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NUCLEAR ENERGY AGENCY
RADIOACTIVE WASTE MANAGEMENT COMMITTEE

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IGSC Working Group on Measurement and Physical Understanding of Groundwater Flow through Argillaceous Media (CLAY CLUB)

SELF-HEALING TOPICAL SESSION
PROCEEDINGS

Nancy-FRANCE
16 May 2001

English - Or. English

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Foreword

A Topical Session focused on the "Evidence of, and Approaches to Self-Healing in Argillaceous Media" was organised in the framework to the 11th meeting of the Clay Club. It was held at Nancy in France on 16th May 2001 at the invitation of the French Organisation for Radioactive Waste Management (ANDRA).

Twenty-six participants representing several national waste management organisations, regulatory authorities, geological surveys as well as academic community took part in the session.

The Topical session was mainly aimed at exchanging information on:

- The general point of view on self-healing from geomechanical and geochemical experts;
- The approaches that are or will be followed by the various organisations in order to deal with self-healing.

The geological settings covered in the presentations concerned the whole range of argillaceous media, from soft, plastic clays to indurated clay-stones, currently studied with respect to deep disposal of radioactive waste.

The Topical Session showed the importance of a multidisciplinary approach to this topic. The presentations emphasised the interest of a state-of-the-art report on self-healing to provide a sound and disposal-dedicated scientific framework for subsequent studies related to this area.

Acknowledgement

The NEA expresses its gratitude to:

- The French Organisation for Radioactive Waste Management (ANDRA) which hosted the Topical Session;
- Marc Thury (NAGRA, Switzerland) who chaired the Topical session
- The speakers for their interesting and stimulating presentations
- The Clay Club participants for their constructive contribution

The Proceedings and the synthesis have been prepared by Sylvie Voinis (OECD/NEA), Scientific Secretary of the Clay Club with the help of Philippe Lalieux (ONDRAF/NIRAS, Belgium), Chairman of the Clay Club, Marc Thury (NAGRA, Switzerland), Chairman of the Topical Session and Steve Horseman (BGS, United Kingdom).

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PART A

SYNTHESIS

1. INTRODUCTION

To prevent radioactive contamination and undue exposure to the public, it is required that long-lived and/or high-level radioactive wastes be isolated from the human environment for a very long period of time. For the purpose of isolating such wastes, the basic concept of deep disposal is to place packaged waste in a geological formation such as clay. One of main functions of the geological formation is to isolate waste from moving groundwater, thus minimising lixiviation of waste and advective radionuclide transport and, hence the amount of radionuclides that could reach the human environment. Improving our understanding of processes that might affect the containment properties of the geological barrier can reduce uncertainties about the performance of the repository.

In particular, during the stepwise development of the research programme, it is important to clarify if fractures that might be induced by the excavation of the underground facilities might have a significant impact on the radiological safety of a repository in a host formation such as clay. In this framework, the self- healing properties of argillaceaous media – often quoted as one of the advantages of such host formations – play a major role, notably in reducing the long-term impacts of such induced fracturation.

Specific interest in the self-healing behaviour of argillaceous media was expressed at the 9th meeting of the Working Group on Measurement and Physical Understanding of Groundwater Flow through Argillaceous Media ("Clay Club") in Madrid, Spain, 25th to 28th May 1999 [see document NEA/RWM/CLAYCLUB(99)1].

Based on the outcomes of the 1996 workshop on "Fluid Flow through Faults and Fractures in Argillaceous Formations" and the 1998 Topical Session on "Detection of Structural and Sedimentary Heterogeneities and Discontinuities within Argillaceous Formations", interest was expressed in the preparation of an overview and synthesis of the current understanding of, and conceptual approaches to, the processes that lead to self-healing of natural and induced fractures in typical repository conditions. The issue of the applicability of the understanding that exists within the oil and gas industry to repository-relevant conditions was also clearly asked.

The Topical session focused on the **"Evidence of, and Approaches to, Self-Healing in Argillaceous Media"** was organised n the framework of the 11th meeting of the Clay Club. It was held at Nancy in France on 16th May 2001 at the invitation of the French Organisation for Radioactive waste Management (ANDRA).

Twenty-six participants representing several national waste management organisations, regulatory authorities, government agencies and the academic community from the OECD member countries and the EC took part in the session.

The Topical Session was mainly aimed at exchanging information on:

- The general point of view on self-healing from geomechanical and geochemical experts;
- The approaches that are or will be followed by the various organisations in order to deal with the self-healing.

The geological settings covered in the presentations related to the whole range of argillaceous media relevant to the disposal of radioactive wastes, including poorly indurated clays and indurated mudstones, and shales.

The Chairman of this Topical Session was Marc Thury (NAGRA, Switzerland).

The purpose of these proceedings is to provide on the one hand a brief summary of the technical presentations and a record of the main conclusions and outcomes and, on the other hand, a compilation of the presentations' abstracts.

The abstracts are compiled without further elaboration from the Secretariat. The list of participants for the Topical Session is given at the end of the document.

2. TENTATIVE DEFINITIONS

Steve Horseman (BGS, UK) explained at the Topical Session that two phrases appear in the specialist literature. In order to be clear in our terminology it is necessary to attempt working definitions of the phrases "self-sealing" and "self-healing" in the context of natural and induced fractures in argillaceous rock. No formal definitions are available.

For him, self-sealing might be defined as a spontaneously-occurring process, with a number of contributory underlying mechanisms, that leads to a reduction in the hydraulic transmissivity of a fracture. A fully self-sealed fracture does not act as a preferential pathway for fluid movement. A partially self-sealed fracture does act as a pathway, but its transmissivity is less than that of the newly formed fracture.

In his opinion, fracture self-sealing is largely a hydromechanical process, involving changes in the stress field, local movements of the porewater and inelastic deformation of the rock. Self-sealing is only really significant in comparatively weak argillaceous rocks capable of plastic or viscoplastic deformation. The stress path and final sate of stress are important considerations in assessing capacity to self-seal. Swelling of clay minerals can sometimes be a contributory factor.

In this same context, the phrase self-healing has somewhat broader connotations. Self-healing may be defined as a spontaneously-occurring process, with many possible contributory underlying mechanisms, that leads to a reduction in the impact of a fracture on both the hydraulic and the mechanical properties of the rock mass. The rock-mass properties (including geophysical) of a volume of rock containing fully self-healed fractures may be virtually indistinguishable from those of the same rock with no fractures. In the case of partial self-healing, rock-mass properties assume values that are intermediate between those of newly fractured and fully self-healed material.

Self-healing of argillaceous rocks is a complex process, which can involve hydraulic, mechanical, chemical and mineralogical changes occurring within the system. Minerals can be transported into the fracture in solution and precipitated as cementing agents. The composition and fabric of the fracture wall rock can also be altered. Given a long enough period of time and a suitable geochemical environment, it is possible for self-healing to occur in virtually all rock types regardless of diagenetic alteration, degree of lithification and ductility. Many of the underlying mechanisms of self-healing are, again, time dependent.

By analysing these two working definitions, it is evident that self-sealing can sometimes contribute to the partial self-healing of argillaceous rocks[1]. Indeed, the hydromechanical response to the altered stress field often precedes the longer-term chemical and mineralogical responses of the

1 It can be argued that self-sealing is likely to be the more important process affecting fluid movement in fractured clays and mudrocks over the time scale of repository performance assessment.

rock. It is possible, however, to have fracture self-healing with no significant involvement of mechanical processes.

In his presentation, Lazlo Kovaks (Mecsek Ore Environment, Hungary) proposed a more general definition of the term self-healing that was: “Self-healing means the capability of the host formation to heal the newly formed discontinuities, restoring the original confinement performance”.

3 GEOCHEMICAL AND GEOMECHANICAL PERSPECTIVES

Michel Cathelineau (CREGU and UMR, France) presented the general point of view concerning the geochemical aspects and in particular the way in which the original geochemical conditions of the host rock formation could be affected by the opening of a repository. Two main processes were presented, which could lead to self-healing: a restoration of the initial permeability of the rock block by reducing the transmitivity of the discontinuity down to values equivalent to that of the homogeneous medium before fracturing, or the sealing of the open discontinuity by precipitation of newly formed minerals.

Steve Horseman (BGS, UK) presented the geomechanical point of view. In the absence of any form of consensus opinion in the published literature, he attempted to distinguish the meanings of the two phases “self-healing” and “self-sealing” (see above). Then he described how the hydromechanical response of the rock to the altered stress field often precedes longer-term chemical and mineralogical readjustments and also emphasized that there is no established theory describing fracture self-healing and self-sealing processes in mudrocks and no currently available methodology to assess the conditions under which these processes might be important.

4. ORGANISATION’S APPROACHES

Andreas Gautschi (NAGRA, Switzerland) presented evidence of self-sealing of faults in the Opalinus Clay, which is considered as a potential host formation as part of the Swiss programme. He described the results of investigations on the hydrogeological and hydrochemical characteristics of the Opalinus Clay formation. The extensive hydrogeological data base, part of which derives from strongly tectonised geological environments, suggests that advective transport through faults in the Opalinus Clay at depths greater than 200 m is insignificant. This conclusion is also supported by independent evidence from clay porewater hydrochemical and isotopic data. The lack of hydrochemical anomalies and the lack of extensive mineral veining suggest that there was also no significant paleoflow through such faults. These observations can only be reconciled with a strong self-sealing capacity of the rock subsequent to faulting. Therefore it is concluded, that reactivated existing faults or newly-induced fractures will not act as pathways for significant fluid flow at anytime due to self-healing processes.

Regarding the Wellemberg site (marls), Martin Maruzek (University of Bern, Switzerland), explained why frequency and geological characteristics of faults are not a function of depth below surface. Considering any single fault, its structure and transmissivity are heterogeneous. The hydraulic characteristics of faults strongly depend on the overburden and it exists a good consistency between hydraulic and hydrochemical evidence. Drill core evidence does not provide any criteria regarding hydraulic characteristics and, fault breccias and gouges are ubiquitous. Faults, which were originally sealed at depth, seem to have opened up during regional uplift. Fracture transmissivities are enhanced at depths of burial less than 500 - 700m.

Concerning the Opalinus Clay at the Mont Terri (a rock laboratory that permits international collaboration on many experiments), Peter Blümling (NAGRA, Switzerland) and Kun Su (ANDRA, France) presented the findings of experiments dealing with self-healing of an indurated mudstone. Particular relevances of these experiments are linked to self-healing of the excavation disturbed zone (EDZ) and of gas-induced fractures. These experiments conducted in Mont Terri were targeted at the provision of basic information on the behaviour of Opalinus Clay (Swiss) and the Callovo-Oxfordien (French) argilites (France) formations. The experiments show that closure of fractures or micro-cracks within the EDZ should occur through clay swelling phenomenon or the precipitation of calcite.

The Boom Clay is considered as a potential host-rock for the disposal of Belgian radioactive waste. During the sinking of a new shaft to extend the underground research facility HADES, significant fracturing was observed around the shaft excavation. Fracturing had been observed previously, but to a much lesser extent. The low support pressure imposed by the primary shaft lining, combined with the large time over which this support condition was held, favoured the decompression of the clay mass through delayed effects, leading to the development of fractures. In the context of the overall performance of a radioactive waste repository, it is very important to understand the process of fracture development in Boom Clay, together with the subsequent self-healing behaviour. Given that background, Frederic Bernier (Euridice-GIE, Belgium) presented future work that will be conducted within the SELFRAC EC project (Fractures and Self-healing within the Excavation Disturbed Zone in Clays). The SELFRAC project aims at understanding and quantifying the increase in permeability resulting from crack development around excavations in clays and the self-healing processes that can in turn reduce permeability in time. Two clay types will be studied and compared: the Opalinus Clay at Mont Terri (Switzerland) and the Boom Clay (Belgium).

Laszlo Kovaks (Mecsek Ore Environment, Hungary) ended the session by presenting evidence for the partial self-healing of a claystone formation (Buda Clay Formation, BCF) revealed by *in situ* measurements. The highly indurated and over-consolidated character of the BCF is not favourable for an occurrence of the classical, quasi-instantaneous self-healing mechanism such as occurs in soft argillaceous formations. However, it was observed during the characterisation program (1993-1999) that a number of natural processes took place, including the degradation of non-swelling materials, re-hydratation of clay minerals and precipitation processes. Collectively, these processes could explain the observed partial self-healing effect. Some consideration is therefore needed of self-healing processes when undertaking performance assessments relating to the more indurated argillaceous rocks.

5. CONCLUSIONS/FUTURE WORK

Members thanked the speakers for their very informative presentations and noted that the session:

- Provided an overview of the spectrum of the topic ; such multidisciplinary overview was – to the knowledge of the Clay Club members – not available before the session;
- Demonstrated the necessity to consider self-healing in all types of argillaceous media considered as potential host formation;
- Illustrated the need to reconcile the geomechanical and the geochemeical approaches vis-à-vis the self-healing.

The discussions focused initially on the clarification of the two phrases “self-healing” and “self-sealing” (see item 2 above).

The term of which the agreement was the most consensual was “self-healing”. In that frame, the definition proposed by Lazlo Kovaks in his presentation received a good support. Marc Thury pointed out, that the phrase “self-healing” was used since many years by the Clay Club members, and the advantage of this phrase is that it is well understood by the public and contributes very much to confidence-building. Replacing this phrase could be confusing. For the purposes of future initiatives regarding these matters, the largely hydromechanical process of self-sealing will therefore be regarded as specific contributory mechanism within the overall context of fracture self-healing in argillaceous rocks. In any case, any of such initiatives should further clarify these concepts and phrases.

As proposed by Steve Horseman before the closure of the Topical Session, future effort on the self-healing topic many focus on the production of a multidisciplinary (and multi-authored) synthesis report entitled “Potential for Self-healing of Fractures in Plastic Clays and Argillaceous Rocks under Repository Conditions” [see NEA/RWM/CLAYCLUB(2001)6]. This is a new area of applied science and there are very few publications that cover the topic and none that address fundamental aspects of material behaviour. Furthermore, the applicability of knowledge and concepts used by this oil and gas industry to repository relevant conditions (temperature, pressure, time frame) is not straightforward. The proposed report aims to bring together and synthesise information from very diverse sources in order to provide a sound scientific basis for future safety assessment and site understanding activities. These aims clearly go well beyond those of a basic literature review. The report will examine the broad class of host media relevant to the disposal of radioactive wastes, including plastic clays, mudstones, clayshales and shales. A suitable rock classification system will be used as the basis for comparisons between rock types. This initiative was further discussed at the Clay Club plenary meeting.

It was also noted that the issue of fracture self-healing is strongly linked to other key Clay Club topics of interest, including episodic flow, palaeo-circulations, the long-term significance of the excavation disturbed zone (EDZ), and rock-water interactions. Close links with EU initiatives (e.g. SELFRAC[2] Project), company-sponsored R&D projects (e.g. FORPRO[3], France) and ongoing studies in underground laboratories (e.g. Mont Terri Laboratory, Switzerland) are a must in order to benefit from information exchange and avoid any duplication of effort.

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2 **SELFRAC** is a project that has been submitted to the EU in relation to 5th Framework R&D activities. The project specification is focused on fracturing and healing processes in Boom Clay and Opalinus Clay. The programme includes laboratory-scale and URL-based experiments, together with predictive modelling activities. (see F. Bernier’s presentation)

3 **FORPRO** (**FOR**mations géologiques **PRO**fondes) is an ANDRA-CNRS research initiative with a number of French university inputs aimed at improving knowledge of the behaviour of deep geological formations. Some laboratory work is presently underway on the problem of fracture sealing.

PART B

COMPILATION OF ABSTRACTS

Fracture Sealing in SHALES: Geological and Geochemical Factors

Michel Cathelineau
CREGU and UMR; France

The so-called self-sealing processes can be re-examined at the light of geological and geochemical consideration about the past history of the rocks. The concept of "self sealing" needs to consider the formation and the sealing of fractures, especially three main stages: (i) the initiation of the fracture (development of micro-cracks initiated from previous heterogeneities up to fracturing), ii) the fracturation processes which occur generally at depth in presence of a fluid phase, iii) the healing or sealing of the fractures which corresponds basically to two main processes: a restoration of the initial permeability of the rock block by reducing the transmitivity of the discontinuity down to values equivalent to that of the homogeneous medium before fracturing, or the sealing of the open discontinuity by precipitation of newly formed minerals. In the latter case, the evolution of the open fracture is driven by re-arrangement of particles or precipitation of newly formed material, either by dissolution/crystallisation processes or by crystallisation from the percolating fluids (advective processes). Such processes are governed by chemical processes, especially the rate of precipitation of minerals which depends of the degree of saturation with respect to the mineral, and the kinetics of precipitation.

How fractures have formed in shales?

The understanding of the past formation of fractures in shales may be documented on the basis of:

i. Elementary concept about the physical-properties of the shales, unherited from the sedimentation, diagenesis, and subsequent evolution of properties during burial (pressure-temperature time evolution). The role of specific properties of shales on fracturation style of clay rich material is obvious when series of rocks of similar origin and clay content are examined. Previous geologic history is of primary importance on the acquisition or modification of the main physical properties (rigidity, resistance to traction and compression) which depend on the water content, the percentage of clay (especially swelling clays), the nature of the bounding between particles (cements and their evolution during diagenesis and burial).

ii. The intensity and orientation of the stresses, and its consequences on development of fractures (orientation, dip, frequency, clustering, opening).

Most sealing processes are linked to specific stages of fluid migration, linked to major geodynamic events, during which thermal or thermodynamic changes (fluctuation in pCO2, dilution during mixing of two fluids…) in the circulating fluids which provoked the saturation of the fluid with respect to some minerals (mostly carbonates, especially calcite, sulphides and sulphates).

How fractures can eventually form and heal in the future

"Self"-sealing, especially in "EDZ"?

Specific geometry of fractures, now well known, develops during the opening of the galleries, and is linked to subsequent extensional tectonics related to the differential stress regime between zones under load pressure and the gallery walls.

Textural re-organisation and /or mineral crystallisation can occur in these zones. However, the amount of water in the "EDZ" is very low and no evident sealing process can be considered.

In most concepts of gallery closing, the oxidised "EDZ" will be rehydrated after a certain amount of time. The rehydratation will induce a microscopic swelling of the swelling clays followed during the rehydration of the macropores, and the subsequent the swelling of the clay material which will increases its volume, reducing then the permeability, and resulting in the mechanical healing of fractures by increase of the lateral pressure on the fracture walls.

During this stage the most likely geochemical process is the simple closing of fractures by swelling of the shales (hydration of cations, osmotic and capillary pressures). Desiquilibrium of the solution with respect to minerals is rather weak and will mostly result in the dissolution of the newly formed mineral assemblages (sulphates) rather than in the precipitation newly formed phases except if hydratation/dehydratation cycles occur.

Self-healing of Fractures in Argillaceous Media from the Geomechanical Point of View

Steve Horseman
British Geological Survey, UK

Presently, there is no established theory describing fracture self-healing and self-sealing processes in mudrocks (clays, mudstones and shales) and no methodology to assess the conditions under which these processes might be important. The author suggests that the modified Cam-Clay approach provides a useful conceptual and theoretical framework for the analysis of the largely hydromechanical process of self-sealing. Three basic hypotheses are proposed and applied to the problem of fracture self-sealing in the repository *EDZ* and to the more general question of fault sealing.

1. INTRODUCTION

Self-sealing may be defined as a spontaneously-occurring process, with a number of contributory underlying mechanisms, that leads to a reduction in the hydraulic transmissivity of a fracture. A fully self-sealed fracture does not act as a preferential pathway for fluid movement. A partially self-sealed fracture does act as a pathway, but its transmissivity is less than that of the newly formed fracture. Self-sealing is largely a hydromechanical process, involving changes in the stress field, local movements of the porewater, and elastic/inelastic deformation of the rock. Self-sealing is only really significant in comparatively weak rocks capable of plastic or viscoplastic deformation. The stress path is an important consideration in assessing capacity to self-seal. Swelling can be a important contributory factor.

The phrase self-healing has somewhat broader connotations. Self-healing may be defined as a spontaneously-occurring process, with many possible contributory underlying mechanisms, that leads to a reduction in the impact of a fracture on both the hydraulic and the mechanical properties of the rock mass. The rock-mass properties (including geophysical) of a volume of rock containing fully self-healed fractures may be virtually indistinguishable from those of the same rock with no fractures. Self-healing of argillaceous rocks is a complex process, which can involve hydraulic, mechanical, chemical and mineralogical changes occurring within the system. Many of the underlying mechanisms of the self-healing are time dependent

It is evident that self-sealing can contribute to the partial self-healing of argillaceous rocks. Indeed, the hydromechanical response of the rock to the altered stress field often precedes the longer-term chemical and mineralogical readjustments.

2. FRACTURE PERMEABILITY AND DILATANCY

We examine the behaviour of a volume element of intact mudrock. Suppose that stresses applied to the faces of the element are increased in a way that causes fracturing. Fractures are considered to be hydraulically significant if the overall permeability of the fractured volume element is greater from that of the intact element. This demands that one or more flow channels of finite aperture must pass through the element. Fracture porosity is the total volume of the flow channels divided by the total volume of the element. The development of fracture porosity is almost invariably associated with an increase in the size of the volume element. This size increase, caused by fracturing, is known as "dilatancy" or "dilatation".

This line of reasoning leads to a very simple observation. In order for fractures to be hydraulically significant, the rock must have undergone at least some degree of dilatation at the time of fracture development. If we are able to identify the stress conditions that promote dilatation in mudrocks, then we should be able to associate these conditions with those of enhanced fracture permeability (Lalieux and Horseman, 1996). Mudrocks also exhibit "contractancy" which can be defined as a reduction in volume caused by shear-assisted consolidation[4]. It seems reasonable to assume that the stress conditions for contractancy can be associated with reduced fracture permeability and a capacity to self-seal.

3. CRITICAL STATE CONCEPTS

The "state" of a mudrock subject to a simple axisymmetric stress field[5] is defined by its coordinates in the p', q' or v parameter space (see Table 1). A change of state is represented by a "path" and the projection of a path in the p', q' plane is referred to as a "stress path". When a mudrock is loaded under conditions that prevent any movement of the porewater (typically, the load is applied rapidly), the change in state is represented by an undrained stress path. When the rock is loaded under conditions that allow the porewater pressure to remain constant, the change in state is represented by a drained stress path.

The critical state concept is founded on the supposition partially confirmed by experimentation that, when sheared, a clay sample will eventually reach a critical state at which large shear distortions will occur without any further changes in p', q' or v (Roscoe and Burland, 1968; Schofield and Wroth, 1968). The critical state line (*CSL*) is the locus of all possible critical states in p', q', v parameter space. Cam-Clay models are based on the critical state concept and provide a useful theoretical framework for the study of hydromechanical phenomena in clay-rich media. The material is assumed to be isotropic, to deform as a continuum, and to display elasto-plastic volumetric strain-hardening behaviour (Azizi, 2000). The original models were developed using experiments on reconstituted clays and diagenetic modifications of clay fabric such as cementation, can lead to a number of complications in interpretation (Burland *et al*., 1996). Models based on critical state concepts are widely applied to overconsolidated clays, soft rocks and shales (Pender, 1978; Johnston and Novello, 1985; Steiger and Leung, 1991).

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4 Burland *et al*. (1996) use the adverb "contractant" in their discussions.

5 Extension of these concepts to more general states of stress is beyond the scope of this short paper.

3.1 Consolidation, swelling and position of the *CSL*

The drained path of clayey sediment undergoing mechanical dewatering under gradually increasing isotropic effective stress is known as the normal consolidation line (*NCL*). It is idealised as a straight line on a plot of v against the natural logarithm of p' with a negative slope of λ. The volumetric strain during consolidation is considered to have elastic (recoverable) and plastic (non-recoverable) components. If the clay is unloaded, then only the elastic[6] strains are recovered. The drained path then follows the rebound-reconsolidation line (*RRL*), also known as the swelling line. This is idealised as a straight line on a plot of v against $\ln(p')$ with a negative slope of κ (Schofield and Wroth, 1968). The magnitude of κ has been shown to depend on the amount of swelling clay minerals present (Olgard *et al*., 1995). The *NCL* and the *RRL* intersect at the isotropic preconsolidation stress[7], p'_c. The projection of the critical state line (*CSL*) is also idealised as a straight line running parallel to the *NCL* and crossing the *RRL* at a particular value of specific volume (Schofield and Wroth, 1968).

3.2 Overconsolidated domain

A mudrock is overconsolidated when the current mean normal effective stress, p', acting on the material is less than the preconsolidation stress, p'_c. Under natural conditions, the commonest cause of overconsolidation is erosion of the overlying sedimentary column. The overconsolidation ratio is given by $OCR = p'_c / p'$. The mudrock is therefore normally consolidated when $OCR=1$ and overconsolidated when $OCR>1$. The *RRL* is effectively split into two sections by the projection of the *CSL*. A mudrock in a state between the *CSL* and the *NCL* is termed lightly overconsolidated (Azizi, 2000). The mudrock will generate positive porewater pressure when subjected to undrained shearing and will expel water when drainage is allowed to take place. This is the so-called “wet” side of the *CSL*. Heavily overconsolidated mudrocks are characterised by brittle failure and their states are on the “dry” side of the *CSL*. Undrained shearing of such materials can produce negative porewater pressures inside the sample (Burland *et al.*, 1996). Specific volume therefore increases when drainage is allowed (Mesri *et al*., 1978). This swelling (or rebound) response can be very important when examining the potential for self-sealing.

Table 1. **Symbols and abbreviations**

Symbols		**Abbreviations**	
Specific volume	$v = 1+e$	Normal consolidation line	*NCL*
Void ratio	e	Rebound-reconsolidation line	*RRL*
Mean normal effective stress	p'	Critical state line	*CSL*
Preconsolidation stress	p'_c	Engineering damage zone	*EDZ*
Critical state friction parameter	M		
Deviatoric stress	q'		
Negative slope of NCL	λ		
Negative slope of RRL	κ		
Overconsolidation ratio	*OCR*		

6 The term “elastic” is used fairly loosely in relation to the stress-strain behaviour of overconsolidated mudrocks. In shales, volumetric strains associated with movement along the *RRL* may be partly determined by changes in the hydration state of the clay minerals. This could explain the known relationship between • and the percentage of swelling clay minerals present in a particular mudrock.

7 The laboratory-determined preconsolidation stress can be substantially larger than the value calculated from a reconstructed burial history. This is explained by diagenetic modification of the clay fabric.

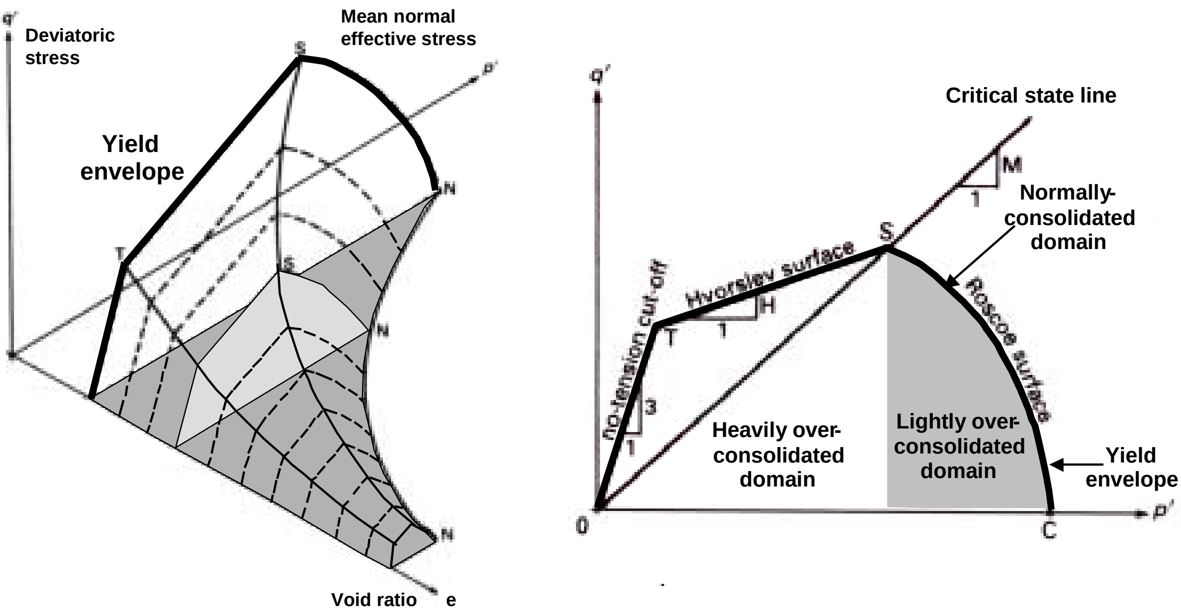
3.3 Complete state boundary surface

Plastic yield occurs when a stress path reaches the state boundary surface. Because of the major differences in behaviour "wet" and "dry" of the *CSL*, two different mathematical functions are selected to describe the two parts of the state boundary surface. In the modified Cam-Clay approach examined here, the yield criterion for normally consolidated and lightly overconsolidated mudrock on the "wet" side is quantified by the Roscoe surface and that of heavily overconsolidated mudrock on the "dry" side by the Hvorslev surface (Atkinson and Bransby, 1978). The complete state boundary surface is shown in Figure 1.

3.4 Transition in behaviour

When mudrock samples are tested in triaxial compression under a range of confining pressures, there is a very noticeable transition in behaviour with increasing mean normal effective stress, *p'*, and decreasing *OCR*. Highly overconsolidated mudrocks are characterised by a sharp peak in their stress-strain curve followed by very pronounced strain softening (Bishop *et al.*, 1965; Burland, 1990; Horseman *et al.*, 1993). The reduction of strength that takes place from peak to post-rupture shear strength is due primarily to the breakage of interparticle bonds (Burland *et al.*, 1996). Failure is always inhomogeneous and characterised by one or two more well-developed dilatant shear fractures. As confining pressure is increased, the stress peak gradually broadens and becomes less pronounced. Discrete fractures are replaced by shear bands, which are regions of intense shear deformation. When confining pressure is further increased so that *OCR* = 1, the peak in the stress-strain curve is often absent and shear deformation is usually more (macroscopically) homogeneous. Although Cam-Clay models cannot represent inhomogeneous deformation explicitly, it is clear that the appearance of the well-defined peak in the stress-strain curve, the development of dilatant shear fractures and the strain-softening behaviour are each symptomatic of shearing on the "dry" side of the *CSL*.

Figure 1. **Complete state boundary surface comprising the Roscoe surface on the "wet" side of the *CSL* and the Hvorslev surface on the "dry" side.**



3.5 Conditions for self-sealing

A substantial amount of work has been expended over the years in quantifying the strength and deformation of overconsolidated mudrocks. Drawing on these findings, three hypotheses are advanced in this paper: (a) Shear fractures in mudrocks will be hydraulically tight when deformation takes place exclusively on the "wet" side of the *CSL*, (b) Fractures will tend to self-seal by localised swelling (i.e. rebound) when water moves into dilatant rock formed during undrained shear deformation on the "dry" side, and (c) Fractures will tend to self-seal when a temporal change in the stress field (i.e. increase in *p'* and decrease in *q'*) causes the stress path to move towards to the "wet" side and away from the Hvorslev surface. Validation will require systematic analysis of case histories.

4. APPLICATION TO THE EDZ

Consider the stress path of an element of mudrock close to the internal surface of a repository access tunnel. During tunnelling operations, the undrained stress path associated with rapid excavation of the mudrock will reach the state boundary surface (the Hvorslev surface) on the dry side of the *CSL*. The rock will dilate and the local porewater pressure will fall in response to changes in both *p'* and *q'*. A skin of rock around the tunnel may be subject to evaporative water losses associated with tunnel ventilation and local desaturation seems probable. Unloading fractures are likely to develop. After the installation of the sprayed concrete lining, very slow readjustment of porewater pressure is anticipated as water is drawn down the hydraulic gradient. After backfilling with bentonite or bentonite/sand mixture, the radial stress exerted by the backfill on the rock will slowly rise as the clay becomes hydrated and the swelling pressure develops. Given the low hydraulic conductivity of the host-rock, full hydration is likely to take many years. Stresses acting within the zone of stress concentration (EDZ region) will adjust to the gradually increasing radial stress and porewater pressure will slowly rise so as to eliminate the radial hydraulic gradient.

The endpoint of this evolution will depend on the magnitude of the backfill swelling pressure in comparison with the far field stresses. If the swelling pressure is of similar magnitude to the far-field stresses, then *p'* will show a significant increase and *q'* will decrease. Hydromechanical self-sealing seems probable as the stress path moves towards the "wet" side and away from the state boundary surface. Excessively high backfill swelling pressure could lead to radial tensile fracturing of the host-rock.

5. QUALITATIVE APPLICATION TO NATURAL FAULTING

Although there are relatively few examples of the application of critical state concepts to geological problems, there would seem to no real scientific obstacle preventing us from making inferences about the behaviour of the natural system from our knowledge of the geotechnical properties and responses of these rocks. We therefore anticipate that a mudrock undergoing faulting will display either "dry" side or "wet" side responses, depending on the current value of *p'* and *OCR*. Dilatant fracturing associated with undrained shear deformation on the "dry" side is likely to lead to short-term permeability enhancement. However, it is a common observation that the wall-rocks of shear fractures in heavily overconsolidated mudrocks become softened by movement of groundwater into the region of shear dilation, leading to swelling and a general tightening of fractures. Whether it is possible to reconcile large-scale field observations of mudrock tightness at current depths >200 m with these concepts remains to be shown (see this volume).

6. CONCLUSIONS

There is no established theory describing fracture self-healing and self-sealing processes in mudrocks and no methodology to assess the conditions under which these processes might be important. It can be argued that the largely hydromechanical process of self-sealing is likely to be the more important process affecting fluid movement in fractured mudrocks over the typical time scale of repository performance assessment. The modified Cam-Clay approach provides a useful conceptual and theoretical framework for the analysis of hydromechanical problems. Drawing on the available body of knowledge, three hypotheses are advanced: (a) Shear fractures in mudrocks will be hydraulically tight when deformation takes place exclusively on the “wet” side of the critical state line, (b) Fractures will tend to self-seal by localised swelling (i.e. rebound) when water moves into dilatant rock formed during undrained deformation on the “dry” side, and (c) Fractures will tend to self-seal when temporal changes in the stress field cause the stress path to move towards the “wet” side and away from the Hvorslev surface. These ideas can be applied to fracture sealing within the *EDZ* and to the general problem of fault sealing. Validation by the analysis of case histories would seem appropriate.

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Self-sealing Faults in the Opalinus Clay – Evidence from Field Observations, Hydraulic Testing and Porewater Chemistry

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1. INTRODUCTION

As part of the Swiss programme for high-level radioactive-waste, the National Cooperative for the Disposal of Radioactive Waste (Nagra) is currently investigating the Jurassic (Aalenian) Opalinus Clay as a potential host formation (Nagra 1988, 1994). The Opalinus Clay consists of indurated dark grey micaceous claystones (shales) that are subdivided into several litho-stratigraphic units. Some of them contain thin sandy lenses, limestone concretions or siderite nodules. The clay-mineral content ranges from 40-80 weight per cent (9-29% illite, 3-10% chlorite, 6-20% kaolinite and 4-22% illite/smectite mixed layers in the ratio 70/30). Other minerals are quartz (15-30%), calcite (6-40%), siderite (2-3%), ankerite (0-3%), feldspars (1-7%), pyrite (1-3%) and organic carbon (<1%). The total water content ranges from 4-19% (Mazurek 1999, Nagra 2001). Faults are mainly represented by fault gouge and fault breccias, partly associated with minor veins of calcite. A key question in safety assessment is, whether these faults may represent preferential pathways for radionuclide transport.

2. HYDROGEOLOGICAL PROPERTIES OF FAULTS

Investigations in near-surface Opalinus Clay demonstrate that advective fracture flow and matrix diffusion are the dominant processes at shallow depths (Mazurek *et al.* 1996; Hekel 1994). The extensive data available indicate that these fractures are permeable due to surface-related decompression and weathering effects. On the other hand, the large number of faults and joints penetrated by deep boreholes and intersected by 6 600 m of tunnels in the Swiss Folded Jura revealed only five indications of minor seepage, all of which are associated with zones with an overburden of less than 200 m. All these field observations lead to a conceptual flow model with a strong depth dependence of the permeability of the Opalinus Clay, which is also represented by a marked hydrochemical depth zonation (Gautschi 2001).

This means that at depth >200 m, advective transport through fractures (faults, joints) is not a critical issue. Typically, faults have hydraulic properties similar to those of the undisturbed rock matrix, but permeable faults with $T \leq 10^{-9}$ m^2/s cannot be excluded, because the detection limit for a visual identification of damp patches along faults in ventilated tunnels is at a transmissivity of roughly 10^{-9} m^2/s (assessment by Eugster and Senger 1994). However, all hydraulic tests in deep boreholes and in the Mont Terri underground research laboratory yielded hydraulic conductivities $<10^{-12}$ m/s, even though joints and faults were included in some of the test intervals.

3. EVIDENCE FROM HYDROCHEMICAL INVESTIGATIONS

Faults that are acting or have acted as preferential pathways for fluids may be identified by anomalies in the hydrochemical or isotopic signature of the formation. Current geochemical investigations on the Opalinus Clay and adjacent aquifers at Mont Terri and Benken provide large-scale profiles of various porewater components (chloride, •^{2}H and •^{18}O of water, ^{4}He, and •^{37}Cl) across the formation. Strong evidence exists that diffusion is the major process governing solute transport in the Opalinus Clay (Rübel 2000; Rübel and Sonntag 2000; Nagra 2001; written commun. A. Bath 2000, Willoughby-on-the-Wolds, UK; written commun. M. Coleman 2001, University of Reading, UK). Although some of the porewater samples in the studies referenced above derive from faulted test intervals or from cores of faults or their neighbourhood, no hydrochemical or isotopic anomalies have been identified in the Opalinus Clay. This means that there is no hydrochemical evidence of a significant paleoflow along these faults.

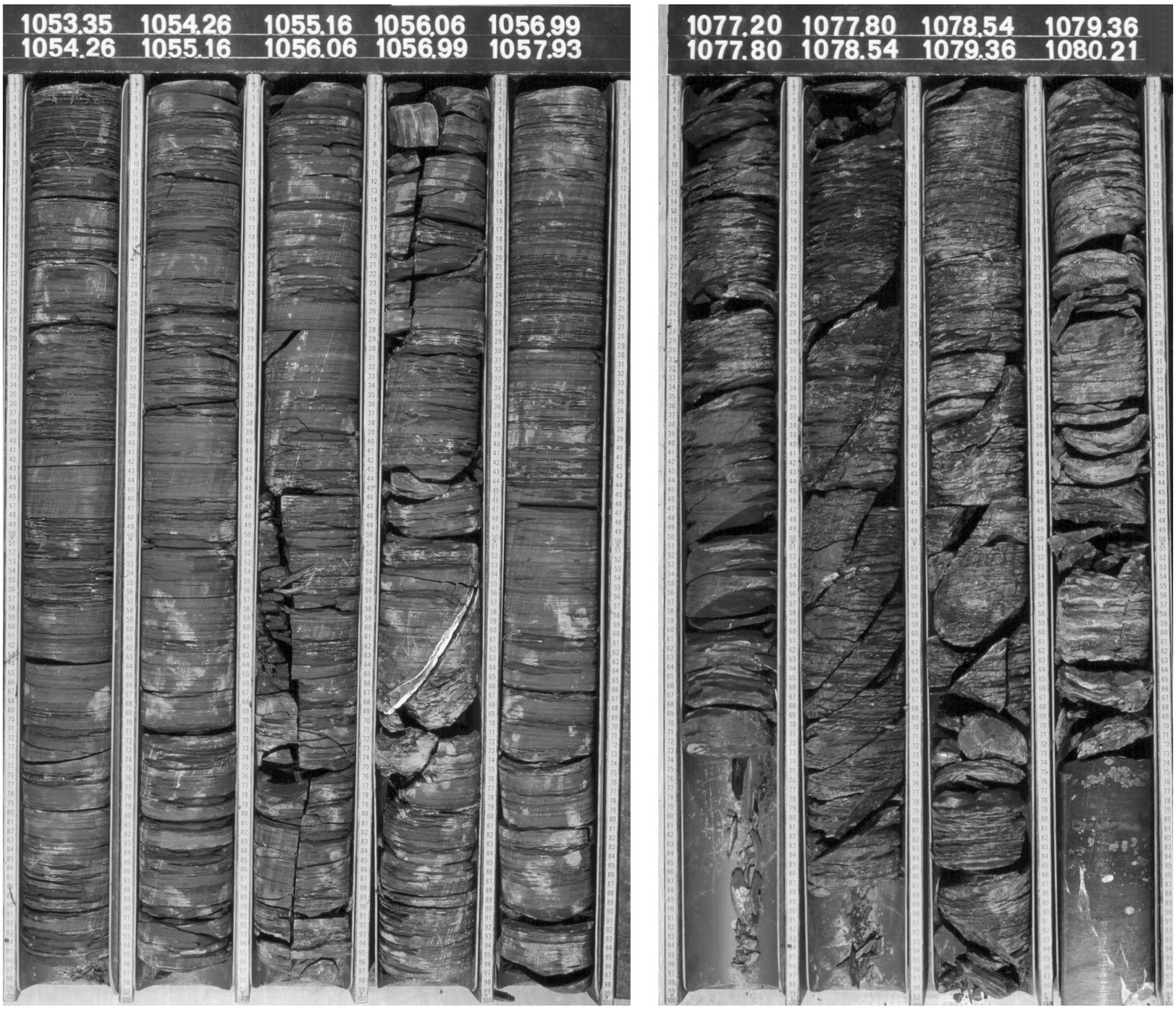
4. MINERAL VEINS IN FAULTS

Faults that have acted as preferential pathways during past hydrothermal events or episodic events related to earthquake induced fluid expulsion are often characterised by extensive mineral veining with open channels, incremental mineral deposition or multiply recemented wallrock breccias (e.g. Sibson 1981, 1994). In the Opalinus Clay, there are no indications of such mineral vein systems. Minor calcite veinlets, with or without quartz, occasionally with celestite, with width in the mm range (rarely > 1 cm), are partly present in fault zones (Waber and Schürch 1999, Mazurek 2001) (Figure 1). Furthermore, no indications exist of narrow flow channels within veins, like those observed in crystalline rocks of northern Switzerland (Thury *et al.* 1994, Mazurek 2000). These minor veins in tight faults can be attributed to minor episodic (local?) fluid flow during fracture formation or to local pressure dissolution/precipitation processes. No evidence of significant episodic paleoflow exists.

5. CONCLUSIONS

An extensive hydrogeological data base - part of which derives from strongly tectonized geological environments - suggests that advective transport through faults in the Opalinus Clay at depth > 200 m is insignificant. This conclusion is also supported by independent evidence from clay porewater hydrochemical and isotopic data. The lack of hydrochemical anomalies and the lack of extensive mineral veining suggest that there was also no significant paleoflow through such faults. These observations can only be reconciled with a strong self-sealing capacity of the faults. Therefore it is concluded, that reactivated existing faults or newly induced fractures will not act as pathways for significant fluid flow at anytime due to self-healing processes. These conclusions are supported by results from laboratory hydro-frac and flow-through tests, and from field-tests in the Mont Terri underground research laboratory (Blümling and Hoteit, this volume), where short-term self-sealing (hours to months) of artificially induced fractures has been identified.

Figure 1. **Fault zone in the Opalinus Clay, Schafisheim borehole, Northern Switzerland. The calcite vein at 1056.7 m is the most significant vein observed so far in the Opalinus Clay of northern Switzerland.**



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Geological, Hydrogeological and Hydrochemical Field Evidence for Fault Sealing in Marls from Wellenberg, Switzerland

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Among the various clay-rich formations that are considered worldwide as host rocks for the deep disposal of radioactive waste, the Palfris formation at Wellenberg (Central Swiss Alps) is the one that experienced the deepest burial and the highest degree of induration. While the sedimentary thickness is ca. 200 m, the Palfris formation at Wellenberg is accumulated to a thickness of ca. 1 000 m by tectonic processes. Being an incompetent rock unit sandwiched between limestone units to the south and north, it has been folded and thrusted intensely during the Neoalpine orogeny some 20 Ma b.p. Thrusting occurred at a depth of ca. 10 km and burial temperatures of ca. 200 - 250°C. The deformation was mostly ductile, with pressure solution and reprecititation in veins as one of the most effective deformation processes. Given the substantial burial, matrix porosity of the formation is only ca. 1 - 2 vol%.

During the late stages of the orogenic events, the formation was affected by substantial brittle faulting. Many of the faults are currently hydraulically active, and the formation as present today can be conceived as a fractured medium. The number of faults is ca. 5 - 15 per 100 m along a vertical borehole, resulting in an average fault spacing in the order of 10 m. Many of the faults reactivate pre-existing ductile thrusts and consist of a central zone made up of fault gouge/breccia, embedded in a damage zone (containing fractures and joints). Fault thickness typically lies in the range of centimeters to decimeters, but major faults more than 1 m thick also occur. There is no systematic relationship between fault size or frequency as a function of depth.

On the basis of fluid logs, discrete water inflow points into boreholes could be localized precisely, and most of them turned out to be related to faults. However, only a fraction of all faults observed in the cores correlates with inflow points into the boreholes. The ratio of observed inflow points to the total fault inventory in a specific borehole interval is termed the “channeling fraction”, and it varies from close to 1 at shallow levels to almost 0 at a depth of several hundreds of meters (Figure 1). This means that in the uppermost 100 - 200 m, the largest part of all faults present is transmissive, while at depth levels below ca. 500 - 700 m, only a minor part of all faults have a transmissivity in excess of the detection limit of the fluid logging technique (ca. 1E-9 m^2/s). While the fault network is very dense even at greater depth, its permeability is very low, and this is attributed to an efficient self-sealing mechanism of the faults. The systematic increase of hydraulic conductivity towards shallower levels, which is identifiable in all boreholes drilled to date, is attributed to the decrease of normal stress acting on the fault planes. As the region has been (and still is) uplifting, the progressive exhumation of originally deep-seated faults results in an increase of hydraulic conductivity.

Due to the small hydraulic conductivities, all hydraulic tests in the deeper parts of the boreholes characterize only the immediate surroundings of the boreholes (radii of investigation in the range of centimeters - decimeters). Constraints regarding the nature of the hydraulic regime on a large scale can be derived from 1) hydrochemical evidence and 2) observed head distributions:

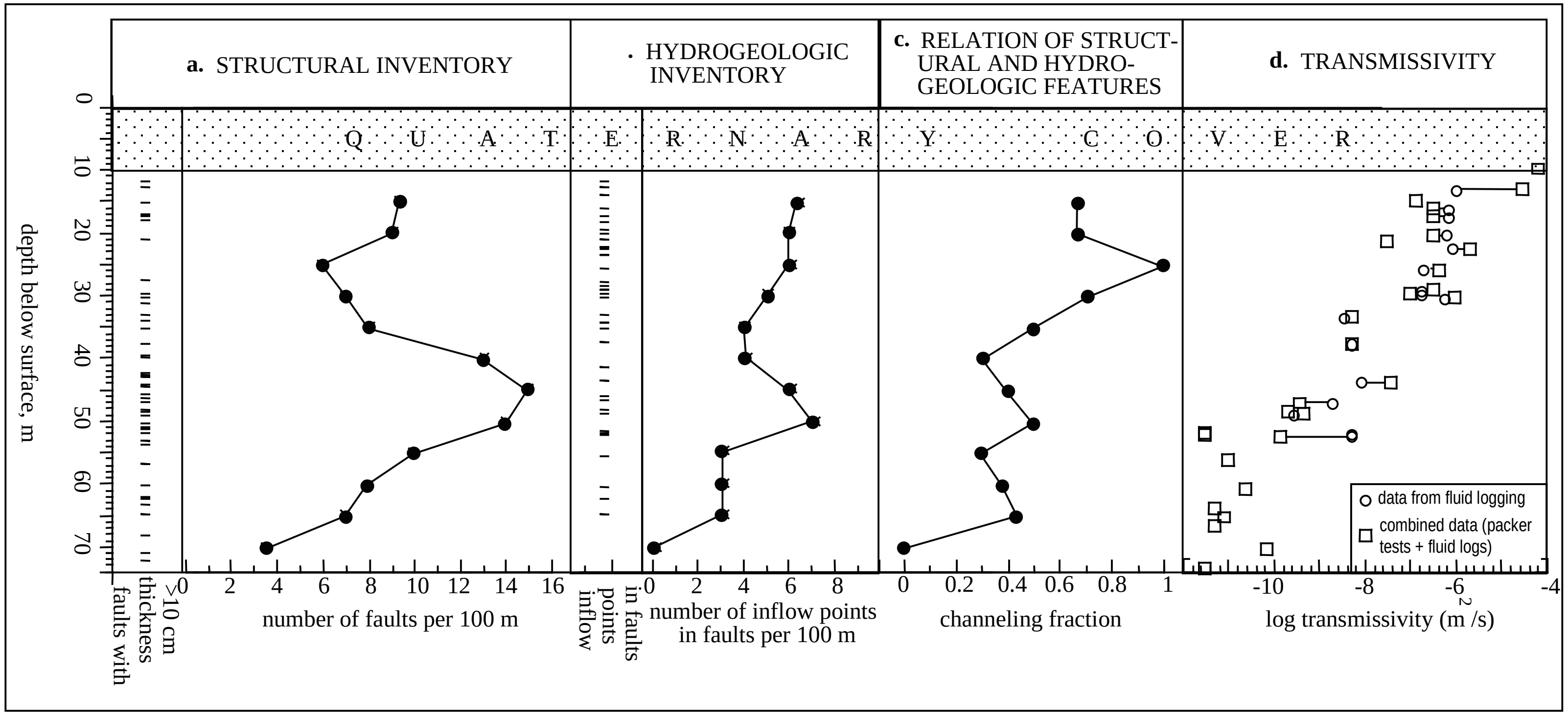
1) Pore fluids residing in the present-day fracture and matrix porosity at larger depth consist of methane-saturated Na-Cl water with minute amounts of free methane gas which occurs in druses. Their chemical and isotopic compositions are very similar to those of metamorphic fluids observed in fluid inclusions, suggesting a common origin. Post-metamorphic admixtures of externally derived waters cannot be identified, and it is suggested that present-day Na-Cl groundwaters that occur in the central parts of the marl have resided in the formation since the time of metamorphism some 20 Ma b.p. The only major change in the fluid composition has been the outgassing of methane from the formation, most probably by diffusion.

2) The deeper parts of the host-rock body, approximately coinciding with the region where Na-Cl groundwaters occur, have sub-hydrostatic pressures today, as indicated by hydraulic tests in the deep boreholes. It is unclear as yet whether the underpressures are due to erosional or glacial unloading, but they are clear evidence of very small large-scale hydraulic conductivities of the host rock.

In order to formalise and quantify the hydrochemical information, the flow model was run backwards in time, and the underground pathways of groundwaters sampled down-hole were traced back to their infiltration points (particle backtracking). The calculated times since infiltration were compared to the age structure of the groundwater as constrained by isotopic dating techniques. While only a limited number of test cases were quantifiable, none of them resulted in inconsistencies between the hydraulic and hydrochemical evidence. Moreover, Sr isotopes were used to constrain the possible fluid exchange between the Palfris formation and the embedded limestones, which places constraints on possible flow directions and thus represents another consistency check between hydrochemical evidence and flow modelling.

Both the closed-system behaviour derived from the chemical and isotopic characteristics of the deep groundwaters and the (recurrent or continuous) existence of hydraulic underpressures suggest very low permeabilities of argillaceous rocks during metamorphism and throughout subsequent uplift and exhumation. All fluids present in the deeper parts of the formation are either connate or produced *in situ*. Even though major events of brittle faulting and unloading due to uplift occurred since the peak of metamorphism, fluid flow through the formation has been negligible, in spite of the existence of a fault network. Only as soon as the formation is exhumed to depths of less than ca. 500 - 700 m, faults become hydraulically active.

Figure 1. **Distribution of faults, water inflow points and transmissivities in borehole SB4a/v. Data points in a-c refer to vertical intervals 100 m long**.



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Self-healing: Experiments at the Mont Terri Underground Laboratory

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1. INTRODUCTION

The Mont Terri Rock Laboratory is a generic rock laboratory in the Swiss Jura. It is an international research site, operated by nine different institutions, namely – Andra (France), BGR (Germany), Enresa (Spain), IPSN (France), JNC (Japan), Nagra (Switzerland), Obayashi (Japan), SCK•CEN (Belgium) and SNHGS (Switzerland). The laboratory is operated under the patronage of the Swiss National Hydrogeological and Geological Survey (SNHGS) and has the authorisation of the Government of the Republic and Canton of Jura, Switzerland.

At Mont Terri Rock Laboratory (Thury and Bossart, 1999), an argillaceous formation is investigated with respect to its potential to serve as a host rock for a repository of high radioactive waste. Numerous experiments were carried out to investigate the Opalinus Clay at this site, to evaluate the geological, hydrogeological, geochemical and mechanical properties and to improve process understanding of coupled processes.

The Opalinus Clay can be characterised as a transversly isotropic, overconsolidated clay shale that contains about 50-70% clay minerals. The geomechanical properties of the rock are strongly dependant on the water content. Low water content leads to high rock strength and brittle behaviour while higher water content successively decreases strength and causes ductile behaviour. Hydraulic tests indicate that the intact rock and natural faults have a very low hydraulic conductivity. Increased hydraulic conductivity can only be observed in induced fractures created from stress redistribution in the vicinity of the tunnel and from overpressure.

2. OBJECTIVES

During the development of the research programme it became clear that induced fractures have an significant impact on the performance of a repository in such a formation and that it would be necessary to conduct tests on the proposed self-healing capacity of such features. Therefore, two different experiments were conducted to investigate the effect of induced fractures

- Self-healing of the excavation disturbed zone
- Self-healing of induced gas-fracs

The excavation disturbed zone (EDZ) is a common feature around underground structures which is caused by the redistribution of stresses around the free surfaces of openings. The redistribution leads to areas of highly deviatoric compressive and/or tensile stresses, which can cause fractures and joints with highly increased hydraulic permeability along the tunnels. The objective of the first experiments was to investigate if these fractures change their hydraulic properties with time due to swelling or creep during the resaturation of the EDZ.

The second experiment was designed to investigate a different situation. Gas produced by the waste within the repository can create an overpressure situation in the sealed repository and cause fracturing of the formation. The objective of the second experiment therefore was to evaluate if such fractures also show a indication of self-sealing.

Meanwhile, in order to transpose results observed in situ on opalinus Clay to Callovo-Oxfordien argillites, ANDRA conducted some self-healing tests on samples taken from deep boreholes during the preliminary step of geological investigation of Haute-Marne/Meuse site. These tests were performed on triaxial device with artificial fractures.

3. CONCEPTS

3.1 EDZ Self-healing

The tunnels at Mont Terri were excavated with different techniques (drill and blast, road header, pneumatic hammer). In a first step, different sites at the underground laboratory were characterized using a pneumatic test procedure to find suitable experiment sites including conductive fractures or an interconnected network of fractures in the EDZ (Meier *et. al.* 2000). An initial characterization of these sites to delineate the properties and the geometry of such fractures was followed by a re-saturation of the EDZ and an observation of the development of the hydraulic permeability with time.

3.2 Gas-frac Self-healing

Laboratory tests were conducted on tensile and shear fractures to evaluate the processes of self healing using different water chemistry. These processes were then verified *in situ*. After a hydraulic characterization of the test site, a hydrofrac was induced which created an artificial flow path between 4 boreholes. The changes of the hydraulic permeability were measured as a function of time to evaluate the self-healing of the rock. Before and after the self-healing process gas entry pressures and possibly gas permeability of this induced fracture were measured.

3.3. Self-healing on samples from callovo-oxfordien argillites

Two self-healing mechanisms were studied: with sulfate and carbonate in triaxial device fit out with pore pressure cells. Tests were conducted with confining pressure which varies from 10 to 20 MPa.

4. RESULTS

4.1 EDZ Self-healing

Two experimental sites were selected for the final tests (Meier *et al*., 2000). One site contained a single fracture at a depth of about 0.7 m from the tunnel wall, while the other site containing a fracture network in the EDZ. Both fracture systems were unsaturated. The re-saturation was achieved using two types of water with different water chemistry. Nevertheless, a self-healing was observed at both sides. The transmissivity of the single fracture decreased by about one order of magnitude to 1E-9 m^2/s within approximately 1 year. The transmissivity of the fracture network decreased from about 5E-7 to 1E-8 m^2/s within 110 days.

4.2 Gas-frac Selfhealing

The central borehole BGS 2 (Figure 1) was used for the injection to induce the fracture. Figure 2 shows the pressure time plots of the active intervals in boreholes BGS 1 and 2. As the hydraulic equipment was limited to pressures of about 10 MPa, the creation of the fracture was quite difficult. By increasing and decreasing the pressure for several times we were able to fracture the rock. The result of the fracture initiation can be seen in borehole BGS 1 (at approx. 2.5 h) as well as during the reopening of the fracture (two refrac cycles). The mechanical measurements in fig 3 show the fracture opening as well.

It can be noted that the fracture does not close totally after the depressurisation but remains partly open. Long-term observations indicate clearly that the fracture continuously closes during time. This fracture closing can be observed over approximately 5 months. The tests after fracture initiation indicate that the transmissivity of the fracture is pressure dependant (Figure 4). For a injection pressure below 2 MPa the transmissivity is very similar to the transmissivity of the intact rock (5 E-13 m^2/s). Increasing injection pressure constantly leads to an increased transmissivity until a reopening pressure of about 5 MPa is exceeded. The open fracture has a transmissivity of about 2 E-8 m^2/s. Test, conducted about 6 month following the fracture initiation, do not show significantly different transmissivity than tests immediately after fracturing.

Figure 1. **Schematic test configuration for the gas-frac self-healing test (BGS 2: injection borehole, BGS1: hydraulic observation borehole equipped with multi-packer system, BGS 3 and 4: mechanical observation boreholes, equipped with 3 fixed installed micrometers each)**

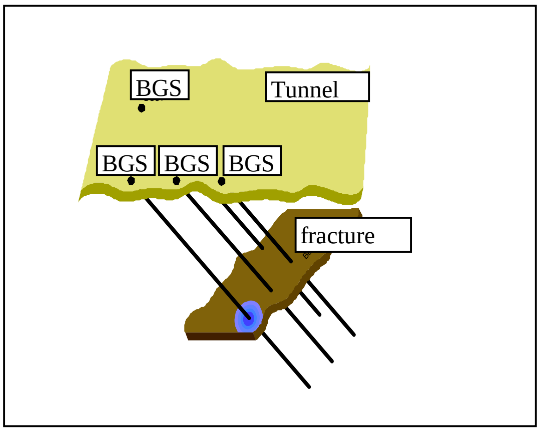


Figure 2. **Hydraulic response fracture initiation**

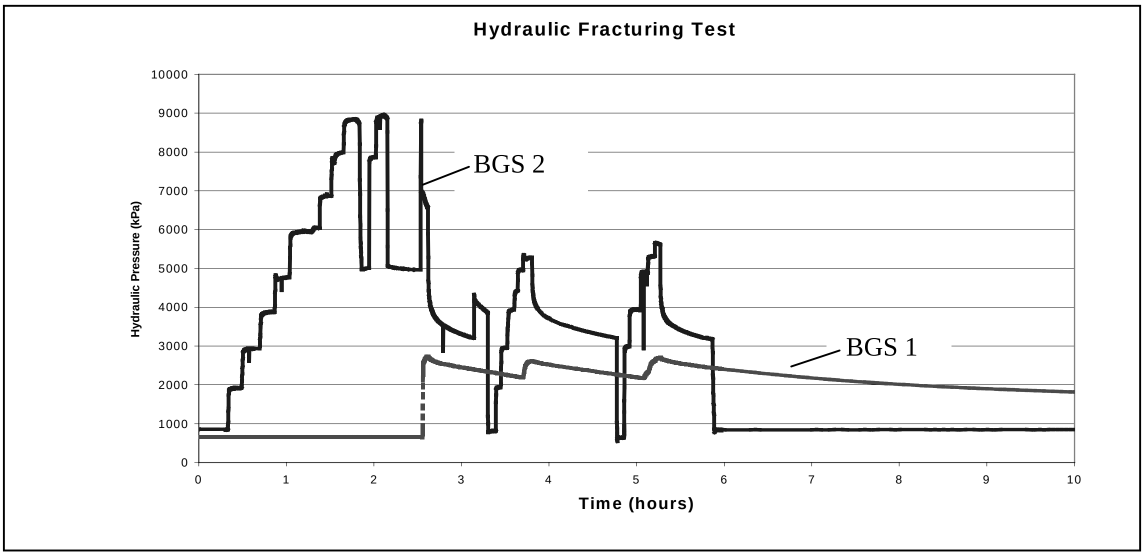


Figure 3. **Mechanical response during fracture initiation**

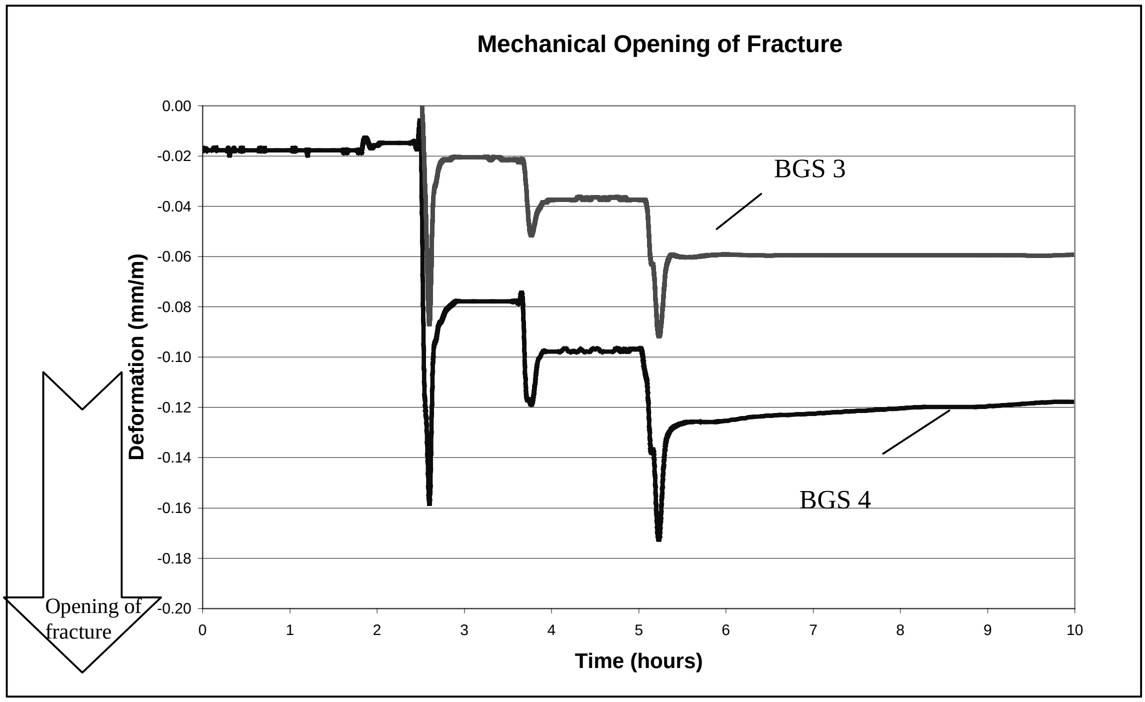
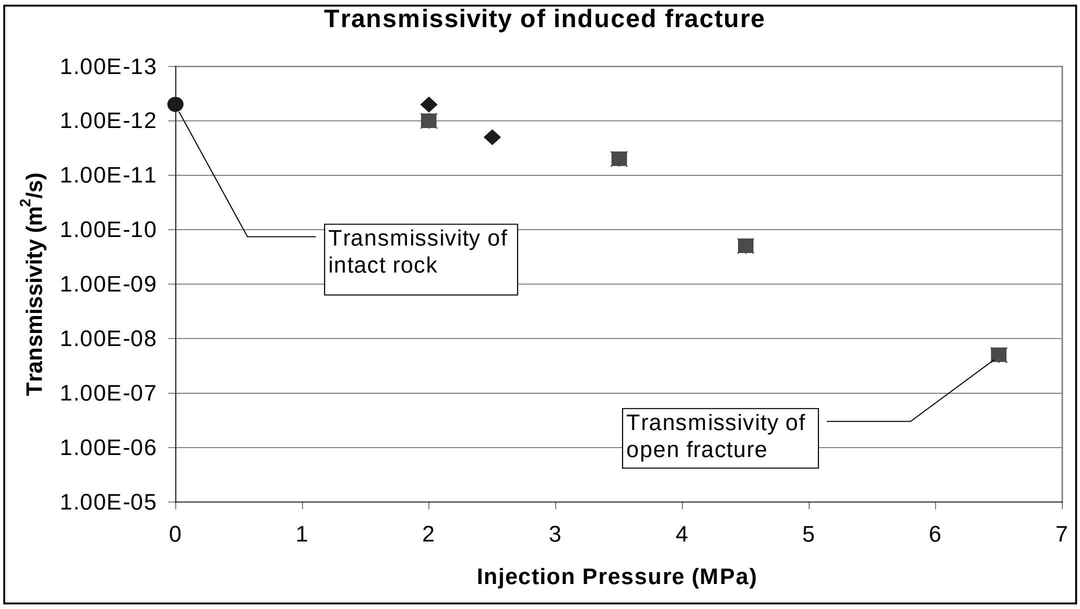


Figure 4. **Transmissivities measured in the gas-frac self-healing test (squares: test results immediately after frac initiation, diamonds: test results 6 month after fracturing)**



4.3. Self-healing observations on samples: preliminary results

A water charged with sulphate was injected in artificial fracture induced perpendicularly or parallel to the stratification. Fracture was closed by swelling phenomenon. Meanwhile, a gypsum crystals organised in thin layers were observed, especially in some micro-cracks.

On the other hand, with water charged with carbonates, fracture and micro-cracks were closed by calcite crystals which crust over carbonate minerals.

All tests were timed, but others tests must be performed to establish a relationship between closure and closure speed. These tests have to carry out under mechanical loading which represents in situ behaviour in vicinity of underground construction.

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Fracturing and Self-Healing in the Boom Clay: Evidences and Further Studies

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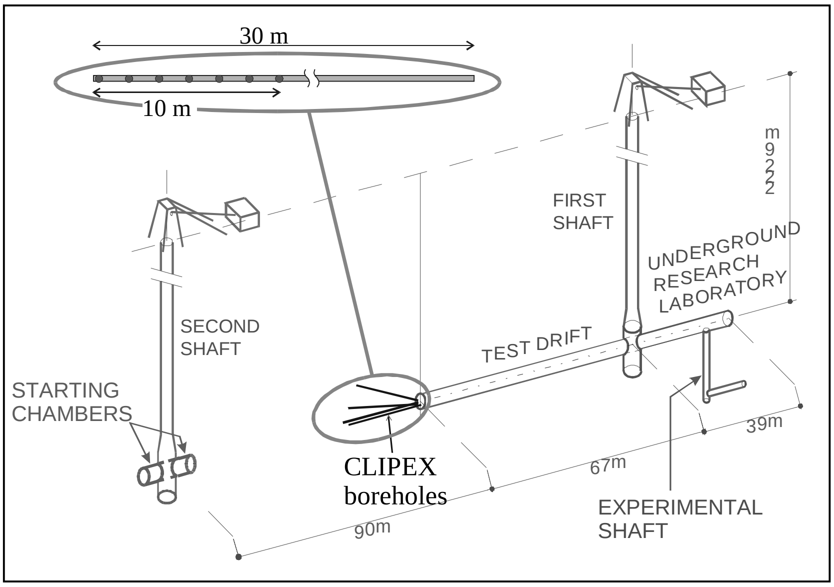
1. INTRODUCTION

The Boom Clay is considered as a potential host-rock for the disposal of Belgian radioactive waste. During the sinking of a new shaft to extend the underground facility HADES, an important fracturing has been evidenced around the excavation. Fracturing was already observed previously but to a lesser extent. The low support pressure imposed by the primary shaft lining, combined with the large time over which this support condition held, has favoured the decompression of the clay massif through delayed effects, and therefore the development of fracturing. In the frame of the overall performance of a radioactive waste repository, it is of prime importance to understand the fracturing process induced by excavation in Boom Clay, as well as the self-healing process. This will be done in the SELFRAC EC project (Fractures and Self-healing within the Excavation Disturbed Zone in clays).

2. FRACTURING OBSERVED DURING THE CONSTRUCTION OF THE NEW SHAFT

A view of the present-day underground installations at the Mol site is presented on Figure 1.

Figure 1. **View of the underground facility HADES in the Boom Clay at the Mol site**.



The second shaft has been sunk in 1998-99. Its bottom part (-218 / 228 m - excavated in 1999), entirely located in the clay host-rock, consists of an excavation with an internal radius r_i = 4 m, which was primarily lined (from top to bottom) with sliding ribs (i.e. a relatively soft lining). After completion of the excavation, a secondary rigid lining (reinforced cast concrete) was placed from the bottom. The time span between the placement of the primary and secondary lining was around two months, which allowed an important convergence (about 30 cm on the diameter) of the clay. From the bottom of the second shaft, the excavation of two opposite starting chambers led to front stability problems resulting in significant fracturing of the clay host rock close to the excavation. This fracturing appeared as large fracture surfacesvisible at the front of each starting chamber (see Figure 2). Importantly, they showed very clear indicators of movements indicating a radial sliding, and an axial symmetry around the main shaft axis. The fracturing also appeared as fracture traces in the lateral walls of the starting chambers (see Figure 3). These two starting chambers cross-cut the plastic zone generated by the excavation of the main shaft along its radial direction. Consequently, the observed fractures could therefore be related to the excavation of the shaft.

Figure 2. **View of the fracture surface in the South starting chamber (the thick black curves visualise the trace of horizontal planes on the fracture surface).**

Figure 3. **Traces of the fractures (indicated by the black arrows) in the lateral wall of the South starting chamber.**

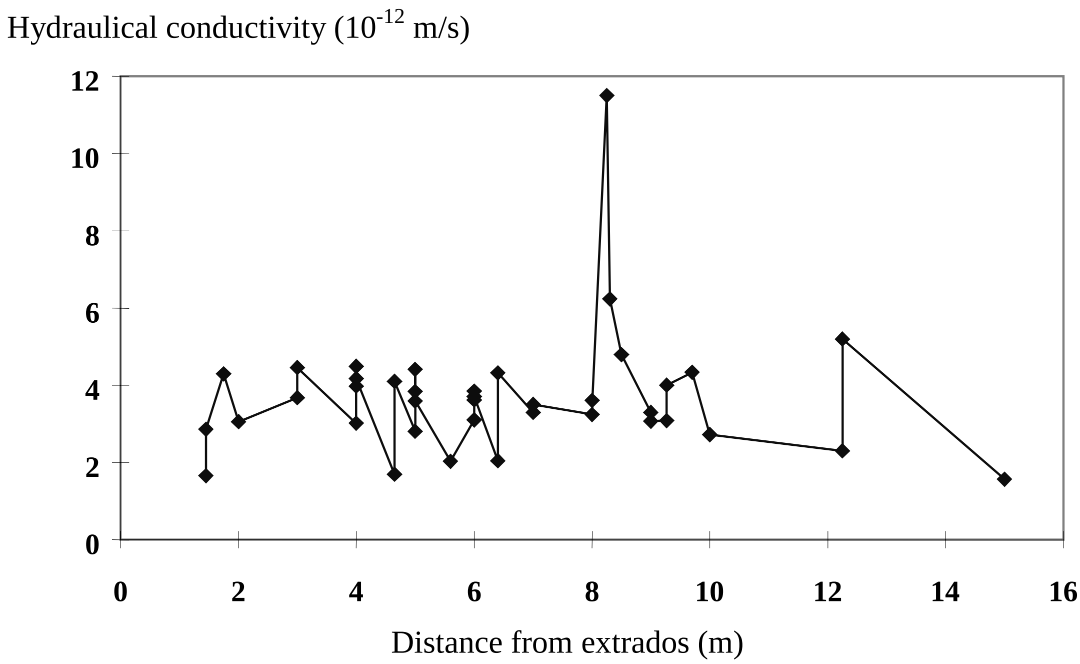
The excavation of the starting chambers is also correlated to hydraulic perturbations in the far field. A pressure drop of maximum 0.2 MPa at 60 m radius is shown by some piezometers of the CLIPEX instrumentation programme (see Figure 1 – Bernier and Van Cauteren, 1998). Simple poroplastic models that predict a maximum perturbation extent of 25 m under full deconfinement cannot explain these observations. Skeleton viscosity and fracturing in the near field have to be taken into account (Barnichon and Volckaert, 2000).

3. SELF-HEALING EVIDENCES OBSERVED AROUND THE HADES UNDERGROUND LABORATORY

Hydraulic conductivity measurements have been performed in the EDZ (Excavation Disturbed Zone) of the present HADES underground facility. The measurements have been performed at different time several years after its construction. We do not observe a significant variation of the hydraulic conductivity in the EDZ (see Figure 4). The higher value measured at a distance of 8.5 m correspond to a more silty clay layer. These measurements have been confirmed by a macropermeameter test around the small experimental shaft (see Figure 1). A hydraulic permeability about 1.36×10^{-12} m/s was measured. This value is in perfect agreement with the value measured on classic piezometers (Ortiz, 1997).

In the MEGAS EC experiment, some evidences of self-healing have also been observed. This experiment aims to study the migration of gas in the host rock. Gas flows through preferential pathways orthogonal to the lowest component of the effective stress sensor. Restoration of the initial properties after gas fracturing in terms of hydraulic conductivity, gas diffusion and radionuclide migration has been observed (Ortiz *et al.*, 1995).

Figure 4. **Hydraulic conductivity measurements around HADES**



4. THE SELFRAC EC PROJECT

The SELFRAC project aims at understanding and quantifying A) the increase of the permeability, related to crack proliferation around excavation in clays and B) the self-healing process that can in turn reduce the permeability in time. Two clays will be studied and compared: the Opalinus Clay at Mont Terri (Switzerland) and the Boom Clay (Belgium).

Laboratory tests will be performed to characterise processes A and B in order to give the necessary data to improve and calibrate constitutive models. When developed, these models will allow to predict the occurrence and the intensity of these processes. This is particularly important in terms of performance assessment and public acceptance of deep radioactive waste repositories.

To characterise the self-healing effect, triaxial and isostatic tests will be performed on sample with a longitudinal fracture. The initial hydraulic conductivity of the sample is then measured by applying a water pressure gradient. The evolution of the water flow rate is measured in time both during transient and steady state phases.

In-situ tests will be performed both at Mont Terri research facility and the underground laboratory HADES in Mol, to quantify processes A and B under realistic conditions. Experimental results will be compared with numerical predictions.

Finally the significance of the Excavation Disturbed Zone will be put in the context of the long-term performance of a radioactive waste repository. Recommendations for the excavation techniques and design of deep radioactive waste repository will be formulated.

5. CONCLUSIONS

Fractures can develop, even in plastic clays, around underground openings by virtue of stress readjustments due to the excavation process. Such changes alter the mechanical and hydraulic properties of the surrounding rock mass and also influence geochemical conditions. Fractures determine the dominant flow paths and are therefore of major importance for fluid transport in these systems. Fortunately argillaceous host-rock formations present self-healing properties, which should reduce the permeability in time.

It is important to study these processes to assess the performance of a radioactive waste repository. Some self-healing evidences have been observed around the HADES underground laboratory but need further investigation to be confirmed. This will be done in the SELFRAC EC project.

ACKNOWLEDGEMENTS

The European Commission is greatly acknowledged for funding of the SELFRAC project projects, together with the following respective partners: Katholieke Universiteit Leuven, NAGRA, SOLEXPERTS, Ecole Polytechnique de Lausanne, Laboratoire 3S de Grenoble, G3S.

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Partial Self-Healing Effects of a Highly Indurated Claystone Formation (BCF) Discovered by *In Situ* Measurements

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1. INTRODUCTION

All those recent characteristics, which determine the natural isolation performance of a potential host formation and its wider environment locating on the possible pathways can be summarised under the term “primary confinement properties” (before development of the first underground openings). But there are lots of physical, geochemical and microbiological processes deteriorating these advantageous features later on. The recently undetectable potential migration pathways can be generated in many ways:

- by the mechanical (EDZ) and thermal (TDZ) disturbance of the final disposal of HLW’s;
- by the long-term geological evolution of the investigated area (earthquakes, re-activation of tectonic elements, mechanical changes caused by uplift, etc.).

One of the most important question in the characterisation of a site is, whether any subsequent processes occur (and if they exist, to what extent) along the pathways that are able to minimise or eliminate the negative consequences of those. The phrase “self-healing” means the capability of the host formation to heal the newly formed discontinuities, restoring the original (or a more advantageous) confinement performance. By the literature there are some simple observations to reveal the presence of the perfect self-healing: for example the lack of visible seepage in an underground opening and/or the homogeneous distribution of hydraulic conductivity indicates it [1].

Perfect self-healing can be expected in every argillaceous formation under a certain depth depending on the stress field, the geometry of discontinuities and the mechanical, mineralogical-petrographical and geochemical properties of those. Consequently the so-called self-healing depth is proven to be very different in each formations. While it eventuates in the younger, underconsolidated host formations at the real depth interval of final disposal in all cases, it is not sure at all in the case of overconsolidated, highly indurated claystones, mudstones or shales.

Boda Claystone Formation (the potential host rock for final disposal of HLWs in Hungary) belongs to the latter group [2]. The perfect self-healing cannot be proved even at 1 000m depth, where the URL was developed. Therefore it is really great challenge to understand the recent confinement performance of BCF and describe the future scenarios. During the characterisation programme performed between 1993 and 1999 special attention was paid to this topic applied in situ methods as well [3]. It can be stated on the basis of these experiences that ***partial*** self-healing processes improving the efficiency of confinement can be observed inside these kind of formations, too.

2. SOME POSSIBLE SELF-HEALING MECHANISMS

The most obvious self-healing results in the *rock deformation controlled by the stress field*. Its most probable way is when the rock properties and stress conditions define a general latent plastic state. (It is also possible, however, that only the infilling material of fractures are deformable enough to re-close the discontinuities.) This is an instantaneous mechanism, moreover the original confinement performance can remain ceaseless while the faults moving if the closing rock stress is large enough.

Because of the basic mechanical conditions of stress-controlled self-healing it eventuates most frequently in the younger, soft clays of high swelling clay-mineral content. Consequently the distinction between the stress-controlled mechanism and *fracture-elimination caused by swelling* (that is practically also a quasi-instantaneous phenomenon) is really hard in the case of underconsolidated clays.

Swelling is primarily the characteristic feature of argillaceous rocks. However, not all of the clay minerals are inclined to swell. The intra-crystalline swelling capability is a conspicuous property mostly of the minerals of Smectite-group. The generally low Smectite-content of overconsolidated rocks does not allow a prompt self-healing controlled by swelling. But a relatively slow *rehydration process* can take place in these cases on the surface of newly formed rock surface. The rate of this process depends on the quantity, geochemistry and pressure of “extra-water” and the properties of the newly formed rock surface. Generally these rocks need a few days or months to swell responding to the hydration caused by the humidity redistribution after the deterioration.

There is some additional process that has the swelling became effective in longer term. The *degradation of non-swelling clay minerals* (e.g. Illite or Chlorite→Smectite) originated during the consolidation requires large fractured surface and appropriate geochemical and thermal environment. It takes place within longer periods (sometimes in geological ages) as a consequence of stress-rearrangement caused by uplifting or tectonic events. A special case of the degradation is the near surface *weathering processes*, accelerating by the penetration of oxygenated meteoric water [4].

One more non-clay-specific phenomenon can be also mentioned finally: The newly developed fissures and fractures may filled by the generating of *infilling materials precipitating from the solutions* flowing along them and having appropriate confinement properties (e.g. carbonates, quartz, anhydrite, barite, etc.). This mechanism is very complicated: it passes off primarily as a function of chemism, velocity, pressure and temperature of solutions, but numerous other environmental parameters can have effect on it as well.

Some other physical and geochemical processes are also possible to influence the confinement properties of newly formed discontinuities positively. The listed mechanisms do not occur separately, but simultaneously and complementing each other in general. In the case of argillaceous formations being in different consolidation rate several ones can play the dominant role in the existence of self-healing. The perfect self-healing effects occurring inside the softer clays can be explained mostly by the first two mechanisms. However, the importance of latter ones is not negligible for overconsolidated argillaceous host rocks.

3. MAIN PROPERTIES DETERMINING THE MECHANICAL AND HYDRODYNAMICAL BEHAVIOUR OF BCF

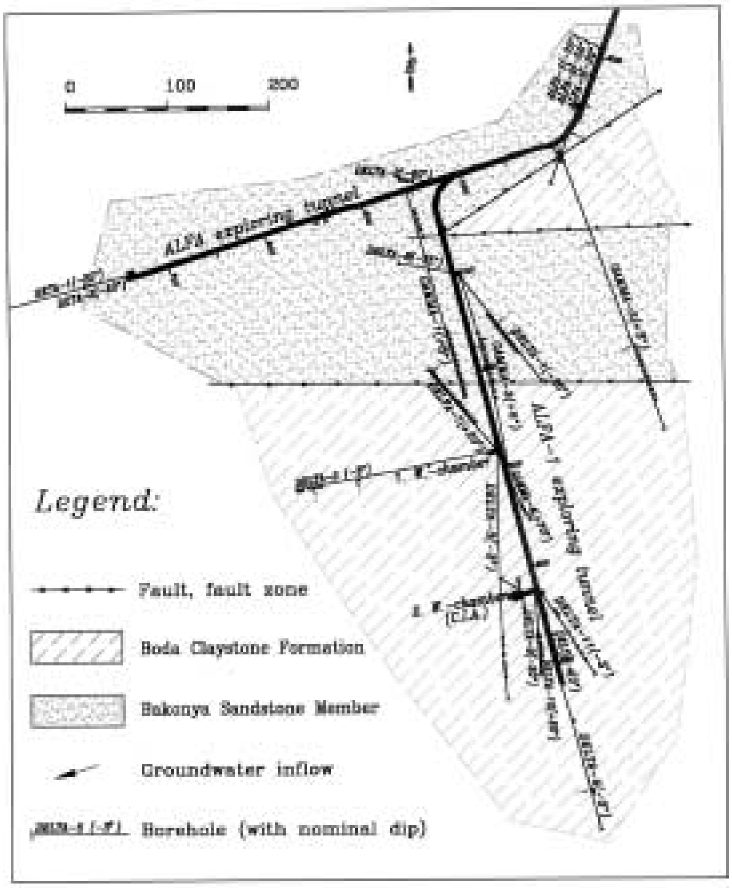
The recently 700-1 000 m thick layers of the BCF were settled in an alkaline (or playa) basin under extreme climatic, inflow and geochemical conditions, and later they were buried to at least 3.5 to 4.5 km depth. The diagenesis of sediments occurred at high temperature (approx. 150 to 200°C) and at high pressure (120-150 MPa). This situation resulted in the present overconsolidated, highly indurated character of BCF. Bulk-porosity and hydraulic conductivity of intact rock-matrix is very low (0.6–1.4%; $\approx 10^{-15}$ m/s). The typical interval of Young-modulus is between 30-40 GPa and the average unconfined strength exceeds 100 MPa [3]. Of course, these mechanical properties are not favourable for the primary, stress-controlled self-healing processes.

Composition of the 35–50% clay-mineral content is also fit to the burial history: According to the mineralogical tests (X-ray diffractometry, thermal analysis and electron microscopy) the dominant clay mineral of the unweathered rock types of BCF is Illite (25–40%). The Chlorite content is 5–15%. Smectite and Chlorite-Smectite mixed layer also were detected in every sample. With the exception of some special places (see below), however, the proportion of the swelling clay minerals is near the detectable limit (>1%) [5]. Thus self-healing caused by the swelling theoretically may occur, but it does not seem to be important at first sight.

Due to its eventful tectonic history BCF has a general discontinuous character presenting itself both on micro- and macro-scale. The URL was developed in the most tectonised zone of the investigated area at 1 000 meters depth below the surface. Hitherto relicts of four main, differently featured tectonic periods have been discovered by the detailed surface and underground geological mapping. The formation had been affected by tectonic events mostly under the self-healing depth. Owing to the paleo-self-healing processes, most of the explored discontinuities of tectonic (and lithological) origin are entirely closed and watertight. The joints and fractures are generally completely filled by various (clayey, carbonate or sulphatic) infilling materials. Depending on the density, type, infillings and orientation of discontinuities the measurable hydraulic conductivity of real rock body can fluctuate within a relatively wide interval (typically 10^{-10}... 10^{-13} m/s). The complexity of the tectonic structure makes the hydraulic characterisation of BCF more difficult.

At certain, well defined points of the URL some persistent water inflows were documented in the range from a few ml/min to 1-2 dl/min, on each separate entering points (Figure 1). Thus it is unambiguous that in the real depth interval of final disposal there is no entire and general self-healing in BCF. The locations producing visible water inflow can be clearly identified with the youngest, sinistral strike-slip fault of Miocene-Paleogene age and of ENE-WSW strike, and with its accompanying phenomena. The infilling material is generally chloritic, but only inconsiderable crushed and re-consolidated rubble has been documented here. The persistent yields of the order of dl/min are connected to the shear zone in all cases. On the basis of hydrodynamic tests performed in the boreholes Delta-5 and Delta-7 the hydraulic conductivity of this type of the discontinuities is in the range of 10^{-8}-10^{-9} m/s. Consequently no any significant self-healing mechanisms have been working here even on long time-scale that are able to recover the original confinement properties.

Figure 1. **Map of the URL with the places of more significant water inflows**



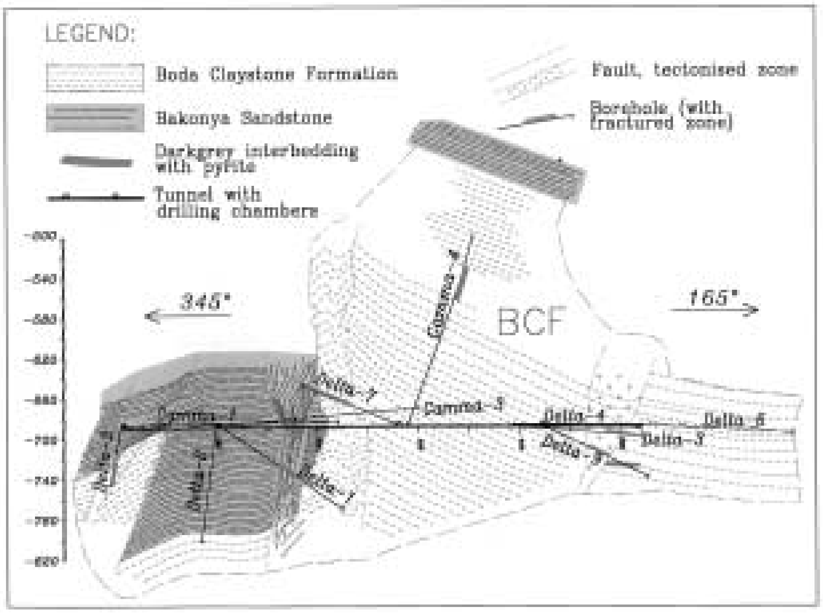
In spite of the afore-mentioned facts some evidences of the recently working self-healing phenomena have been documented in the framework of the characterisation programme of BCF.

4. *IN SITU* OBSERVATION AND MEASUREMENTS REVEALING THE SELF-HEALING MECHANISMS OF BCF

4.1. Degradation of clay minerals and its consequences

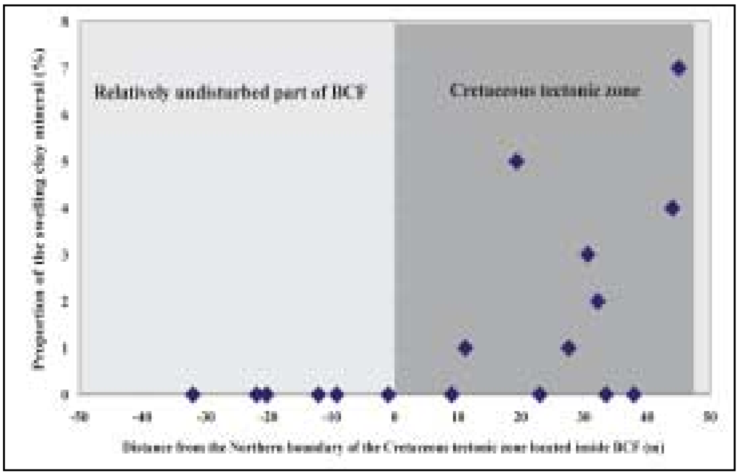
The Alfa-1 exploring tunnel opened the BCF through the overlying sandstone–BCF tectonic transition from the Cretaceous period that is the largest tectonic zone of the whole wider region (Figure 2). It has steep dip and compression character with 300-400 meters vertical and more than 1000 meters horizontal offset. Another similar (but less significant – with 150m vertical offset) fault zone inside the BCF was explored by the southern part of Alfa-1 tunnel, too. These tectonic zones are primarily filled by the subsequently re-consolidated fault breccia with own matrix. The traces of fluid flow can be seen here only in negligible extent. Presumably they have developed below the perfect self-healing depth limit. The hydraulic conductivity calculated from the pressure build-up records of boreholes crossing such a type of tectonic zone (Delta-9, -10, 11) are in the order of 10^{-10} m/s.

Figure 2. **Geological cross section in the vertical plane of Alfa-1 tunnel**



Quasi-horizontal sections were marked out through the zones in order that rock samples could be gained systematically along them. The relatively low number of tested samples render the correct evaluation difficult, but the main tendencies can be ascertained. According to the mineralogical tests of these samples it was surprising that the proportion of swelling clay minerals (mostly Smectite and Chlorite-Smectite ML) was much higher (2-7 %) as usual in the undisturbed blocks (see in Figure 3). In addition the quantity of Chlorites decreased significantly. Inside the large tectonic zone traces of acidic solutions could be detected. The proportion of Illite diminished there moderately, while the Illite-Smectite ML and the Kaolinite also appeared. Thus the considerable degradation of the formerly consolidated clay minerals is confirmed by the mineralogical tests.

Figure 3. **Evidences of the degradation of clay minerals taking place inside tectonic zones**



In spite of their inhomogeneous and fractured character, the Cretaceous tectonic zones did not prove to be a critical element of the performance of BCF. Besides the compressive stress state and the re-consolidated infilling materials all this is owing to the relatively high proportion of swelling clay minerals. The positive effects of this advantageous situation upon the recent confinement properties can be demonstrated with some results of pressure build-up tests performed in boreholes crossing the tectonised zones:

- *Delta-1* was the first underground borehole investigated in details. It was drilled (at –32° dip) to cross the mentioned large tectonic zone before the development of first section of tunnel exploring the BCF (Figure 1 and 2). A multipacker-set with five zones have been installed to monitor the pressure build-up processes. The P1 and P2 packers surrounding the upper zone (Z1) were installed into the overlying sandstone, while P3 into the transitional section. The upper packer of Z4 (P4) was located in 11 meters, while the P5 in 20 meters distance from the sharp tectonic border. Figure 4 shows that not more than 11 meters of highly fractured rocks of BCF proved to be appropriate protective layer to prevent the equalisation of pressure-differences. (Unfortunately the multipacker-set had damaged before the pressure build-up would have completed, due to the unexpected pressure differences.)

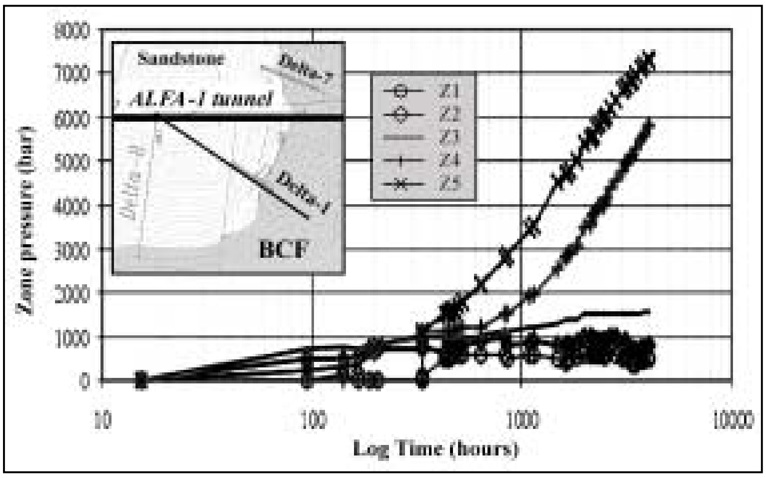
- A comprehensive test programme was performed to investigate the extension and hydraulical properties of EDZ in the rock blocks being in different mechanical condition. In the framework of this project 3 underground boreholes (Delta-9, -10 and –11) were drilled from the actual face (426. meters) of Alfa-1 tunnel. All of them explored the southern Cretaceous tectonic zone inside BCF. Multipacker-sets were installed into each borehole to monitor the hydraulical consequences of tunnelling performed by drilling-blasting technique. After the stabilisation period of multipacker-sets the Alfa-1 tunnel was extended with 100 meters crossing the investigated tectonic zone as well. The final situation, where the boreholes surrounded the extended tunnel can be seen in Figure 1 and 2.

  The closest point between the extended Alfa-1 tunnel and the Z4 zone of the horizontal *Delta-11* borehole was 21 m. Inside this zone a small degradation of pressure built-up rate could be observed while the tunnel was crossed the tectonic zone. Zooming in the process it can be also seen that simultaneously with blasting (depending on the distance from the tunnel face) a sudden pressure drop of the order of 10 kPa develops. Later it recovers slowly (within some hours) until the next blasting (see in Figure 5.). After the completion of tunnelling the rate of pressure built-up process reset to the original value.

  Similar process could be observed in the Z3 zone of Delta-10 borehole (drilled at +20°) and the Z4 zone of Delta-9 borehole (drilled at –30° dip). In these cases, however, the original rate was not recovered entirely later. The closest points of these zones to the Alfa-1 tunnel are 24 and 41 meters.

  This phenomenon can be interpreted in many ways. It is most likely, however, that the blastings effected dynamic pressure increases inside the isolated zones of borehole. It resulted in some “mini-hydrofracturing” along the pre-existent discontinuities of tectonic zone. The detected partial self-healing mechanism eliminated these new, hydraulically opened pathways. Besides the advantageous stress field, swelling probably plays an important role in this process, due to the above-mentioned degradation of clay minerals.

Figure 4. **Pressure build-up process detected in borehole Delta-1**



Unfortunately there was no systematic sampling across the *stratigraphic boundary* between the overlying sandstone and BCF. According to the few mineralogical tests performed on those samples it has to be emphasised that the proportion of swelling clay minerals indicates the presence of degradation process even inside this zone. Nevertheless it is also imaginable that the original composition of stratigraphic boundary was irregular.

In the samples of *weathered surface outcrops* of BCF the amount of Chlorite-Smectite mixed layer clay mineral and of Smectite (Montmorillonite) increased strongly (the maximum is 30 %), while the proportion of chlorite decreased more considerably than in the case of underground samples (down to zero in some cases). According to the mineralogical studies, the Chlorite→Chlorite/Smectite ML or Smectite transformation could be detected in the maximum 10 m thick, upper zone of BCF, as a result of the weathering processes. $\delta^{13}C$ and $\delta^{18}O$ stable isotope measurement were performed from the carbonate of rock samples gained from the shallow surface borehole Bat-14. The data of these measurement show, that the meteoric waters were able to penetrate down no more than several meters into the rock, which is otherwise extremely fractured on the surface.

4.2. Rehydration processes

One year after the end of tunnelling water seepage appeared at the 243. meters of Alfa-1 tunnel that was absolutely dry previously. By analysing the chronological order, it became obvious that the seepage was generated by drilling of Delta-7 borehole (using water flush), and later the pressurisation (maximum: 6,3 MPa) of multipacker-zones installed into the borehole. The closest zone is located at 17 meters distance from the location of seepage altogether. The water conducting fracture had sharp and solid surface in the beginning. During the less than three years between the appearance of seepage and the closure of URL, the surface of fracture became soft and plastic with clayey features**.** As this process progressed, the flow rate of seepage was reduced to zero. (In the meantime, environmental conditions did not change; the affected zones of Delta-7 remained nearly under constant pressure in the period of observation). According to the tests, the mineralogical composition of the investigated fracture did not changed during this time. The proportion of swelling clay minerals was 2% in the samples collected from there. Thus the only one possible explanation is the rehydration of the almost completely dehydrated clay minerals.

The second group of observations connected to an unexpected technical problem. Some of the installed packers could not be inflated satisfactorily at the settling depth, despite the accurate preparation work including geophysical logging and core examinations. The chosen parts of the boreholes seemed to be appropriate even with the application of down-hole camera. Mechanical parameters (including deformability) of BCF had been previously examined both by in situ and laboratory methods. The experiences excluded that extensive rock deformation would cause the observed phenomena. The control sleeve fracturing tests, however, indicated extreme softening at some point of boreholes that have been closed under water pressure (p>2 MPa) for a longer period (during moths or years) before the described event occurred.

There is another good example for the effects of rehydration process. Preparing micro-sections for the microscopic tests BCF plates were glued on glass slides by two-component plastic resin. When the thickness of plates decreased to 50-100 micrometers, they often broke the glass slide during the wet polishing. Frequency of the glass breaking is directly proportional with the swelling clay mineral content. It occurred most frequently in the case of samples gained from the weathered outcrops and tectonic zones.

The above-mentioned experiences indicate that only a minimal proportion of swelling clay minerals is enough to generate a significant modification in the hydrodynamical and mechanical properties of rock surface, touching with free water. (Nevertheless the Chlorite and Illite have also some capacity to hydrate [4].) This information may also be important for the evaluation of long-term effects of EDZ.

4.3. Precipitation of non-argillaceous infilling materials

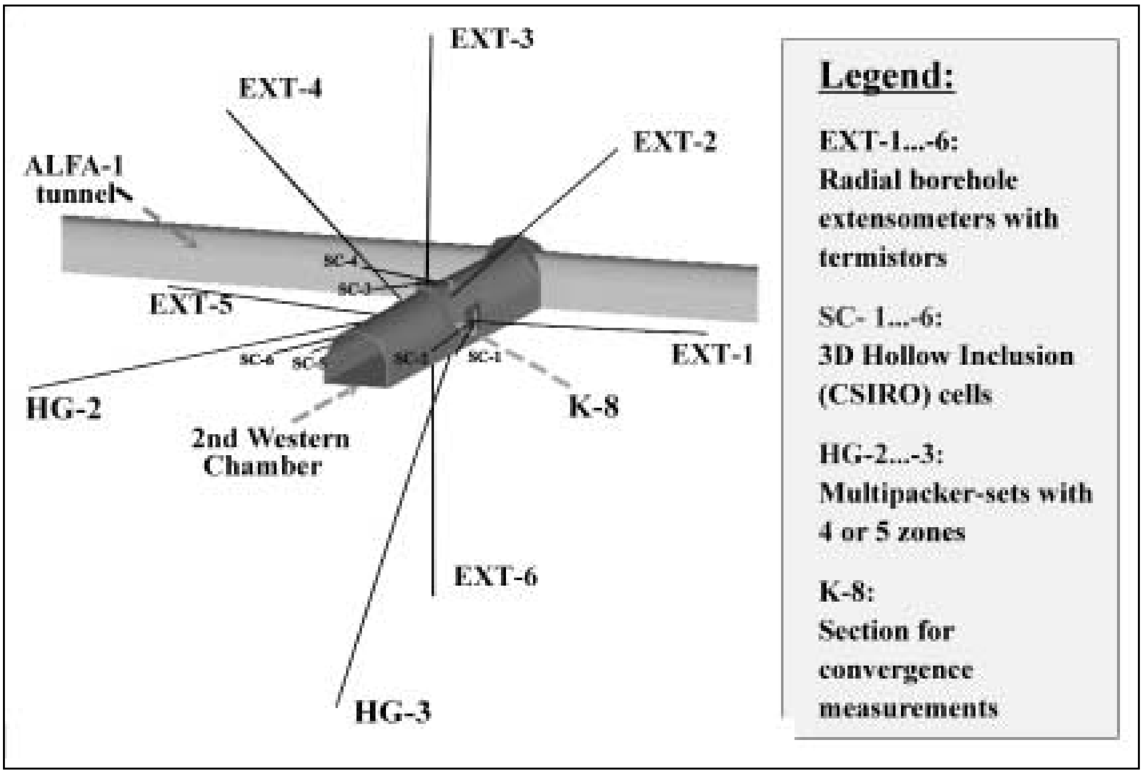
A complex system of lithoclases has been documented in the tunnels and boreholes of URL. Obviously these are originally the shearing or tension accompanying phenomena of large fault systems. At present, primary state the lithoclases filled by non-argillaceous infilling materials (mostly calcite) show favourable confinement properties. However, the presence of infilling materials proves that there was fluid flow along the lithoclases, when the studied blocks of BCF didn’t show perfect, stress-controlled self-healing anymore, because the slow uplift. Several generations can be distinguished even visually on a part of the calcite veins, because they generally consist of layers and lamellas of different colours. Thus it is sure that the rupture and the re-filling of fissures repeated cyclically.

^{14}C dating has been performed on the closed carbonate infillings gained from the zone of URL. 4 samples collected near from the overlying sandstone–BCF tectonic boundary contained measurable amount of ^{14}C. This data unambiguously verifies that young (<40 000 years) fluids were also present at the forming of veins. Moreover the ^{14}C age hardly exceeded the 20 000 years in one case. It calls the attention to the fact that inside the strongly tectonised Cretaceous tectonic zone, in certain directions having in less advantageous stress state cyclically repeated, but not too intensive fluid flows occurred scarcely several 10 000 years before. Nevertheless, the measurements also mean that these fluid flows just continued until the precipitation of carbonate veins have closed the pathway. Thus it can be considered as a self-healing phenomenon working under the present conditions, too. However, the knowledge is very incomplete concerning the velocity of occurring processes and the environmental conditions. It would be also very important to separate the layers and to determine the age of different generations by U/Pb dating. Accordingly, the spatial and temporal extrapolation of processes is not possible yet.

4.4. "Technical self-healing" caused by the rearrangement of stress field due to the tunnelling

The measurements of Complete Instrumentation Array (CIA) suggested and partly installed by the Canadian AECL proved to be one of most important parts of the characterisation programme of BCF. CIA was a classical mine-by experiment that allows the simultaneous measurement and evaluation of mechanical, hydraulical and thermal changes of the EDZ caused by tunnelling. CIA was established at a tunnel face of 15m in 2nd Western Chamber that was driven nearly perpendicular to the Alfa-1 tunnel. The main elements of instrumentation can be seen in Figure 6.

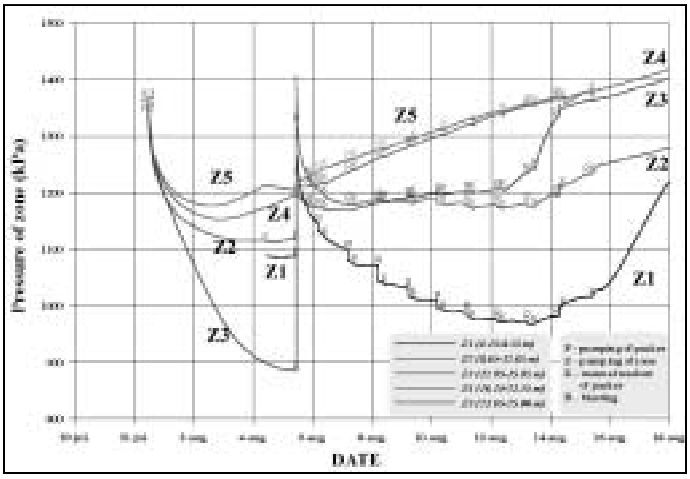
Figure 6. **Geometry and instrumentation of the CIA**



In the framework of project ten controlled blastings were performed to extend the chamber after the installation and stabilisation period of monitoring devices.

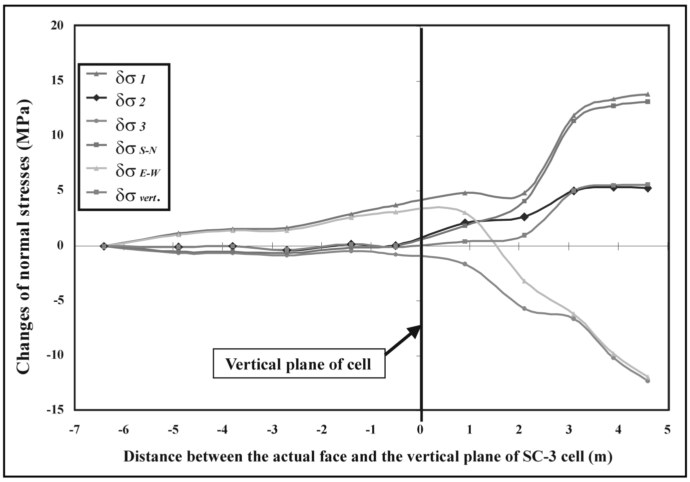
Hydraulic changes in EDZ were checked by a multipacker-set installed into the HG-3 borehole. HG-3 was drilled at the initial face, in the footwall at an angle of -45°, towards the new section of chamber to be driven. The upper zone (No. 1) of the multipacker set began at a depth of 3,4 m below the footwall. In the first phase of a test series a significant drop of starting pressure could be observed. After the 8th blasting, however, the tendency reversed, and a relatively intensive rise of the pressure took place (Figure 7.). After a few months the pressure reached a much higher level than in the initial stabilisation period preceding the tests.

Figure 7. **Pressure changes inside the zones of multipacker-set installed into the borehole HG-3**



To interpret the phenomenon, we needed a comprehensive understanding of stress conditions and geological environment of CIA. The rearrangement of stress field due to tunnelling were measured by six 3D Hollow Inclusion cells (SC-1…-6), settled around the tunnel. According to the measurements performed in the roof, in the first phase of the test series the rise of the normal stress component of E-W direction was the determining event (see in Figure 8.). Later, however, a significant reduction of E-W normal stress was observed, while a drastic increase had been measured for the normal stresses in the two other directions. The detailed geological section of 2nd Western Chamber and its vicinity indicated a significant vertical, very dense joint system of nearly E-W strike. According to the interpretation this system played an eminent role in developing the hydraulic connection in the initial phase. Later the stress component working at right angles to the critical plane excluded any further communication. This phenomenon can be interpreted as a self-healing of technical origin.

Figure 8. **Development of secondary stress field in the roof during the tunnelling recorded by SC-3 cell**



5. CONCLUSIONS

The highly indurated, overconsolidated character of BCF is not favourable for the occurrence of “classical”, quasi-instantaneous self-healing mechanisms that generate the perfect elimination of newly formed pathways in the case of younger, soft argillaceous formation. Thus in the real depth interval of final disposal there is no entire and general self-healing in BCF. Therefore the establishment of a transitional safety concept for BCF (and for all the other overconsolidated and highly indurated argillaceous host formations) seems to be reasonable.

Besides the obvious relicts of paleo-self-healing caused by the large maximal burial depth, currently working physical and chemical mechanisms have been also recognised in the framework of characterisation program of BCF that can positively influence the overall confinement performance of the site. These natural processes taking place on different time-scales and with different intensity are:

- the degradation (weathering) of non-swelling clay minerals,
- re-hydration processes of clay minerals and
- the precipitation of non-argillaceous infilling materials.

They can be interpreted as *partial self-healing* phenomena that certainly have to be taken into account in the more developed and more detailed phases of performance assessment. Consequently the classical definition of self-healing is needed to be extended in the case of the overconsolidated argillaceous host rocks.

It is also imaginable that a self-healing of “technical origin” caused by the stress changes around the openings can also be occurred. Perhaps this information can help for the design of geometry and technologies of the repository.

Currently only the revealing of basic mechanisms of the above-mentioned processes is done, but they are not known appropriately neither qualitative, nor quantitative sense.

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