19} 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. Figure 12 shows the tunnel in indurated clay at the Tournemire Site, Southern France, where tunnel sections excavated in 1881, 1996, and 2003 are compared. They display different fracture patterns (Rejeb, 2003; Rejeb and Cabrera, 2006). Attempts to model such observations were made by Massmann et al. (2009) and Rutenberg et al. (2009).

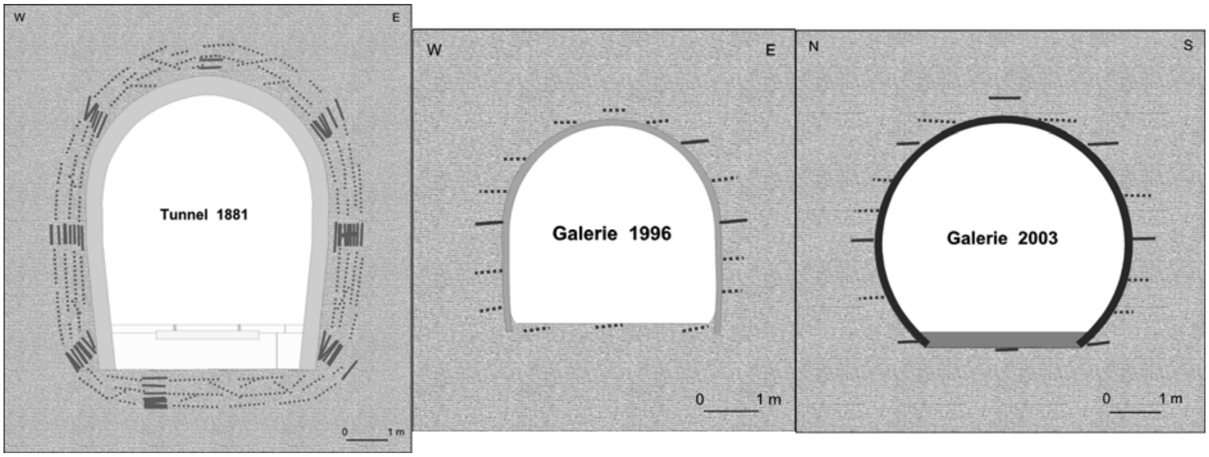

Figure 12: Types of rock mass failure around the different drifts at the Tournemire site (from Rutenberg et al., 2009; Rejeb and Cabrera, 2006)

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, as the EDZ permeability decreases. A number of studies have been conducted to investigate swelling behavior and permeability evolution (SELFRAC, 2007; Meier et al., 2000; Lanyon et al., 2009; Zhang and Rothfuehs, 2008, Zhang et al., 2009b; Bock et al., 2010).

Creep occurs especially in plastic clays, but also in indurated clay, possibly leading to long-term tunnel convergence for unsupported tunnel walls and an increase in the extent of EDZ. For walls supported by rigid lining, large back pressure may build up on the support, with stress recovery in the rock and the resulting fracture sealing. A number of studies have been conducted to investigate sealing of fractures (e.g., Naumann et al., 2007; Labiouse et al., 2009). Figure 13 shows results from a set of laboratory experiments on fractured Opalinus Clay samples from Mont Terri conducted under confined conditions. 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 (Gräsle, 2009) as a function of deviatonic stress for undrained and drained samples (Figure 14). Generally, the creep rate can be an order of magnitude larger for undrained than for drained conditions, because the presence of water facilitates the creep process.

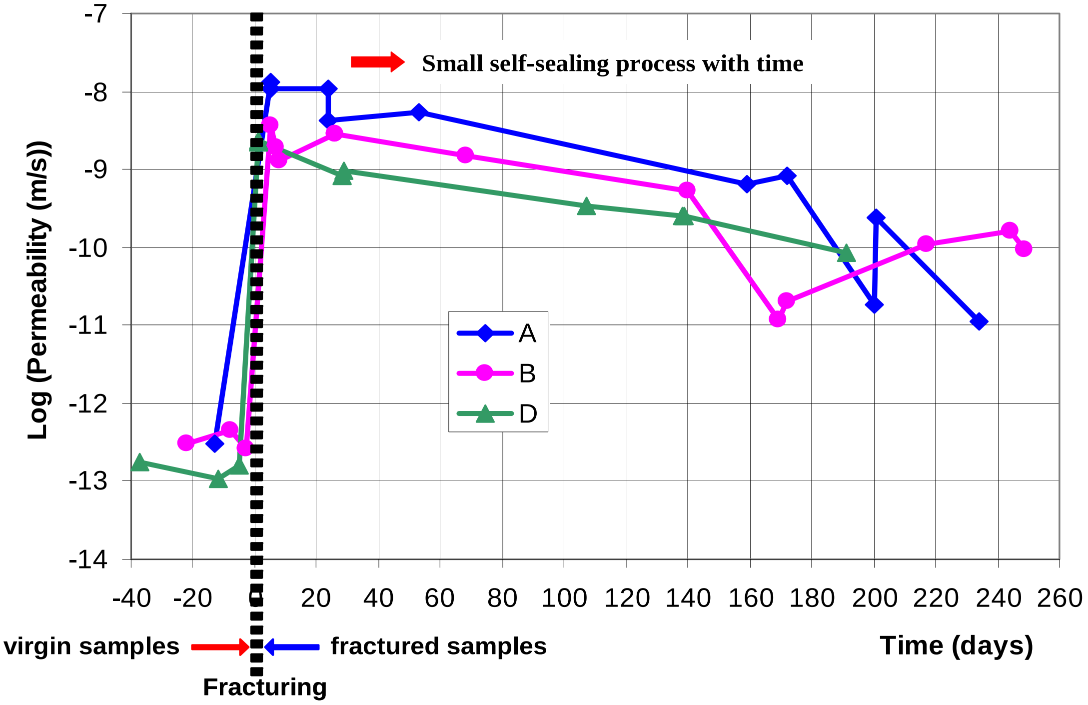

Figure 13: Evolution of hydraulic conductivity with time in fractured Opalinus Clay samples (from Labiouse et al., 2009)

Operationally, careful control of air humidity in the tunnel during this period is important for a repository in clay. 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 pressure dissipation and subcritical microfracturing under saturated-unsaturated conditions. Clay rock mechanical behavior is also sensitive to moisture content and local geochemistry, so that an adequate description of the nonequilibrium interface with atmospheric air is an important (and unsolved) research topic.

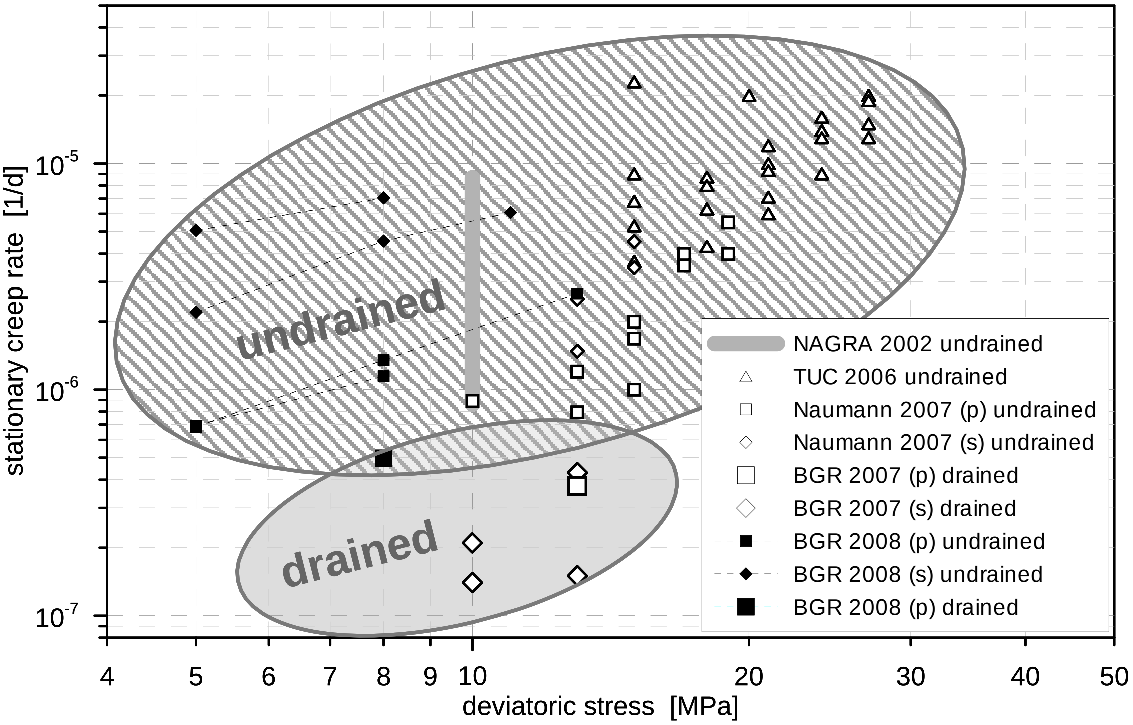

Figure 14: Comparison of measured creep rates (from Gräsle, 2009)

6. Key Process and Outstanding Issues after Waste and Buffer Emplacement

Waste emplacement represents the start of a period with thermal perturbation of the repository environment. Decay heat from radioactive waste has to diffuse away through the buffer and the near-field rock to the far field. Heating may cause rock desaturation in the near field, with associated mechanical effects discussed in the last section. Resaturation is a slow process governed by low rock permeability and buffer characteristics, and will not be uniform over the repository domain. Further, heating may induce differential expansion and pore-pressure buildup, leading to changes in compressive and tensile stresses. Heating may affect some relevant processes discussed in the previous section, e.g., possibly changing creep rate and strength. Studies addressing heating effects by laboratory measurements and field tests include those by Collin et al. (2002), Delage et al. (2009), Zhang et al. (2009a), Gens et al. (2007), Sultan et al. (2002), Tang et al. (2008), and Cui et al. (2009).

Figure 15 shows the layout of the heater experiment HE-D at Mont Terri URL (Zhang et al., 2007; 2009a). 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 to 1.4 m from the heaters, pore-water pressure rise of 1 to 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.

The very complex thermo-hydro-mechanical processes occurring in the clay rock in this experiment were reasonably reproduced by coupled model calculations. Zhang et al. (2007) suggested that there is a need to further investigate (1) the thermal effects on 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 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 (Sillen, 2010b) 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 and also revealed anisotropic stress changes in the closest observation borehole. 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.

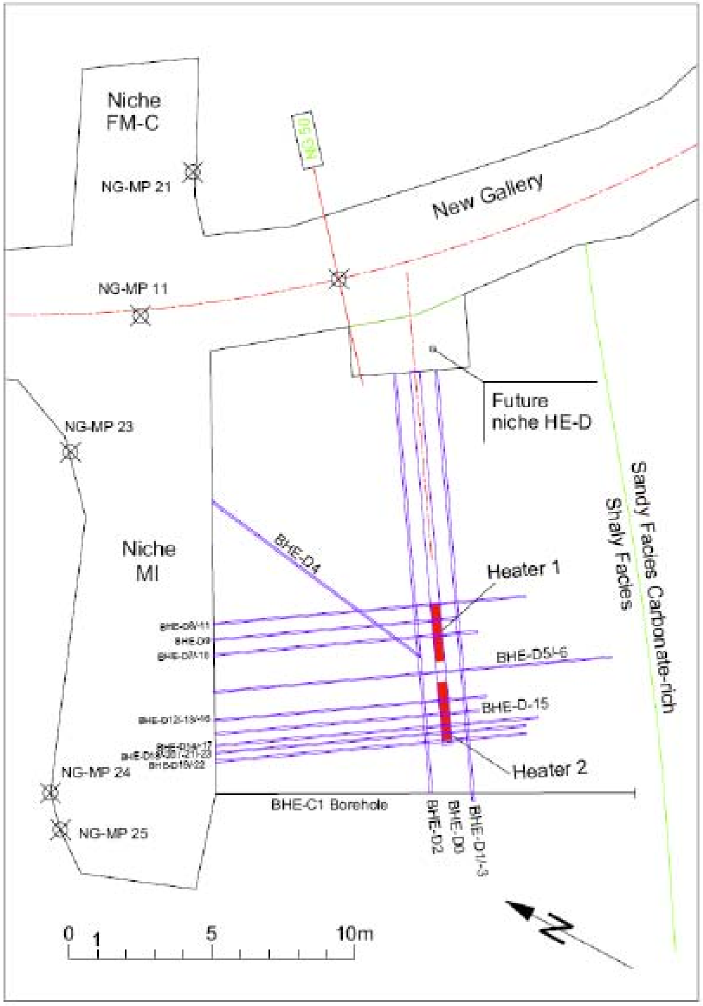

Figure 15. Layout of HE-D heater experiment at Mont Terri URL (from Zhang et al., 2009a)

Currently at the Mont Terri and HADES URLs, large long-term heater tests, named FE and Praclay, respectively, are being planned, which may offer interesting collaborative research opportunities for the geologic disposal program in the United States.

Summarizing, the outstanding issues at this stage include the need to consider anisotropic thermal conductivity and expansion coefficients, and the need to evaluate the thermal behavior of the complex system of waste canister, buffer, lining, and host rock, each with its own thermal properties. In general, how temperature and temperature gradients will change clay properties and behavior is still not well known, though there have been many efforts in this direction.

7. Key Processes and Outstanding Issues during the Post-closure Stage

Some time after the closure of a nuclear waste repository in clay, the tunnels will be saturated with water, resulting in buffer swelling and a return of pore-water pressure to the original hydrostatic level. Most fractures will probably be sealed due to clay swelling and enhanced creep processes in the presence of water and heat. Long-term deformation behavior of the rock is of concern. Possible driving mechanisms for coupled hydromechanical time-dependent deformation of argillaceous clays are discussed in Czaikowski and Wieczorck (2010) and Czaikowski and Lux (2006).

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. Confirmatory studies with natural analogues 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 (e.g., Marschall et al., 2005; Shao et al., 2009; Hoxha et al., 2010; Duveau et al., 2010).

Of particular interest is the international cooperative project named FORGE, which is under way to study this problem (Shaw, 2010). 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.

Apart from gas transport, the postclosure period is also concerned with radionuclide transport in solution through the clay repository. In intact unfractured clays, radionuclide transport will be slow and dominated by diffusion, because of the low permeability and high retardation capacity of the rock (e.g., Van Loon et al., 2004; Wersin et al., 2008). 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 processes and outstanding issues related to radioactive waste repositories in clay formations, with particular focus on the characteristics and evolution of the near-field EDZ. 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, mostly in Europe, several outstanding issues remain. These were discussed above for each of the four stages of repository development. Below, we shall summarize them in a number of major research areas.

- Constitutive relationships for 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. The impact of hydromechanical, chemical, and thermal effects also needs to be considered.
- Long-term (slow) clay property changes, such as creep in plastic clays and subcritical crack growth in indurated clays. The effects of moisture changes and temperature

gradients and chemical environments need to be studied and formulated. How to handle anisotropy and bedding planes (or in general, planes of weakness) has to be resolved.

- 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 on a proper basis. The possible nonequilibrium condition at the rock wall in contact with the tunnel atmosphere, directly or through tunnel lining, is yet to be understood and formulated.
- Thermo-hydro-mechanical processes in clays. These include damage mechanisms, phase changes, and interaction of multiple materials (such as those in the engineered barrier system). This 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 URL observations. The thermal and geochemical effects on (long-term) EDZ evolution need to be considered. Potential occurrence of a geochemical damage zone cannot be ruled out, and its long-term effects must be evaluated.
- Impact of rock-property heterogeneity as well as *in situ* stress fields. The permeability of indurated clays can vary over two orders of magnitude, while mechanical properties can vary by a factor of five or more. Spatial variability may have some characteristic length or may have a fractal character. Understanding clay variability could be key to predicting strain localization and fracturing processes. The stress field may also be spatially varying, depending on local structures and temporal changes in clay properties.

Many, though perhaps not all, of the above research needs are being addressed (or are planned to be addressed) at the major URLs in Europe. It would be mutually beneficial if close cooperation and scientific exchanges can be established between these European efforts and the geologic disposal research to be conducted in the United States.

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