2 Swiss Geological Survey

Berichte der Landesgeologie
Rapports du Service géologique national
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Reports of the Swiss Geological Survey

Mont Terri Project – Proceedings of the 10 Year Anniversary Workshop

16th / 17th May 2006, St-Ursanne (Switzerland)

M. Hugi, P. Bossart and P. Hayoz (editors)

2007

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Acknowledgement

The valuable contribution of Linda McKinley (Nagra) and Bruno Kunz (Nagra) to the final editing of the report is gratefully acknowledged.

Preface of the Editors

As part of the international Mont Terri research project (St-Ursanne, Canton Jura), geoscientific investigations have been ongoing since 1996 in an underground facility adjacent to the security gallery of the Mont Terri motorway tunnel. The aim of the project is the geological, hydrogeological, geochemical and geotechnical characterisation of clay formations, in particular the Opalinus Clay. Today, twelve partner organisations from six countries are involved in the project. The Swiss National Geological Survey, a division of the Federal Office of Topography swisstopo, supports hydrogeological investigations of low conductivity geological formations and, for this reason, has been involved as a partner since the start of the Mont Terri project. Swisstopo has acted as the operator of the rock laboratory since the beginning of 2006 and is responsible for the implementation of the research programme defined by the partners.

On the occasion of the 10-year anniversary of the Mont Terri project and its underground rock laboratory, the Swiss project partners (the Federal Office of Topography swisstopo, the Swiss Federal Nuclear Safety Inspectorate/HSK and the National Cooperative for the Disposal of Radioactive Waste/Nagra), together with Canton Jura, organised a series of events in St-Ursanne in spring 2006:

16th/17th May	Technical-scientific anniversary workshop
18th May	Official anniversary celebration of the partner organisations, with representatives from the Swiss political and economic sectors and guests from neighbouring countries
19th May	Open day for authorities and politicians from Opalinus Clay investigation regions
20th May	Open day for the people of the Clos du Doubs region (Canton Jura)

The anniversary workshop was dedicated to the scientific community of the Mont Terri partner organisations, their management and scientific/technical staff, involved research organisations and key contractors. The main objectives of the event were (i) to acknowledge the valuable research work that has been carried out in the rock laboratory over the last 10 years on issues related to disposal of radioactive waste in clay formations, (ii) to evaluate the current state of knowledge in selected research areas (coupling of thermo-hydro-mechanical phenomena, transport processes, demonstration experiments) and (iii) to investigate the possibilities for future joint research projects.

This report documents the contributions made by the invited speakers during the workshop in the form of extended abstracts. As editor of the report, the Federal Office of Topography swisstopo would like to sincerely thank the authors and all those who cooperated in the production for their great effort. We would also like to express our gratitude to the Mont Terri partner organisations for their valuable collaboration and loyalty, and to the federal and cantonal authorities for supporting the project.

The authors accept sole responsibility for the content of the report. Further information on the Mont Terri project can be found on the website www.mont-terri.ch.

Préface des éditeurs

Dans le cadre du projet international de recherche du Mont Terri (St-Ursanne, canton du Jura), des études géologiques sont menées depuis 1996 dans une extension de la galerie de sécurité du tunnel autoroutier du Mont Terri. L'objectif principal du projet est la caractérisation géologique, hydrogéologique, géochimique et géotechnique d'une formation argileuse et en particulier les Argiles à Opalinus. Douze partenaires de six pays différents collaborent au projet. Rattaché à l'Office fédéral de la topographie swisstopo, le Service géologique national soutient les études hydrogéologiques des formations géologiques à faible perméabilité et collabore dès le début comme partenaire au Projet Mont Terri. Depuis début 2006, swisstopo s'occupe de l'exploitation du laboratoire souterrain et est responsable de la mise en œuvre des programmes de recherche développés par les partenaires.

A l'occasion du 10ème anniversaire du projet Mont Terri et du laboratoire souterrain, les partenaires suisses du projet (l'Office fédéral de la topographie swisstopo, la Division principale de la sécurité des installations nucléaires/HSK et la Société nationale coopérative pour la gestion des déchets radioactifs/Nagra) ont organisé en collaboration avec le canton du Jura différentes manifestations au printemps 2006 :

16/17 mai	Workshop scientifique et technique
18 mai	Festivités officielles avec les partenaires du projet, les représentants de la politique et de l'économie suisse ainsi que des invités des zones frontalières
19 mai	Journée de visite pour les autorités et les représentants politiques des régions concernées par les études sur les Argiles à Opalinus
20 mai	Jour de visite pour la population du Clos du Doubs (canton du Jura)

Le workshop cité ci-dessus s'adressait à la communauté scientifique des partenaires du Projet Mont Terri, à leurs managers, au personnel scientifique et technique, aux organismes de recherche impliqués dans le projet et aux prestataires principaux. Les objectifs de cette manifestation cherchaient (i) à mettre en évidence les précieux travaux de recherche menés sur le site pendant ces 10 dernières années en relation avec l'entreposage des déchets radioactifs dans des formations argileuses (ii) à évaluer l'état des connaissances dans des domaines choisis (couplage des phénomènes hydromécaniques, processus de transport, expériences de démonstration, et (iii) à examiner les différentes possibilités de futurs projets de recherche en commun.

La présente publication regroupe les contributions, sous la forme de résumés étendus, des différents orateurs invités pour le workshop. En tant qu'éditeur, l'Office fédéral de la topographie swisstopo tient à remercier les auteurs ainsi que les personnes qui, par leur engagement, ont permis la réalisation de cette publication. Nous remercions aussi les partenaires du projet Mont Terri pour leur précieuse collaboration et leur fidélité ainsi que les autorités fédérales et cantonales pour leur soutient au projet.

Les auteurs sont seuls responsables du contenu du texte et des illustrations. Pour toute information supplémentaire, veuillez consulter le site internet www.mont-terri.ch.

Vorwort der Herausgeber

Seit 1996 werden im Rahmen des internationalen Forschungsprojekts Mont Terri (St-Ursanne, Kanton Jura) in einem erweiterten Teil des Sicherheitsstollens des Mont-Terri-Autobahntunnels geowissenschaftliche Untersuchungen durchgeführt. Das Hauptziel dieses Projekts ist die geologische, hydrogeologische, geochemische und geotechnische Charakterisierung von Tongesteinen, im Speziellen des Opalinus-Tons. Heute sind zwölf Partner aus sechs Ländern am Forschungsprojekt beteiligt. Die schweizerische Landesgeologie innerhalb des Bundesamts für Landestopografie swisstopo unterstützt allgemein hydrogeologische Untersuchungen von gering durchlässigen geologischen Formationen und arbeitet aus diesem Grund von Anbeginn als Partnerin im Mont Terri Projekt mit. Seit Anfang 2006 wirkt swisstopo als Betreiberin des Felslabors und ist verantwortlich für die praktische Umsetzung des von den Projektpartnern entwickelten Forschungsprogramms.

Aus Anlass des 10-jährigen Bestehens des Mont Terri Projekts und des dazugehörigen untertägigen Felslabors haben die Schweizer Projektpartner (Bundesamt für Landestopografie/swisstopo, Hauptabteilung für die Sicherheit der Kernanlagen/HSK und die Nationale Genossenschaft für die Lagerung radioaktiver Abfälle/Nagra) zusammen mit dem Kanton Jura im Frühling 2006 in St-Ursanne verschiedene Veranstaltungen organisiert:

16./17. Mai	Technisch-wissenschaftlicher Jubiläumsworkshop
18. Mai	Offizieller Jubiläumsanlass der Partnerorganisationen mit Vertretern aus der Schweizer Politik und Wirtschaft sowie Gästen aus dem grenznahen Ausland
19. Mai	Besuchstag für Behörden und Politiker aus den Untersuchungsregionen des Opalinus-Tons
20. Mai	Besuchstag für die Bevölkerung des Clos du Doubs (Kanton Jura)

Der erwähnte Workshop war der wissenschaftlichen Gemeinschaft der Mont Terri Partnerorganisationen, deren Management und wissenschaftlich-technischen Personal, den beteiligten Forschungsorganisationen sowie den massgebenden Auftragnehmern gewidmet. Die Ziele der Veranstaltung bestanden somit (i) in der Anerkennung der wertvollen Forschungsarbeiten, welche vor Ort in den vergangenen 10 Jahren im Hinblick auf die Lagerung radioaktiver Abfälle in Tongesteinen abgewickelt wurden, (ii) in der Bewertung des aktuellen Kenntnisstandes in ausgewählten Forschungsgebieten (Kopplung von thermo-hydro-mechanischen Phänomenen, Transportprozesse, Demonstrationsexperimente) und (iii) in der Erkundung von Möglichkeiten für zukünftige gemeinsame Forschungsvorhaben.

Der vorliegende Bericht dokumentiert die Beiträge der für den Workshop eingeladenen Referenten in der Form von erweiterten Kurzfassungen. Das Bundesamt für Landestopografie (swisstopo) als Herausgeber möchte den Autoren sowie allen Beteiligten, die an der Ausarbeitung des Berichts mitgewirkt haben, für den grossen Einsatz bestens danken. Ebenfalls danken möchten wir den Mont Terri Partnerorganisationen für ihre wertvolle Zusammenarbeit und Treue sowie den eidgenössischen und kantonalen Behörden für die Unterstützung des Projekts.

Für den Inhalt des Berichts sind die Autoren allein verantwortlich. Weitere Informationen zum Mont Terri Projekt sind unter www.mont-terri.ch abrufbar.

Prefazione dell'editore

Dal 1996, nell'ambito del progetto internazionale Mont Terri, vengono effettuate delle ricerche in un prolungamento della galleria di sicurezza del traforo autostradale del Mont Terri. Il laboratorio sotterraneo si trova vicino a St-Ursanne (Canton Giura, Svizzera). Lo scopo principale del progetto è di determinare le caratteristiche geologiche, idrologiche, geochimiche e geotecniche dell'argilla, in particolare dell'argilla opalina. Attualmente dodici partner provenienti da sei nazioni partecipano al progetto. Il Servizio geologico nazionale dell'Ufficio federale di topografia swisstopo supporta in generale le ricerche nelle formazioni geologiche poco permeabili ed è presente dall'inzio in qualità di partner nel progetto Mont Terri. Swisstopo gestisce dal 2006 il laboratorio ed è responsabile della realizzazione dei programmi di ricerca definiti dai partners.

In occasione del decimo anno di attività del progetto Mont Terri e del laboratorio sotterraneo, i partner svizzeri del progetto (Ufficio federale di topografia swisstopo, Divisione principale della Sicurezza degli Impianti Nucleari/HSK e la Società cooperativa nazionale per lo stoccaggio dei rifiuti radioattivi Nagra) assieme al Canton Giura hanno organizzato nella primavera 2006 a St-Ursanne diverse manifestazioni:

16/17 maggio	seminario tecnico-scientifico del giubileo
18 maggio	cerimonia ufficiale delle organizzazioni partner con i rappresentanti della politica e dell'economia svizzera come anche di ospiti dai paesi stranieri limitrofi
19 maggio	giornata di visita per le autorità ed i politici delle regioni di ricerca sull'argilla opalina
20 maggio	giornata di visita per la popolazione del Clos du Doubs (Canton Giura)

Il seminario citato era rivolto alla comunità scientifica del Mont Terri, alle organizzazioni partner, ai loro quadri dirigenti e personale tecnico-scientifico, alle organizzazioni di ricerca coinvolte così come agli esecutori delegati dei mandati.

Gli obiettivi della manifestazione erano (i) il riconoscimento del prezioso lavoro di ricerca svolto in sito nel corso degli ultimi dieci anni nella prospettiva dello stoccaggio dei rifiuti radioattivi nell'argilla opalina, (ii) la valutazione delle attuali conoscenze in domini di ricerca definiti (accoppiamento dei fenomeni termo-idro-meccanici, processi di trasporto, esperimenti), (iii) l'identificazione di possibili futuri progetti di ricerca comune.

Il rapporto presenta i contributi, sottoforma di ampi riassunti, dei relatori invitati al seminario. L'Ufficio federale di topografia swisstopo quale editore desidera ringraziare gli autori e tutti i partecipanti, che hanno contribuito alla stesura del rapporto, per il loro profuso impegno. Inoltre vogliamo ringraziare le organizzazioni partner del progetto Mont Terri per la preziosa collaborazione e fedeltà così come le autorità cantonali e federali per aver sostenuto il progetto.

Gli autori sono gli unici responsabili del contenuto dei testi e delle illustrazioni. Ulteriori informazioni sono pubblicate all'indrizzo www.mont-terri.ch.

Federal Office of Topography swisstopo
Head of the National Geological Survey
Dr. Christoph Beer

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Foreword of the Workshop Coordinator

Markus Hugi

Nagra, Hardstrasse 73, 5430 Wettingen, Switzerland

During the third week of May 2006, the Mont Terri Rock Laboratory celebrated its 10th anniversary. Several events were held to commemorate these ten years of outstanding geoscientific research in the argillaceous rock formation *Opalinus Clay*. Among these events was a two-day scientific/technical workshop organised on the 16th and 17th of May in St-Ursanne (Switzerland).

Objectives

The workshop was dedicated to the scientific community of the Mont Terri partner organisations, their management and scientific/technical staff, involved research organisations and key contractors. The purpose of the event was to acknowledge the excellent research work that has been performed over the last decade, to evaluate and discuss the present state of knowledge in selected research areas and to explore the potential for future research activities.

The topical areas addressed in the workshop are of particular importance with regard to deep geological disposal of radioactive waste and focused on the issues of coupled phenomena and transport processes in argillaceous rock and the demonstration (in underground rock laboratories) of disposal feasibility.

Programme

In the context set by the special (i.e. scientific/technical but also festive) character of the anniversary workshop, discussions started from a fairly distant point in the geological time frame as the participants were introduced to the early history of the development of the *Clos du Doubs* region. The mechanisms that were, and still are, responsible for the present features of the particular geological setting of scientific interest, namely the *Opalinus Clay* at Mont Terri, were explained.

The two-day workshop did not aim to address all the scientific issues that are currently under investigation within the Mont Terri Project. However, with the focus on thermo-hydro-mechanical coupled phenomena and transport processes of dissolved constituents, in particular gases, two topical areas were covered that are of particular interest to a large research community and are of fundamental importance with regard to the long-term safety of deep geological repositories for radioactive waste in argillaceous rocks.

A panel session with invited experts stimulated discussion among the workshop participants on strategic and scientific issues relating to future research activities in underground facilities.

Conclusions

At the end of the two days, it was possible to look back on an event that had been a resounding success and had achieved most of its original objectives. Regarding the number of participants, the workshop surpassed all expectations – confirmation of the scientific relevance and strong international position of the Mont Terri Project.

The presentations confirmed that substantial progress has already been made in understanding many important scientific/technical issues and that the current state of knowledge is already high. Waste management organisations should continue to move forward in a timely manner to the next steps in repository implementation and ultimately to construction and operation of disposal facilities. However, remaining uncertainties must be further investigated over the coming years and, in this respect, future research activities in underground research laboratories such as Mont Terri will play an important role. This was a conclusion, for example, of the panel discussion on future research needs.

Acknowledgments

Mention was made of the large number of people who provided extensive support to the anniversary event, making the workshop possible through their dedication. Sincere thanks and deep gratitude were expressed to the following

- Colleagues on the Swiss organisation committee for their valuable input and for supporting the idea of a scientific/technical workshop within the context of the Mont Terri 10 year anniversary celebration.
- The invited speakers, who were willing to contribute their scientific expertise to the event. They were thanked for excellent presentations and for efforts in documenting the contributions in the form of extended abstracts that are now available to all and will undoubtedly be very helpful for future reference.
- The panellists for their engaged discussions on future research and demonstration needs and for their ability to initiate lively discussion among the scientific audience on topics that will hopefully influence the future direction of the Mont Terri Rock Laboratory.
- The chairpersons for introducing the audience to the sessions, for presenting the speakers and for steering the course of events in such a way that the time schedule was always met.
- All the participants – a critical end engaged scientific audience – for their interest in the anniversary workshop, for their valuable contributions to the scientific debate and for their steady support of the international Mont Terri Project.

Regret was expressed that, for medical reasons, Marc Thury, the initiator of the Mont Terri Project and former Project director, was unable to attend the event.

Finally, mention was made of colleagues who were involved in the organisational and administrative aspects of the workshop, working quietly and unobtrusively in the background and making the smooth running of the event possible. Thanks were extended to the secretaries, technicians and other staff at Nagra, to colleagues from the Geotechnical Institute in St-Ursanne and to the management and staff of the *Hôtel du Boeuf* and *Hôtel de la Couronne* who cared solicitously for the physical well-being of the participants.

The proceedings concluded with the hope that the lessons learned from the two days of intensive scientific debate – combined with a variety of lasting impressions from the charming *Clos du Doubs* region – would make the workshop an unforgettable experience for all participants.

Participants

Last Name	First name	Organisation		Country
Alheid	Hans-Joachim	Bundesanstalt für Geowissenschaften und Rohstoffe	BGR	Germany
Alonso	Eduardo	Universidad Politécnica de Catalunya	UPC	Spain
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Brewitz	Wernt	Gesellschaft für Anlagen- und Reaktorsicherheit mbH	GRS	Germany
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Charlier	Robert	Université de Liège		Belgium
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García-Siñeriz	José Luis	Asociación para la Investigación y el Desarrollo Industrial de los Recursos Naturales	AITEMIN	Spain

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Kiho	Kenzo	Central Research Institute of Electric Power	CRIEPI	Japan
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Meier	Olivier	Geotechnisches Institut AG	GI	Switzerland

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Zuidema	Piet	Nationale Genossenschaft für die Lagerung radioaktiver Abfälle	Nagra	Switzerland

Programme

Opening	Tuesday, 16 May 2006, 12:00 h
Closing	Wednesday, 17 May 2006, 17:00 h
Venue	Hôtel du Boeuf, St-Ursanne/Switzerland

Tuesday, 16 May 2006

Opening	P. Bossart (Mont Terri Director)
Mont Terri project history Milestones and research highlights *(cancelled)*	M. Thury (Nagra, Mont Terri project initiator and former director)
Invited lecture **Geology of Northwestern Switzerland** with special emphasis on Opalinus Clay	M. Burkhard (Univ. of Neuchâtel)
Topical session 1 **Coupled phenomena in argillaceous rock** Introduction and observations	S. Löw (ETH Zürich, Chairman)
Keynote presentation **Modelling the fracture generation in EDZ**	R. Charlier (Univ. de Liège)
Presentation **A THMC stress-strain framework for modelling the performance of argillaceous materials in deep repositories for radioactive waste** Experimental evidence and modelling capabilities	L. Laloui (EPFL, Lausanne)
Presentation **Experiments related to EDZ evolution at Mont Terri** Overview and results	P. Blümling (Nagra)
Discussion	
Laboratory visit	Ch. Nussbaum (Mont Terri Project Manager)

Wednesday, 17 May 2006

Topical session 2 **Transport processes in argillaceous rock** (RN diffusion & retention, gas migration) Introduction	Annette Johnson (EAWAG Dübendorf, Chairperson)
Keynote presentation **Gas migration in argillaceous rocks**	Ed. Alonso (UPC Barcelona)
Presentation **Diffusion experiments at Mont Terri** Overview and results	S. Savoye (IRSN)
Presentation **Transport of solutes and gas in soft clay** Experience from HADES URL	P. de Cannière (SCK·CEN)
Discussion	
Topical session 3 **Demonstration of disposal feasibility in underground rock laboratories** (geological data source and process understanding, demonstration of waste emplacement, … remote handling, monitoring, public acceptance and confidence building) Introduction	W. Brewitz (GRS & TU Braunschweig, Chairman)
Keynote presentation **Advancements in deep geological disposal of radioactive waste through international co-operation** The role of underground rock laboratories	P. Zuidema (Nagra)
Presentation **Large-scale demonstration experiments at Mont Terri rock laboratory** Achievement and future perspectives	J. C. Mayor (Enresa)
Presentation **Research programme carried out at Bure by Andra** Comparison of the Bure and Mont Terri rock laboratories	J. Delay (Andra)
Discussion	
Panel session **Research Needs and the Mont Terri Rock Laboratory**	J. Hadermann (PSI Villigen, Chairman)
Wrap-up and farewell	M. Hugi (Nagra, Workshop Coordinator)

Milestones and research highlights

Mont Terri project history

Mont Terri project history – Milestones and research highlights

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In the rock laboratory of the international Mont Terri research project, twelve organisations from six countries (ANDRA, BGR, CRIEPI, ENRESA, GRS, HSK, IRSN, JAEA, NAGRA, OBAYASHI, SCK·CEN and SWISSTOPO) are jointly investigating a Mesozoic shale formation, the Opalinus Clay. The project started in 1995 and the present contribution provides an overview of the evolution of the project during the last ten years, with some research highlights and lessons learned.

Initiation and organisation of the project

In 1989, the reconnaissance gallery of the Mont Terri motorway tunnel was constructed and, during its excavation, detailed geological and hydrogeological mapping of the Opalinus Clay section was carried out jointly by the SNHGS (Swiss National Hydrological and Geological Survey) and NAGRA. The entire Opalinus Clay section revealed itself to be practically impermeable, with no groundwater inflows or damp spots on the tunnel wall. Furthermore, it proved unnecessary to apply a strong concrete liner, as was originally planned by the engineers; a shotcrete layer was sufficient to stabilise the tunnel wall. It was concluded that the Opalinus Clay would potentially be a very suitable host rock for a geological repository, due to its reasonable mechanical stability and more favourable hydrogeology than previously expected.

Also at this time, evaluation of argillaceous formations as potential host rocks for radioactive waste repositories was being initiated in several other countries and, in 1991, the NEA (Nuclear Energy Agency) of the OECD created a working group on the Measurement and Physical Understanding of Groundwater Flow through Argillaceous Media – the "Clay Club". The possibility of a joint research programme at Mont Terri was discussed within this working group and several "Clay Club" member organisations announced their interest.

In the autumn of 1994, the SNHGS submitted a project proposal to the *République et Canton du Jura*, the owner of the motorway tunnel, to excavate niches in the Mont Terri reconnaissance gallery and to start an international research programme. Authorisation was granted a few months later. In spring 1995, an initial research programme was proposed to the *Clay Club* and five organisations (SNHGS, ANDRA, NAGRA, PNC (now JAEA) and SCK·CEN) agreed to initiate a joint project. An international cooperation agreement was drawn up and approved and excavation work and the first experiments began in January 1996.

The five initial partner organisations agreed that the project would have a democratic set-up. Unlike other similar projects, where one organisation is the operator of the rock laboratory and other organisations may join the project to carry out experiments, at Mont Terri all partners had the same rights and duties. The project was under the patronage of the *Swiss National Hydrological and Geological Survey* (SNHGS, integrated in 2000 into FOWG, Federal Office for Water and Geology), which was responsible for contact with the cantonal authorities and the applications for the annual authorisations. In spring 2001, an agreement was signed between the Swiss Confederation, represented by FOWG, and the *République et Canton du Jura*, whereby it was agreed that FOWG would take over the direction of the project and the responsibility for the rock laboratory. At the end of 2005, FOWG was closed down and the Federal Office of Topography, SWISSTOPO, took over the management of the research programme and became the new operator of the rock laboratory.

The rock laboratory and the research programme

The geographic location of the Mont Terri rock laboratory is shown in Figure 1. The Mont Terri motorway tunnel is one of several tunnels of the A16 "Transjurane" motorway, which links the Swiss plateau (Bern, Biel) with the Ajoie (Porrentruy) and France (Belfort).

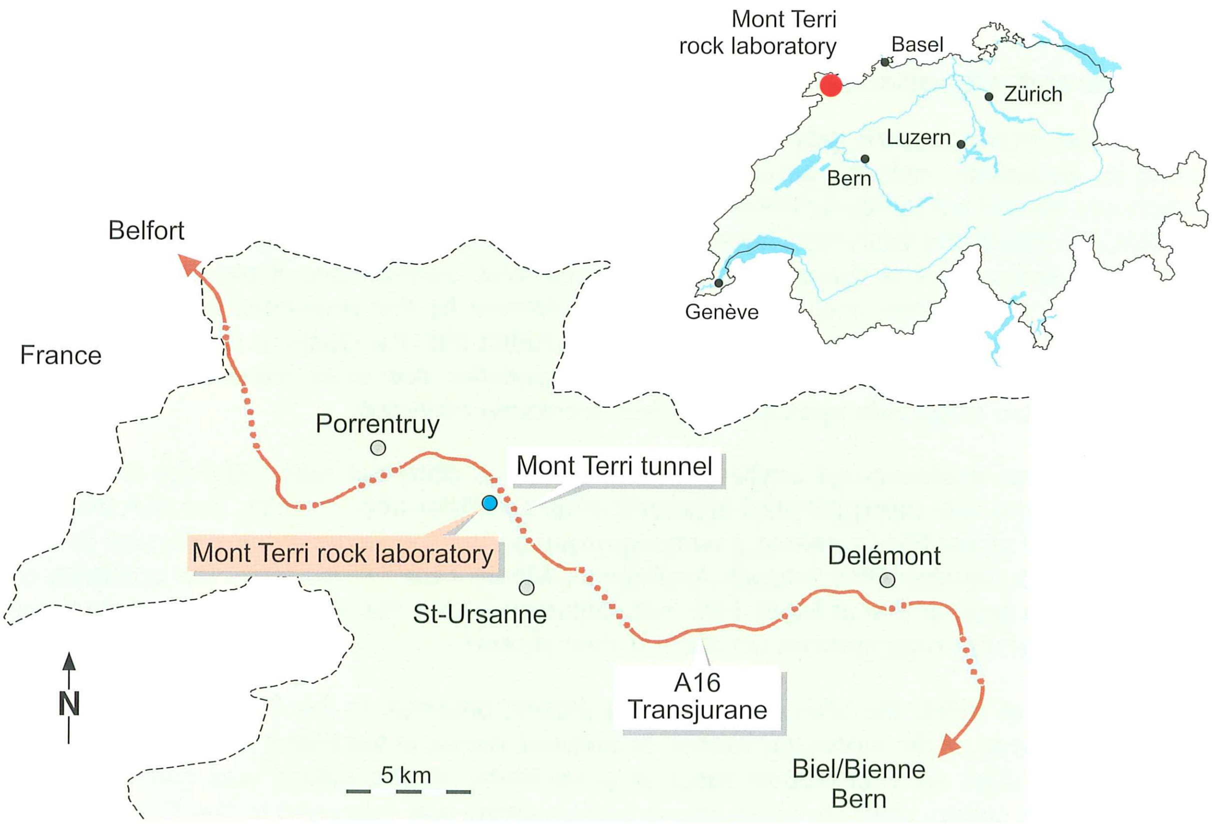

Fig.1: Geographic location of the Mont Terri rock laboratory

A geological profile along the Mont Terri tunnel is shown in Figure 2. The Mont Terri anticline formed during the folding of the Jura Mountains, between 10 and 5 million years ago. This anticline was sheared off and thrust over the Tabular Jura. In the area where the laboratory is located, the bedding of the Opalinus Clay dips with an angle of 45 degrees to the south-east. A larger fault zone, called the "main fault", was observed in the centre of the Opalinus Clay, indicated by the red line in the profile.

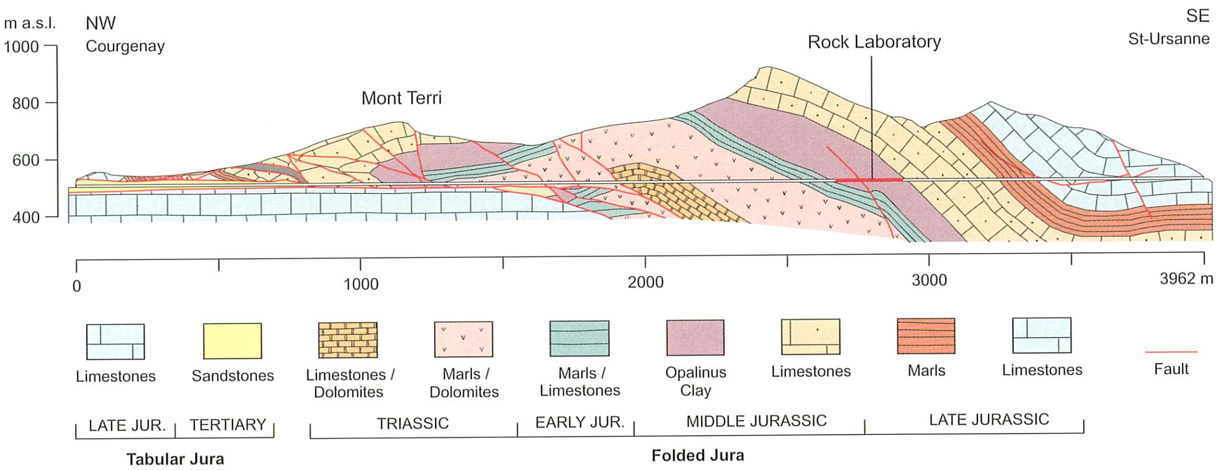

Fig. 2: Geological profile along the Mont Terri Motorway tunnel, with the location of the rock laboratory (after Freivogel et al. 2003).

The rock laboratory is located in, and adjacent to, the security gallery (initially the reconnaissance gallery) of the Mont Terri motorway tunnel (Figure 3), which was opened to traffic at the end of 1998. The laboratory was constructed in four major steps. The total length of the galleries and niches is about 350 m, consisting mainly of:

- eight small niches along the security gallery, excavated in 1996
- the Gallery 98 and 5 lateral niches, excavated in 1997/98
- a gallery for the EZ-A experiment, excavated in 2003
- the Gallery 04 and 4 lateral niches, excavated in 2004

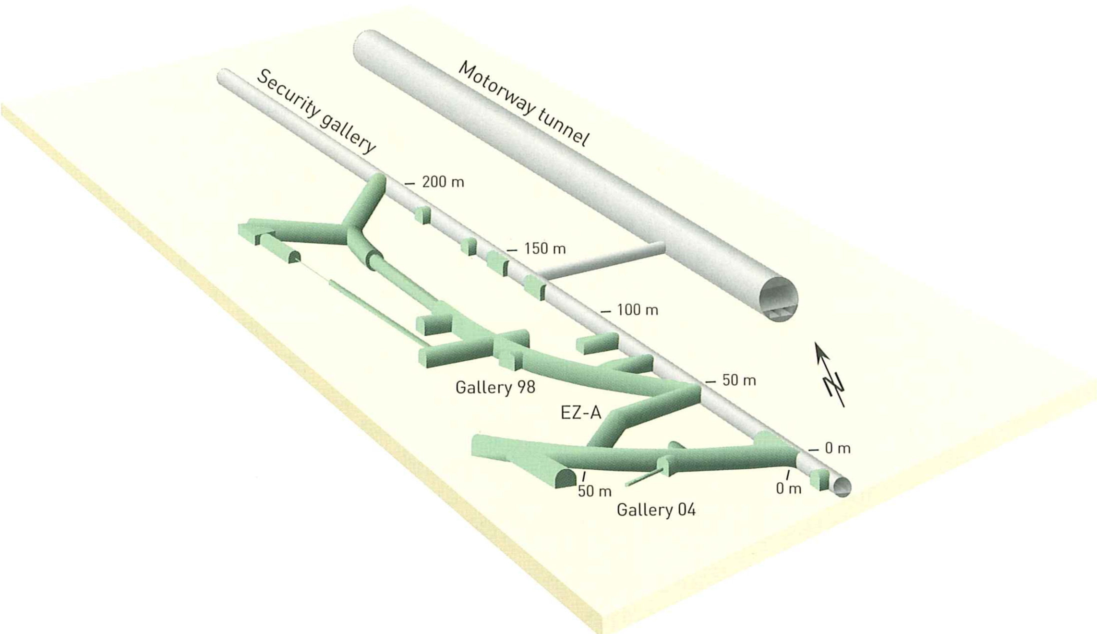

Fig. 3: Layout of the Mont Terri rock laboratory

The aims of the research programme are to analyse the hydrogeological, geochemical and rock mechanical properties of the Opalinus Clay and the changes induced by the excavation of galleries and by heating of the formation, to test sealing and canister emplacement techniques and to evaluate and improve appropriate investigation techniques and methodologies. The programme consists of a series of individual experiments. To date, 47 experiments have been successfully completed and 31 are currently underway. The total investment of the partners in work mandates to more than a hundred universities, national research institutes and companies amounts to around 25 million Euros.

In spring 2003, a new long-term research programme was elaborated and approved. The programme started in autumn 2003 and some experiments will continue for at least ten years. It is also planned to carry out long-term experiments to confirm and improve current process understanding and conceptual models, for example radionuclide retention and diffusion experiments, gas transport experiments and large-scale sealing experiments of emplacement and access tunnels.

For major new experiments, particularly demonstration experiments, there is no longer any space available and an extension to the Gallery 04 is therefore planned for the near future.

Research highlights

After ten years of research at Mont Terri, some of the many lessons that have been learned include:

- Excavation of galleries using blasting, pneumatic hammer and road header techniques is feasible. The preferred technique is the road header, which results in the most regular tunnel profiles and minimum breakouts. In tectonically undisturbed zones, the galleries are generally stable if lined with a layer of shotcrete 15 - 20 cm thick, reinforced with steel or plastic fibres.
- Several drilling techniques were tested. Drilling with dry, hydrocarbon-free compressed air resulted in the most stable boreholes, which are suitable for testing purposes. For geochemical experiments, drilling with nitrogen is now a well developed method for avoiding oxidation.
- Key lessons have been learned in the development of novel methodologies, including the manufacturing of new surface and downhole equipment specially designed for installation in boreholes drilled in clays and the application of new material technologies. New methods for hydraulic testing, porewater pressure measurements, geophysical rock characterisation, in-situ water sampling from packed-off boreholes, porewater sampling using high-pressure squeezing and leaching of core samples, gas sampling and direct in-situ analyses, diffusion characterisation and EDZ (excavation damaged zone) characterisation have been developed to meet the particular challenges presented by performing experiments in a clay formation with swelling, chemico-osmotic effects and disaggregation on contact with water. Material science plays an important role in the development and application of surface and downhole equipment (for details see also Bossart & Thury 2006).
- The results have allowed the characterisation of the Opalinus Clay and the development of a conceptual understanding of the various processes occurring in the Opalinus Clay and in similar formations. After around five years of research, synthesis reports on geochemistry,

hydrogeology and rock mechanics were prepared, allowing identification of key open questions to be addressed in future research phases.

- The Opalinus Clay at Mont Terri has a very low hydraulic conductivity in the order of 1E-13 m/s and no discrete water inflows or damp patches have ever been observed in the rock laboratory, not even in a major tectonic fault. From these observations, and from a series of experiments, it can be concluded that no significant advective groundwater flow is to be expected and the porewater in the clay is practically stagnant. Radionuclides potentially released from a repository in Opalinus Clay would be transported through the clay effectively by diffusion only.
- Natural diffusion profiles across the Opalinus Clay formation were measured. Chlorides of extracted porewaters, for example, revealed high concentrations in the Opalinus Clay, with the concentration becoming smaller towards the formation boundaries. This pattern is best interpreted by molecular diffusion. Diffusion started about 3 million years ago (formation and uplift of the Mont Terri anticline), when the bounding karst formations came into contact with fresh water. This natural diffusion analogue corroborates the findings of diffusion experiments carried out with radionuclides such as tritium, strontium and cobalt.
- A partly interconnected open fracture system was observed in the excavation damaged zone (EDZ) behind the tunnel walls, which could allow advective groundwater flow and radionuclide transport. However, on contact with water (e.g. resaturation of a repository after closure), swelling and disaggregation of the clay seem to lead to efficient self-sealing of this fracture system.

In addition to the scientific and technological progress at Mont Terri, it is worth emphasising the very close and intensive collaboration among more than a hundred scientists from partner and contractor organisations in jointly planning, steering, performing and interpreting the experiments: *Mont Terri – Connecting Scientists*.

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Invited lecture

Geology of Northwestern Switzerland

Speaker

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† On 24th August 2006, Prof. Martin Burkard tragically lost his life while rock-collecting in his beloved Tessiner Alps.

Geology of Northwestern Switzerland – with special emphasis on the Opalinus Clay

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Introduction

The geology of Switzerland is dominated by the formation of the Alps (Fig. 1). Mont Terri is currently separated by some 160 km from the more famous Matterhorn but both of these mountains are best explained within the framework of the same tectonic "Wilson cycle": assembly of Pangea in Late Paleozoic times culminating in the Variscan orogeny, collapse and decay of this earlier mountain chain, peneplanation and new rifting leading to the opening of the alpine Tethys Ocean during the Mesozoic, followed by plate convergence, subduction, collision and new mountain-building in the Neogene. Mont Terri was never as deeply involved as the Matterhorn, but all of its geology bears witness to the same suite of events; tectonically speaking, Mont Terri is part of the Alps. The Matterhorn still stands high, Africa continues to push Apulia against the larger European plate and the question arises as to what the geological future has in store for our hills and mountains: is it really just erosion and decay, as recent GPS data lead us to believe?

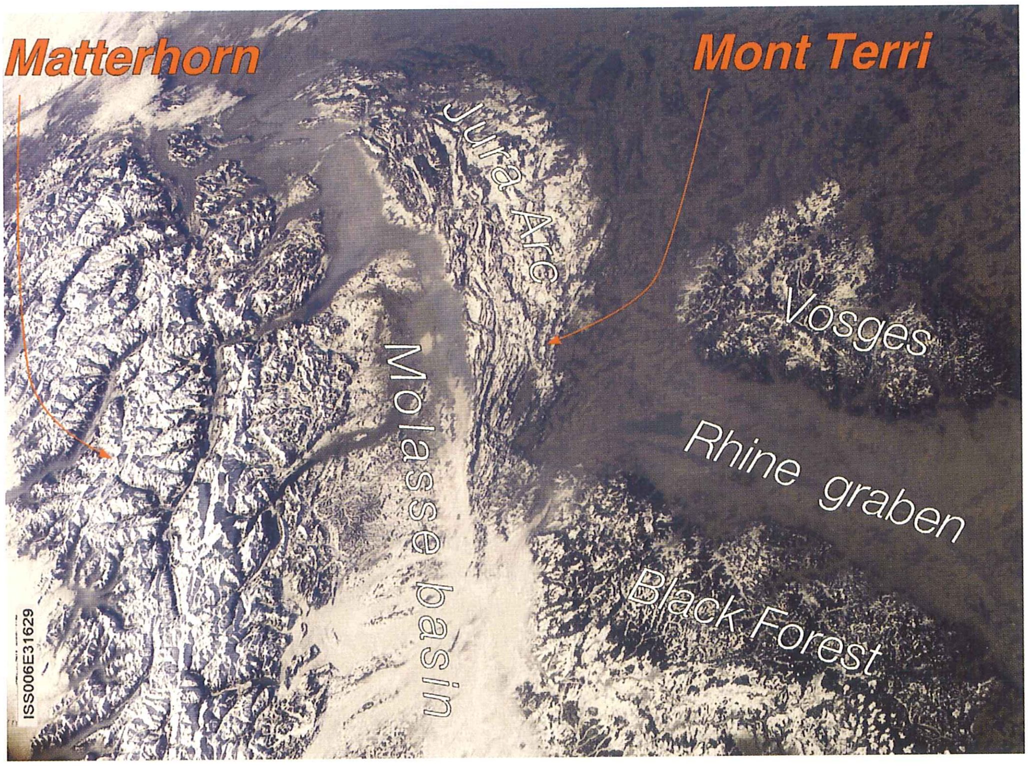

Fig. 1: Northwestern Switzerland as seen from the International Space Station. View to the W; true photo taken on 23rd February 2003. (Source: http://eol.jsc.nasa.gov/sseop/clickmap/)

Basement and cover rocks

Crystalline rocks do not crop out in Northwestern Switzerland, but seismic reflection profiling and drilling have provided an increasingly detailed picture (in the study area of Nagra 2005) of the basement configuration hidden below cover series up to three kilometers thick. Basement, as seen in the nearby Vosges and Black Forest inliers and boreholes, is made up of a complex assembly of metamorphic and igneous rocks, strongly affected by the Variscan orogeny. The collapse of this earlier mountain chain also led to the formation of the so-called Permo-Carboniferous grabens. These form an entire network of narrow, ENE-WSW trending, fault-bounded troughs filled with up to 3 km of continental series including conglomerates, sandstones, shales and coal. Many such grabens and the details of their geometry remain to be mapped below the central Jura and Molasse basin.

The cover rocks of Northwestern Switzerland are mainly carbonates and marls, deposited during Mesozoic times in a shallow marine, epicontinental sea, most of the time punctuated by landmasses and islands of variable size and position. After a major phase of erosion and peneplanation in Late Permian times, removing about 1500 m of overburden from the Permo-Carboniferous grabens and their shoulders, a marine transgression set in from the NE during the Triassic. This lead to a major unconformity of basal sandstones over Paleozoic basement rocks and structures. Northern Switzerland long remained separated from the open sea further to the southeast by the Vindelician and Alemanic lands, possibly a northern rift shoulder of the newly opening alpine Tethys Ocean. Mesozoic subsidence was quite modest and mostly thermal, with minor contributions of tectonic stretching in several pulses. Eustasy and climate change in combination with inherited crustal heterogeneities and subtle reactivation of pre-existing faults led to the complexities in vertical and lateral facies changes seen within the Mesozoic layercake of sediments (Wetzel et al. 2003). Deposition centers shifted in space and time in ways that remain difficult to explain in terms of either remote effects of alpine Tethys rifting and/or thermal subsidence following the Permo-Carboniferous rifting.

In Triassic times, up to 1 km of evaporite series, including two salt horizons, were accumulated in a prominent elliptical basin, a.k.a. the "Burgundy trough", predefining the basal décollement level and the map view shape of the future Jura arc.

Up to 120 m of "Aalenian" black shales were deposited in a shallow, muddy epicontinental sea covering parts of Germany and Switzerland (Fig. 2). The mud was provided by erosion of surrounding landmasses, maybe including contributions from as far away as Fennoscandia. The Aalenian sea was still separated to the south from the alpine Tethys by remains of the Vindelician and Alemanic lands. To the west, it was connected with the Paris basin over the Lotharingian carbonate platform.

Similarly complex paleogeographies prevailed throughout the rest of Jurassic and early Cretaceous times, but never returning back to quite as muddy as the Aalenian style "black shale" conditions. At times, during the Upper Jurassic, dinosaurs left their tracks on the shores of shallow lagoons and seaways with clear blue waters, the factory for some 150 m or so of Malm limestones, the future backbone of the Jura folds.

From the Middle Cretaceous to the Oligocene, northern Switzerland fell dry and marine incursions became restricted to rare and short intervals of maximum sea-level high stands. Erosion was quite moderate, however: the Malm limestones were karstified and covered in a blanket of red lateritic soils – the so-called "Bohnerz" formation.

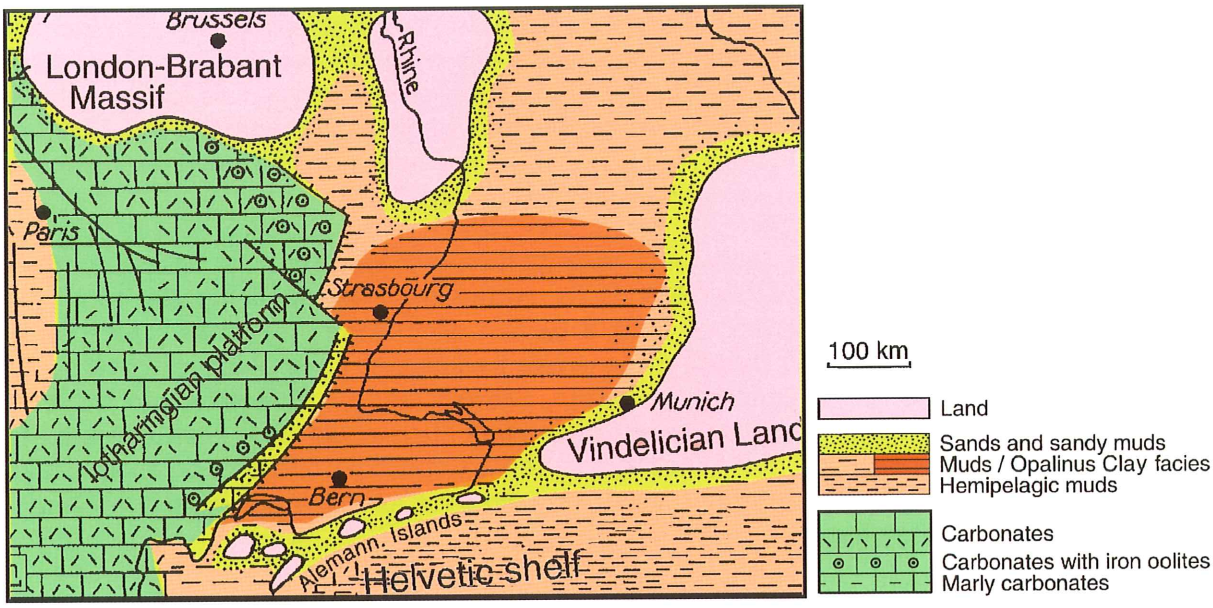

Fig. 2: In Aalenian times, northern Switzerland and adjacent southern Germany were the site of a shallow marine, "muddy" sea, surrounded by landmasses and a carbonate platform to the west (modified from Wetzel et al. 2003).

Subsidence and sedimentation resumed in Neogene times, in a completely different geodynamic context: to the north and west, isolated centers of volcanism, large-scale upwarping and the opening of the Rhine – Bresse grabens are all seen as manifestations of the larger Central European rift system. Still far to the southeast, subduction started within the alpine Tethys Ocean, with the European plate moving southwards beneath the Apulian plate. The Mont Terri region was caught between these two influences, without being too much involved in either the Rhine graben formation and its rift sediment accumulation or the evolution of the alpine Flysch – Molasse foredeep with its clastic wedges. Faults of NNW-SSE orientation seen throughout Northwestern Switzerland are associated with minor "rhenish" stretching, while E-W oriented fractures are interpreted as either left-lateral transform faults connecting the Rhine and Bresse grabens and/or as extensional faults developed on the forebulge of the European lithosphere, bent downwards beneath the Alps. The latter advanced steadily at a pace of some 30 to 10 km/My to the NNW.

The Alps – Jura thrust system

In Middle Miocene times, some 12 Ma ago, the alpine thrust front hit the weak Triassic evaporites and salt layers of the "Burgundy trough", to the northwest of the former Alemanic land. The entire Mesozoic layercake and Molasse basin fill of Northwestern Switzerland were subsequently incorporated into the alpine thrust wedge, pushed northwestwards and uplifted. Due to this thrust system re-organisation, the Swiss Molasse basin was bypassed and erosional products of the rising Alps were exported much further (Berger, J. P., private communication, 2006): to the Mediterranean (Rhone), to the Black Sea (Danube) and eventually to the Atlantic (by way of the Rhine graben). Folding and thrusting was most intense at the toe of this wedge, leading to the formation of the Jura Mountains.

The latest and most external front of thin-skinned alpine deformations mimics the salt pinchout of the Burgundy trough, thereby defining the present-day shape of the Jura arc. Gross horizontal shortening of up to 30 km in the cover series of the western central Jura fold and thrust belt is clearly accommodated in a thin-skinned fashion (Burkhard & Sommaruga 1998). This Jura shortening decreases eastwards to zero, but an equivalent amount of horizontal shortening is taken up by the more internal (subalpine Molasse) thrust system.

The internal structure of the Jura Mountains, with its rhomb-shaped synclinal basins, complex interference patterns of cross folds and tear faults, is best explained as being due to all the inherited heterogeneities and deviations from a perfect sedimentary layercake. Quite interestingly, however, in folding and thrusting the entire package of up to 2 km of cover rocks essentially behaved as a single, concordant "layer", without being split further into duplexes along secondary décollement horizons. The Aalenian black shale could have been expected to act as such a duplex detachment, but it does so only very exceptionally and only on a local scale. *(The Aalenian black shales south of the Alemanic land did serve as THE major basal décollement level of the Helvetic nappe system).*

Thin-skinned vs. thick-skinned tectonics

Given the lack of seismic data for large parts of the central Jura (and Molasse basin), there remains some room for speculation about the details of the basement configuration below the Triassic salt décollement (Fig. 3). Many variants of thick-skinned basement involvement in Jura folding have been proposed over the years.

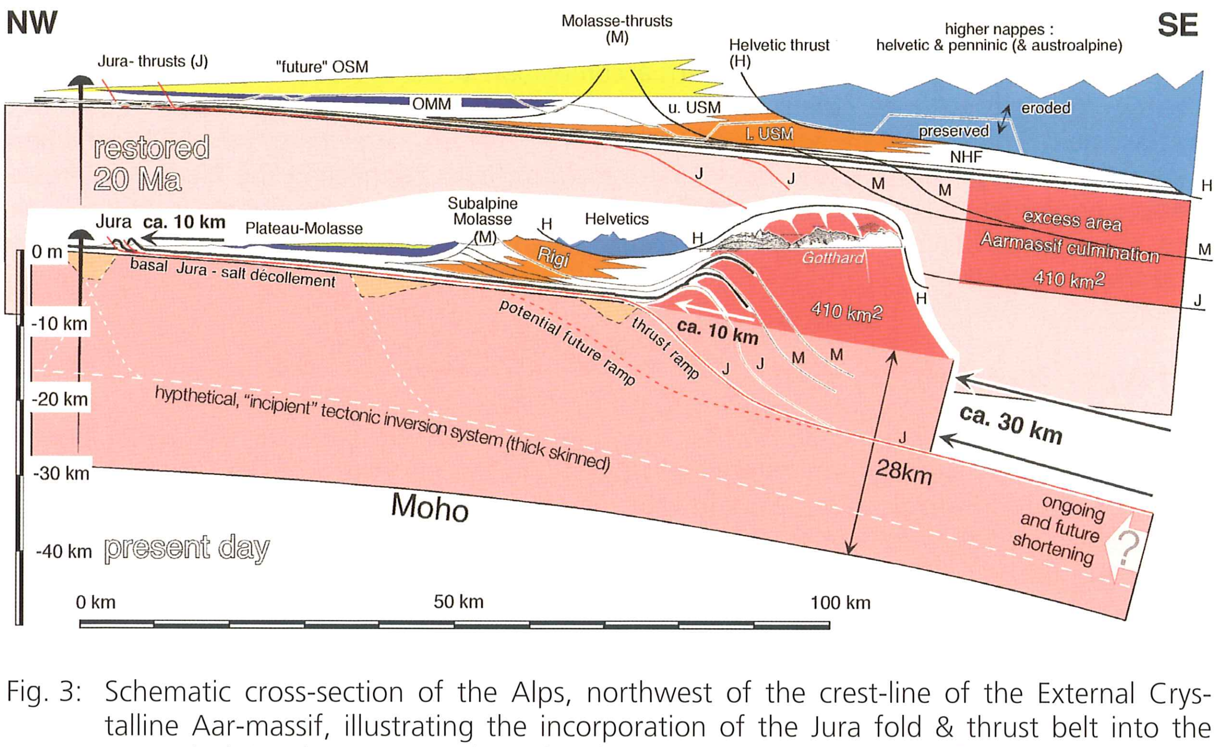

Fig. 3: Schematic cross-section of the Alps, northwest of the crest-line of the External Crystalline Aar-massif, illustrating the incorporation of the Jura fold & thrust belt into the general Alpine thrust system (modified from Löw & Wyss 1999, p. 47).

They range from the extreme *"all thick-skinned wrench folding – no distant push at all"* hypothesis to the most subtle *"incipient stage of transition between a past thin- to a future thick-skinned, inversion tectonic regime"*. There is some evidence for the former Permo-Carboniferous grabens and their boundary faults playing a subtle role in cover tectonics, but no true tectonic graben inversion has been documented so far.

The orientation of many folds or faults in the cover reflects, in some way or other, the long history of events going all the way back to the Variscan orogeny.

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Topical session 1

Coupled phenomena in argillaceous rock

Chairman Simon Löw, ETH Zürich, Switzerland

Speakers

Robert Charlier (Univ. de Liège, Belgium)

Modelling the fracture generation in EDZ

Lyesse Laloui (EPFL Lausanne, Switzerland)

A THM stress-strain framework for modelling the performance of argillaceous materials in deep repositories for radioactive waste

Peter Blümling (Nagra, Switzerland)

Experiments related to EDZ evolution at Mont Terri

Modelling the fracture generation in EDZ

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Introduction

Fractures are observed for a long time around tunnel or well opening in brittle rocks (e.g. Fig. 2). More recently, similar observations have been pointed out in ductile / argillaceous rocks, especially in Mol URL (Fig. 1) (Mertens et al. 2004, Bastiaens et al. 2006). This highlights the question of the excavated damaged zone (EDZ) formation and role in the radionuclide transfer. An aspect of this problem is the necessity to evaluate how gallery excavation damages the host formation. Indeed if some fracturation processes appear, they will constitute preferential paths for pollutant migration like radionuclide. The tunnelling method should then minimize the damaged zone around the excavation.

In the first part, the presentation will focus on the strain localisation modelling, the constitutive modelling and the hydromechanical coupling the excavation process. The relation between sealing / healing and the coupled constitutive framework will be commented in the second part.

Fig. 1: Mol / Boom clay: Fractures observed during connecting gallery drilling

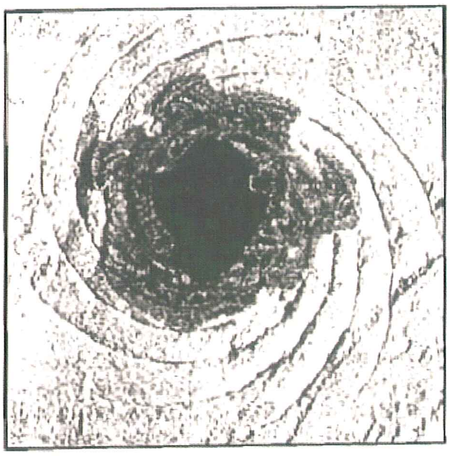


Fig. 2: after van den Hoeck PJ et al., 1994

Strain localisation modelling

Strain localisation is a fracturation precursor. It may appear under certain conditions that are described by the Rice criterion of bifurcation from diffuse to localised mode: only some constitutive models allows strain localisation, among them non associated plasticity, softening plasticity and damage. Strain localisation simulations with classical finite element codes are pathologically mesh dependent. Enhanced models are necessary for an objective post-localization modelling (see Zervos et al. (2001) for an example of excavation and Zhang & Schreffler (2004), Chambon & Collin (2004), Collin et al. (2006) for coupled second grade enhanced models). However this does not restore unicity of the solution.

Constitutive equations

An excavation process has been modelled with a very simple strain-softening constitutive law in order to exhibit the progressive decrease of material strength during testing and the strain localisation. The proposed constitutive law is a very simple elastoplastic strain-softening model. The cohesive-frictional yield criterion is a Drucker-Prager model. The material strength alteration is modelled thanks a decrease of the cohesion as a function of the equivalent deviatoric strain. Other results have been obtained without any softening.

Hydromechanical coupling – Influence of hydric boundary condition

In clayey rocks, hydromechanical coupling has to be taken into account. The water flows are computed thanks to the Darcy's law and a monolithical scheme is chosen for the coupled FE formulation. A detailed description of the FE code for coupled HM simulations can be found in Li (2000) and Collin et al. (2002). For some conditions, the pore pressure may become negative: suction appears and the constitutive model has to be adapted. Moreover, strain localisation in dilatant material allows permeability increase of several orders of magnitude.

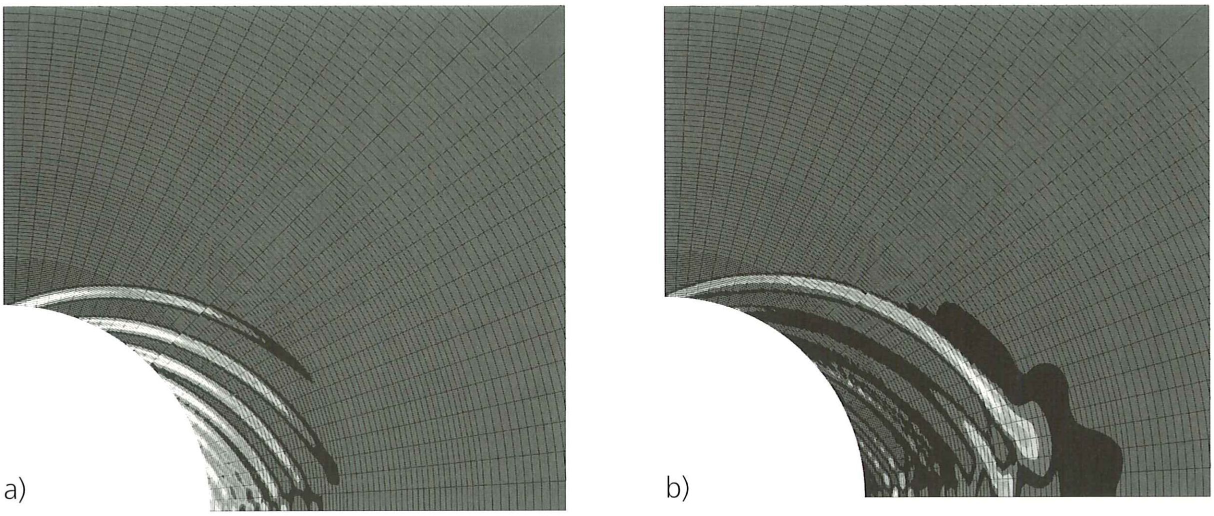
Hydraulic boundary conditions are important. The water exchange condition at the tunnel wall is: Case A) a decrease of the pore pressure from its initial value till the atmospheric pressure; Case B) a dripping boundary condition: a water flow can be created only if the pore pressure in the formation is greater than the atmospheric pressure, which is a unilateral flow condition; Case C) for long-term predictions, one can assumed an equilibrium between the pore pressure at the tunnel and the relative humidity of the cavity atmosphere. Indeed, this relative humidity can be controlled in waste disposal galleries: a negative pressure of –5 MPa may be imposed as boundary condition.

Tunnelling simulation – Numerical results

The presented simulation has been performed within a benchmark exercise proposed by the GDR-Momas and organized by EDF-CEA (Chavant & Fernandes 2005). A cylindrical unsupported cavity of 3 m diameter (2D plane strain) is located in a homogeneous low permeability formation. The initial state of stress is anisotropic. The excavation process is modelled by progressively decreasing both radial total stress and the pore pressure at the cavity nodes. The excavation duration T is equal to about 17 days and the final modelling time is about 9.5 years. During this latter phase, only the pore pressure is evolving but due to the HM coupling, the cavity convergence is still increasing.

During the excavation, the behaviour of the material becomes plastic near the tunnel and permanent strains are created. The yield criterion is first met where the orthoradial stress is the major principal stress. Dilatancy effects are evidenced, and the pore pressure becomes negative at the end of the tunnelling. Then, during the remaining modelling time, the pore pressure increases progressively. During the tunnelling phase, cavity convergence remains around 1,5 cm. Most of the convergence appears later and reaches 22,6 cm. Indeed, negative pore pressure allows an additional cohesive strength; this effect is maximum just after excavation and decreases then progressively.

The hydro-mechanical coupling also influences shear band localization. Indeed, at the end of excavation, there is no clear localization patterning even if the Rice's criterion is verified. After that phase, pore pressure increases progressively and a patterning is gradually created. Fig. 3-a presents a map of equivalent strains, where the different shear bands appear clearly. The Vilotte's indicator is shown in Fig. 3-b; this indicator evidences the strain activity of the shear band. One can see that only the external shear band is active at the end of the simulation and a chip is finally created. Similar results have been obtained for the connecting gallery in the Mol URL. Unicity checking shows that different figures may be obtained (Al Holo – Al Radi 2005).



a) b)

Fig. 3: Equivalent strain and Vilotte's indicator for active shear band (t = 300Ms)

The boundary condition for Fig. 3 results is Case A. Due to the hydro-mechanical coupling (dilatancy effect), this implies an injection of water into the formation. In Case B, the pore pressure becomes negative near the cavity at the end of the excavation. Then pore pressure increases progressively. In case C, the results are similar at the end of the excavation. However, after this first phase, the pore pressure remains negative as it is imposed by the boundary condition and the suction diffuses in the formation. These pore pressure distributions have a direct influence on the convergence predicted. Table 1 presents the results for the three cases. Moreover, some boundary conditions inhibit totally the creation of shear bands pattern.

Tab 1: Cavity convergence for Cases A, B and C.

	Case A	Case B	Case C
Tunnelling end	1.5 cm	1.26 cm	1.42 cm
After 9 years	22.6 cm	12.8 cm	1.44 cm

How to model healing and sealing?

Sealing is mainly a question of fracture closure. Then it is necessary to model the link between the strains and the fracture hydraulic transmissivity or the strain localised zone permeability. This is a question of coupling law in a hydromechanical model.

On the other hand, healing would mean that the localisation and / or fracturation process history would be removed: the memory disappears. In other word, the general state parameters of the constitutive model recover their initial values. That question will be discussed at the light of a generalised framework for coupled CTHM elastoplasticity constitutive models (Collin et al. 2005).

Conclusions

Tunnelling in clay formations may induce strain localisation and fracture, as recently observed in Mol URL. An hydromechanical modelling with a strain softening constitutive model allows to reproduce such phenomena. The results are strongly dependent on the hydraulic boundary condition at the tunnel face, which has to be better analysed.

Deep underground storage of (high level and long life) nuclear waste induces severe conditions on the host rock (especially of clay/claystone) and on the engineered barrier, which is generally made of swelling clay. The long-term integrity of the permeability barriers has to be proved. The good understanding of such disposal needs high-level numerical models, includeing different aspects: thermal and partial saturation hydraulics effects, suction-mechanics interaction, strain localisation and fracture prediction. Highly coupled non-linear finite element codes are today necessary to tackle such challenge.

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A THM stress-strain framework for modelling the performance of argillaceous materials in deep repositories for radioactive waste

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Introduction

Performance assessment of deep repositories for heat-generating radioactive waste requires the capability of reliably predicting the thermo-hydro-mechanical (THM) behaviour of the clay barriers as well as that of the host rock/clay. This represents an important element of the waste isolation system. In order to provide reasonable assurance that clay barriers and the host material will ensure waste isolation, it is essential to understand their behaviour under a variety of environmental conditions. Due to the complexity of the phenomena that take place in a waste repository, an adequate understanding of the constitutive behaviour of clays and the capability to model their evolution are challenging tasks. The stress-strain material behaviours that need to be understood and modelled include: i. isothermal wetting; ii. saturated heating; iii. non-isothermal suction variations; iv. induced cracks, and v. the role of the material structure and its multi-porosity. The difficulty of some of these tasks is increased by the fact that some effects are coupled.

This lecture mainly focuses on induced thermal disturbance. The basic phenomena of the clay behaviour under non-isothermal conditions are first identified and highlighted in the case of deep repository experiments. A mechanical stress-strain constitutive framework is proposed to model the behaviour of clay barriers as well as that of the host rock/clay. It includes several aspects, such as the thermo-plastic behaviour of saturated and unsaturated materials.

Thermal disturbance in the stress field of clays

High Level Radioactive Waste (HLW) emits heat of variable power depending on the delay time with respect to the discharge from the reactor (temperatures yield 100 to 150°C at the contact of the waste package with the soil). A principal repository design factor is the temperature developing within the soil mass. This determines the spacing of tunnels and/or boreholes. In the commonly accepted concept of multiple barriers (waste package, engineered barrier of backfill and buffer, and clay host formation), the barriers may fail, releasing the radioactive contaminant. In this case, the ultimate containment barrier is the indigenous clay formation itself.

Basic THM stress-strain behaviour of argillaceous materials

Thermo-mechanical behaviour of saturated argillaceous materials

Under normally consolidated conditions (NC), clay contracts when it is heated and a signifycant part of this deformation is irreversible upon cooling (Fig. 1). This behaviour over the whole cycle is representative of thermal hardening. Another important non-isothermal behaviour is the fact that the preconsolidation pressure decreases with increasing temperature, while the isotropic compressibilities don't seem to be significantly affected by temperature changes (Laloui & Cekerevac 2003).

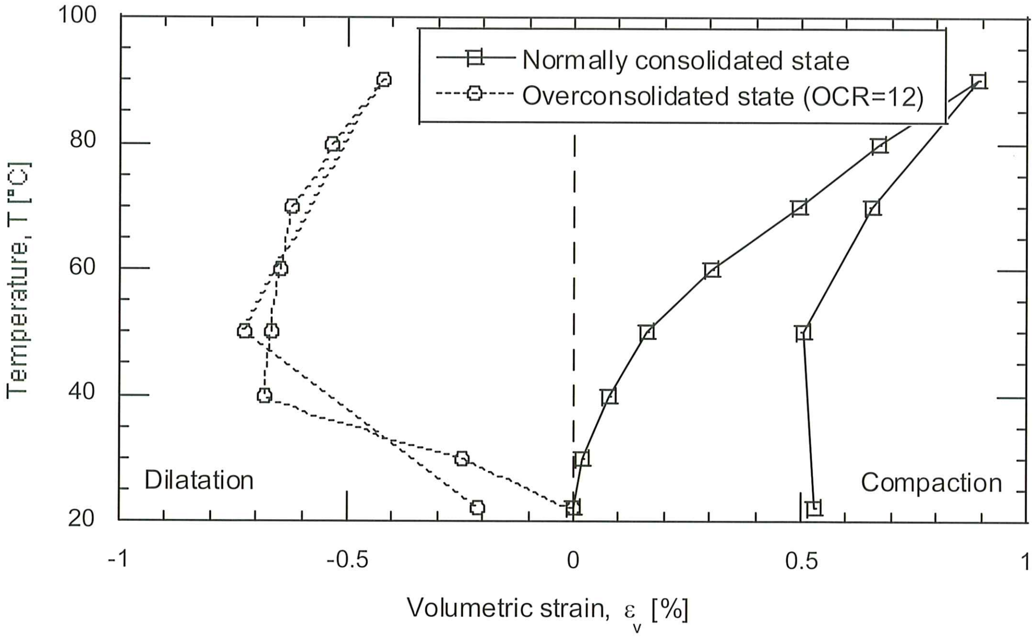

Fig. 1: Typical thermal behaviour of argillaceous materials during a heating-cooling cycle – Kaolin clay

Thermo-mechanical behaviour of unsaturated argillaceous materials

In addition to the observed features of behaviour of unsaturated soils at constant temperature and of saturated soils under non-isothermal conditions, some coupled effects must be considered. The retention capacity of soils diminishes with temperature increase, mainly because the interfacial tensile between the water and the grains decreases as long as temperature increases (Romero et al. 2001). This thermal effect indirectly influences the mechanical response of the soils by changing the suction value for the same degree of saturation.

ACMEG-TS – A THM stress-strain constitutive framework to model the non-isothermal behaviour of argillaceous materials

Even if natural host clays are different from the engineered clay barriers with respect to mineralogical composition and consolidation history, they both exhibit a close THM stress-strain behaviour. Thus, they could be modelled using the same theoretical framework.

The « generalized » effective stress

The non-saturation state within the soil means that a second fluid phase appears in the inter-particular spaces. The difference of pressure between these two fluid phases (air and water) induces a new stress variable, suction: $s = u_a - u_w$ which modifies the preconsolidation stress values. To take into account this contribution of suction in the thermo-mechanical behaviour of the soil, the generalized Bishop stress approach is used (Bishop 1959):

$$\sigma'_{ij} = \left(\sigma_{ij} - u_a \delta_{ij}\right) + S_r \left(u_a - u_w\right) \delta_{ij}$$

where σ_{ij}, u_a, u_w, S_r are the mechanical external load, the pore air, the pore water pressures and the degree of saturation, respectively. This effective stress depends here on the thermal, the hydric and the mechanical histories of the material. Indeed, the retention capacity of the soil (e.g. the degree of saturation at a given suction) depends on its dry density, on the suction level and on the temperature. Therefore, this single stress approach converts a complex multi-phase and multi-stress medium in which multi-physics processes occur into a single mechanical state using several coupling equations.

The ACMEG-TS constitutive framework

The concept of the ACMEG-TS model is to consider that the thermal as well as the hydric loads exclusively involve volumetric effects in clayey soils. These considerations are introduced in a thermo-hydro-mechanical (THM) elasto-plastic framework where each T-H-M loading (external mechanical load σ, temperature T and suction s) may induce reversible and irreversible changes of the THM state of the material. Within this elasto-plastic framework, the total strain rate tensor, $\dot{\varepsilon}$, due to the THM loading is split into non-linear thermo-elastic, $\dot{\varepsilon}^e$, and thermo-plastic, $\dot{\varepsilon}^p$, components. The material plasticity is induced by two coupled mechanisms: an isotropic one which may be activated by any mechanical, thermal or hydric loads and a deviatoric mechanism acting only under a mechanical loading having a deviatoric component (Laloui et al. 2005). The yield functions of the two mechanical thermo-plastic mechanisms have the following expressions:

$$f_{iso} = p' - \sigma'_c \, r_{iso} \quad ; \quad f_{dev} = q - Mp'\left(1 - b \, Log \frac{d \, p'}{\sigma'_c}\right) r_{dev} = 0$$

where the preconsolidation pressure σ'_c depends on the volumetric plastic strain ε_v^p, the temperature T and the suction s:

$$\begin{cases} \sigma'_c = \sigma'_{c0} \exp\left(\beta \, \varepsilon_v^p\right)\left\{1 - \gamma_T \log\left\{\dfrac{T}{T_0}\right\} + \gamma_s \log\left\{\dfrac{s}{s_{e0}}\right\}\right\} & \text{if} \quad s > s_{e0} \\ \sigma'_c = \sigma'_{c0} \exp\left(\beta \, \varepsilon_v^p\right)\left\{1 - \gamma_T \log\left\{\dfrac{T}{T_0}\right\}\right\} & \text{if} \quad s \le s_{e0} \end{cases}$$

r_{iso} and r_{dev} are the degree of mobilization of the isotropic and the deviatoric mechanisms and are hyperbolic functions of the plastic volumetric strain induced by the isotropic mechanism and of the plastic deviatoric strain, respectively. In terms of hydric or thermal response, the desaturation and the heating processes are also seen as yielding phenomena. The yielding mechanisms (deviatoric and isotropic) are coupled through the volumetric plastic strain. With this ACMEG-TS framework, The THM response of the soil is totally described through an elasto-plastic model in the hydric, temperature and mechanical planes (Fig. 2).

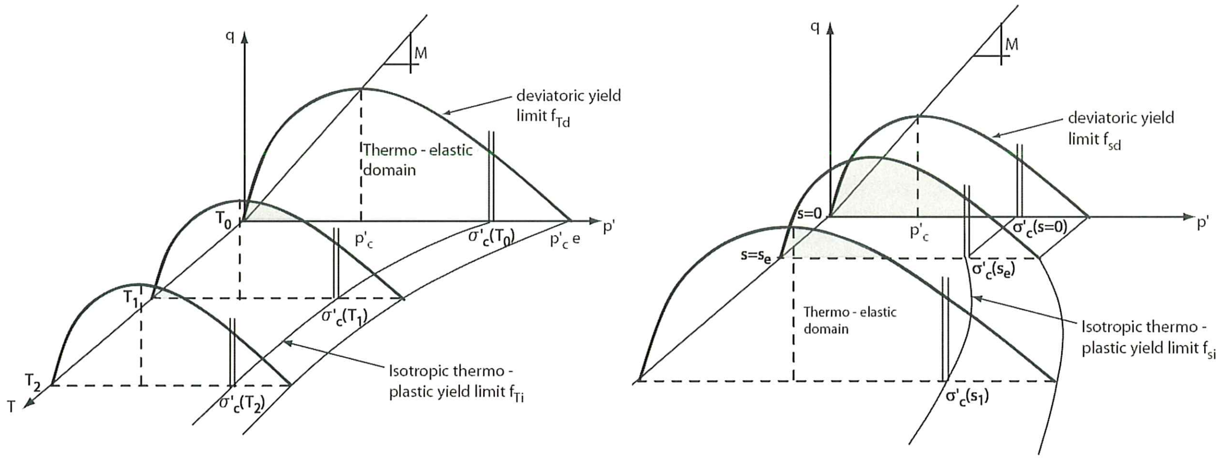

Fig. 2: Yield limits for the THM elasto-plastic framework

Figure 3 shows, as an example of the performance of the THM stress-strain model, the numerical prediction of the coupled drained mechanical-thermal behaviour of Boom clay.

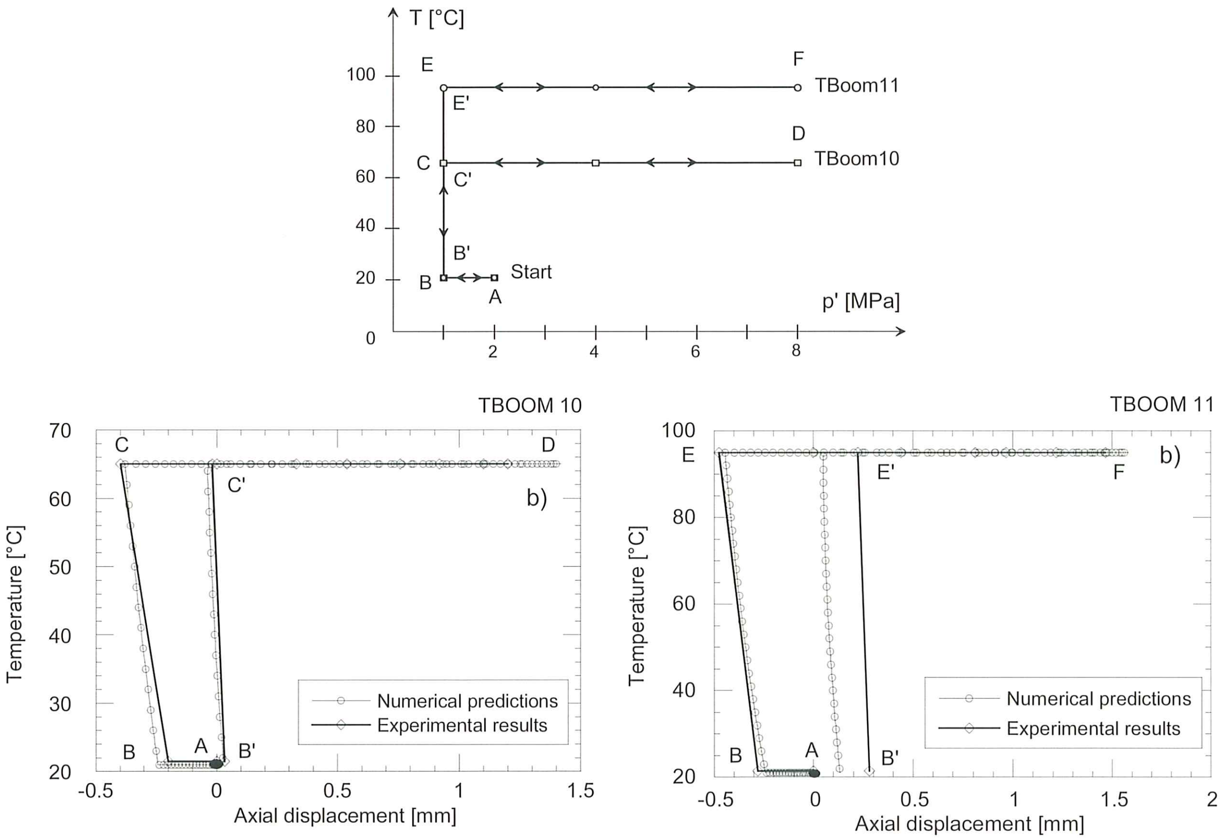

Fig. 3: An example of the numerical prediction of coupled THM paths – Boom Clay
Experimental results (Baldi et al. 1991) – Numerical predictions (Laloui 1993)

Conclusions

In the scenarios for deep, geological nuclear-waste repositories, clayey soils will be hydrated, heated, cooled and dried. The numerical modelling of these mechanical processes is a key issue. Performance assessment of deep repositories for heat-generating radioactive waste would benefit from improvements in mechanical stress-strain constitutive modelling of the coupled thermo-hydro-mechanical behaviour. The presented ACMEG-TS framework allows progress in understanding the most involved phenomena relevant to nuclear-waste repositories and their coupled nature. It could be used both in the design and in the performance assessment of repositories. It may be applied to disposal in clay formations and to hard-rock repositories where artificially compacted clay is to be used as buffer and backfill. Such a constitutive framework may help in understanding some unexplained or controversial behaviours and in defining experimental programmes to answer key questions.

Acknowledgements

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Experiments related to EDZ evolution at Mont Terri

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Introduction

Clay formations like the Opalinus Clay in their natural state exhibit very favourable conditions for the disposal of radioactive waste, as they generally have a very low and uniform hydraulic conductivity, low diffusion coefficients and good retention capacity for radionuclides. An undisturbed clay or clay rock could thus be a particularly good host rock for a nuclear waste repository. Nevertheless, one concern regarding waste disposal is that, due to the necessary underground excavations and the associated disturbance and damage in the area close to these excavations, the favourable properties of such formations could change and the host rock could lose part of its barrier function and thus negatively influence the performance of a repository (Blümling et al. 2006).

Areas around underground excavations affected by such processes are generally called excavation disturbed (EdZ) or damaged zones (EDZ). There is an international consensus to relate the definition of the EDZ with processes which are important for the long-term safety of a repository for the geological disposal of radioactive waste (Tsang & Bernier 2005). It is important to differentiate the two zones with regard to their flow and transport characteristics, admitting that areas of hydro-mechanical and geochemical modifications with major changes in flow and transport properties (EDZ) should be distinguished from those without negative effects on the long-term safety (EdZ).

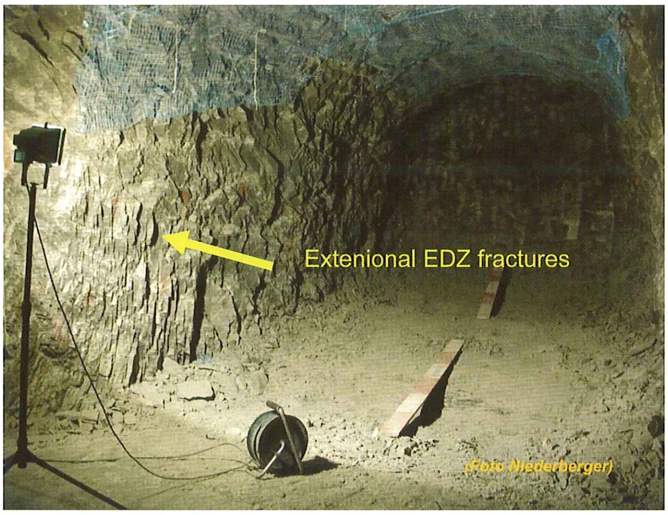
It has to be pointed out that the EDZ develops with time even in a relatively competent claystone. Processes like time-dependent deformations (compaction and creep) may lead to ongoing convergence during the open drift phase and to compaction of the buffer and self-sealing after waste and buffer emplacement. These processes will be controlled by the intrinsic properties of the rock, the rock rheology but also by the ventilation of the tunnels, the resaturation process of the repository and the effects due to the heat generation.

The EDZ during the construction phase

During tunnel construction new surfaces will be created leading to substantial stress redistribution along the underground opening. Depending on the in-situ stress field and the direction of the tunnel axis increase or decrease of the mean effective stress can be observed around the circumference of the tunnel causing significant local pore pressure changes. In addition, the shear stresses will locally increase because of the reduction of the radial stress component at the tunnel wall to zero and the change of the tangential stress component. Due to the relatively low strength of the rock and the material anisotropy induced by the existence of weak bedding planes, failure will occur in the vicinity of the tunnel.

The importance of the EDZ in Opalinus Clay was pointed out already in the very beginning of the experimental work. After a successful feasibility study (ED-A experiment) a comprehensive mine-by experiment (ED-B and ED-C experiments) was carried out in the Mont Terri rock laboratory during the construction work in 1998. Martin et al. (2002) analysed this experiment and helped to develop a basic understanding of the EDZ development at Mont Terri.

The failure mechanism observed is extension in the sidewalls of the tunnel and activation of bedding planes (extension and shear) in the roof and floor. Figure 1 demonstrates these mechanisms and it can clearly be seen that after the creation of EDZ features tangential to the tunnel wall or the reactivation of the bedding, the tunnel wall starts to buckle and bend.



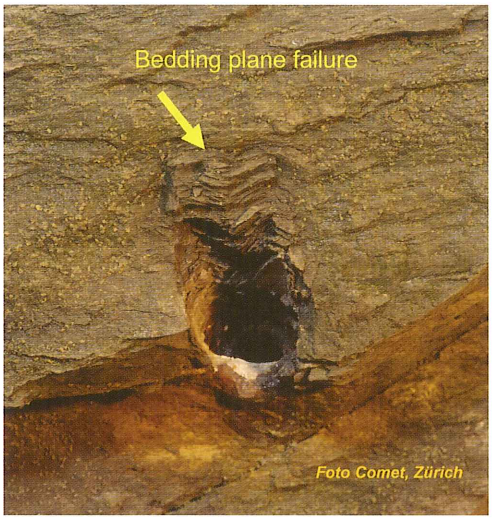


Fig. 1: EDZ features observed in the Mont Terri rock laboratory. Left: Extensional features at the intersection of the DI and EB niches. Right: Bedding plane failure at along a small borehole.

The influence of the tunnel direction with respect to the stress field and the material anisotropy has clearly been demonstrated at the Mont Terri Site. Tunnels running parallel to the security tunnel in northwest-southeast direction (e.g. main part of the gallery 98 or the horizontal raise-boring (RB) tunnel) display relatively minor EDZ extension and the best tunnel stability. Excavations normal to this direction which are more or less parallel to the strike of the bedding show large EDZ and severe stability problems especially if natural fractures sub-parallel to these bedding planes exist. Material laws describing such failure behaviour with an ubiquitous joint model are able to describe such a behaviour as shown in figure 2.

A more detailed investigation of the fracture nucleation, coalescence and propagation in the EDZ is being developed within the on-going EZ-B experiment to investigate the role of material heterogeneities at different scales in the development of the EDZ. Geophysical characterisation methods play a key role in the determination of such heterogeneities. These methods are also used in the EZ-G experiment to detect the geometry and the characteristics of the EDZ.

The time-dependent development of the EDZ

After the initial, mainly undrained deformation of the tunnel during construction, deformations will continue over several months to several years. During this period formation water will be drained to the tunnel (at very low flow rates) and the pore pressures will reduce in the vicinity of the tunnel. Due to the ventilation, the area very close to the tunnel will partly de-saturate causing changes in apparent material parameters and changes of the effective stress. In addition, drying will cause shrinkage and therefore shrinkage cracks along the tunnel wall.

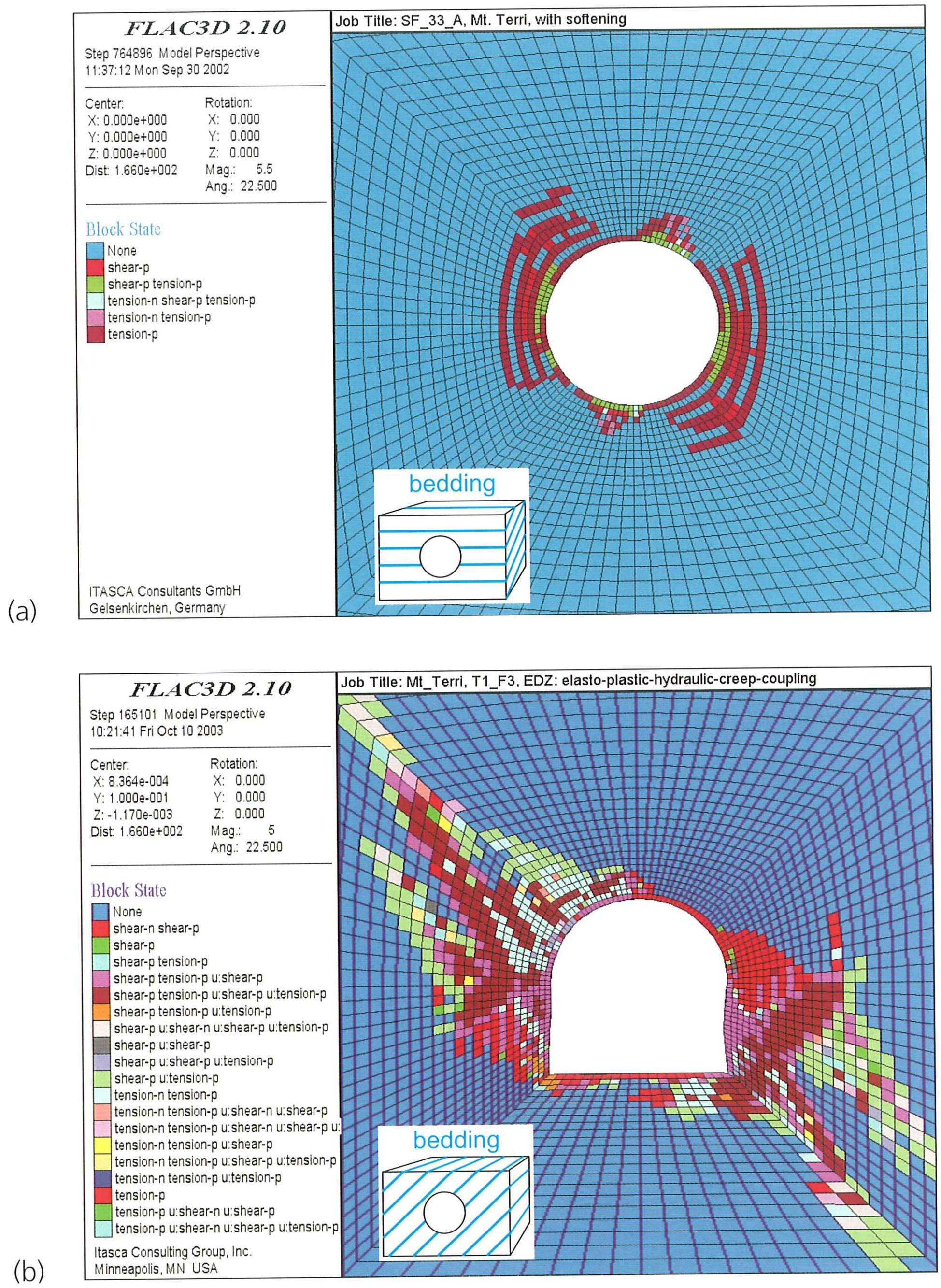


Fig. 2: Modelled EDZ for tunnels at Mont Terri. (a) Principal failure pattern for NW-SE oriented tunnels with mainly extensional fractures in the sidewalls of the tunnel (Nagra 2002). (b) Failure pattern for tunnels running NE-SW where the predominant failure mode is an activation of the bedding planes (combination of shear and tension) (Blümling et al. 2006)

In the long run, after the backfilling of the tunnels with bentonite and the re-saturation of the host rock and buffer material, the Opalinus Clay shows a tendency to self-seal the induced fractures in the EDZ. Meier et al. (2002) documented this process within the EH experiment at Mont Terri and observed a reduction in fracture transmissivity of about two orders of magnitude during 3 years. Within the SELFRAC experiment at Mont Terri, Bühler et al. (2004) conducted a plate loading test at the EH-experimental site (Figure 3) and demonstrated that the mechanical loading of the EDZ will additionally contribute to the reduction of the EDZ transmissivity (another two orders of magnitude).

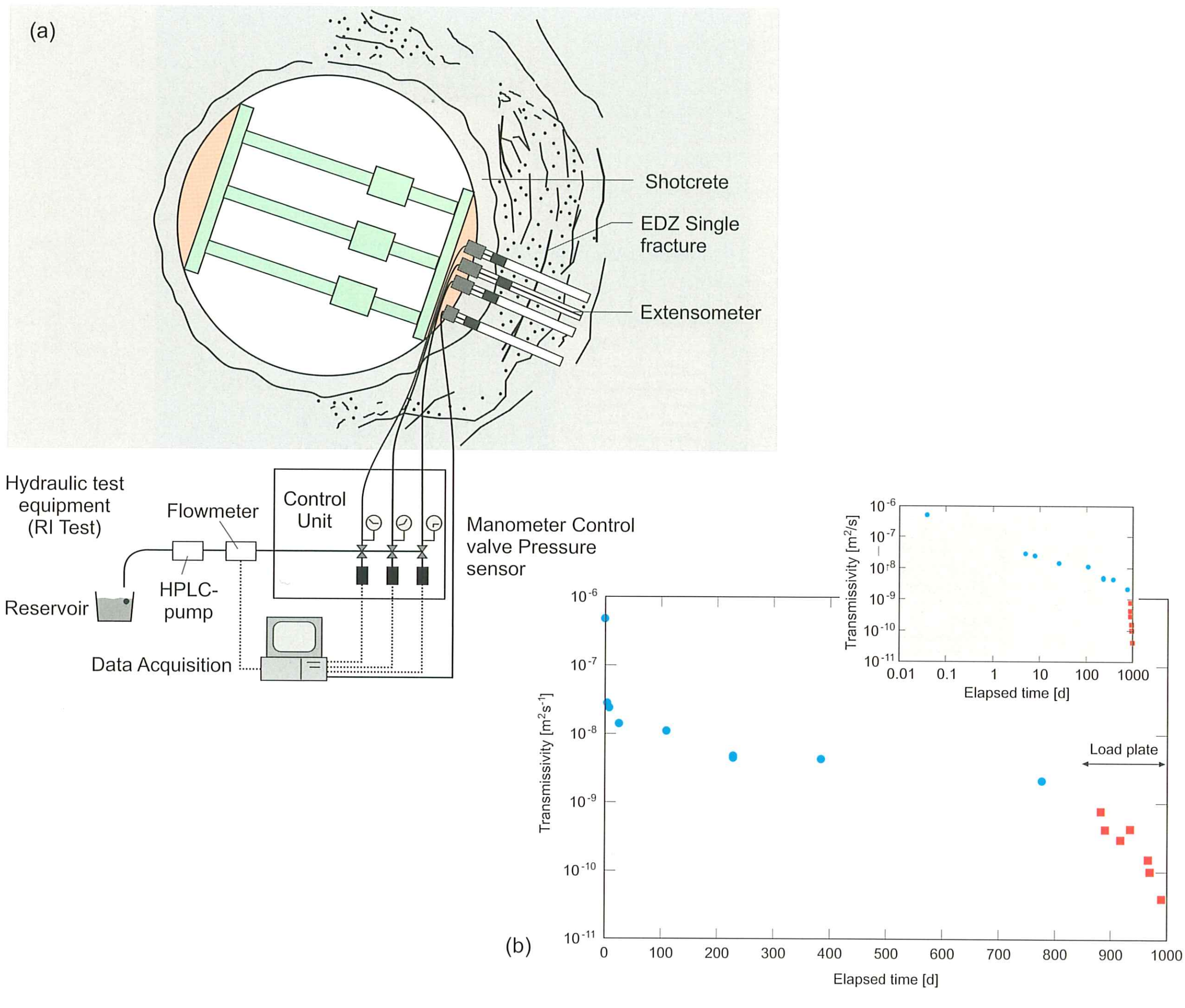


Fig. 3: Results of the EH and SELFRAC experiments according to Nagra (2002) and Bühler et al. (2004). (a) Experimental layout of the SELFRAC experiment. (b) Results from the re-saturation experiment (EH - blue dots) and the loading experiment (SELFRAC – red dots)

The self-sealing capacity of Opalinus Clay was also shown in other experiments (EZ-A and EB experiments; Mayor et al. 2005) although this process was not the main goal of these experiments. The EZ-A experiment was designed by Andra to demonstrate that the EDZ in claystone could be cut-off by engineering means (several slots filled with a bentonite-sand mixture) to interrupt the axial flow along seal sections of emplacement tunnels or disposal cells.

Results and conclusions

The EDZ was identified as an important feature for a repository in claystone and was investigated from the beginning of the Mont Terri Project. During the last 10 years it was possible to understand the underlying deformation and failure processes and to delineate the main features of the EDZ development during the construction phase of the tunnels. The influence of the bedding planes as given planes of weakness and the importance of natural fractures was shown. Interestingly, the EDZ development was observed in a very similar way on different scales. The general EDZ geometry seems to be independent from the size of the underground opening – a borehole EDZ of a borehole with a diameter of a few centimetres looks identical to an EDZ of tunnels with a diameter of 5 meter.

The rheology of the Opalinus Clay was investigated and a significant time-dependent deformation was observed resulting from changes in mean stress as well as from changes in deviatoric stress. Such processes will lead to on-going convergence during the operational period of the tunnels until they are backfilled.

After backfilling, different processes like swelling, disintegration and mechanical loading from buffer swelling and rock creep will lead to significant self-sealing of the initial EDZ causing a reduction of axial flow and of advective transport of radionuclides along tunnels.

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Topical session 2

Transport processes in argillaceous rock

Chairperson Annette Johnson, EAWAG Dübendorf, Switzerland

Speakers

Eduardo E. Alonso (UPC Barcelona, Spain)

Gas migration in argillaceous rock

Sébastien Savoye (IRSN, France)

Diffusion experiments at Mont Terri: Overview and results

Pierre de Cannière (SCK·CEN, Belgium)

Transport of solutes and gas in soft clay: Experience from HADES URL

Gas migration in argillaceous rock

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Introduction

Argillaceous rocks involved in nuclear waste isolation often present a distinctive fissured pattern, which is likely to control, to a large extent, its transport properties. Rock fissuring, however, extends to lower scales and the notion of "matrix" permeability is also dominated by cracks and fissures. Consider, for instance, the gas flow experiments reported by Renner et al. (2000) on specimens of cretaceous marls and tertiary shales from the Swiss Central Alps. Specimens were trimmed in different orientations, compared with the macroscopic foliation of the rock (parallel (P), normal (S) and at 45° (Z)). Gas permeability was measured on isotropically compressed, and previously oven-dried, specimens by means of a steady state gas inflow technique. Test results indicate that flow normal to the main foliation is "only" one order of magnitude smaller than that flow parallel to the macroscopic foliation.

Laboratory gas flow experiments are often conducted on dried specimens. This practice introduces some difficulties to interpret the results because oven-drying is capable of inducing major damage on rock microstructure. In practice, the natural rock will be exposed to gas flow without such a previous preconditioning. The point to highlight, however, is that fissuring at all scales controls gas flow.

Given an initial state of fissuring, fissure aperture and the development of additional fissuring are also fundamental factors controlling flow properties. These phenomena are stress-related effects. Stress changes are a consequence of all the envisaged operations and changes in boundary conditions, implied by a repository installation, but also on the gas migration process itself. The whole problem becomes then highly coupled and hardly a partial approach to gas flow (for instance, purely based on flow analysis) would provide a satisfactory answer. Recognizing these facts, the presentation prepared will concentrate on coupled mechanical - flow phenomena in gas propagation.

Stress and deformation effects

General changes in stress and strain states may be grouped into two phenomena:

- Isotropic stress changes which tend to mainly induce volumetric strains;
- Deviatoric stress changes that induce both shear and volumetric deformations (dilatancy).

We will be mainly interested in volumetric deformations, because they can open or close fissures and path-ways. It will be also very relevant for modelling purposes to distinguish, in the two cases mentioned, between recoverable (elastic) and irrecoverable (plastic) strains. Unfortunately, many tests reported in the literature only offer information on one-way loading, making it impossible to distinguish the elastic and plastic components of deformation.

Isotropic compression leads to a decrease in intrinsic permeability, as shown in Figure 1. Unloading is expected to increase permeability. In general, clayey rocks, with its elongated microcracks, will be especially sensitive to these effects.

Shear effects are illustrated in Figure 1, from Renner et al. (2000). Intrinsic permeability, determined in gas (argon) pulse tests performed during loading in a triaxial test, follows the macroscopic volumetric strains of the specimen. The initial (elastic) volumetric compression implies a (small) reduction in permeability and the onset of dilatancy results in a permeability increase. Dilatancy becomes very relevant after peak conditions and the generation of open "channels" leads to a fast increase in permeability.

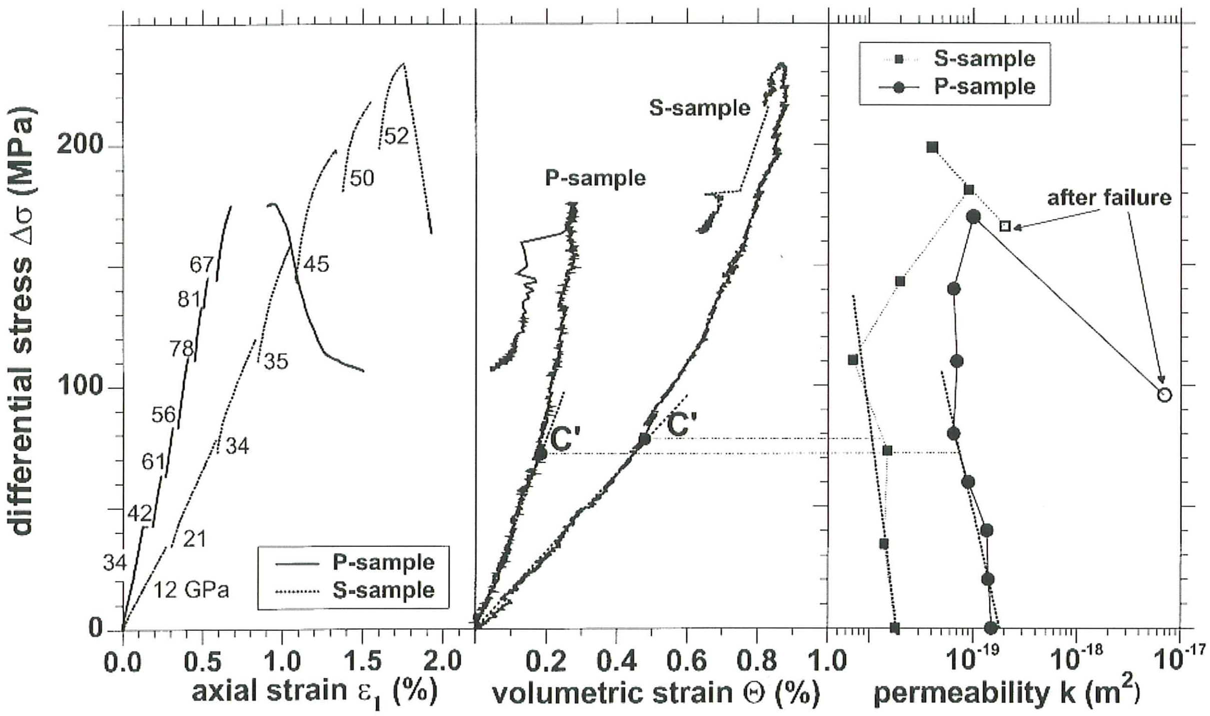

Fig. 1: Evolution of permeability during triaxial testing of oven-dried specimens. Transient flow method: decay of a transient argon pulse (Renner et al. 2000).

Similar results have been reported by other groups (Uehara & Shimamoto, 2004; Coll et al., 2003a, b). Experimental work describing dilatancy in argillaceous rocks is also often reported.

Under general repository conditions, stress paths in the vicinity of the disposal area (near yield conditions) will not conform to isotropic or triaxial states and, therefore, general formulations are required in order to develop predictive models. One approach is outlined below.

A field case of gas flow-mechanical interaction

Gas permeability tests were performed in boreholes located in the vicinity of the heated area of the Drift Scale Test (DST) performed in the Yucca Mountain (Olivella & Gens 2005). The test layout is shown in Figure 2. Gas flow tests were performed in Boreholes 74 and 78 but also in

Boreholes 57 and 59, located in a parallel section. Two interconnected continua (one for the matrix and one for the tuff fracture network), were considered in the analysis. Changes in matrix porosity and fracture aperture control the overall permeability. Volumetric deformations are assumed to be distributed in equal proportions between matrix and joints. Matrix permeability changes with the updated porosity (Kozeny's approach) whereas a cubic law is adopted for the changes in fracture permeability. The analysis, a thermo-elastic calculation, was performed with the finite element code CODE_BRIGHT. However, volumetric deformations were approximated by means of a simplified equation:

$$\Delta\varepsilon_v = \frac{\Delta p}{K} + \frac{\tan\psi\,\Delta q}{3G} + 3\alpha\,\Delta T$$

(K: Bulk modulus; G: shear modulus; ψ: dilatancy angle; α: coefficient of thermal expansion; p, q: mean and deviatoric stresses; T: temperature) which introduces dilatancy effects by means of a parameter (ψ) identified as a dilatancy angle (24° assumed in calculations). Elastic compressibility and thermal dilation is also included. Figure 3 shows a comparison between measured and calculated values of permeability. The important point to highlight is that the observed variation of permeability with time in boreholes 57 and 74 cannot be reproduced if a constant intrinsic permeability is assumed (in fact, in this case, constant gas permeability along time is predicted). It should be added that the calculated evolution of permeability in Figure 3 includes two effects: changes in degree of saturation, which may be approximated by a non-coupled two-phase flow analyses and the mechanical effects just described.

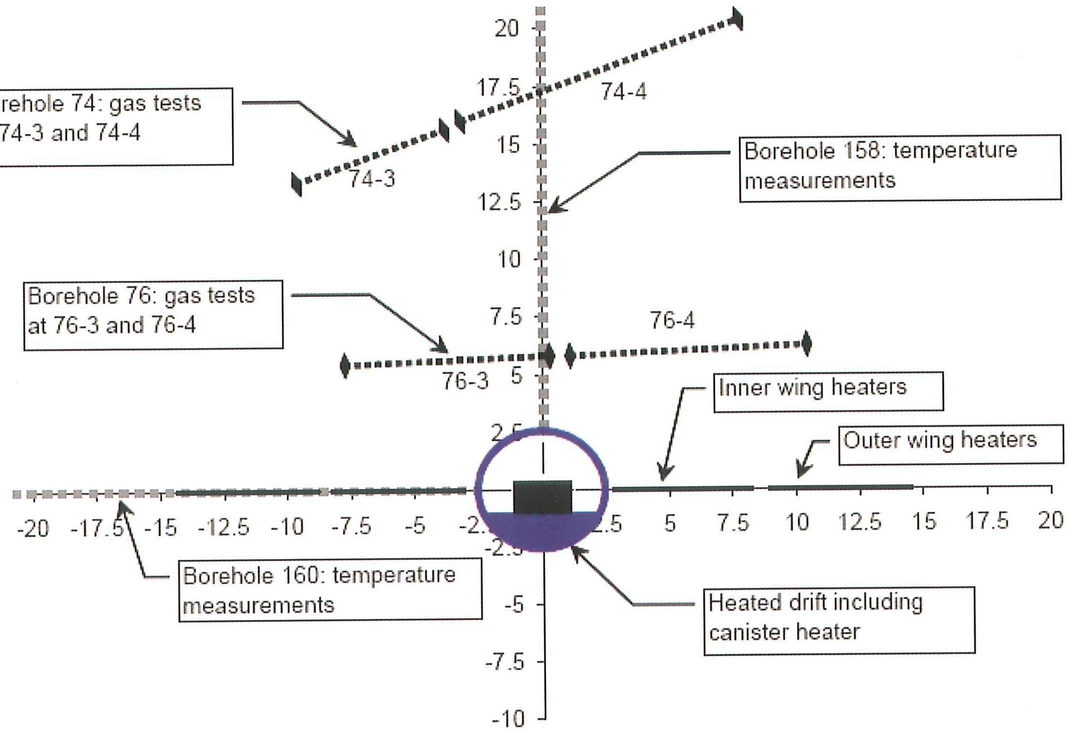

Fig. 2: Drift Scale Test; Yucca Mountain. Location of gas permeability tests. Olivella & Gens, 2005.

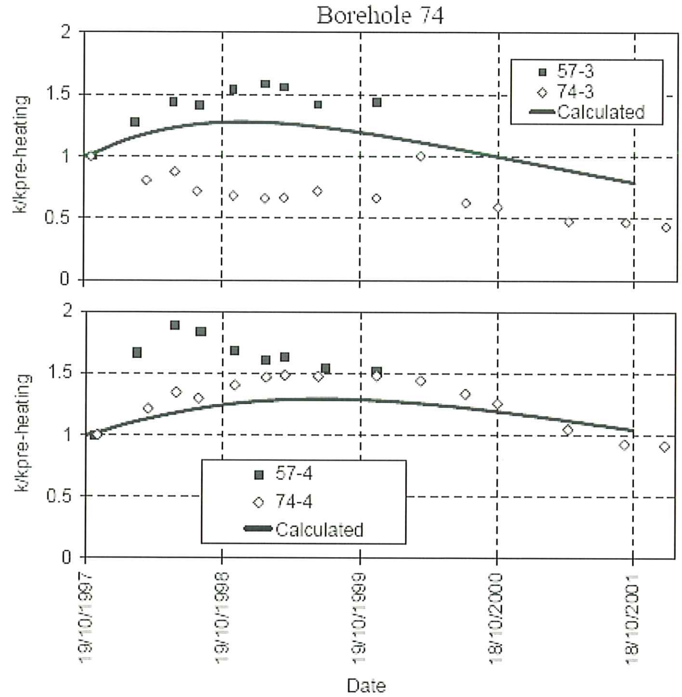

Fig. 3: Drift Scale Test; Yucca Mountain. Location of gas permeability tests. Comparison of permeability calculations and measurements. Variable intrinsic permeability (Olivella & Gens 2005).

Modelling approaches

Two general approaches for gas flow in fractured rock have been described in the literature: an idealized network of interconnected channels, which individually may be saturated when a capillary pressure is exceeded, and a "continuum" or "macroscopic" approach, which models the rock by means of a finite element (or finite difference) procedure.

Examples of the former have been given by Gascoyne & Wuschke (1997) and Brown (1999). When this approach is used, difficulties to incorporate couplings with overall mechanical rock behaviour, as induced by stress and thermal changes are met. Despite the difficulties to introduce discontinuities in continuum models, the macroscopic approach is preferred here, because it may introduce in a systematic manner all the couplings generally observed in porous and fractured media.

The challenge in continuum approaches is to make them consistent with the existence and development of discontinuities. A procedure described in Olivella & Alonso (2004) and Alonso & Olivella (2005) has demonstrated its capability and flexibility to describe gas flow in a variety of circumstances. The idea was to embed a discontinuous flow fracture into an otherwise continuum "THM" element. The discontinuity plays the role of a "damaged" zone (Fig. 4) and it may represent interfaces, shear zones, schistosity planes or sedimentation surfaces. Normal deformations to the reference discontinuity result in finite fracture opening, which, in turn, modify the flow properties. An appropriate elastoplastic continuum constitutive law defines the damaged zone. If a model for saturated/unsaturated states is introduced, suction changes (drying, wetting), as well as mechanical effects, may be simulated. Figure 4 indicates how tension opening, as well as plastic dilatancy effects, may be taken into account. Such a model has been introduced into the general purpose THMC Program CODE_BRIGHT.

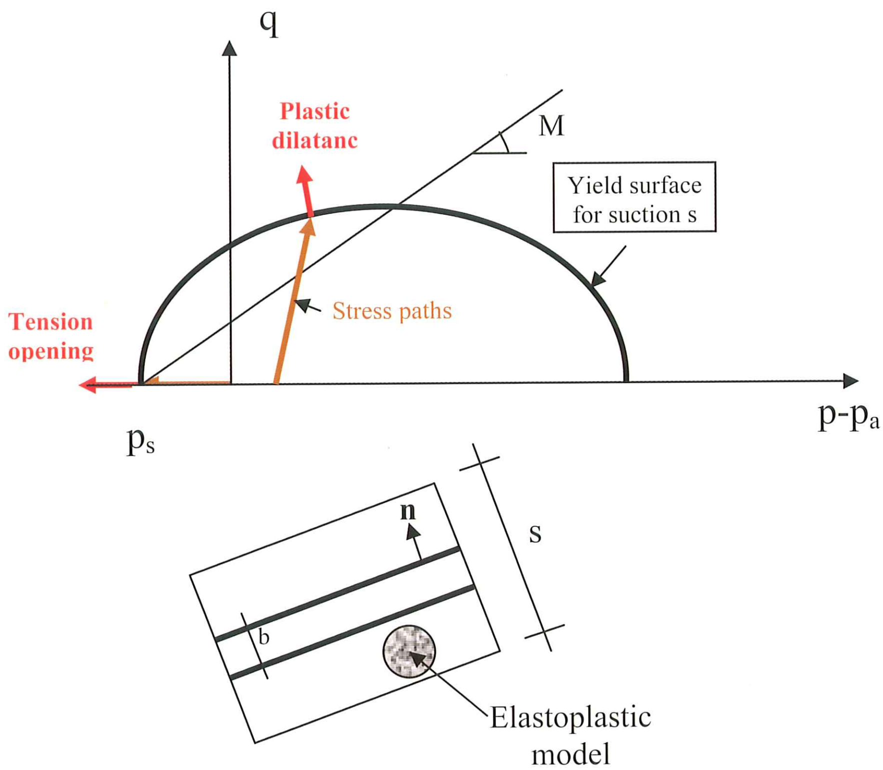

Fig. 4: A model for an embedded discontinuity in an elastoplastic element. A. Element geometry. B. Yielding conditions of damaged zone.

Gas flow tests on rock samples reported by Rummel & Weber (2000) have been simulated through this approach. Some preliminary results were described in Alonso & Olivella (2005). Additional results are given in the presentation. Recognizing that crack heterogeneity at small scale controls gas flow mobility, the specimen tested by Rummel & Weber is conceived as a set of elements, each of them having an embedded discontinuity. In addition, some degree of heterogeneity is introduced, by means of a random spatial distribution of the hardening parameter.

The first stage of the simulation involved a gas pulse test of the intact specimen followed by a specimen fracture under triaxial compression and further gas pulse tests, once the specimen has been damaged. A comparison of measured and calculated gas pressure records during the first stage of tests is given in Figure 5.

When the specimen is loaded in compression plastic shear (and volumetric) strains localize in bands and the macroscopic gas permeability increases fast (Fig. 6). This is reflected in the last phase of the test stage reproduced in Figure 5, which shows a rapid decrease of gas pressure, due to the macroscopic increase in permeability. Note, in Figure 5, that the increase in permeability concentrates in bands which experience an increase in porosity. Changes in permeability are however very relevant since they reflect the opening in discontinuities

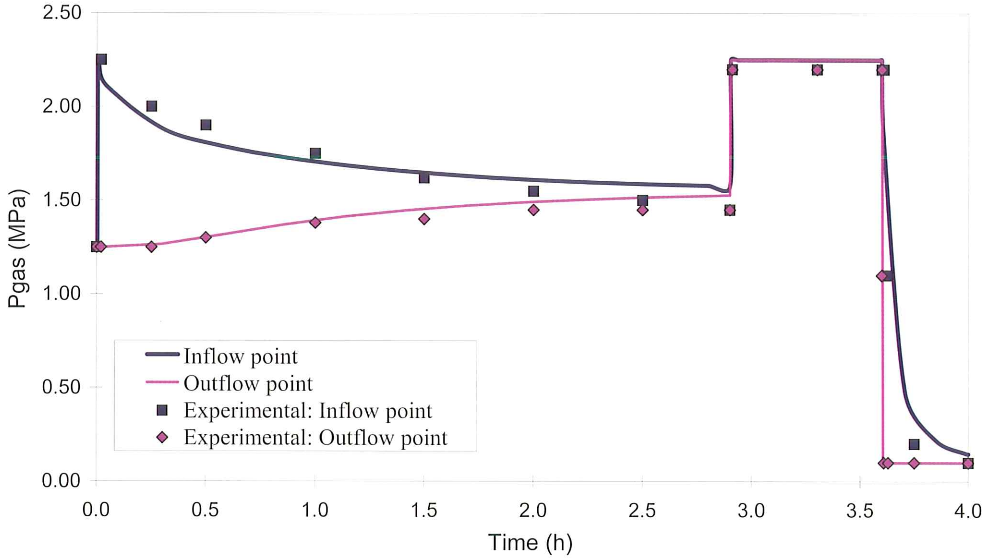

Fig. 5: Measured and calculated evolutions of gas pressure in first stage of Rummel & Weber tests (Rummel & Weber 2000).

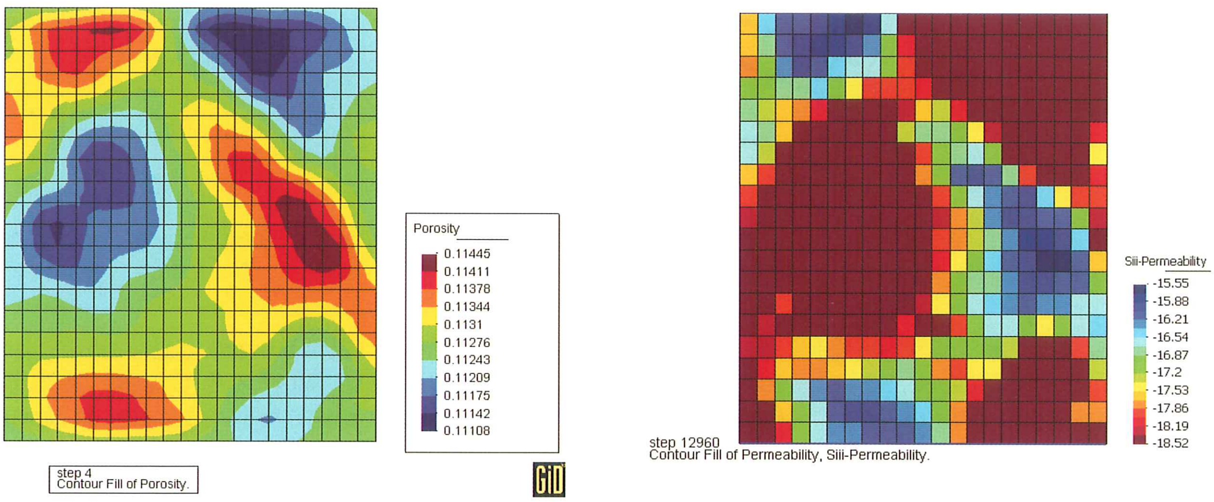

Fig. 6: Calculated porosity distribution of the rock specimen after failure conditions (left) and associated permeability. First stage of the gas flow/triaxial test (Rummel & Weber 2000).

Conclusions

The intrinsic gas permeability of fractured argillaceous rocks depends on the current structure of micro-cracks and fissures of the rock. They are a consequence of the initial state and the subsequent deformations induced by stress and gas pressure changes. Stresses are also coupled with fluid pressures and, therefore, gas flow and mechanical behaviour are intensely coupled.

Laboratory experiments, aimed at determining intrinsic permeability, show the relevant effect of volumetric deformations induced by isotropic, as well as deviatoric stress changes. The relevance, in practice, of the flow-mechanical coupling has been illustrated by means of some results obtained during the performance of the DST test in fractured tuff in the Yucca Mountain facility

The technique of embedding discontinuities in continuum THM elements is capable of reproducing observed features of gas flow migration in clayey rocks. An example is described. It is believed that the developed approach provides a powerful computational procedure to handle complex gas phenomena in clayey rocks.

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Diffusion experiments at Mont Terri: Overview and results

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Introduction

One of the key issues for a repository's safety assessment is to determine the predominant radionuclide-transport mechanism. Transport could occur either by molecular diffusion through the pore water or by advective flow within the rock matrix and/or fractures. Several studies indicate diffusion to be the dominant transport mechanism in Opalinus clay. Firstly, large-scale profiles of natural tracers, such as chloride, bromide and stable isotopes can be explained by slow diffusion process from the saline Opalinus Clay pore water to the young ground water of the adjacent limestone formation (Rübel et al. 2002; Degueldre et al. 2003). Secondly, the very low hydraulic conductivity measured in the clay formation limits the contribution of advective transport.

The diffusion parameters are generally derived from laboratory measurements on centimetric rock samples. As these values are required in the modelling at the scale of rock formations for performance assessment, their reliability has to be verified, especially regarding potential upscaling effects. Hence, since the beginning of the Mont Terri Project, several diffusion experiments have been performed at the field scale either in the undisturbed rock matrix (DI, DI-A, DI-A2, DI-B, DR) or in a highly fractured zone (FM-C) to acquire such in-situ diffusion parameters.

Concept of in-situ diffusion experiments

The general concept of all the experiments is based on the first in-situ experiment, the so-called DI (Palut et al. 2003).

A tracer cocktail is injected into a packed-off section of a borehole as a pulse-test. Pressure in this interval is maintained equal to the pore pressure of the surrounding rock in order to prevent any hydraulic gradient around the borehole and to avoid advective transport processes. The evolution of the tracer concentration in the injection system is monitored over time with a set-up allowing fluid circulation from the interval to the surface (Fig. 1). After a certain period of diffusion (from 10 months to 2 or 3 years), the claystone section surrounding the interval is retrieved by overcoring the whole borehole and is subsequently analysed for the tracer profiles. Then, both the tracer decrease in the interval and tracer profiles in rock are simulated with the same diffusion parameters in 2D or 3D. Finally, the obtained diffusion data are compared with lab diffusion data.

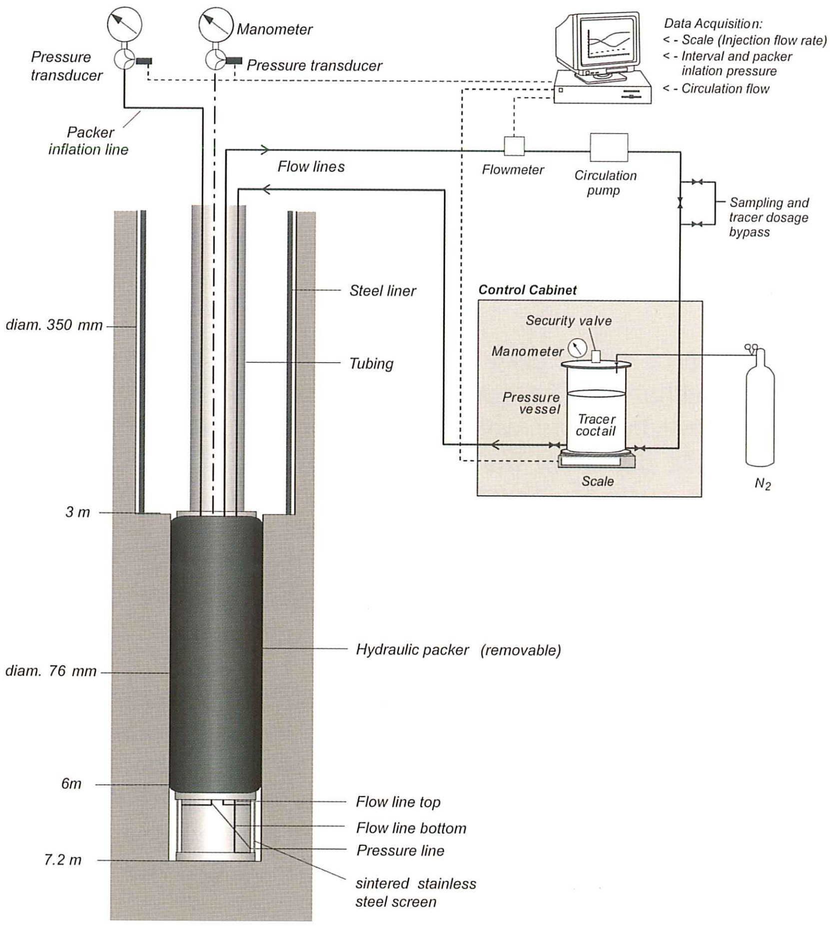

Fig. 1: Example of experiment test set-up (DI-A, Wersin et al. 2005a; van Loon et al. 2004)

Location and specification of diffusion experiments

Figure 2 shows the location of the six different diffusion experiments performed at Mont Terri since 1998 and specifications are summarized in Table 1.

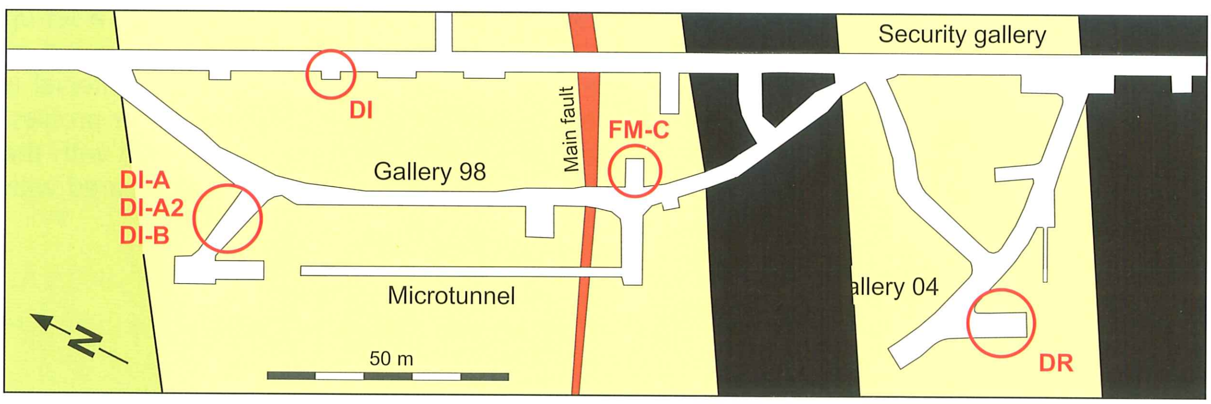

Fig. 2: Location of diffusion experiments

Tab. 1: Main specifications of diffusion experiments performed at Mont Terri.

	DI[a]	FM-C[b]	DI-A[c]	DI-A2[d]	DI-B[e]	DR
Facies	Shaly	Shaly & major fault zone	Shaly	Shaly	Shaly	Shaly
Orientation of Bh axis / bedding	56°	?	58°	60°	58°	90°
Hydro-test K ($m.s^{-1}$)	No	No	3.10^{-13}	$2.4.10^{-13}$	No	6.10^{-13}
Tracers	^{3}H, I^{-}	^{3}H, I^{-} (+He)	^{3}H, I^{-}, ^{22}Na, Cs	^{3}H, I, ^{22}Na, Cs, Br, Eu, ^{85}Sr, ^{60}Co	^{2}H, I^{-}, ^{6}Li	^{3}H, I, ^{22}Na, ^{85}Sr, Br, ^{75}Se & ^{18}O ^{60}Co, ^{137}Cs, ^{133}Ba, ^{2}H , ^{152}Eu
Duration	Dec 98 12 months	June 2000 8 months	Jan 2002 10 months	Apr 2004 12 months	Sept 2002 13 months	April 2006 > 24months

References: [a] Palut et al. (2003); [b] Gomez-Hernandez et al. (2004); [c] van Loon et al. (2004); [d] Wersin et al. (2005b); [e] Yllera et al. (2003).

For technical constraints, due to the overcoring operation, most of boreholes are drilled vertically, i.e. inclined with regard to the bedding plane. Only the last DR experiment is performed perpendicular to the bedding in an inclined borehole.

Since the first DI experiment, the tracer cocktails have successively become more complex in terms of their chemical behaviour and now include very strongly-sorbing and redox-sensitive tracers. As certain tracers are injected as radio-isotopes, on-line measurements have been carried out with γ detectors (DIA-2 and DR).

Results and conclusions

Figure 3 gives an example of both the tracer evolution in the circulating fluid in the interval vs time and of a tracer profile in the rock.

The observed tracer patterns follows the generally expected trend: the flux of anions (bromide or iodide) is lower than that of HTO due to anion exclusion effects and their penetration depth in rock can reach some 15 cm, while HTO can penetrate until some 20 cm after 1 year. The analysis of DI data revealed the occurrence of a disturbed zone around borehole in which the tracer diffusivities were higher. This disturbance was attributed to an oxidation/de-saturation process occurring for 1 month after the drilling and before installation of completion. Concerning the cations, one observed that when the interaction of these species with clay surface was stronger, their decrease relative to HTO in interval was faster and their penetration depth was lower (max 3 cm after 10 months for Cs^{+}). Analyses of such thin profiles in rock have necessitated the development of new approaches such as micro-spectroscopic techniques that led to high-quality data consistent with bulk data obtained from sliced rock samples.

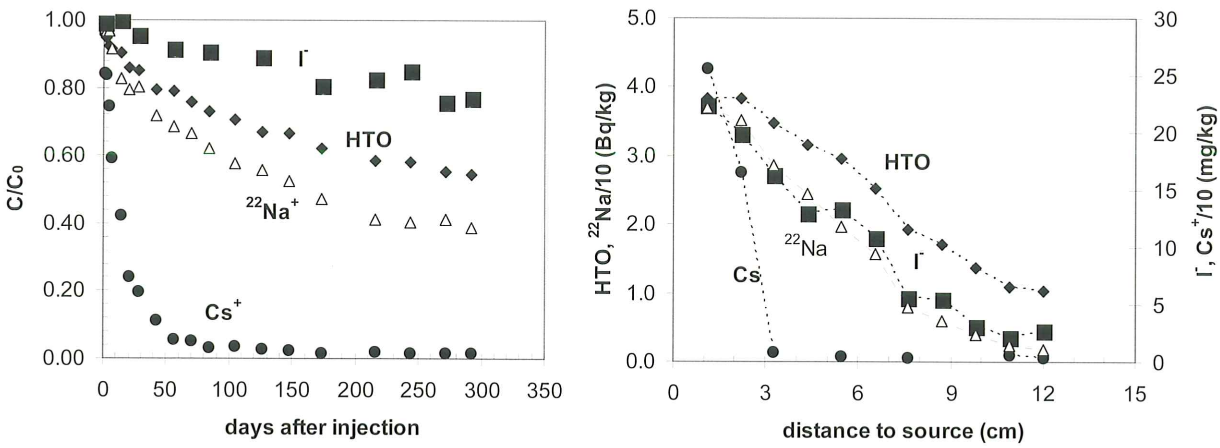

Fig. 3: Evolution of tracer concentrations (left) in interval vs time and (right) in rock vs distance to source (DI-A, Wersin et al. 2005a).

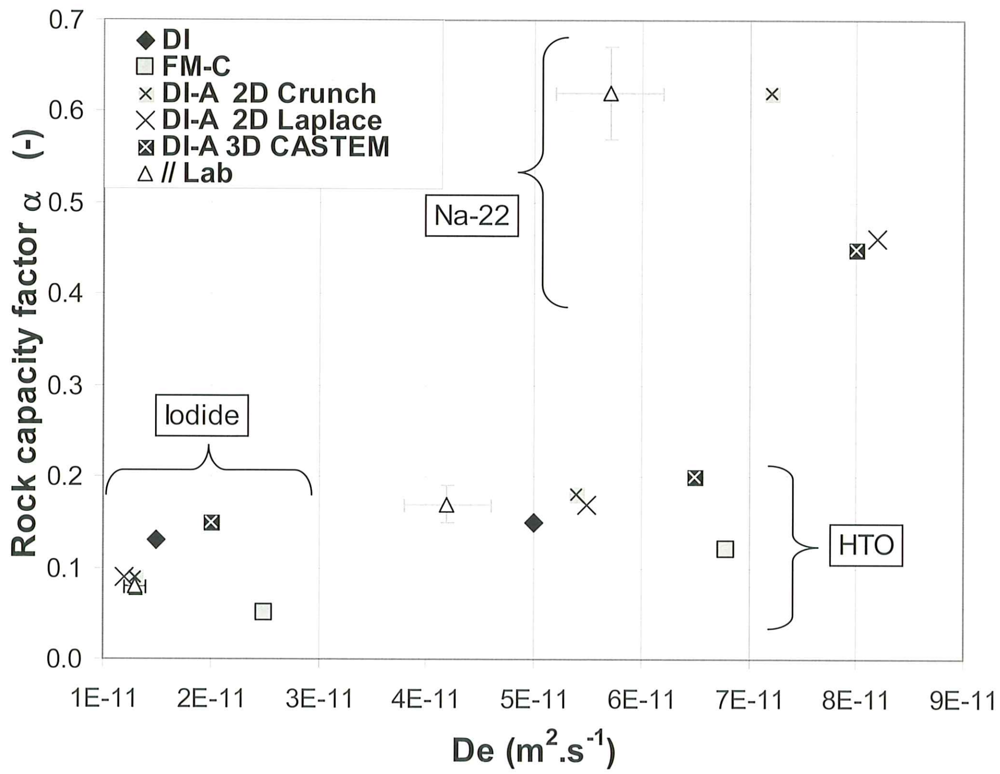

Fig. 4: Rock capacity factor α vs effective diffusion coefficient D_e from small-scale through-diffusion experiments (lab) and several in-situ experiments.

Figure 4 shows a comparison between published data derived from in-situ and lab experiments. They are limited to HTO, iodide and Na-22. Lab data obtained at 23°C were re-calculated at 14°C (the temperature of the water in the circulation system of DI-A) using the measured apparent activation energies for diffusion. It appears that in-situ data were found to be consistent with small-scale lab diffusion experiments performed parallel to the bedding plane. The new DR experiment will address the measurement of diffusion anisotropy in-situ by using both shorter injection intervals and a borehole normal to the bedding planes. Concerning the cations, modelling of in-situ data led to higher diffusivities than HTO as already noted at lab scale.

All these in-situ experiments have proven to yield suitable results and to estimate the scale effect from lab to in-situ-conditions.

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Transport of solutes and gas in soft clay: Experience from the HADES URL

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Introduction

In the absence of water conducting features, low-permeability clay formations provide a low flow environment essential for the very long-term containment of radioactive waste. Comprehensive understanding of the physical and chemical processes that control water, gas, and solute transport through deep argillaceous formations is a key factor for assessing their suitability as host rocks for radioactive waste. The Boom Clay, an over-consolidated marine Oligocene deposit (30 - 35 Ma), is presently considered as the reference host formation for the studies on the radioactive waste disposal in Belgium (ONDRAF-NIRAS 2001). For more than 25 years, an extensive experimental research program has been carried out in the Boom Clay at the HADES Underground Research Laboratory (URL) in Mol (Belgium). One of the main objectives of the experiments conducted at the HADES URL is to assess the transport mechanisms of radionuclide, water and gas in this soft clay formation (Henrion et al. 1985; De Cannière et al. 1996; Ortiz et al. 2002). Hydraulic tests are carried out at different scales to characterize the *in situ* hydrogeological conditions and to determine the associated parameters (De Cannière et al. 1995). In parallel, geochemical studies are performed to understand the mechanisms controlling the water-rock interactions and the composition of the Boom Clay porewater (Griffault 1996; De Craen et al. 2004). Thermo-hydro-mechanical experiments and large-scale demonstration tests are also conducted to determine the technical feasibility and the long-term safety of the repository system. The present paper describes the different approaches developed for the migration tests made *in situ* with unretarded tracers at large scale and strongly sorbed tracers at small scale. The main outcomes of *in situ* gas injection experiments with helium are also presented.

Large-scale *in situ* migration experiments with non-sorbed tracers

Large-scale diffusion tests with non-sorbed tracers (tritiated water, $^{125}I^-$, $H^{14}CO_3^-$ and ^{14}C-labelled organic matter) have been performed in the Boom Clay formation from the main gallery of the HADES URL located at -223 m below the ground level (De Cannière et al. 1996). The objective of these experiments is to verify that the results of the tests previously performed in a surface laboratory on small clay cores (3 - 7 cm) can be confirmed at the scale of the meter. Blind predictions based on the transport parameters (ηR, D_{app}) determined in the laboratory for HTO, $^{125}I^-$, and $H^{14}CO_3^-$ are compared with the concentrations of these tracers measured at different distances from the injection filter as a function of time. Figure 1 illustrates the results obtained with tritiated water (HTO) in the so-called CP-1 experiment where HTO was injected 18 years ago.

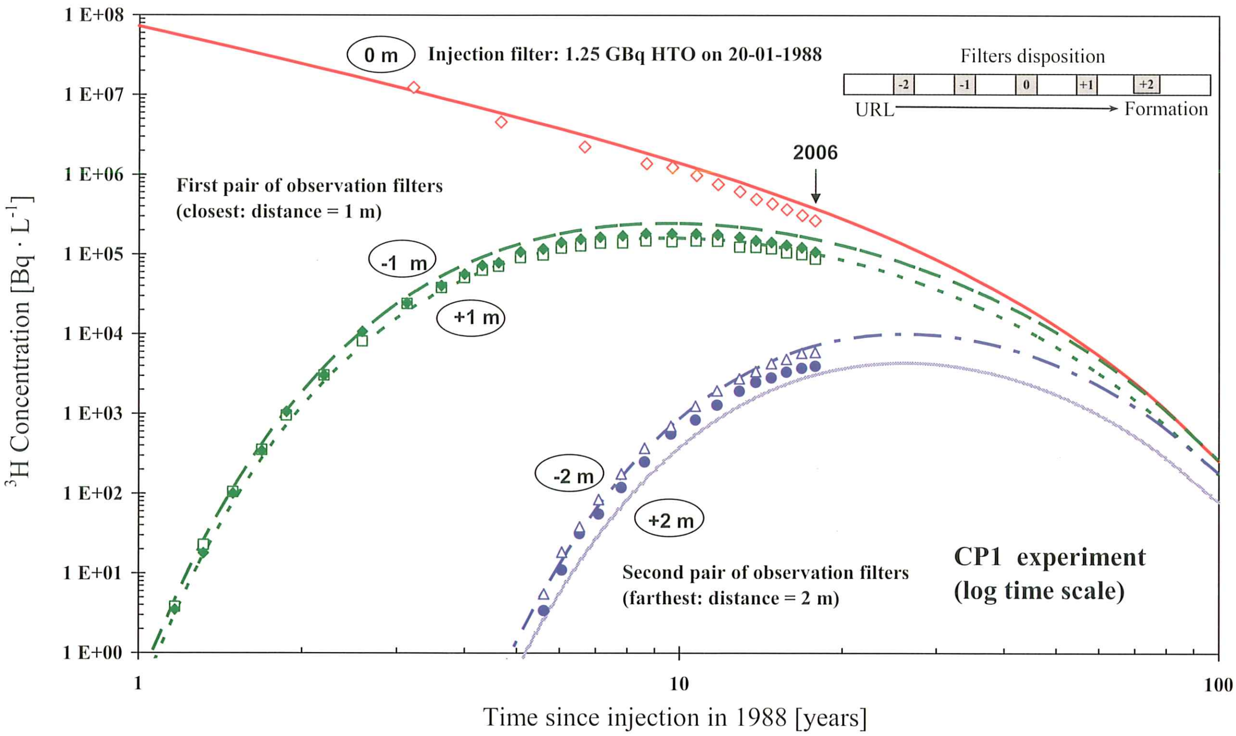

Fig. 1: Large-scale and long-term *in situ* diffusion experiment with tritiated water in Boom Clay.

A good agreement is obtained between the model predictions and the concentrations measured in water for HTO at distances up to 2 m. This allowed to validate the use at the metric scale of the analytical code (Micof) previously developed at SCK•CEN (Henrion et al. 1985) to interpret the small-scale laboratory experiments. It also clearly shows that in the low-permeability Boom Clay, diffusion is the process dominating the transport of radionuclide (HTO: D_p = 2.3 ± 0.3 × 10^{-10} m^2 s^{-1}; η = 0.37 ± 0.03; D_{eff} = 8.51 ± 0.33 × 10^{-11} m^2 s^{-1}) (Aertsens et al. 2004).

Similar types of experiment have been performed in the vertical and the horizontal directions from the Test Drift (ring 41) of the HADES URL to determine the anisotropy of the diffusion coefficient of $^{125}I^-$ in Boom Clay (D_p = 1.4 ± 0.2 × 10^{-10} m^2 s^{-1} ; η = 0.16 ± 0.02; D_{eff} = 2.24 ± 0.22 × 10^{-11} m^2 s^{-1}). The anisotropy for the diffusion of $^{125}I^-$ is about the same than for the hydraulic conductivity of Boom Clay: D_{hor} ~ 2.4 × D_{ver}. Due to the process of anionic exclusion, the diffusion accessible porosity (η) of iodide is less than the half of that of tritiated water.

The hydraulic conductivity (K) of Boom Clay in the direction perpendicular to the bedding plane is about 1.7 × 10^{-12} m s^{-1} and 4.1 × 10^{-12} m s^{-1} parallel to the stratification (De Cannière et al. 1995; Aertsens et al. 2004).

Small-scale *in situ* experiments with strongly sorbed radionuclides

In situ conditions are difficult to reproduce and to maintain on the long term in the surface laboratory and some parameters such as P_{CO_2}, pH, E_h and T cannot always be correctly preserved in long-lasting diffusion experiments with sorbed tracers on small clay cores. One main advantage to perform directly *in situ* diffusion experiments with strongly sorbed tracers, and certainly with redox-sensitive nuclides, is to better guarantee the correct speciation of the radionuclides and to minimize oxidation risks of the clay. For this reason, small-scale experiments, where a source of the radionuclide of interest was previously loaded in the surface laboratory in sandwich between two fresh clay cores, have been reinstalled *in situ* in direct contact with the Boom Clay formation at the extremity of the chamber of a piezometer equipped with a metallic grid. Water was then allowed to continuously percolate from the clay formation through the cell hosting the small clay core, and was sampled in the gallery by means of a tubing equipped with a valve. The radionuclide concentration was measured as a function of time allowing to determine solubility controlled concentration as in an experiment loaded with a mixture of ^{241}Am and ^{99}Tc (Cerberus Test with a source of heat and intense γ-radiation). At the end of the experiment, the small-scale experiment is easily overcored and recovered with a minimum of risk, the clay core extracted from its confinement cell, cut in thin slices (0.5 mm), and analysed.

Figure 2 shows a smooth diffusion profile obtained in Boom Clay after a long-term *in situ* diffusion experiment made with $^{134}Cs^+$. The apparent diffusion coefficient (D_{app}) determined for Cs^+ from this experiment is about 1×10^{-13} m^2 s^{-1} and the effective diffusion coefficient, D_{eff} = 1.1×10^{-10} m^2 s^{-1}, is about 5 times higher than that obtained for HTO. The reason of effective diffusion coefficient higher for cation than for HTO remains presently poorly understood.

Much more complicated migration profiles in clay have been obtained with ^{241}Am and ^{99}Tc sources, but very constant concentrations were measured in the percolation water: in the range 10^{-14} – 10^{-13} mol dm^{-3} for ^{241}Am and 10^{-9} – 10^{-8} mol dm^{-3} for ^{99}Tc, respectively (Noynaert et al. 2000). No significant effect of temperature (80 °C) and radiation have been observed when comparing the results of the migration experiment installed nearby the Cerberus Test and with another reference experiment installed *in situ* at 16 °C in undisturbed Boom Clay.

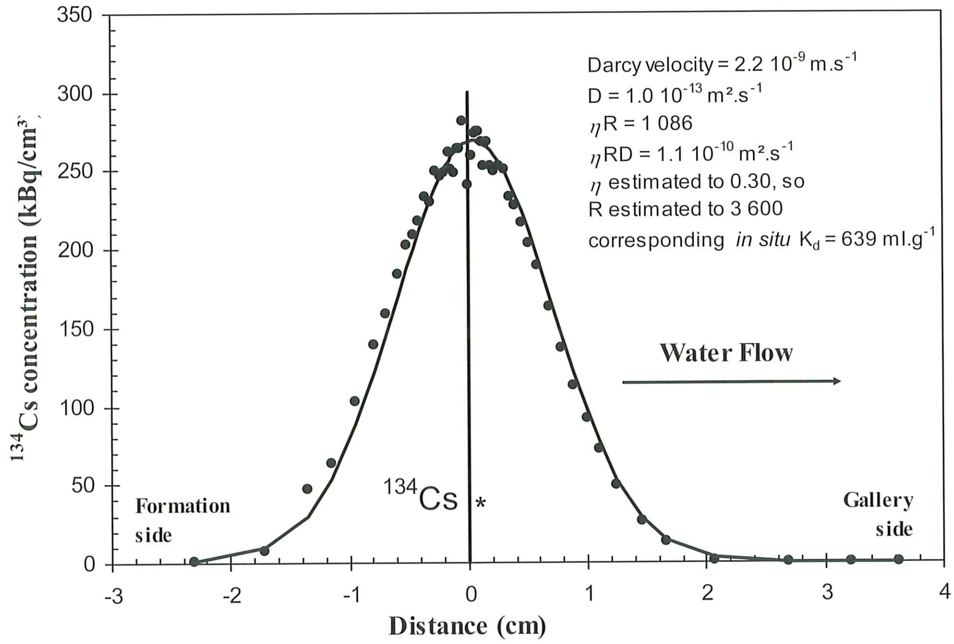

Fig. 2: Long-term *in situ* diffusion experiment with ^{134}Cs on a small Boom Clay core.

In situ gas injection experiments

Large quantities of hydrogen are expected to be produced in an underground repository, mainly from anaerobic corrosion of carbon-steel and to a lower extent because of water radiolysis. The question arises thus if the so-produced hydrogen can dissipate in the clay formation at a rate equal or greater that the H_2 production rate to avoid problems of gas overpressure.

In the frame of the European projects Megas and Progress on the gas migration in clay, several *in situ* helium gas injections have been performed from the HADES URL. Gas breakthrough has been observed in the directly adjacent filters installed on the same multi-piezometer as the helium injection source, but not between different parallel multi-piezometers (*i.e.*, no cross hole helium breakthrough observed). It indicates that the excavation disturbed zone (EDZ) around a borehole, and likely also around a disposal gallery, will constitute a preferential pathway for the migration of gases. Some time after the gas breakthrough, tritiated water (HTO) was injected in the same filter used for the helium gas injection. Measurement of the evolution of HTO concentration in adjacent filters did not provide evidence of preferential pathways for the migration of that tracer. It suggests that Boom Clay rapidly seals again after the gas breakthrough and that diffusion remains the dominating transport process for radionuclide after the gas breakthrough.

Conclusions

Diffusion is the process dominating the transport of radionuclides in Boom Clay. Good agreement is obtained between model predictions and the results of large-scale migration experiments performed *in situ* with non-retarded tracers. Small-scale experiments installed at the extremity of boreholes have allowed to successfully measure diffusion profiles for strongly sorbed tracers. After helium injection in multi-piezometers up to gas breakthrough, no preferential pathway is detected for tritiated water.

Acknowledgments

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Topical session 3

Demonstration of disposal feasibility in underground rock laboratories

Chairman Wernt Brewitz, GRS & TU Braunschweig, Germany

Speakers

Piet Zuidema (Nagra, Switzerland)

Advancements in deep geological disposal of radioactive waste through international co-operation: The role of underground rock laboratories

Juan Carlos Mayor (Enresa, Spain)

Large-scale demonstration experiments at Mont Terri rock laboratory

Jacques Delay (Andra, France)

Research programme carried out at Bure by Andra: Comparison of the Bure and Mont Terri rock laboratories

Advancements in deep geological disposal of radioactive waste through international co-operation: The role of underground rock laboratories

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Introduction

For HLW (spent fuel, vitrified HLW from reprocessing), no repository is yet in operation. However, for long-lived alpha-bearing wastes the WIPP facility in New Mexico, USA has been successfully in operation for several years and has recently been re-certified.

Also for the disposal of HLW, however, over the last 30 years much progress has been made and a significant level of scientific maturity has been reached. This has allowed some countries to make major steps forwards, see e.g. Finland, where a decision in principle for implementing a HLW repository in the community of Eurajoki has been ratified by the Finnish Parliament in 2001 and the construction of an underground rock characterisation facility is now underway. In Sweden, site characterisation work is underway at 2 sites and a siting decision is expected in 2008. In the USA, Yucca Mountain has been chosen as the site to develop a license application. The level of maturity in these (and other) programmes is documented in many milestone reports. For argillaceous media, this includes extensive studies in Belgium, France and Switzerland covering geological syntheses, assessments of engineering feasibility and safety analyses that are based on geological investigations from the surface and on experimental results from underground rock laboratories (see ONDRAF-NIRAS (2001), Andra (2005), Nagra (2002, a, b, c)); these studies are part of government decisions and have been reviewed by national and international bodies. In all the programmes international co-operation is considered essential and the results from URLs play a very important role (see e.g. NEA (2001)).

Elements of a successful repository project

A successful project for a deep geological repository has to be safe and feasible, must be based on a sound scientific and technological basis and must find sufficient societal acceptance.

Sufficient safety and feasibility are achieved by choosing an adequate host rock in a suitable geological environment combined with a system of engineered barriers that is compatible with the wastes to be disposed of and with the geological situation.

Acceptance is a key issue and requires a scientifically sound project and an adequate process of implementation. This includes transparency and public involvement in the site selection and implementation process. The process should also allow the public to become familiar with the repository project and to interact with the organisation in charge of implementing such a repository.

Both international co-operation and URL's contribute to successful projects. They are essential for developing an adequate scientific and technological basis. Experimental programmes in URLs are often the subject of international co-operation (see e.g. European Commission (2002)). The results of URLs also contribute to the confirmation of disposal concepts and designs. URL's can furthermore provide an excellent platform for interacting with the public.

The role of international co-operation and the contribution of URL's in developing a repository project

International co-operation

International co-operation can help to make available the world wide knowledge in the area of waste management. In some areas, it is beneficial that not only the waste management organisations participate in such co-operation but also that the scientific community is involved. A good example of involving the international scientific community is the international research project at Mont Terri where besides the waste management organisations, numerous scientific organisations are involved in the programme in one way or another (either on site, through complementary lab studies or in the analysis and interpretation of results).

The role of underground research laboratories

When discussing the role of URLs in developing a repository project, it is convenient to group the URLs into first and second generation URLs: First generation URLs are not connected to potential sites for repositories but purely serve for research purposes whereas second generation URLs are developed at potential sites and serve also as rock characterisation facilities. Work in first generation URLs started in the sixties (e.g. Asse, Germany) and has played since then an important role (see the contributions e.g. by HADES/Mol in Belgium, the "Underground Research Laboratory" Pinawa in Canada, Tournemire in France, Horonobe, Mizunami (both under construction) and Tono in Japan, Stripa and Aspö in Sweden, Grimsel and Mont Terri in Switzerland, etc.). Some of these facilities were implemented in existing mines (e.g. Asse, Stripa, Tono, Tournemire) or take advantage of existing tunnels (Tournemire, Grimsel, Mont Terri), the latter ones having the advantage of being very easily accessible also with large and heavy equipment. Second generation facilities exist in Bure (France), at Yucca Mountain (USA) and a facility (ONKALO) is under construction at Olkiluoto (Finland).

First generation URL's are used to develop and test site characterisation methods and tools (e.g. drilling technology, pore water sampling methods, testing methodology, benchmarking of geophysical exploration methods and tools, etc.) and serve as a "play ground" to prepare for characterising potential sites (including training of the teams). They are essential in developing the scientific and technological basis. In a URL, relevant processes and phenomena can be studied in the surrounding rock. However, the results on processes and phenomena related to the geological environment are only applicable to potential sites, if the first generation URL is constructed in an adequate environment: The rock studied in the URL has to be sufficiently similar to the host rock under investigation and also the geological environment (e.g. overburden) has to be adequate. In any case, the issue of transferability is a very important issue (see e.g. Mazurek et al. 2006). Also the behaviour of systems of engineered barriers can be investigated as well as their interaction with the surrounding rock.

Furthermore, the technology for emplacing the engineered barriers can be tested under real conditions. A very important aspect is also the testing of excavation technology and the investigation of the effects excavation has on the surrounding rock. To be successful, the investigations in a URL are often complemented by laboratory and modelling studies. This normally leads to complex interdisciplinary projects that also have significant requirements on project management.

With respect to public involvement in the decision-making process for repository implementtation, URL's can play an important role. They provide an excellent platform for interaction with the public. A visit to a URL combined with a broad and open-minded discussion between visitor, scientist and implementer can contribute much to a better understanding for the need of a repository project and to a better appreciation of the scientific basis and the nature of work behind such projects.

Summary and conclusions

- A successful repository project requires a good repository system (an adequate site combined with a suitable system of engineered barriers), a sound scientific and technological basis and sufficient political/public support.
- International co-operation and underground research laboratories are very beneficial in developing a sound scientific and technological basis and in confirming the feasibility of design concepts e.g. through demonstration projects. URLs can also be useful in achieving political and public support.
- Taking maximum advantage of international co-operation and participation in joint underground research laboratory programmes still requires waste management organisations that are dedicated to develop their own repository projects and have the necessary technical, scientific and communication skills.

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Large-scale demonstration experiments at Mont Terri rock laboratory

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Introduction

In the framework of the Mont Terri Project, two large scale demonstration experiments have completed its first phase, namely the Engineered Barrier Emplacement (EB) experiment (October 2000 – November 2003) and the Ventilation (VE) experiment (December 2001 – May 2004). Both experiments were co-funded by the European Commission (5th Framework Programme Euratom, contracts FIKW-CT-2000-0017 and FIKW-CT-2001-0126, respectively) and by the Swiss Federal Office for Education and Science. A prime motive for seeking EC involvement in this type of R&D work is the networking, which promotes utilisation of joint resources and results in knowledge transfer. This in turn is seen as an important tool for confidence building (Andersson 1999).

Several Mont Terri Project partners have participated in this research, namely BGR and GRS (Germany), IRSN (France), Nagra (Switzerland) and Enresa (Spain), who was acting as project coordinator in both experiments.

The EB experiment

The EB experiment (Mayor et al. 2005a) is a full-scale demonstration, in a horizontal drift, of the use of a Granular Bentonite Material (GBM) as clay barrier. The test has been carried out in a 6 m long section of a niche excavated in the Opalinus Clay of the Mont Terri Rock Laboratory. A dummy canister (same dimensions and weight as the reference canister) was placed on top of a bed of bentonite blocks (in turn lying on a concrete bed), and the rest of the clay barrier backfilled with a GBM, made of pellets of different sizes (average D_{95} = 10 mm; D_{50} = 6,3 mm; and D_{10} = 0,25 mm). A hydration system (to accelerate the clay barrier saturation) and hydromechanical instrumentation were installed (Figure 1), and the test section sealed with a concrete plug. The evolution of the hydromechanical parameters along the hydration have been monitored during 1,5 years, and modelled with the CODE-BRIGHT code (Olivella et al. 1996).

For the GBM definition, specific tests were performed. It was shown that the fabrication (in an industrial plant) of a bi-modal mixture of high-density bentonite pellets produced the required material, with a good packing. Emplacement trials with the chosen GBM and with three types of equipment (conveyor, auger and pneumatic) were done, using a full-scale wooden model of the upper part of the EB test section. Better results (dry density of the emplaced GBM ≈ 1,40 g/cm^3) were obtained with the auger.

After the excavation of the test section with a road header, the characterization of its EDZ, and the installation of the rest of the test elements, the GBM was emplaced using the selected auger. A dry density = 1,36 g/cm^3 was obtained. This value is 3 % lower than the one achieved in the previous model trials, due to the presence in the test section of the hydration tubing, which restricted the good working conditions of the auger. According to the laboratory characterization of the GBM, for a dry density = 1,36 g/cm^3, it is estimated that its hydraulic conductivity is lower than 5×10^{-12} m/s, and its swelling pressure about 1,3 MPa.

The CODE-BRIGHT modelling, performed considering the double structure (macro and micropores) of the GBM, provides reasonably good estimations of the initial EDZ extent, and of the suction and swelling pressure evolutions during the test; although the observed heterogeneous behaviour of the clay barrier could not be reproduced.

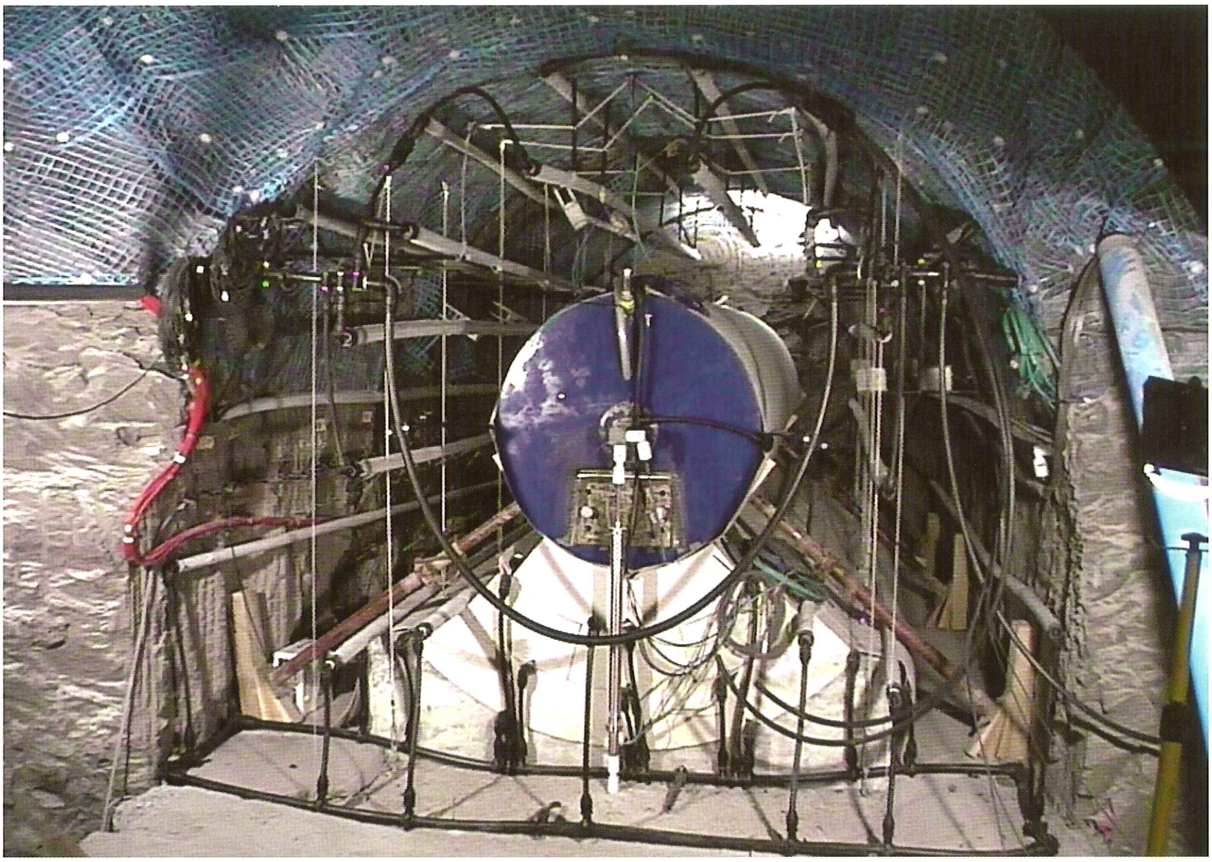

Fig.1: Pre-conditions of the granular bentonite material emplacement

The VE experiment

The required ventilation of the underground drifts during the construction and operational phases of a radioactive waste repository could produce the partial desaturation of the rock around the drifts, modifying its thermo-hydro-mechanical properties, especially in clayey rocks. This change of rock properties may have an impact on the design of the repositories (drift spacing and repository size), which depends on the thermal load that the clay barrier and the rock can accept.

The VE experiment (Mayor et al. 2005b) has been performed to evaluate "in situ" the desaturation of a hard clay; generating a flow of dry air throughout a 10 m long section of a non-lined microtunnel (diameter = 1,3 m) in the Opalinus Clay of the Mont Terri Rock Laboratory. This test section was sealed off and monitored, measuring (in a rock thickness of about 2 m) the rock relative humidity, pore pressure, moisture content, temperature and displacement (Fig. 2). The ventilation equipment generates a flow of air (Q_{in}) with specified values of the relative humidity (RH_{in}) and temperature (T_{in}), which is sent to the test section through an inflow pipe, flows along the test section, and then it is evacuated with an outflow pipe. Values of Q_{out}, RH_{out} and T_{out} are also measured in the outflow pipe. The desaturation period (Q_{in} = 30 m^3/h) had a phase (≈ 2 months) where RH_{in} was set equal to 30 % and another one (≈ 5 months) with air inflow almost dry (RH_{in} = 1 – 3 %). Afterwards, the test was finished with a 3-months resaturation period (Q_{in} = 20 m^3/h; RH_{in} ≈ 100 %).

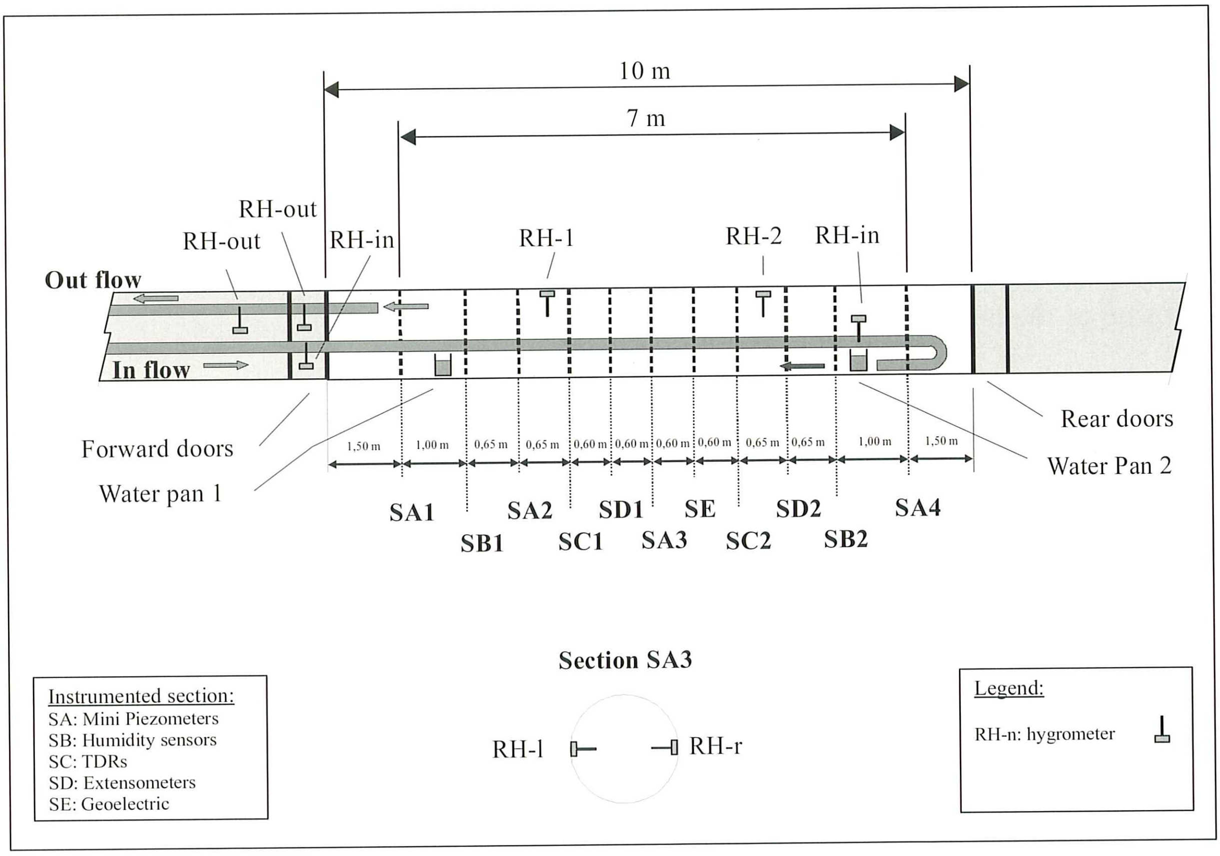

Fig. 2: Instrumented sections of the VE test

Hydraulic, geochemical and geoelectrical laboratory tests were done to characterize the Opalinus Clay properties. Besides, the VE test has been modelled with several numerical codes.

The monitoring has shown that, after the desaturation period, the rock degree of saturation was less than 95 % only in a small ring (thickness less than 40 cm); although a suction state developed up to a radial distance of ≈ 2 m. During this period, rock outflow rates of vapour between 4 and 2 g/m^2h were measured; and in the resaturation phase the inflows were smaller than 1 g/m^2h after one month. Very small shrinkages of the rock (mean value = 0,9 mm) were registered in the desaturation period; while along the resaturation the enlargements were even smaller (mean value = 0,1 mm). Not relevant rock failures nor far reaching cracking were observed on the rock walls. On the other hand, elevated chloride and sulphate contents were detected up to a 20 cm depth.

The numerical codes have modelled sufficiently well the actual rock hydraulic behaviour. The modelling has allowed to estimate a value of the hydraulic conductivity of the Opalinus Clay equal to $2,5 \times 10^{-13}$ m/s, which is similar to laboratory and other field determinations. Besides, the calculated rock desaturation, vapour flows and the development of suctions agree well with the actual behaviour. Only the calculated rock displacements are much lower than the measured data.

On the other hand, an independent calculation has been done, to assess the behaviour of future ventilated galleries. A virtual gallery (diameter = 2,4 m) in a rock similar to the Opalinus Clay has been modelled. Assuming 12 months of ventilation (RH = 80 %) the calculated rock degree of saturation is higher than 95 %; even on the gallery wall.

Conclusions and future perspectives

The EB experiment has demonstrated that using a GBM is a viable option for clay barriers in consolidated clayey rock formations. To further complete the already gained knowledge, dismantling of the test is envisaged in the near future. The following objectives have been identified:

- Determination of the values "in situ" and after saturation of the GBM key parameters (hydraulic conductivity, dry density and moisture content)
- Improvement of the understanding of the GBM saturation process and related modeling
- Gas permeability of the dismantled GBM
- EDZ evolution before dismantling of the GBM

On the other hand, the most important finding obtained from the VE experiment is the following: the desaturation of clayey rocks of low hydraulic conductivity ($K < 10^{-12}$ m/s) due to ventilation is very small. Under real repository conditions, the rock characteristics will not be practically affected by the ventilation of the disposal drifts. To complete this research, a second phase of the experiment is in progress (as part of the NF-PRO integrated project), the main objectives being:

- Assessment of the impact of chemical processes due to ventilation on hydro-mechanical properties
- EDZ evolution during the desaturation/resaturation cycle

Finally, a logical continuation of the research described, particularly of that of the EB experiment, would be the launching of a full-scale heater test including the interaction of the EBS and the geosphere (like for example the PRACLAY and the FEBEX projects). This is perfectly in accordance with the general trends of in situ experiments, where the emphasis is now on understanding the interaction between the EBS and the geosphere and on the testing of models for certain key processes, which inevitably involves the examination of processes that are coupled (NEA 2001).

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Research programme carried out at Bure by Andra: Comparison of the Bure and Mont Terri rock laboratories

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Introduction – Presentation of the Bure URL Project

In November 1999 Andra began building an Underground Research Laboratory (URL) on the border of the Meuse and Haute-Marne departments in eastern France. The research activities of the URL are dedicated to reversible, deep geological disposal of high-activity, long-lived radioactive wastes in an argillaceous host rock. The Laboratory consists of two shafts, an experimental drift at 445 m depth and a set of technical and experimental drifts at the main level at 490 m depth.

The main objective of the research is to characterize the confining properties of the clay through *in situ* hydrogeological tests, chemical measurements and diffusion experiments. In order to achieve this goal, a fundamental understanding of the geoscientific properties and processes that govern geological isolation in clay-rich rocks has been acquired.

After establishing the geological conditions, the underground research programme had to demonstrate that the construction and operation of a geological disposal will not introduce pathways for waste migration. Thus, the construction of the laboratory itself serves a research purpose through the monitoring of excavation effects and the optimization of construction technology. These studies are primarily geomechanical in nature, though chemical and hydrogeological coupling also have important roles.

The objectives of the URL for the 1999-2005 years were mainly the *in situ* characterization of the physical and chemical properties of this rock. This involved achieving a level of knowledge that may be used to develop disposal designs and perform safety studies. The results should make it possible to assess the safety of a disposal over several tens and even hundreds of thousands of years. Figure 1 presents the overall layout drawing of the drifts in the Meuse/Haute-Marne URL.

Studies and experimental work cover three major aspects in the URL drifts:

- **Containment capability of the host formation**
  This containment capability comes from the specific physical characteristics of the rock and the physico-chemical characteristics of the interstitial fluids and their interaction with the rock. The chemical characteristics of the interstitial fluids condition the mobility of the various radionuclides likely to be found in the natural environment (Pearson et al. 2003). The studies focus on knowledge of the geochemistry of the interstitial fluids in equilibrium with the minerals in the rock and on the diffusion and retention capabilities of the radionuclides.
- **Creation of damaged and disturbed zones associated with drift excavation**
  The main purpose of the studies on this topic is to investigate how the rock reacts to the excavation of shafts and drifts, and the associated development of the damaged and disturbed zone (Tsang & Bernier 2005). Several techniques and methodologies used at Bure

URL had been previously developed at Mont Terri Rock laboratory (Thury et al. 1999). Damaged zone (EDZ) and disturbed (EdZ) (Blümling et al. 2006) were characterized during monitoring of the shaft and excavation of the experimental drifts.

- **Assessment of sealing zone concept**
  The sealing of a drift is a major issue when considering the disposal construction options. It involves designing systems to re-establish the original low permeability of the formation by overcoming potentially negative effects from the damaged zone surrounding the drifts and shafts.

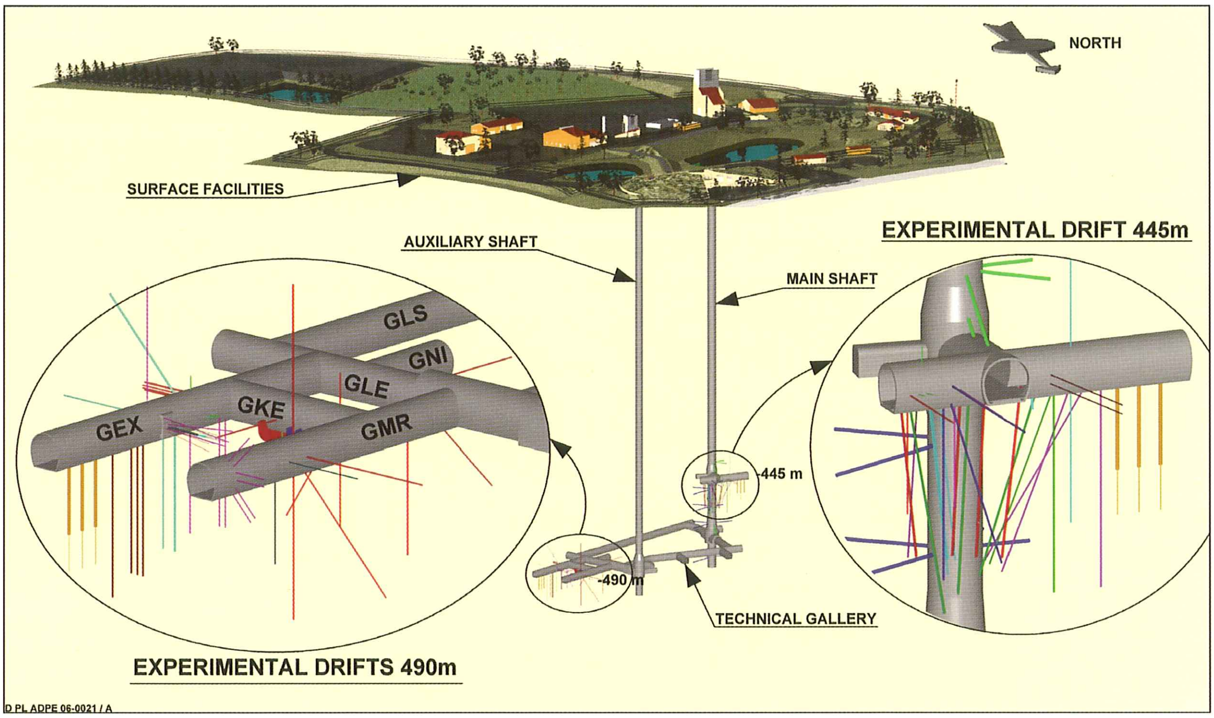

Fig. 1: Layout of the experimental drifts

Lessons learned from the Mont Terri Project

The objective of Andra's activities at Mont Terri is to develop through scientific experimentation measurement tools and methodologies for acquiring the physical and chemical properties of the rock. The aim is to apply these tools to the specific physical characteristics of argillaceous rock such as that found at the Meuse/Haute-Marne site.

The Mont Terri experiments concern:

- The preparation of instrumentation tests for scientific measurements,
- The refinement of experimental concepts,
- Data and scientific approaches.

Considering a possible transposition of the results obtained at Mont Terri to the Meuse/ Haute-Marne site relies on the fact that the confinement characteristics of the Callovo-Oxfordian argillaceous rock, as well as those of the Opalinus clays, result from (i) characteristics intrinsic to their various components (ii) and the geometry of their porosity. This transposition also addresses factors liable to modify confinement characteristics on a large scale, such as faults. Defining the possibilities and limits of data transposition from one site to the other involves confronting the genesis and evolution conditions of both rock formations which determined the nature and organization of their mineral components and the circulation of their interstitial fluids throughout their history.

Until the end of the Cretaceous, both formations underwent a gradual burying process (Thury et al. 1999). While the burying of clays at Opalinus reached 1350 m (or a maximum temperature of 85 °C), the burying of the Callovo-Oxfordian argillaceous rocks is only 750 – 800 m (or a maximum temperature of 40°C). The formation of the Alps drastically modified the situation of both sites. The Meuse/Haute-Marne site kept at a distance from the major orogenesis effects. It emerged as early as the beginning of the Miocen (20 million years ago) and only later underwent a 250 - 300 m erosion. On the other hand, the Mont-Terri area was submitted to an uplift that induced a cumulated erosion of 1,100 m of the ground, but it only emerged actually during the Tortonian (10 million of years). At Mont Terri, the uplift brought about a major tectonic compression phase associated with the development of fault systems. This led to the current highly contrasted situation of both sites, namely to different natural stress fields.

Example of transposition of the approach and comparison of results: Geochemical logging of the interstitial waters

In both cases, the formation studied is a fine rock consisting for the greater part of clay minerals which formed almost at the same geological period. This layer settled in a marine environment still identifiable today at Mont Terri. Both formations are surrounded with more permeable limestone formations through which rainfall water that infiltrated at outcrop level has been circulating for several million years.

In both cases also, the evolution mechanisms of the interstitial fluids are related to diagenetic compaction phenomena associated with the expulsion of water and mobile ions. They are also related to water/rock reactions resulting from the diffusion originating in boundary layers. Owing to the extremely slow process involved, we notice that although these systems cannot be considered as entirely closed at the scale of geological times, they remain sufficiently confined for isotopic fractionning processes to occur and to continue. Owing to the similarities between the mineral components of both formations, the chemical composition of their interstitial waters is controlled by the same water/rock interaction mechanisms. The only significant difference between chemical compositions is a higher dilution rate of the Callovo-Oxfordian fluids.

Example of limitation of the transposition of the approach and results: Damaging induced by the construction of a drift

The topographical and tectonic context of Mont Terri is very different from that of Meuse/ Haute-Marne. The capping is limited (200m on average, whereas the Meuse/Haute-Marne URL lies at 490m depth). Therefore, Mont Terri has a particular natural stress field showing a major vertical stress, strong anisotropic stresses and tensor rotation with respect to the stratification.

The natural stress field of the Meuse/Haute-Marne site is less complex: the orientations of the major stresses are in accordance with the stratification, the main stress is horizontal and the stress anisotropy is weak (ranging between 1 and 1.3).

At Mont Terri, EDZ fractures at the walls are essentially extension fractures resulting from the mechanical removal associated with the excavation. The mean extension of the damaged zone is less than 1 m, ranging between 0.1 m and 1.25 m (Bossart et al. 2004). Constraint at the walls is mostly controlled by ruptures of the sedimentary planes associated with fractures parallel to the bedding. The combination of both phenomena may cause block to fall.

At Bure, at 445 m depth, the damaged zone is very limited, almost nonexistent, and it only shows at the intersection of drifts through a network of vertical fractures parallel to the orientation of the main horizontal stress. At 490 m the situation is very different. We notice at low depth (40 to 70 cm at the most) the development of extension fractures, but mainly a significant development of shearing fractures ("chevron type fractures") all along the excavation at a maximum depth of two meters. Though this fracture geometry developed in clays considered as soft (Mol), it also developed at Bure in hard clays but under a much greater lithostatic stress. It is worth noting that it has been observed on cores both at Mol and at Bure. The complexity of the situation is compounded by the superposition of fractures induced by the horseshoe-shaped drifts and the absence of support of the floors.

At any rate, and more particularly in the latter case, the extension of the damaged and fractured zones are closely associated with excavation and support techniques and the orientation of the drifts with respect to the natural field of constraint (Blümling et al. 2006). This has led Andra to propose for Level 490 m a EDZ conceptual model quite different from the one proposed for Mont Terri (Fig. 2).

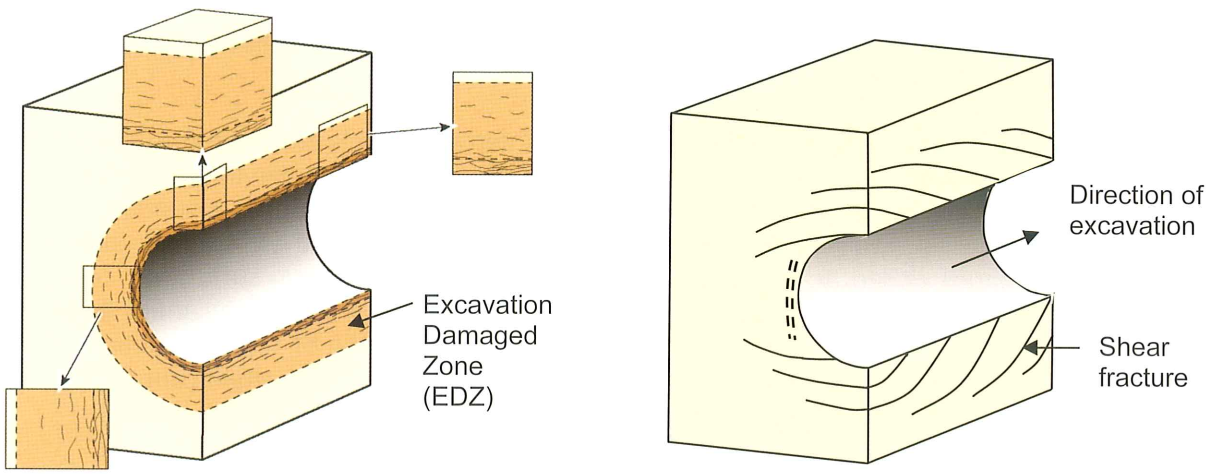

Fig. 2: EDZ conceptual model around a circular drift at Mont Terri (left) and at 490 m at Bure (right)

Results and conclusions

The sedimentological and geochemical context and more specifically the organization of the porosity, the fluid/rock interactions, and diffusion and retention characteristics of the rock make it possible to propose the transposition of the phenomenological design approaches and the comparison of results between Mont Terri and Bure. However, the difference in tectonic historical background leads to completely different situations concerning both the state of *in situ* natural stresses and the mechanical behaviour of the shafts and drifts. The large amount of work carried out at Mont Terri for the past ten years has helped Andra to submit an overall report for the Bure site. The global knowledge acquired and the lessons learned at Mont Terri provided the required relevant data and analyses for proposing a scientific approach for the design, evolution and safety assessment of a deep geological disposal.

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Panel session

Research needs and the Mont Terri rock laboratory

Chairman Jörg Hadermann, Paul Scherrer Institute, Switzerland

Panellists

Wernt Brewitz (GRS & TU Braunschweig, Germany)

Christophe Davies (European Commission, Brussels/Belgium)

Philippe Lalieux (Ondraf/Niras, Belgium)

Patrick Landais (Andra, France)

Piet Zuidema (Nagra, Switzerland)

Research needs and the Mont Terri rock laboratory

Jörg Hadermann

Paul Scherrer Institute, 5232 Villigen PSI, Switzerland

Summary

The workshop concluded with a panel session, the general theme of which was the future role of underground research laboratories (URLs). The panellists were asked to highlight, in introductory statements, the importance of URLs in the context of national and international waste management programmes. Each of the five panellists focused on a specific theme.

It is convenient – although not always strictly possible – to distinguish between URLs which are not located at potential repository sites (so-called 1st generation URLs, for example Mont Terri, Tournemire and Asse) and those which are. What is the future role of 1st generation URLs? Are they still needed as national programmes become more and more site-specific? **Wernt Brewitz** (GRS) made a strong case for such facilities. He pointed to the need for strategic research and basic tasks, such as further development of the state-of-the-art in sciences related to the safety case, the investigation of long-term processes, training of scientists and technical staff and demonstration of system performance, also within the context of stakeholder involvement. He argued that, in these areas, 1st generation URLs have considerable advantages in being very flexible. He proposed the development of a specific URL network group with the primary emphasis on public relations and stakeholder information. There was consensus that 1st generation URLs will continue to play an important role in waste management and in providing a context for science in relevant fields.

The operation of a URL represents a significant financial commitment. Do we need experiments that extend over decades and costly installations for experiments with radioactive materials/tracers? Or are these merely a means for long-term occupational therapy? **Philippe Lalieux** (Ondraf/Niras) gave an answer based on many years of experience in Belgium. The key goal is to ensure credible argumentation in a safety and feasibility case. From a scientific viewpoint, as well as for purposes of technological demonstration, this cannot be achieved without the use of radioactive materials. Similarly, decade-long experiments help in model confirmation and public acceptance, although the representativeness of the time span can always be called into question. Long-term tests are also a prerequisite for developing monitoring systems under realistic conditions and help in optimising the engineered barrier system. Within the framework of the stepwise licensing process, part of the disposal facility could be used as a URL when building the next licensing case.

The projects within the 6th Euratom Research Framework Programme are nearing completion. What is the role of URLs in FP7 (2007-2011) and what scientific plans and structures are there? **Christophe Davies** (EC) addressed these questions. The objectives of FP7 are geared towards supporting implementation-oriented research and technological development. URLs have a role to play in the areas of geological disposal infrastructure, and human resources and training. On the shorter term (2007/2008), many projects on geological disposal are already ongoing and have a component of research in URLs. The activity area "infrastructures" is new, offering many possibilities for networking and training in URLs. Over the same time span, the establishment of

a Technology Platform on geological disposal is foreseen, in particular by and for the end-users. This Platform will elaborate and implement a Strategic Research Agenda, mobilise the necessary critical mass of research and innovation efforts and give feedback to the annual programmes. This also includes coordination of URL activities.

The starting-point for **Patrick Landais** (Andra) were the evaluations of Dossier 2005 Argile. Four national and international bodies had identified priority research themes, calling *inter alia* for further URL investigations. During the period 2007 – 2010, technological tests and demonstrations will be implemented (e.g. with respect to excavation and lining, backfill, disposal cells) at the Bure site. On the research side, the major themes are improving the understanding of basic phenomena, TMC coupling and interfaces between repository components, as well as the validity of data on different scales. Ongoing experiments will continue. New investigations on materials behaviour and long-term diffusion and retention will be initiated. The activities foreseen at Bure are related to non-site-specific data acquisition and constitute part of the improvement of knowledge on generic mechanisms and processes, as well as technological development. In this sense, international cooperation and continued comparison between different test sites will also be needed in the future.

The future role of the Mont Terri URL within the Swiss programme was highlighted by **Piet Zuidema** (Nagra). Mont Terri will continue to be the URL in Opalinus Clay until a site-specific URL becomes available (or Opalinus Clay option is dropped). A general theme is, therefore, transferability of information to potential sites. Also in this context, comparison with results from other clay projects is important. The main issues for investigation are gas migration, radionuclide migration, including geochemical aspects, and rock mechanics, including the behaviour of the EDZ and self-sealing. It is important to perform long-term experiments to see to what extent the conclusions from short-term investigations are confirmed. Experiments on different scales, in the laboratory and in the field, have to be integrated and scrutinised with respect to consistency of the conceptual picture and of quantitative data. The investigations need to be coordinated with work in other URLs to see to what extent the overall results can be explained in a consistent manner.

The discussions between the panellists and the audience, as well as amongst the panellists themselves, did not raise any large discrepancies. The technological approaches and the repository designs might have specific national characteristics, but there was wide consensus on the most significant scientific issues, on the role of URLs in addressing these and on their importance for more general issues such as technological development, training and demonstration. This consensus is not only the result of focusing on clay and clay rocks, but probably also the outcome of many years of cooperation among the waste management organisations and the strong long-term involvement of the scientific community.

Poster presentation

Mont Terri partner organisations

Mont Terri Project
Overview

swisstopo
Federal Office of Topography (Switzerland)

Andra
Agence nationale pour la gestion des déchets radioactifs (France)

BGR
Federal Institute for Geosciences and Natural Resources (Germany)

CRIEPI
Central Research Institute of Electric Power Industry (Japan)

Enresa
Empresa Nacional de Residuos Radiactivos (Spain)

GRS
Gesellschaft für Anlagen und Reaktorsicherheit mbH (Germany)

HSK
Swiss Federal Nuclear Safety Inspecorate (Switzerland)

IRSN
French Institute for Radiation Protection and Nuclear Safety (France)

JAEA
Japan Atomic Energy Agency (Japan)

Nagra
National Cooperative for the Disposal of Radioactive Waste (Switzerland)

Obayashi Corporation
(Japan)

SCK·CEN
The Belgian Nuclear Research Centre (Belgium)

RCJU
République et Canton du Jura (Switzerland)

Mont Terri Project

Mont Terri Project
Underground Rock Laboratory
Laboratoire souterrain

Project objectives

An international underground investigation programme consisting of experiments in the security gallery and adjacent research galleries of the Mont Terri motorway tunnel near St-Ursanne (Republique and Cantone of Jura/Switzerland) in a shale formation named "Opalinus Clay", with the objective

- To test and improve techniques for hydrogeolocical, geochemical and geotechnical investigations in an argillaceous formation
- To characterise the hydrogeology, geochemistry and geomechanical behaviour of the Opalinus Clay formation
- To investigate the interaction of the Opalinus Clay with other materials and engineered barrier systems of geological waste disposal facilities.

Partner organisations

Partner organisations	Since
SWISSTOPO Federal Office of Topography	2006
NAGRA National Cooperative for the Disposal of Radioactive Waste	1996
HSK Swiss Nuclear Safety Inspectorate	2003
ANDRA Agence Nationale pour la Gestion des Déchets Radioactifs	1996
IRSN Institut de Radioprotection et de Sûreté Nucléaire	1998
BGR Bundesanstalt für Geowissenschaften und Rohstoffe	1998
GRS Gesellschaft für Reaktorsicherheit und Strahlenschutz mbH	1999
ENRESA Empresa Nacional de Residuos Radiactivos, S.A.	1997
SCK•CEN Studiecentrum voor Kernenergie • Centre d'Etude de l'Energie Nucléaire	1996
JAEA Japan Atomic Energy Agency	1996
OBAYASHI Obayashi Corporation	1998
CRIEPI Central Research Institute of Electric Power Industry	2002

Project Direction and **Operator of rock laboratory**
SWISSTOPO, Federal Office of Topography

Project Authorisation
Republique and Canton of Jura - Département de l'Environnement et de l'Equipement

Project Management
Geotechnical Institute Ltd., St-Ursanne

Mont Terri Project
Underground Rock Laboratory
Laboratoire souterrain

c/o Geotechnical Institute Ltd.
Fabrique de Chaux 65
2882 St-Ursanne (Switzerland)

Phone + 41 32 461 20 40
Fax + 41 32 461 20 42
Internet www.mont-terri.ch

swisstopo

Bundesamt für Landestopografie
Office fédéral de topographie
Federal Office of Topography

Seftigenstrasse 264, 3084 Wabern, Switzerland
Phone +41 31 963 21 11, www.swisstopo.ch

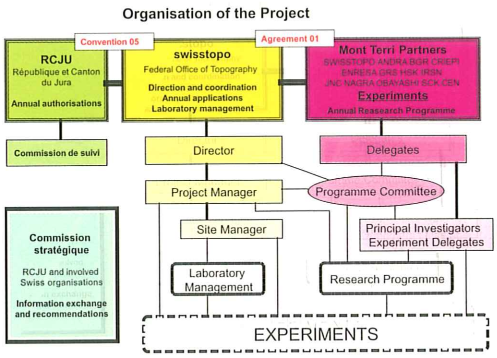
The geologists of the Swiss Geological Survey

Company profile and mission

- Swisstopo is the competence center for geoinformation of the Swiss Federation
- Swisstopo produces spatial reference data and derived products of premium quality
- Tasks of Swiss Geological Survey, a branch of swisstopo:
  - Organization of national surveys
  - Gathering and archiving of the geo-data, its processing and compilation in the form of geological maps
  - Publication of reports, recommendations and guidelines.

Objectives of Mont Terri project participation

- Swisstopo is responsible for the Mont Terri project management and the operation of the rock laboratory
- swisstopo implements the research programs resolved upon by the project partners
- Swisstopo maintains the contractual basis of the Mont Terri project. These are the Co-operation Agreement 2001 (contract between Swiss Confederation and Mont Terri Project Partners) and the Convention 2005 (contract between Swiss Confederation and the Republic and Canton of Jura).



Geological map of the Mont Terri anticline, produced by swisstopo

Present research priorities at Mont Terri

- Understanding of hydrogeological processes in low permeable formations
- Gaining know-how in long-term monitoring of pore pressures and mechanical deformations.

ANDRA

Agence nationale pour la gestion des déchets radioactifs

Parc de la Croix Blanches, 1/7 rue Jean Monnet, 92 298 CHATENAY-MALABRY Cedex
Phone +33 1 46 11 80 00

Company profile and mission

ANDRA is a public establishment (EPIC) under supervision of the Ministries of the Environment, and Industry, and Research, financed by the waste producers. The work force is around 360 people.

The 3 missions are:
- Information: situation of current radioactive waste and recoverable materials in France
- Industry: design, construction, operation & post-closure monitoring of disposal facilities
- Research: feasibility of an underground repository for high-level and long-lived waste.

Objectives of Mont Terri project participation

The purpose of the activities of ANDRA at Mont Terri is to develop tools and methods of the properties of chemical and physical measurements in a geological formation.
The objective being to apply these methods to the stiff, argillaceous rocks such as those of the Bure site.
The method adopted was to confront the models, derived from the Callovo-Oxfordian rocks, with the results of analyses conducted at Mont Terri.

Present research priorities at Mont Terri

The organization at Mont Terri provides a unique exchange between the engineers of the various agencies and scientific organizations. The prime objective is to reinforce these bonds and to create a network of expertise around this project.
Thanks to this network, the engineers of ANDRA were able to attain their high levels of expertise at Bure and acquire international recognition.
Currently, ANDRA is committed to programmes on "diffusion-DIA", "geochemistry of water PC, PC-C", and "migration of gas-HG-A".
Moreover, ANDRA continues the interpretation of thermal and sealing experiments.

BGR Bundesanstalt für Geowissenschaften und Rohstoffe
GEOZENTRUM HANNOVER

Federal Institute for Geosciences and Natural Resources
Stilleweg 2, D-30655 Hannover, Germany
Phone +49 511 643 2420, www.bgr.bund.de, wallner@bgr.de

Company profile and mission

- Central geoscientific authority providing advice to the German Federal Government, other national institutes and industry
- Working on all geoscientific and geotechnical questions related to German activities for the safe radioactive waste disposal in deep geological formations, i.e. focussed research, site selection, site exploration, characterising the barrier properties of potential host rocks and long-term safety analysis
- International cooperation and membership in international committees.

Objectives of Mont Terri project participation

Transfer of 20 years salt expertise to the investigation and characterisation of sites in alternative host rocks (clay and granite). Transfer of know-how in a clay host rock to geological formations at sites in Germany:

- Determine rock parameters
- Develop and test investigation methods and demonstrate their applicability
- Develop international standards
- Exchange experiences and develop the state of the art
- Maintain flexibility with different host rocks (site selection is not controlled by previous host rock determination).

Present research priorities at Mont Terri

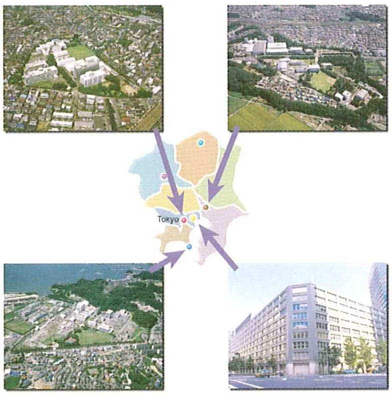
Development and adaptation of methodologies and experimental techniques to determine THMC properties of claystone and their evolution with time:

- Characterisation of the excavation damaged zone
- In-situ gas permeability and gas migration
- In-situ stress measurements
- Laboratory tests to determine THMC properties.

CRIEPI

Central Research Institute of
Electric Power Industry

Ohtemachi Bldg. 7F, 1-6-1 Ohtemachi, Chiyoda-ku, Tokyo 100-8126, Japan
Phone +81 3 3201 6601, http://criepi.denken.or.jp/en/



Organization profile and mission

CRIEPI was established in 1952 as a central research institute for the electric power industry in Japan and it has 7 research laboratories and a research center at 4 districts around Tokyo area.
CRIEPI is engaged in an ongoing program of advanced research on proposed energy policies for Japan, and in a variety of technology development projects, the aim being to facilitate the supply of electricity for higher living standards and a stronger economy.

Objectives of Mont Terri project participation

As one of international collaboration research projects, CRIEPI joined the Mont Terrri project in 2002. The objectives are

- To verify and demonstrate the technology and methodology for the radioactive waste disposal management which was developed by CRIEPI
- To learn new survey technology and estimation method by joining the collaboration researches as a partner
- To collect the technical information about the radioactive waste disposal management.

Present research priorities at Mont Terri

In order to verify and demonstrate the technology and methodology for site characterization in the sedimentary rock which was developed by CRIEPI, we have been conducting following experiment.
CP experiment: Chemical and physical weathering and deterioration along the tunnel wall.
PC-B experiment: Ground water dating by using 4He and 139Cl.
AS experiment: Anisotropy determination of rock and rock stress test taking into account the obtained anisotropy.

enresa
Empresa Nacional de Residuos Radiactivos, S.A.

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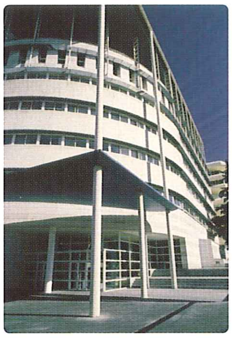
Phone +34 91 566 81 00, www.enresa.es



Company profile and mission

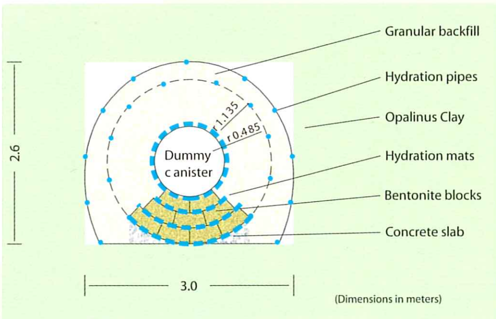
Public company founded in 1985 by the Spanish Government for the management of radioactive wastes, including:

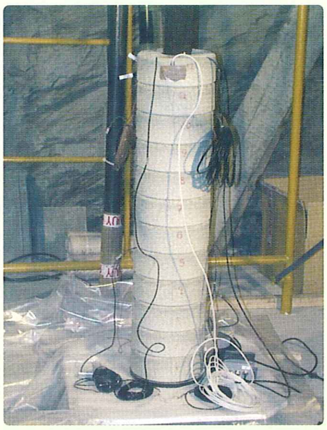
- Design, construction and operation of facilities for the disposal of low-level waste (LLW); interim storage and final disposal of spent fuel, vitrified high-level waste and intermediate-level waste (SF/HLW/ILW)
- Decommissioning of nuclear facilities, including nuclear power plants (NPP)
- Reclamation of old uranium mining sites
- Strong international cooperation, particularly through the EURATOM programme.

Objectives of Mont Terri project participation

The Mont Terri rock laboratory fulfils the following objectives:

- The build-up of know-how in planning, performing and interpreting field experiments in various disciplines (rock mechanics, hydrogeology, geochemistry)
- The acquisition of practical experience in the development of investigation methodologies, measuring techniques and test equipment which will be of use during actual repository site characterization.





Present research priorities at Mont Terri

The following research activities are in progress as part of the international research project at Mont Terri:

- Diffusion and retardation of radionuclides
- Coupling of thermal-hydro-mechanical processes
- Engineered barrier emplacement
- Geochemical and hydrochemical rock characterization.

Gesellschaft für Anlagen und Reaktorsicherheit (GRS) mbH

Schwertnergasse 1, 50667 Köln, Germany
Phone +49 221 20 68 0, www.grs.de

Company profile and mission

- Founded 1976 by Federal Republic of Germany (46%), the federal states of Bavaria (4%) and Northrhein-Westfalia (4%) and the Technische Überwachungsvereine (TÜV) and Germanische Lloyd (together 46%)
- Germany's central scientific-technical expert organization for all issues related to nuclear safety and nuclear waste management
- ...with strong international cooperation based on bilateral and international agreements.

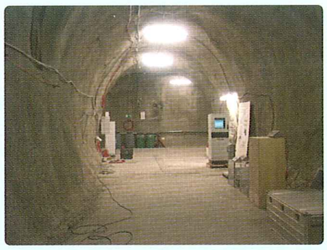
Objectives of Mont Terri project participation

- In Germany, a final decision with regard to the selection of a geological formation as host rock for disposal of radioactive waste has not been made yet
- Participation in international projects in different geological formations such as the Mont Terri Project offers the possibility to improve and develop further own knowledge on basis of the international state of science and technology
- Synergy effects with regard to scientific competence and cost efficiency.

Present research priorities at Mont Terri

Integrity of the argillaceous host rock and coupled hydraulic-mechanical properties of geotechnical barriers represent major issues in long-term safety analyses.
This in mind, GRS is currently

- Testing the suitability of clay/sand-mixtures as sealing materials for repository rooms containing gas generating waste (SB-experiment)
- Participating in the heater experiment HE-D jointly conducted by ANDRA (lead) and GRS
- Participating in the Ventilation Experiment (VE) jointly conducted by ENRESA (lead), BGR, GRS, IRSN and NAGRA
- Preparing investigations on gas migration in the undisturbed host rock beyond the excavation disturbed zone.



Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

HSK

Hauptabteilung für die Sicherheit der Kernanlagen HSK
Division principale de la sécurité des installations nucléaires
Divisione principale della sicurezza degli impianti nucleari
Swiss Federal Nuclear Safety Inspectorate

Organisation profile and responsibilities

HSK is the Swiss government's supervisory authority for nuclear safety in the field of nuclear energy and radioactive waste management and has about 90 employees (physicists, engineers, chemists, biologists, geologists and supporting personal). The main responsibilities of HSK are

- To formulate safety requirements for nuclear installations and waste management
- To provide technical safety assessment for each licensing stage of a nuclear installation
- To supervise safety and radiation protection and to licence operating personnel
- To supervise all activities related to final disposal of radioactive waste (site selection, site characterization, site confirmation)
- To follow the developments in the state-of-the-art of science and technology in the field of nuclear safety, radiation protection and waste management
- To inform the general public and political authorities regarding safety of nuclear installations, radiation protection and waste management.

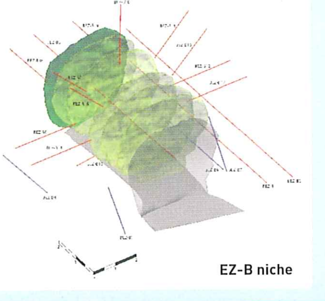
Objectives of Mont Terri project participation

HSK has joined the Mont Terri Project as a new partner in 2003 in order

- To develope and validate adequate numerical modelling tools relevant for reviewing safety assessment in a cooperation with the engineering geology research group of ETH Zürich
- To improve the scientific understanding of the hydraulic, mechanical and chemical behaviour of Opalinus Clay and to keep up to date with new developments in the research of argillaceous rocks.

Present research priorities at Mont Terri

The main research activity of HSK and ETH focuses on the EZ-B experiment, which investigates the formation of new fractures around a tunnel caused by the redistribution of stresses around the excavation. The purpose of this experiment is to monitor the generation and propagation of fractures in the Excavated Disturbed Zone (EDZ), to characterize the geometry of the fracture network and to investigate the impact mechanical heterogeneities may have on the nucleation and propagation of the fracture pattern. A fracture mechanics code will be used to simulate the EDZ fracture pattern, which will then be compared with the observed field data.



EZ-B niche

Mont Terri Project
Underground Rock Laboratory
Laboratoire souterrain

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SWISSTOPO ANDRA BGR CRIEPI ENRESA GRS HSK IRSN JAEA NAGRA OBAYASHI SCK•CEN

IRSN

INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

French Institute for Radiation Protection and Nuclear Safety

77-83, avenue du Général de Gaulle, 92140 Clamart, France
Phone +33 1 58 35 88 88

Company profile and mission

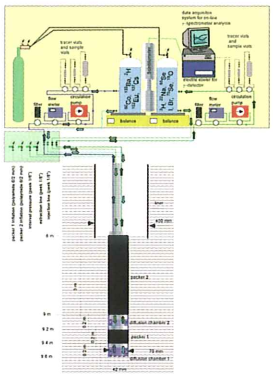
- Public establishment of an industrial and commercial nature created in 2002 and placed under the authority of 5 Ministries (Ecology, Research, Health, Industry and Defence). The Institute works together with the French competent authorities regarding nuclear safety and radiation protection for civil and defence activities.
- At the request of the French authority of nuclear safety, IRSN evaluates the feasibility and safety of a repository of high-level radioactive wastes (HLRW) in deep geological formations. To complete this work, the institute has developed a capacity of expertise covering the technical field concerned with the safety of geological repositories.

Objectives of Mont Terri project participation

Argillaceous formations are the main option for a French repository of HLRW in deep geological formations. The joint R&D study of Opalinus clay at Mont Terri and Toarcian argillites in its experimental station of Tournemire helps IRSN in developing its expertise capacity. The final goal is to assess the Callovo-Oxfordian argillites as a potential host rock for a repository in the east of France. The Mont Terri project is also a good opportunity of exchanging concepts and ideas with other researchers in applied clay sciences.

Present research priorities at Mont Terri

To perform experiments that cannot be conducted at Tournemire. For example, the long term Diffusion and Retention experiment (DR) that uses radioactive tracers. The EC co-financed Ventilation (VE) experiment involving new investigation techniques of the excavation disturbed zone, or again experiments that enable site comparison as in Hydrogeologic Analyses (HA).



Japan Atomic Energy Agency

Tokai-Mura, Naka-Gun, Ibaraki pref, 319-1195, Japan
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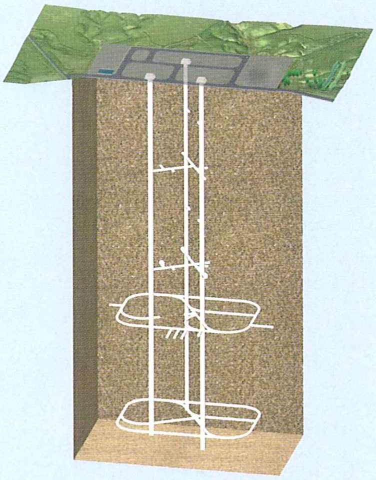


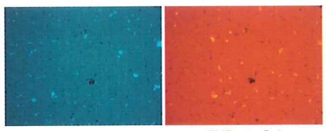
Horonobe URL facilities

Organization profile and mission

- JAEA was established in October 1, 2005, as the result of the integration of the Japan Atomic Energy Research Institute (JAERI) and the Japan Nuclear Cycle Development Institute (JNC). JNC was established as a successor organization of the Power Reactor and Nuclear Fuel Development Corporation (PNC) in October 1998 (participating in the Mont Terri project as PNC).
- JAEA is the only institute in Japan dedicated to comprehensive research and development in the field of nuclear energy.
- JAEA is engaged in R&D for the establishment of nuclear fuel cycles (fast breeder reactor cycle technology and treatment and disposal of radioactive waste), enhancement of the safety of nuclear energy, nuclear fusion reactor engineering, quantum beam technology and others.

Objectives of Mont Terri project participation

- In 1996 JAEA (former PNC) signed a cooperation agreement to perform a joint underground investigation program, "Mont Terri project".
- JAEA is participating in the PC experiment to analyze microbial communities by using molecular methods for better understanding of microbial contribution to the pore water chemistry.

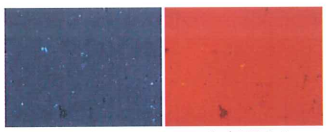


DAPI EUB338-Cy3
Bacterial population = 41% of total Prokaryotes
Observation of Bacteria

Achievement of JAEA for the PC experiment

In the PC experiment (Phase 9) pore water samples are taken from the borehole and directly observed under microscope using two methods: total DAPI count and FISH. The summary of this experiment is listed below.

1 direct DAPI count totaled 3.5 x 105 cells/ml
2 40% of the prokaryotes was identified as (active) Bacteria
3 Archaea was infrequent but active in the pore water sample
4 Sulfate reducing bacteria Desulfotomaculum and Methanogen Methanosarcinales relatives were detected.



DAPI Arch915-Cy3
Archaeal population < 1% of total Prokaryotes
Observation of Archaea

nagra

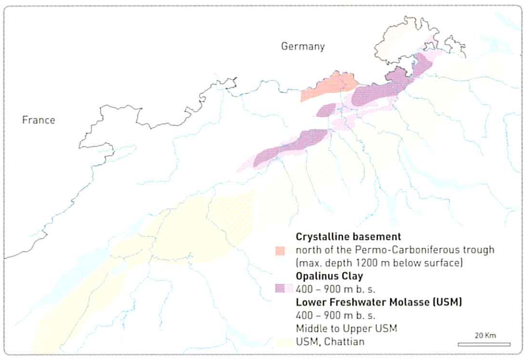
National Cooperative for the Disposal of Radioactive Waste

Hardstrasse 73, 5430 Wettingen, Switzerland
Phone +41 56 437 11 11, www.nagra.ch, info@nagra.ch

Company profile and mission

- Cooperative founded in 1972 by the operators of the five Swiss nuclear power plants and the Federal Government (responsible for the wastes from medicine, industry and research)
- Development of Swiss repository projects for disposal of radioactive waste ...
  i.e. site exploration, repository design, site selection, safety assessment of geological repositories; characterisation and inventorying of Swiss radioactive materials
- ... with strong international cooperation based on bilateral & international agreements.

Objectives of Mont Terri project participation



Potential host rocks and regions

Opalinus Clay is the primary option for the siting of a Swiss national repository for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (SF/HLW/ILW).

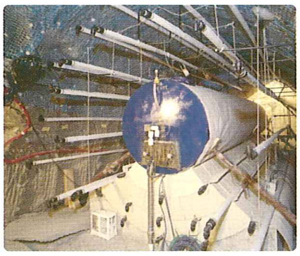
For the national disposal programme, the Mont Terri underground research laboratory fulfils the following objectives:

- Geoscientific research facility for long-term experiments in argillaceous rock
- Public information centre.

Present research priorities at Mont Terri

For confirmation of present knowledge and optimisation of the proposed disposal system with regard to construction, operation and long-term safety, the following research activities are in progress as part of the international research project at Mont Terri:

- Diffusion and retention of radionuclides
- Gas migration
- Evolution with time of the excavation disturbed zone ("self-sealing" of fractures)
- Geochemical and hydrochemical properties of Opalinus Clay.



Engineered Barrier Emplacement experiment

OBAYASHI

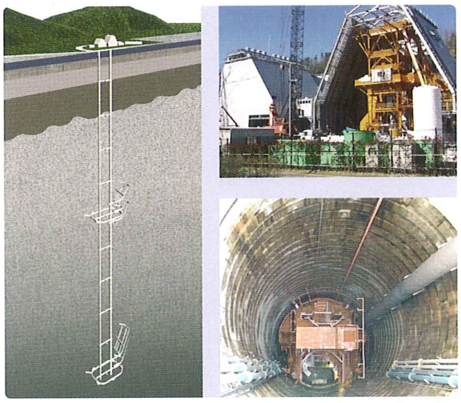
Obayashi Corporation

Shinagawa Intercity Tower B - 2-15-2, Konan, Minato-ku, Tokyo 108-8502, Japan
Phone +81 3 5769 1309, www.obayashi.co.jp

Organization profile and mission

- The Obayashi corporation, founded in 1892 and with 9,600 employees as of March 2005, is a leading general contractor in Japan
- Contribution to radioactive waste disposal projects utilizing a wide range of expertise accumulated through many years of worldwide activities
  e.g. WIPP Construction Project, USA (1982)
  Grimsel Test site, Switzerland (1997-)
  MIZUNAMI URL Project, JAPAN (2003-)
- Technology development and transfer of overseas state-of-the-art scientific and engineering knowledge to Japan.

Tokyo head quarters and overseas offices



Mizunami URL project

Objectives of Mont Terri project participation

Two generic underground research laboratories are under construction and sedimentary rock is one of several potential host rocks for high-level waste disposal in Japan. Specific knowledge on geoscience, repository design and engineering for such formation is important for the national disposal programme.

The Mont Terri Project gives us opportunities to:

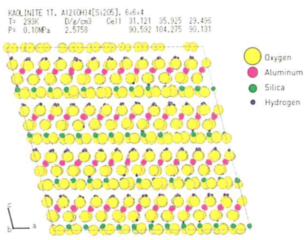
- Be involved in research and development of relevant technologies
- Enhance international collaboration
- Exchange state-of-the-art knowledge.

Present research priorities at Mont Terri

Current focus is to enhance interpretation techniques of field data and numerical modeling techniques to improve the understanding of the geological environment relevant to repository design and long-term safety.

Our involvement in the Mont Terri Project includes following research:

- Application of Molecular dynamics simulation to hydro-mechanically coupled processes of the Opalinus Clay
- Evaluation of hydrogeological data and its modeling
- Evaluation of rock mechanical data and its modeling.



Molecular dynamics model of kaolinite

SCK•CEN

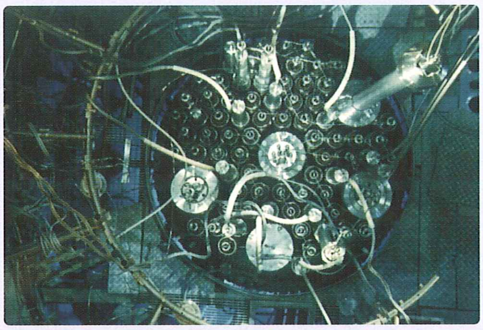
THE BELGIAN NUCLEAR RESEARCH CENTRE

Boeretang 200, 2400 Mol, Belgium
Phone +32 14 33 25 86, www.sckcen.be

Organization profile and mission

SCK•CEN, the Belgian Nuclear Research Centre, was created in 1952 and is currently a Foundation of Public Utility, under the tutorial of the Belgian Federal Minister in charge of energy, with three main research axes:

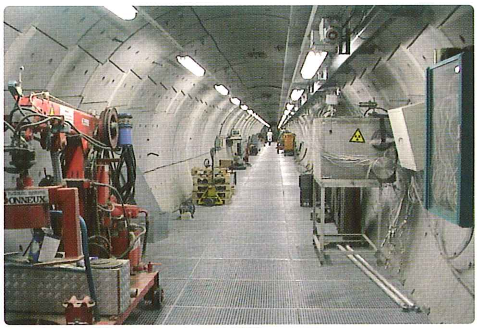
- Safety of nuclear reactors and nuclear fuel facilities
- Safe conditioning and final disposal of radioactive waste, and
- Radiation protection and non-proliferation.



View of the core of the material testing reactor BR2

Objectives of Mont Terri project participation

The Mont Terri Project allows a unique international scientific collaboration with other key organisations in the field of radioactive waste disposal in a clay host rock.



View of the HADES underground research facility in Boom Clay of Mol (Belgium)

SCK•CEN participates in this research to:

- Get a better fundamental understanding in the chemical and hydrogeological processes involved in water flow and solute transport and the mechanical processes in low permeability clay formations
- Compare the governing processes occurring in a plastic clay like Boom Clay with these in a stiff clay like the Opalinus Clay and to determine the main similitude's and differences
- Develop test the reliability of models for assessing the performance of the clay host rocks.

Present research priorities at Mont Terri

The main priorities of SCK•CEN at Mont Terri are presently related to the study of:

- Porewater chemistry under undisturbed and perturbed conditions including the effect of microbial activity on the water chemistry
- Diffusion and retention of radionuclides
- Water and gas flow processes in an indurated clay formation, and
- Self-sealing mechanisms of fractures in the excavation disturbed zone.

Anaerobic surface cabinet of the Porewater Chemistry (PC) experiment used for on-line pH and E_h measurements

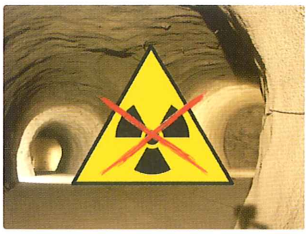
JURA CH RÉPUBLIQUE ET CANTON DU JURA

UN PROJET INTERNATIONAL À HAUTE VALEUR SCIENTIFIQUE

Le canton du Jura est propriétaire du site

Après le percement de la galerie de sécurité du tunnel A16 du Mont Terri, la Confédération a inventorié les roches du massif. Les affleurements des argiles aaléniennes ont particulièrement suscité l'intérêt. Dans le but de pouvoir utiliser le site à des fins de recherche, la Confédération a sollicité le canton du Jura pour obtenir les autorisations d'exploitation d'un laboratoire de recherche dans le domaine du stockage géologique profond, et notamment dans le cadre de la problématique nationale des déchets nucléaires. C'est ainsi qu'a débuté en 1996 le Projet du Mont Terri qui regroupe aujourd'hui douze partenaires de six pays différents.

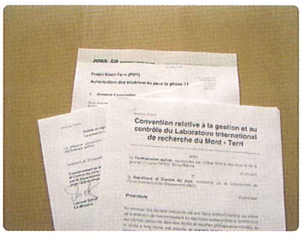
Le stockage strictement interdit!



Dès le démarrage du projet, le Gouvernement jurassien a posé certaines conditions pour l'exploitation du laboratoire. D'une part, en tant que propriétaire du site, il exige que la direction du projet soit assumée par la Confédération, direction qui est exercée aujourd'hui de façon indépendante par l'un des services du Département fédéral de la défense, de la protection de la population et des sports (DDPS), Swisstopo. D'autre part, il exclut strictement le stockage de tout déchet radioactif dans le laboratoire.

Un projet suivi de près

Les conditions d'exploitation sont réglées par des conventions entre le Gouvernement jurassien et la Confédération, en particulier celle du 21 novembre 2005 qui fixe les modalités de gestion actuelles. Le Gouvernement jurassien a institué une Commission cantonale qui accompagne et suit de près les activités du Laboratoire du Mont Terri, tout particulièrement dans les domaines du suivi du programme de recherche, du contrôle, de la sécurité et de l'information du public.



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