

The Excavation-Damaged Zone in Clay Formations – Time-dependent Behaviour and Influence on Performance Assessment

Peter Blümling^{a,1}, Frédéric Bernier^b, Patrick Lebon^c, C. Derek Martin^d

^aNAGRA, Hardstr. 73, CH 5430 Wettingen, Switzerland

^bEURIDICE, Boeretang 200, B-2400 Mol, Belgium

^cANDRA, 1-7 rue J. Monnet, F-92260 Chatenay-Malabry, France,

^dUniversity of Alberta, Department of Civil & Environmental Engineering, Edmonton, T6G2G7 Canada

Abstract

Clay formations in their natural state exhibit very favourable conditions for disposal of radioactive waste. One concern regarding waste disposal is that due to the necessary underground excavations and the associated disturbance and damage in the area close to these excavations, the favourable properties of such formations could change and the host rock could lose part of its barrier function.

Stress redistribution will lead to the creation of a so-called excavation-damaged zone (EDZ) which will be controlled by the initial stress field, the material properties (e.g. material anisotropy), the existence of natural fracture zones or local inhomogeneities of the rock mass and the geometry of the tunnel. Comprehensive investigations at different sites (e.g. HADES, Belgium, Mont Terri, Switzerland, Tournemire, France) have shown that an EDZ occurs in soft or plastic clays as well as in indurated and more brittle claystones or argillites. The short-term excavation-induced reaction of the rock during tunnelling, which leads to the initial EDZ, cannot be avoided but is reasonably well understood and the associated processes can be adequately modelled.

The long-term behaviour of the tunnel near-field can be significantly influenced by adequate support measures and the time-dependent evolution of the EDZ before the emplacement of the

¹ Corresponding author. Tel. +41-56-4371 293; fax: +41-56-4371-345
E-mail address: peter.blumling@nagra.ch

waste and the backfilling of the tunnel can be controlled. The properties of the initial EDZ alter significantly during the transient phase, when the buffer and rock mass are heated by the heat-producing waste and saturated due to flow of formation water from the host rock. Experimental results in the laboratory and in-situ clearly show that (self-)sealing lead to a significant reduction of the effective hydraulic conductivity of the EDZ with time thus reducing the potential flow along underground excavations. Expected long-term conductivities within the EDZ are in the range of 10^{-10} to 10^{-12} m/s.

Performance assessment calculations for different repository designs in different clay host rock formations show that the influence of the EDZ on radionuclide release is quite limited. It has been shown that even for very conservative, so-called “what if?” cases the very stringent regulatory guidelines can be met.

Keywords

Excavation disturbed zone, performance assessment, radionuclide transport, hydraulic conductivity

1. Introduction

Clay formations in their natural state exhibit very favourable conditions for disposal of radioactive waste as they generally have a very low and uniform hydraulic conductivity, low diffusion coefficients and good retention capacity for radionuclides. An undisturbed clay or clay rock could thus be a particularly good host rock for a nuclear waste repository. Nevertheless, one concern regarding waste disposal is that due to the necessary underground excavations and the associated disturbance and damage in the area close to these excavations, the favourable properties of such formations could change and the host rock could lose part of its barrier function. In addition, the associated de-saturation / re-saturation process as well as

heating of the rock and the potential engineered barrier systems are of concern and need a detailed evaluation to assess their influence on the long-term behaviour of the repository system.

One of the challenges for constructing a deep geological repository in weak rocks is estimating the constructability, i.e., support requirements. Balancing the support requirements with the isolation requirements (repository depth) can only be achieved if the properties of the rock mass can be evaluated with confidence. This evaluation is difficult for any type of rock mass as input data have to be inferred from standard laboratory tests. The test samples are in general of relatively small size and do not represent the rock heterogeneity and the influence of potential discrete features or discontinuities. Therefore, up-scaling procedures are necessary in nearly all rock types to evaluate deformation and fracturing associated with tunnelling. In addition to these general problems, clays, clay shales or claystone show even more severe problems. Rock-water interaction, severe influence of de-saturation / re-saturation cycles and mechanical micro-cracking during sample extraction, transport and preparation may lead to significant alteration of the rock properties or state changes. This increases the difficulties in realistically describing the rock mass behaviour and deriving parameters for adequate constitutive laws. For example, Barla et al (2004) have found that laboratory data of an Italian shale could not be used directly to assess the tunnel behaviour and that parameters needed to be scaled up significantly in order to obtain appropriate predictions.

Problems to predict short-term rock mass behaviour during tunnelling are challenging but can be solved in a learning-by-doing procedure during the construction of the first access tunnels and adequate large-scale investigations in an on-site rock laboratory. The long-term behaviour of the rock cannot be observed under realistic scales in space and time but requires adequate process understanding and numerical modelling. In contrast to crystalline rocks, where

deformation in the given stress / temperature regime is mainly elastic or elasto-plastic, clays and clay rock exhibit a much more complex behaviour. Questions on adequate rheological models, changes in time-dependent behaviour due to temperature, stress and associated water content changes, have to be addressed and answered.

2. Mechanical Behaviour of Clay Formations

The main information source for geotechnical parameters of any rock formation are borehole cores taken from deep boreholes. These rock samples are taken with great care by using double and triple core barrels but nevertheless, they will become disturbed when they are retrieved from their natural environment, where they are exposed to a certain stress field and pore pressure.

2.1 Sample disturbance

It is well known that creating any underground excavation disturbs the in-situ stress state. And because stresses at the walls around an underground excavation are independent of the size of the excavation, the same stresses exist around a 100-mm-diameter borehole as those which exist around a 5-m-diameter tunnel. Figure 1 shows the stress path followed by three points around a horizontal hole drilled parallel to the far-field σ_2 : top line - along the top of the opening, side line - along the side of the opening, and centre line - along the centre of the opening. In Figure 1, each of these points starts at the same in-situ stress state but end at a very different stress state. For example the centre-line, which is equivalent to taking a core sample, shows the complete unloading process that a sample will go through, while the side-line results in large tangential stresses that may exceed the strength envelope of the material.

For the case of a drill hole, the centre line shows the stress path the sample follows before being collected. As shown in Figure 1, the drill core will be subjected to a stress path that will create extensional loading conditions, particularly in the vicinity of the drill-bit. Such extensional loading can create microcracking and in severe stress conditions will lead to core dishing (Figure 2). Once the sample has been retrieved it may then be subjected to the laboratory triaxial stress path in order to quantify the in-situ strength and deformation properties.

Core retrieved from such stress conditions show characteristics that indicate that the properties of the clay have been disturbed. Figure 3 shows typical axial stress-strain curves of disturbed samples. Note in Figure 3, the highly nonlinear behaviour of the samples with zero to low confining stress and that this nonlinearity reduces as the confining stress is increased. Such laboratory behaviour has been observed in thermally cracked marble (Rosengren and Jaeger, 1968) and microcracked granite (Martin & Stimpson, 1994). It is important to note that regardless of the amount of confinement, the deformation and strength parameters determined from such samples will be significantly less than the properties of undisturbed samples. When dealing with weak, tight rocks with very fine pores and high reactivity with water, environmental conditions (humidity), pore water pressure, drilling fluids (air or oil), and sample storage and handling, can also significantly decrease the quality of drill core. In weak rock Corkum (2005) has also shown that the unloading process during sampling can lead to the mechanical breakage of diagenetic bonds, which can cause a highly nonlinear elastic response. Hence, it is easy to appreciate why Barla et al. (2004) needed to up-scale their laboratory properties to match the in-situ behaviour.

2.2 *Homogeneity and isotropy of clay formations*

Clay rocks are a result of a complex sedimentation and compaction history which significantly influence their mechanical behaviour. The sedimentation process itself – fluvial or marine environment, deep or shallow water depth, origin of the material – influences the homogeneity and the internal structure of the clay sediments. The burial history – subsidence and uplift processes – control the thermal and mechanical compaction processes and determine whether the material is normal or over-consolidated. Bedded sediments tend to exhibit an anisotropic, mainly transversely isotropic behaviour which may be controlled by diagenetic or low grade metamorphic processes.

Small scale heterogeneity in the clay composition can initiate microfracturing during loading even before the peak strength of the material is reached. For Callovo-Oxfordian argillite, the potential host rock for a repository for radioactive waste in France, differences in stiffness of clay minerals on the one hand, and quartz and calcite on the other hand lead to local strain accumulation (2% in clay agglomerates for a mean strain of 0.76%). This process induces micro-cracks at crystalline interfaces (Figure 4), mainly clay/calcite, or even cleavage of minerals (Chiarelli, 2000). Their general direction is related to the stress field.

The stress damage threshold seems to be correlated to the strength of the argillite but the carbonate content controls the damage – the higher the carbonate content the more severe the damage. For the Callovo-Oxfordian the following relations were observed:

$$q_{\text{dam}} = 0,9 q_c - 13 \text{ (MPa) in the carbonate-rich formation}$$

$$q_{\text{dam}} = 0,6 q_c - 2 \text{ (MPa) in the clay-rich formation}$$

where q_{dam} = threshold of deviatoric stress for the onset of damage

q_c = peak deviatoric strength

The observed non-linear behaviour can be described by elasto-plastic models including anisotropic damage criteria (Chiarelli, 2000; Conil et al., 2004).

When the deviatoric stress reaches 90% of the peak strength, the propagation of cracks becomes unstable. They coalesce in shear bands, creating macro fractures. Mechanical tests on tubes of argillite highlight the geometry of the fracture network (Valès et al., 2005). The main fractures are similar to a logarithmic spiral. Radial and ortho-radial fractures seem to result from interferences with other processes.

3. Basic processes during tunnel construction

During tunnel construction new surfaces will be created leading to significant changes in the local stress field. The stresses normal to the interface (e.g. radial stress in a cylindrical tunnel) have to vanish (for unsupported tunnels) at the interface while tangential stresses may increase significantly. In other words, the confining stress becomes zero and the other stress component increase which may lead to local failure under extension and/or shear. Such processes can be accelerated by hydro-mechanically coupled processes as part of the near-field rock could become compacted and pore water pressure may increase locally thus changing the effective stress.

Areas around underground excavation affected by such processes are generally called excavation disturbed (EdZ) or damaged zone (EDZ). There is now an international consensus to relate the definition of the EDZ with processes, which are important for the long-term safety of a repository for geological disposal of radioactive waste (Tsang & Bernier, 2004). It is

important to differentiate the two zones with regard to their flow and transport characteristics, admitting that areas of hydro-mechanical and geochemical modifications with major changes in flow and transport properties should be distinguished from those without negative effects on the long-term safety.

The proposed definitions are:

- The Excavation Disturbed Zone (EdZ) is a zone with hydro-mechanical and geochemical modifications, without major changes in flow and transport properties. Within the EdZ there are no negative effects on the long-term safety.

- The Excavation Damaged Zone (EDZ) is a zone with hydro-mechanical and geochemical modifications inducing significant changes in flow and transport properties. These changes can, for example, include one or more orders of magnitude increase in flow permeability.

These definitions should be enhanced for each type of rock and each site. In particular, the terms “significant” and “major” should be quantified and the time effect should be discussed for each particular site.

3.1 Formation of EDZ

The geometry of the EDZ can become quite complicated as it is controlled by:

- Stress tensor (anisotropy of stress)
- Material anisotropy (e.g. transverse isotropy of bedded sediments)

- Existence of natural fracture zones or local inhomogeneities of the rock mass
- Geometry of the tunnel.
- Tunnel support and ground interaction

Comprehensive investigations at different sites (e.g. HADES, Belgium, Mont Terri, Switzerland, Tournemire, France) have shown that an EDZ occurs in soft or plastic clays as well as in indurated and more brittle claystones or argillites. Most discrete features in the EDZ in hard and brittle clays are caused directly by the short-term excavation-induced unloading (undrained elasto-plastic response) and are of extensional nature. For weaker rocks or soft clays, these features are mostly replaced by shear failure. In the case of anisotropic rocks (e.g. bedded rocks, low-grade metamorphic rocks), an activation of the planes of weakness can be observed. This failure process can be of extensional or shear origin.

The modelling of the failure process and EDZ creation requires the selection of an adequate constitutive model, its parameterisation and the knowledge of the boundary conditions. In addition, the stress path during tunnel construction has to be taken into account to understand the basic deformation and failure processes. Figure 1 illustrates for a specific case (Mont Terri) the complex stress path at different positions along the tunnel. Within the EDZ, portions of the tunnel wall become partially unloaded (areas in the roof) while other portions (sidewall) are subjected to large increases in tangential stress. Taking such stress paths into account, the failure behaviour can be quite different for different rock types. If it is assumed that the failure behaviour that Diederichs (2003) suggested for crystalline rocks can be generalised for other rock types the following behaviour may be observed. More competent rock like hard clays or clay shale tend to show spalling or extensional failure (Figure 5, left side) as the spalling conditions are reached first, while soft rocks may preferentially fail under shear and form

classical conjugated shear failure as illustrated in Figure 5 on the right side (stress path crosses the shear failure envelope first).

The basic result of such different failure processes is shown in Figure 6 with borehole and tunnel examples for the Opalinus Clay from Mont Terri, Switzerland and the Boom Clay from Mol, Belgium. While the Opalinus Clay shows distinct extensional failure along the tunnel wall (Figure 6a), a transient behaviour is observed for a borehole EDZ of Opalinus Clay with combinations of extensional and shear features (Figure 6b) and clearly a pure shear failure for the Boom Clay leading to characteristic eye-shape fractures (conjugated shear fractures). The different fracture patterns at Mont Terri might be either caused by scale effects or more realistically by different excavation directions leading to different stress situations and stress paths.

These results indicate that the EDZ problem is by far more than a 2-D plane-strain problem leading to axi-symmetrical failure patterns. Due to the complicated secondary stress field in the vicinity of the tunnel face other failure patterns may be observed especially in soft clays. Fracture patterns observed along galleries in the Boom clay are very consistent all along the excavation (Figure 7), and interestingly this pattern is very similar to the fracture pattern observed on a much smaller scale along cores as a result of the drilling (Figure 8).

An additional complication in the creation and understanding of fracture patterns around excavations is given by potential material anisotropy and its direction with respect to the stress field. The anisotropy might be caused by diagenetic processes or metamorphism leading to planes of weakness in the rock. In very fine grained material the bedding planes can be very thin creating an ubiquitous system of potential failure planes. Interesting examples of failure patterns under such conditions are shown in Figure 9. The EDZ in Figure 9a is observed around

a small borehole at the Mont Terri Underground Laboratory. The deformation of the bedding (nearly horizontal in this case) leads to detachment of discrete layers and a buckling of the material into the borehole. On a larger scale and in combination with bedding parallel fractures, instabilities may occur, leading to large scale breakout in the tunnel (Figure 9b).

The general fracture pattern for a transversely isotropic hard clay is shown in Figure 10 (Nagra, 2002) and has been proved by a large number of examples at the Mont Terri site at various scales. In this case the EDZ in the sidewall is mainly controlled by extensional failure while the deformation in the roof and the floor is caused by bedding plane failure.

4. Time-dependent development of the EDZ

Critical to our understanding of the EDZ is defining the boundary between the damaged, disturbed and undisturbed rock mass properties and recognizing that the disturbed or damaged properties will likely undergo significant changes with time. Within the EDZ the stress redistribution may lead to localized consolidation and swelling in the post-closure phase. For example in the region of tangential stress concentration the maximum stress may exceed the previous overconsolidation stress and the material may behave more like a normally consolidated sediment rather than an overconsolidated one. In the unloaded areas, suction may attract moisture and these materials may locally swell. Hence the EDZ may experience several complex processes and the material properties may significantly alter with time. Corkum (2005) has shown that undrained shear strength and deformation modulus of Opalinus clay is sensitive to water content (Figure 11). Hence as the water content changes within the EDZ, as it adjusts to the new stress conditions, the strength and deformation properties will also change.

In general, the water content is a very important parameter to characterise the mechanical behaviour of clay rocks but it may affect the rock in very different ways:

- In a saturated stage the water content describes the total porosity of the rock and therefore the distance between clay particles which strongly influences the distance-dependent inter-particle forces (repulsive and attractive forces)
- Swelling due to water uptake or compaction may change the total porosity and distances between particles and therefore weaken or strengthen the rock, respectively.
- De-saturation may result in large suction pressure which increases the apparent strength while re-saturation of partly saturated samples will have the opposite effect.

Regardless of the detailed process, rock-water interaction will have a severe effect on the mechanical behaviour and the sensitivity of these weak rocks to changing water content or the degree of saturation should not be underestimated. For example Little (1989), reported on the performance of a 11.1-m-wide, 7.5-m-high and 45-m-long test chamber in weak shale. The extensive monitoring revealed that the rock mass response to excavation was essentially elastic with no indication of time-dependent movement and that nominal shotcrete and rock bolt support was an adequate support system. Approximately 1 year after excavation the lower portion of the test tunnel was flooded. Upon dewatering one-year later, major portions of the test chamber had collapsed. Although this example does not directly describe the processes expected during the slow re-saturation of a backfilled tunnel in a repository, it re-emphasizes and highlights the role of water in the determining behaviour and strength of such materials.

It must be anticipated that the characteristics of the EDZ in these materials will change with time and that these changes can be accelerated if the environmental conditions (e.g., humidity)

are also changed. These changes are currently being monitored at Mol (Bastiaens et al., 2005) and at the Mont Terri underground research laboratory in several experiments.

4.1 Operational phase

After construction the emplacement tunnels or drifts have to be kept open for a relatively short time (a few weeks to few years depending on the concept) until waste containers and buffer material have been emplaced. Whereas the instantaneous response and the associated features in the EDZ cannot be avoided, the time-dependent or progressive failure within the EDZ during this open phase of the tunnel or drift can be controlled by using adequate rock support immediately after tunnel construction. Good results have been achieved in soft clays, like the Boom Clay in Belgium, by using massive concrete liners emplaced with the wedge-block technique. In indurated clays, rock bolts and mesh, shotcrete or steel liners may be an adequate solution to limit the size of the EDZ.

4.2 Post-emplacement phase

After the backfill of the tunnels or drifts, the support systems will degrade and the rock will adjust to the new situation to eventually reach a final equilibrium. Within this transient period the heat generating waste may cause an increase of stresses because of thermal expansion of solids and porewater and heating-related reduction of strength. Numerical calculations and in-situ tests indicate that this transient effect is limited as the temperature increase at some distance from the emplacement tunnel is quite moderate. This process could further increase the size of the EDZ but in turn, heating may also increase creep rates and thus accelerate the closure of open fractures and reduce the influence of the EDZ.

In this context, the hydraulic and transport properties along the EDZ need to be investigated, especially the development of the effective axial hydraulic conductivity with time. In Boom clay the hydraulic conductivity in the EDZ varies from 10^{-11} to 10^{-12} m/s while in the Opalinus Clay an increase from a homogeneous hydraulic conductivity of about 10^{-13} m/s to local maximum fracture transmissivities of 5×10^{-7} m²/s have been observed in the initial phase of the EDZ creation. The effective axial hydraulic conductivity, which is controlled by several factors (e.g. the interconnectivity of individual features), has not been measured so far. There are indications from in-situ tests that this property of the EDZ is much lower than the conductivity inferred from locally measured fracture transmissivities.

The first step to investigate the complicated coupled processes in the EDZ during the transient phase is to evaluate the change of hydraulic properties in a single fracture in soft or hard clay. It is obvious that fractures in soft clay are closed comparably fast during saturation and swelling conditions as demonstrated on Boom Clay samples (Figure 12) during the SELFRAC project (Ortiz and Van Geet, 2005) .

Tests were conducted to characterise the sealing processes by monitoring the evolution of the flow properties along an artificially created fracture. Results of these tests show that for Boom Clay sealing occurs very quickly after saturation of the fracture. During sealing the permeability decreases to a value close to that of intact Boom Clay (about 4×10^{-12} m/s). Microfocus X-ray computer tomography has been used to visualise the sealing of the fracture (see Fig. 12a and b). This is a recent technique allowing non-destructive inspection of non-transparent objects.

For overconsolidated claystone such processes are more time consuming but nevertheless they have been observed on several scales – from sample size to meter size. An experiment at Mont

Terri on a single, hydraulically induced artificial in-situ fracture showed a very pronounced stress dependent hydraulic transmissivity. The fracture transmissivity was very similar to the one of the intact rock as long as the effective normal pressure on the fracture surface exceeded a value of about 2 MPa (Enachesu et al., 2002) while at lower effective normal stresses the transmissivity was more than 4 orders of magnitude higher (Figure 13). Such a process is in accordance with geomechanical fracture models relating fracture aperture and therefore fracture transmissivity to effective stress (e.g. Barton-Bandis model).

The tests on the single fracture implied that the hydraulic properties depend mainly on the stress situation but additional laboratory and more complex in-situ tests of the time-dependent development of the EDZ indicated that additional processes may be equally important. Meier et al. (2002) investigated the change of EDZ transmissivity during re-saturation and demonstrated that more than 2 orders of magnitude reduction can be expected just from this process. These results are in good agreement with observations of EDZ transmissivities (Alheid & Blümling, 2004) within the demonstration experiment EB at the Mont Terri underground laboratory, Andra's hydraulic investigations of EDZ development within the Mont Terri EZ-A experiment and new laboratory tests from Skoczylas et al. (2005) as shown in Figure 14. The processes which are responsible for such a permeability reduction during saturation and water up-take are not yet fully understood but may be related to accelerated creep, disintegration of the rock, swelling and shear compaction.

So far, the most comprehensive in-situ testing on time-dependent transmissivity evolution in the EDZ of a hard clay has been conducted at Mont Terri in a 3.5 diameter tunnel. The EDZ transmissivity was first investigated during re-saturation (EH experiment reported by Meier et al. 2002) and then during loading with a plate loading device simulating the mechanical load exceeded by the swelling buffer material (Bühler et al., 2004). As shown above the saturation

resulted in a transmissivity reduction of about 2 orders of magnitude within approximately 3 years and an additional 2 orders of magnitude during loading with about 5 MPa (experiment was terminated before steady-state was reached due to logistical problems). A comparison of the plate loading in-situ test, the single fracture in-situ experiment at Mont Terri and laboratory tests on Callovo-Oxfordian fractured samples (Skocylas et al., 2005) is shown in Figure 15 and summarises the load-dependency of fractures in claystone or argillite. Unloading tests indicate that at least part of this reduction in transmissivity is irreversible.

In addition to the processes described above, chemical reactions could lead to further decrease of the transmissivity of the EDZ. Especially in tunnels where concrete has been used as support (e.g. in intermediate level waste disposal tunnels) the clay or argillite will react with the degradation products of concrete. Recent simulations have been performed coupling geochemical interactions and transport processes into the concrete and the argillite (Jacquot & Dimier, 2005). It has been shown that neoformation of zeolites and saponite with a volume increase and precipitation of calcite will occur enhancing the sealing of the EDZ fractures.

5. Influence on performance assessment

Classically, the assessment of the performance and long-term safety of a repository system involves the evaluation of radionuclide transport from the waste form to the biosphere through the engineered and natural barriers. Due to the very low permeability of clay, water flow rates within and around the engineered barrier system (EBS) will be very small and advective transport is usually negligible. Consequently, the transport of radionuclides through the engineered barriers and the clay host formation is assumed to be mainly driven by molecular diffusion in the groundwater. Diffusive transport might be facilitated or hindered through the

EDZ because of physical and chemical alterations. For instance, the sorption capacity might be affected by oxidation, or the porosity might be different than that of undisturbed clay.

As a comprehensive performance assessment of a repository depends on host rock parameters, the geology surrounding the host rock, waste inventory and repository design it is difficult to make a general statement concerning the EDZ effect on performance assessment (PA). Therefore, results from different assessments in 3 national programs are discussed in the following:

5.1 Boom Clay, Belgium

In-situ observations suggest that no significant chemical alterations occur beyond a couple of metres from the URL. Fractures extending further than that have also been observed to reseal quickly. As the operational period of a disposal gallery before backfilling and sealing is not expected to last longer than the duration of the URL (Mol) exploitation up to now, it seems reasonable to assume that original radionuclide migration parameters will still prevail in Boom Clay at the time of container failure except maybe for the first few metres of the host formation. The uncertainty on the values of the migration parameters in the immediate vicinity of the galleries can be conservatively represented in performance assessments (PA) by reducing the effective thickness of the geological barrier by a couple of metres, provided that further experimental evidences confirm such a limited extent.

The possible role of the EDZ along galleries and shafts as a preferential pathway for advective transport is of more concern to PA. Water flowing through an EDZ which would be more permeable than the host formation could carry radionuclides along the excavation boundaries up to an aquifer more quickly than does diffusion through the host formation. Recently,

SCK•CEN has investigated several poor sealing scenarios in which the hydraulic conductivity of the galleries and the access shaft was raised to values three to six orders of magnitude above the conductivity of Boom Clay. Even in such adverse conditions, calculations indicate a rather limited contribution of such a pathway to the overall releases of radionuclides. This is due in part to the low conductivity of the host formation, which limits the availability of water for advective transport through the near field regardless of the conductivities of the EBS and EDZ. Furthermore, simulations of radionuclide transport through a repository system altered by various water-conducting features such as faults or inadvertent drillings have shown that, unless fairly high flow rates are assumed, the contribution of advective transport is still limited. The reason is that, for radionuclides transported through galleries, shafts or the EDZ by flowing water, the clay acts as a considerable sink all along the pathway. Additional investigations are needed to confirm these first results and to verify that gas-driven flow cannot lead to water velocities high enough for such pathways to become predominant.

Finally, possible mechanical and chemical interactions between the EDZ and components of the EBS may affect the performance these components. In that sense, the EDZ behaviour might be relevant to the assumptions on which PA calculations rest, if not to the calculation process itself (Bernier et al., 2004).

5.2 *Callovo-Oxfordian, France*

Andra performed sensitivity analysis for the performance assessment of the gallery sealing systems. The permeability of these systems greatly depends on the EDZ permeability, which could create a short-cut pathway (Bauer et al., 2004). It was shown by these numerical simulations that the hydraulic heads around the repository are not disturbed as long as the global seal permeability remains strictly lower than 10^{-9} m/s, but it needs to be lower than or

equal to 10^{-10} m/s so that the undisturbed host rock (geological barrier) remains the main radionuclide transport pathway.

In the framework of the European, SAFETI project, the initiation and propagation of a macro-fracture network around a gallery in Callovo-Oxfordian argillites have been numerically simulated with a new combined Continuous media / Discrete element code (Dedecker & Billaux, 2005). Experimental data from Skoczylas et al. (2005) have been used to determine the effective axial hydraulic conductivity of the EDZ in this modelling study. The sensitivity study with these simulations demonstrated that the effective axial conductivity is always lower than 10^{-10} m/s thus indicating that the transport through the intact host rock rather than through the EDZ dominates the radionuclide release into the biosphere.

5.3 *Opalinus Clay, Switzerland*

A comprehensive PA study has been performed within a feasibility study (Entsorgungsnachweis) which was submitted to the authorities for review in 2002. It was shown that during the thermal transient phase the canisters will provide isolation for the radionuclides. In addition, flow will be directed towards the emplacement tunnels because of the existing hydraulic gradient and the high capillary-induced suction in the unsaturated buffer and near-field rock. The re-saturation will take place in about several hundred years but the pore-pressure build-up in the tunnel near-field will need thousands of years.

In addition, it has been demonstrated that for rock masses with low hydraulic conductivity and no natural water-conducting features the flow through the EDZ is mainly limited by the inflow into the tunnels and partly by the effectiveness of the seals (Nagra, 2002). Even without seals the flow along tunnels levels off at effective conductivities of the EDZ of about 10^{-8} m/s

meaning that higher conductivities would not result in an increase in flow through the repository. But flow is not the only parameter that controls transport and therefore radionuclide release from a repository. The retention capacity of the buffer and host rock are at least equally important. It has been shown that especially in the case of long emplacement tunnels (long distance between radionuclide source and the end of the tunnel), radionuclides will be lost from the EDZ into the intact host rock by matrix diffusion. Smith et al. (2004) conducted a sensitivity study to evaluate the effect of the EDZ conductivity on dose for a repository in Opalinus Clay. Figure 16 clearly demonstrates that even for the worst case of an EDZ conductivity of 10^{-8} m/s (flow levels off at this value, see above) the dose stays well below the regulatory guidelines.

6. Conclusion

Stress redistribution around a tunnel will create a significant damaged zone around underground excavations in plastic or stiff clays, claystones or argillites. This EDZ initially has an increased hydraulic conductivity and could act as a preferential pathway for the radionuclide transport. Although the short-term, mainly undrained failure of the rock around the excavation cannot be avoided, the time-dependent development of the EDZ can be controlled by adequate support or lining systems. Soft clays may require massive concrete lining (e.g. concrete segments with wedge-block technique) while drifts in claystone or argillites could be build with significantly lighter support measures (e.g. steel liners of rock bolts and meshes).

In all clay formations, investigated so far, a clear tendency for (self-)sealing processes have been observed while (self-)healing processes are quite limited. Soft clays react very fast in this sense and show fracture closure (sealing) or even indications for healing while hard clays or argillites (Opalinus Clay or Callovo-Oxfordian) require much more time for the (self-)sealing

processes. Nevertheless, observations indicate reductions of transmissivity of several orders of magnitude within a few years. The processes leading to sealing and healing behaviour are not fully understood yet, but possible processes have been identified (e.g. accelerated creep during water up-take, swelling, load-dependent aperture change and disintegration). So far, the different experiments show that the effective hydraulic conductivity of the EDZ in the different rocks will be lower than 10^{-10} m/s within several years after backfilling of the emplacement drifts. The hydraulic parameters of natural fractures indicate (Nagra, 2002) that the long-term conductivity of the EDZ is even lower. The maximum hydraulic conductivity of the EDZ is expected to be approximately one order of magnitude higher than that of intact rock.

Performance assessments for different repository designs in different clay formations (Boom Clay, Callovo-Oxfordian and Opalinus Clay) have demonstrated that even for rather unfavourable EDZ conditions the performance of the repository is not adversely affected and that doses are well below regulatory guidelines.

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Figure Captions

- Figure 1: Illustration of the stresses around a borehole and tunnels
- Schematic view of 3D tunnelling/borehole situation.
 - Generalised stress state for a drill core and in the rock ahead of the drill bit (numbers indicate positions along the stress path shown in d) for the centre line).
 - Generalised stress state along the sidewall of a tunnel (numbers indicate positions along the stress path in d) for the side line).
 - Associated stress paths for three points: top line, side line and centre line. Also shown is the stress path for a standard triaxial test.
- Figure 2: Example of core dinking, an extreme form of sample disturbance.
- Figure 3: Nonlinear behaviour of disturbed samples of Opalinus Clay
- Figure 4: Sample of Callovo-Oxfordian argillite (a) before (b) after a triaxial test : microcracks clearly appear (views of environmental MEB from Bornet 2001)
- Figure 5: Schematic illustration of different failure behaviour of brittle rocks with higher shear strength (left side) and of soft rock (right side). A failure behaviour according to Diederichs (2003) is assumed including shear failure envelopes and a region of failure due to spalling (extension). The green and blue lines represent the stress paths given in Figure 1. point 1 indicates the initial far-field stress, point 2 the initiation of failure and point 3 the final stress state assuming elastic conditions.
- Figure 6: Different fracture behaviour observed in hard (a,b) and soft clay (c)
- Extensional fractures along a tunnel at a tunnel intersection in Opalinus Clay (photo: B. Niederberger)
 - Combined shear / extensional fracturing around a borehole in Opalinus Clay (Thury & Bossart, 1999)
 - Conjugated (eye-shape) fractures around a borehole in Boom Clay
- Figure 7: Fractures pattern around a gallery. Note the similarity between the fracture pattern normal to borehole/tunnel (Figure 6) and along tunnel axis
- Figure 8: Fractures pattern along a Boom Clay borehole core induced by the drilling process similar to the fracture pattern observed around a gallery (Figure 7).
- Figure 9: EDZ caused by the bedding in Opalinus Clay (bedding direction indicated by the green lines, photos: Comet, Zürich)
- Bedding induced EDZ around the top of a small borehole
 - Bedding and bedding parallel fracture induced failure of the EDZ of a formerly horseshoe type tunnel at Mont Terri (white line: approx. the original tunnel cross section)
- Figure 10: Schematic failure pattern in a transversely isotropic hard clay (left) and examples from Mont Terri (photos on the right, B. Niederberger)

- Figure 11: Strength and deformation properties for the Opalinus Clay as a function of water content. Data compiled by Corkum (2005) from confined tests conducted by Rummel et al (1998).
a) Water content versus undrained shear strength
b) Water content versus Young's modulus
- Figure 12: a) Initial fractures within the sample
b) Sealing after saturation of the fracture
- Figure 13: Hydraulic Transmissivity measured for an induced hydraulic fracture at Mont Terri (modified from Nagra 2002) as a function of normal stress on the fracture surface.
- Figure 14: Comparison of re-saturation tests on fractured samples (Skoczylas et al. 2005) and in-situ (EH experiment and EZ-A experiment, Mont Terri)
- Figure 15 Comparison of loading tests on fractured samples (Skoczylas et al. 2005) and in-situ (SELFRAC experiment, Mont Terri (Bühler et al. 2004), the normal stress on the fracture plane is evaluated from the loading stress on the wall and the initial radial stress; and GS experiment (Enachescu et al. 2002)
- Figure 16: Dose curves calculated for a repository in Opalinus Clay for spent fuel (Smith et al. 2004)
a) base case with an EDZ conductivity of 10^{-12} m/s
b) "what if?" case with an EDZ conductivity of 10^{-8} m/s

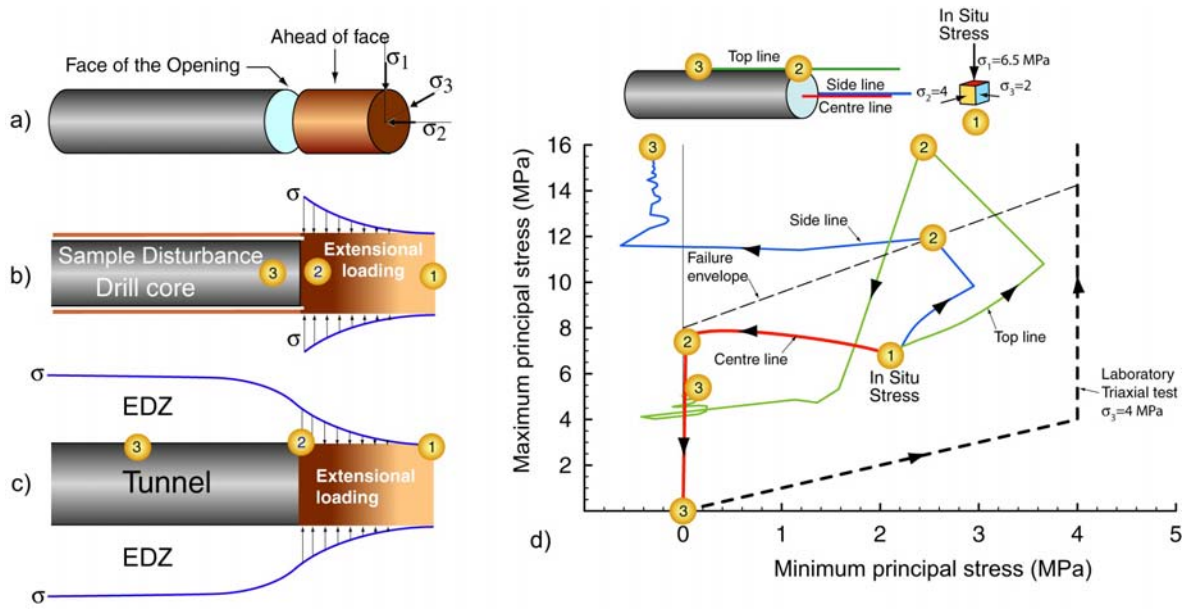


Figure 1



Figure 2

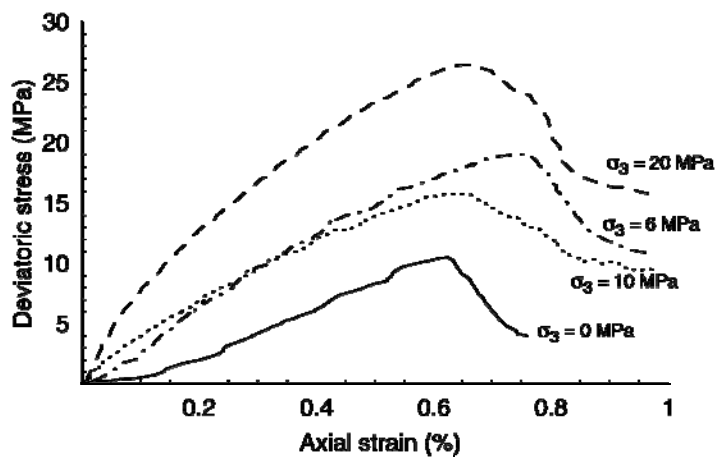


Figure 3

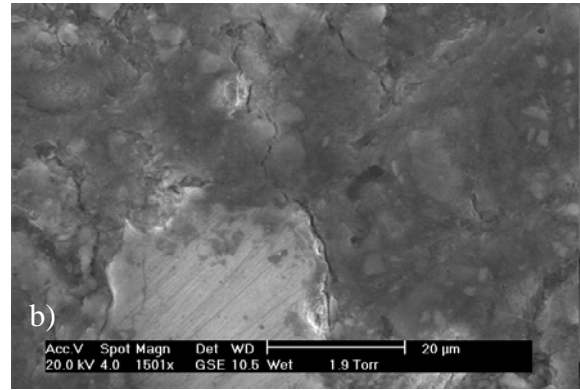
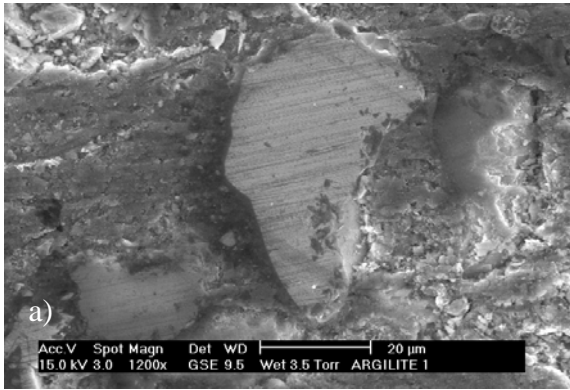


Figure 4

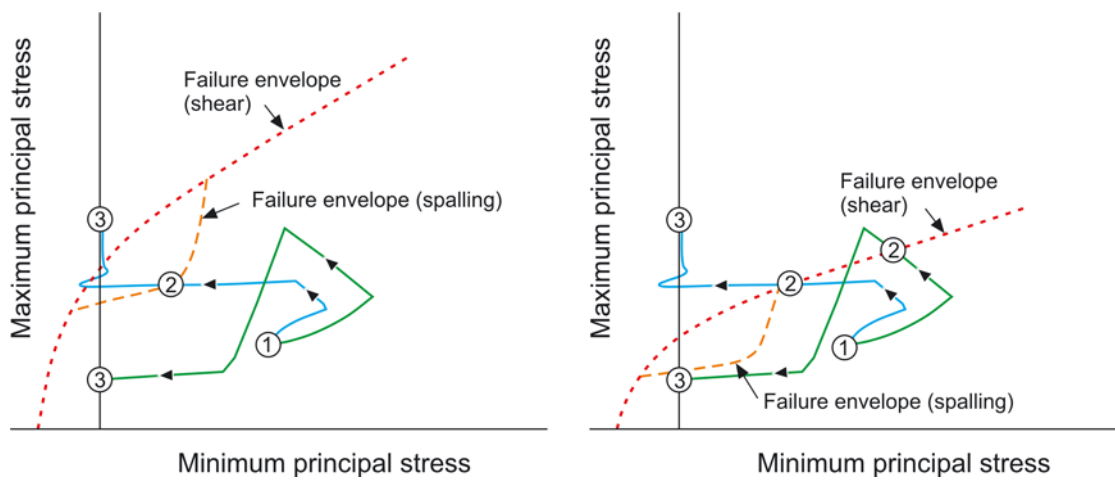


Figure 5

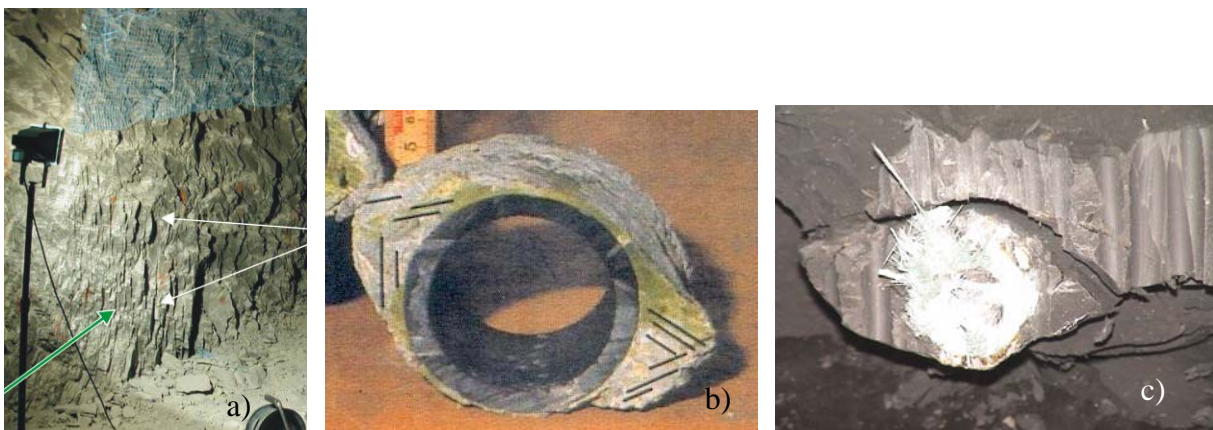


Figure 6

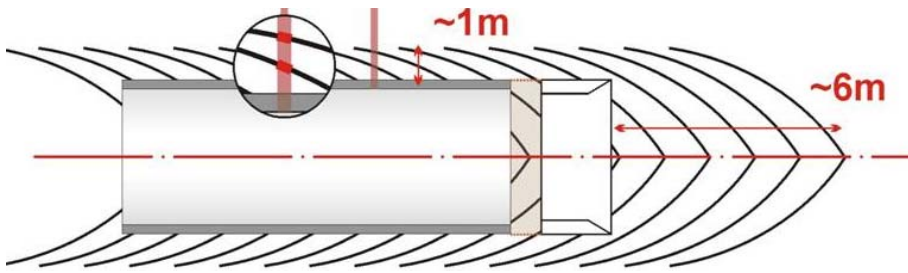


Figure 7



Figure 8

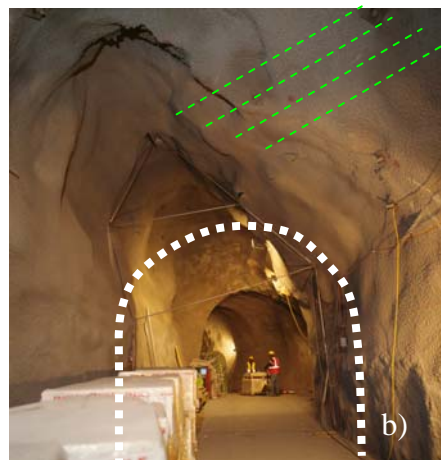
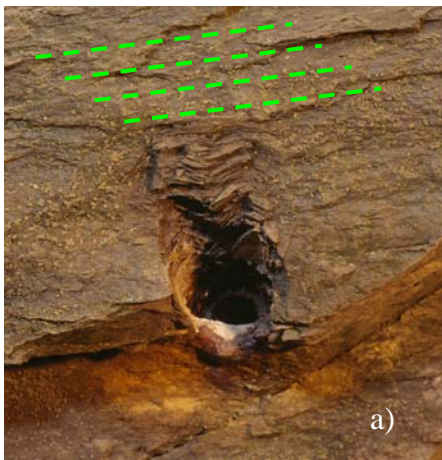


Figure 9

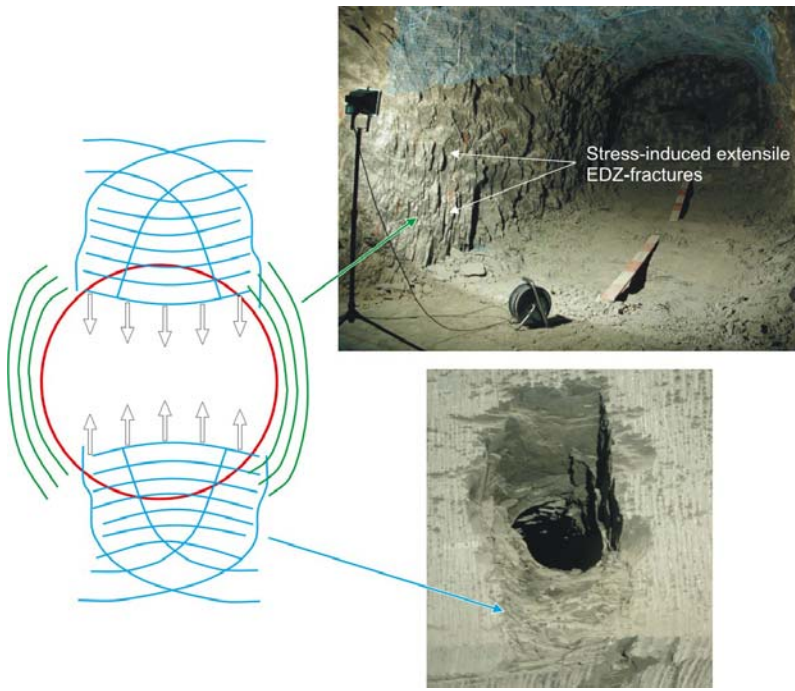


Figure 10

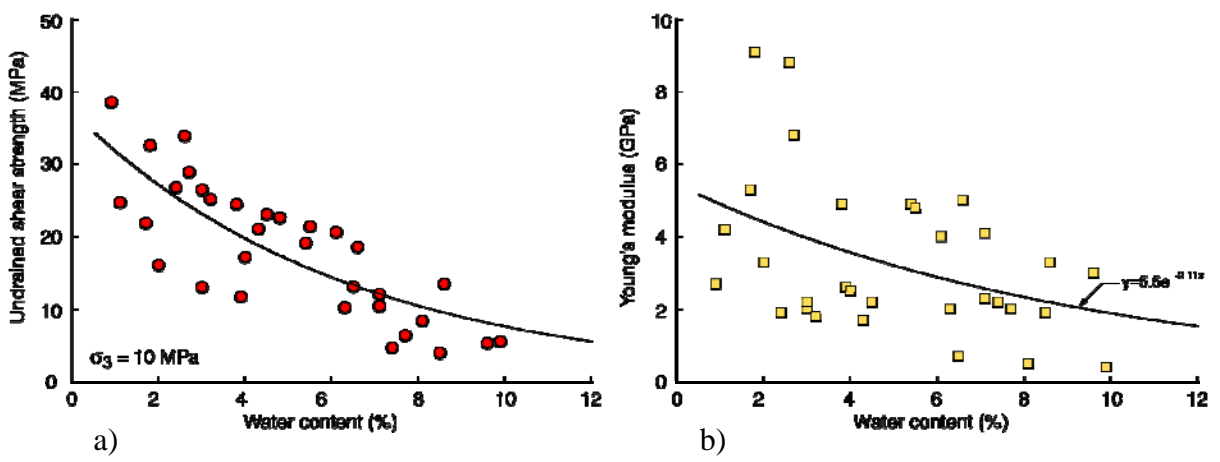


Figure 11

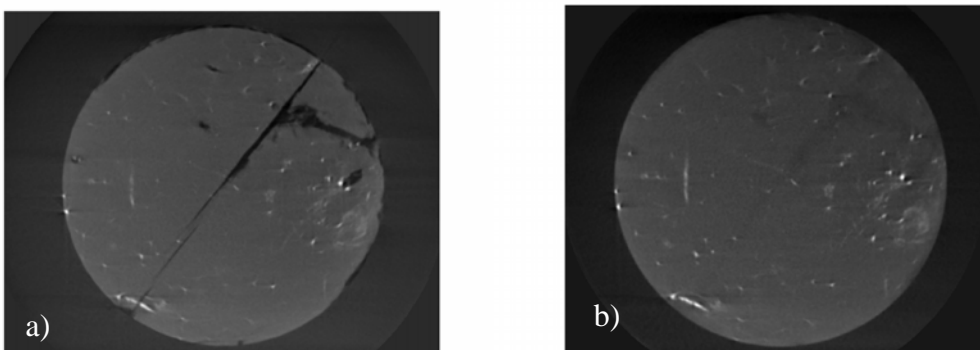


Figure 12

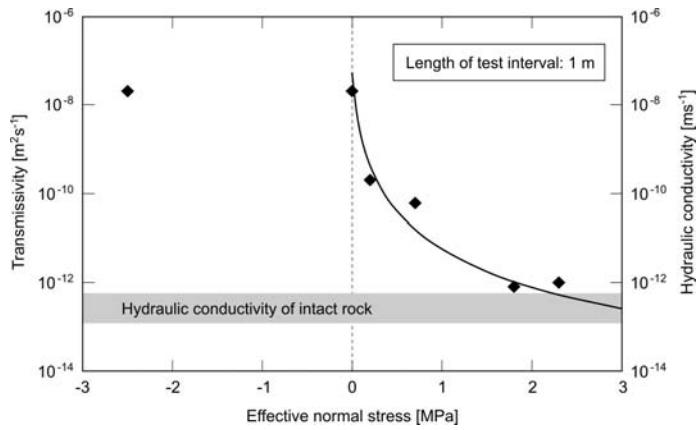


Figure 13

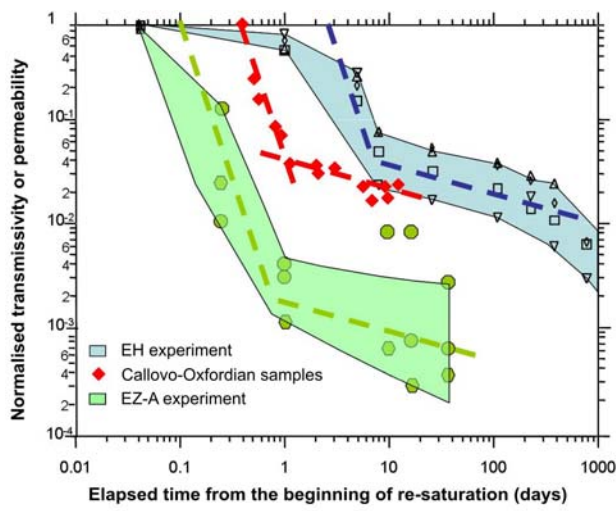


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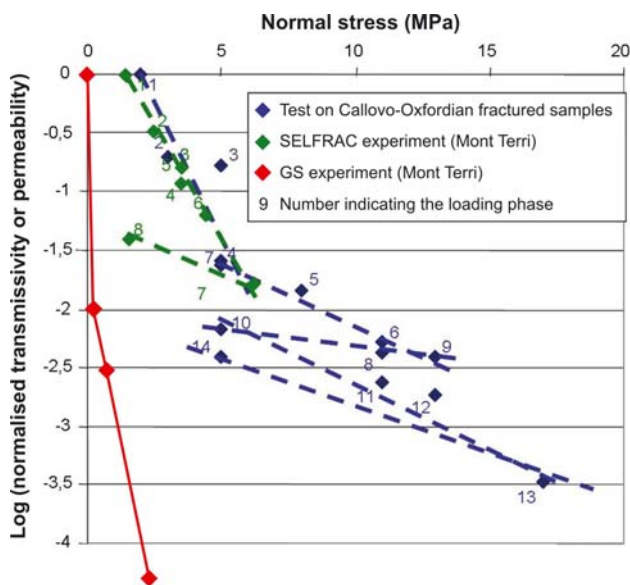


Figure 15

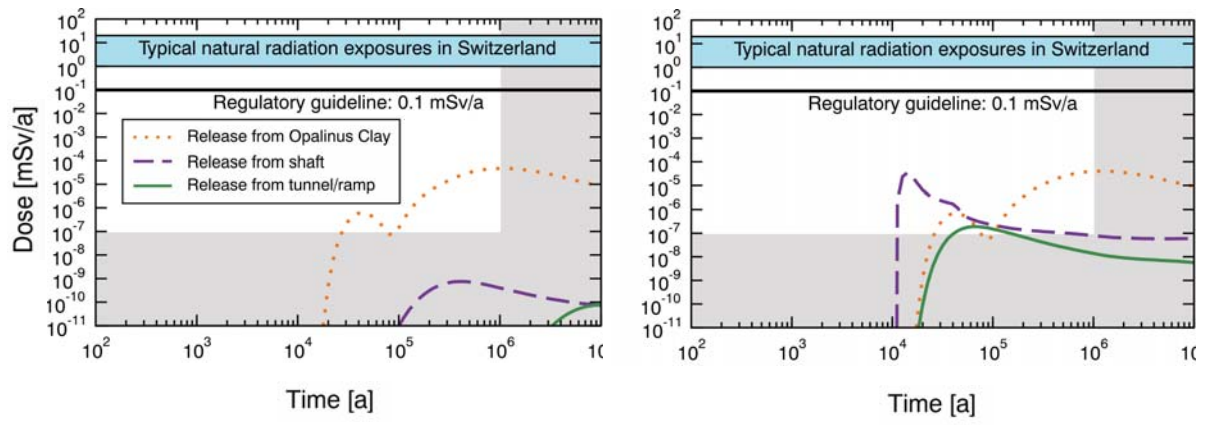


Figure 16