Report Series

Dossier 2005 Granite

Tome

Phenomenological evolution of a geological repository

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ANDRA
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pour la gestion des déchets radioactifs

The present English version is a translation of the original "*Dossier 2005 Granite*" documentation written in French, which remains ultimately the reference documentation.

In order to be consistent through the various documents, while the word ''storage'' (''*entreposage*'' in French) refers only to temporary management (in terms of concept and facility), ''disposal'' (in term of concept) and ''repository'' (in terms of facility or installation) refers to long term management of high level long lived radioactive waste (''*stockage*'' in French for these words).

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1 Introduction

The law of 30 December 1991 entrusted Andra with the remit of assessing the feasibility of HLLL waste disposal in deep geological formation.

This volume of the "Dossier Granite 2005" reports on the study results in phenomenological terms for repository evolution. It makes an assessment of knowledge acquired in this field. Without any specific study site (see background inset), the study approach is generic in nature. It is mainly based on international cooperation especially for collecting data in underground laboratories.

Inset 1.1	***Granite study background***

Within the framework of the 1991 Act, Andra carried out surveys between 1994 and 1996 with a view to installing an underground laboratory in the south of the Vienne. The granite massif chosen was granite overlaid by sedimentary formations, delimited from geophysical and geological data.

In 1997 the National Review Board (CNE) reported unfavourably on the Vienne site, particularly on the risks of fluids circulating between the granite and the aquifers exploited in the sedimentary overlying formations; it underlined the interest of "outcropping" granites that would have more favourable characteristics.

The Government decided officially not to retain the Vienne site on 9 December 1998 and planned for research into other potential sites for a research laboratory in a granite medium. A consultation mission was organised in 1999 to present this project and assemble public opinion on fifteen sites selected on the basis of geological criteria. These fifteen sites, submitted to a committee of national and international experts, were identified from previous selection initiatives and advances in knowledge of the granite medium in France and abroad. The mission report in July 2000 highlighted the consultation process failure.

According to government expectations, Andra designed in 2000 a research programme taking stock of current knowledge acquired in foreign underground laboratories and in various geological environments.

The contextual differences for the studies between the clay and granite formations lead Andra to organise its research into two distinct projects: one to study a repository in a clay medium, based on the Meuse/Haute Marne underground laboratory, and the second to study a repository in a granite medium.

Some studies were common to both projects, especially those involving waste packages and materials, but the results were applied specifically to each project.

In this context, the Dossier Granite 2002 put forward in 2002 a first assessment of the studies and research into a potential repository in a granite medium.

This report draws conclusions from numerous studies conducted since 1991. On this basis, it attempts to assess the assets of a granite medium for a high-level, long-lived waste repository.

1.1 Andra research programme into a repository in a granite formation

Together with clay, granite is one of the geological formations studied by Andra in the context of the Act of 30 December 1991.

Given the lack of laboratory site, studies on the granite medium have not attempted to assess the feasibility of a repository designed to satisfy the specific aspects of a particular location.

1.1.1 A generic study approach

The objective of the research programme has been to assess the interest of the granite medium for a repository. Thus Andra has identified and dealt with the major problem areas surrounding a repository in a granite medium, to check that none of them rule it out as unsuitable and to examine possible technical options.

The approach has been to study generic architectural designs for a repository, based on the properties of the granite medium. The proposed options have formed the basis for analyses to understand the long-term behaviour of a repository and to assess its safety.

In line with this strategy, the research programme is made up of four fields of complementary studies

- Study of the granite medium

  A generic repository design depends on the properties of the granite. The research has included overall studies to understand and model the granite medium and an analysis of the variability in the characteristics of French granites, to adapt the design studies and carry out the safety assessments and analyses.

- The generic design of a repository in a granite medium

From design principles founded on safety, the studies have proposed waste conditioning, generic repository architectures, operating methods and closure of the repository allowing for reversibility.The studies were based whenever necessary on data in common with the project of repository study on the clay medium, especially that concerning packages and materials.

- Repository behaviour and its long-term evolution

  Based on the proposed options, the studies have analysed the long-term repository behaviour, to understand and model the thermal, mechanical, chemical and hydraulic phenomena involved in a repository in a granite medium.

- Long-term safety analyses

  The safety analyses performed in the context of generic studies have not attempted to assess repository performance on one or several specific granite sites: they have identified the major parameters for the performance of a repository in a granite medium compared with the objectives of protecting man and his environment and assessed the robustness of the design options proposed.

1.1.2 Support from international cooperation and mobilisation of the national scientific community

Andra has relied extensively on foreign studies and has played an active part in experimental programmes in the Swedish, Swiss and Canadian underground laboratories.

The main cooperation themes have involved the study of the granite medium: structuring and fracturing of a granite massif, survey methods, underground natural water flows, retention capabilities of radionuclides in the rock (Figure 1.1.1).

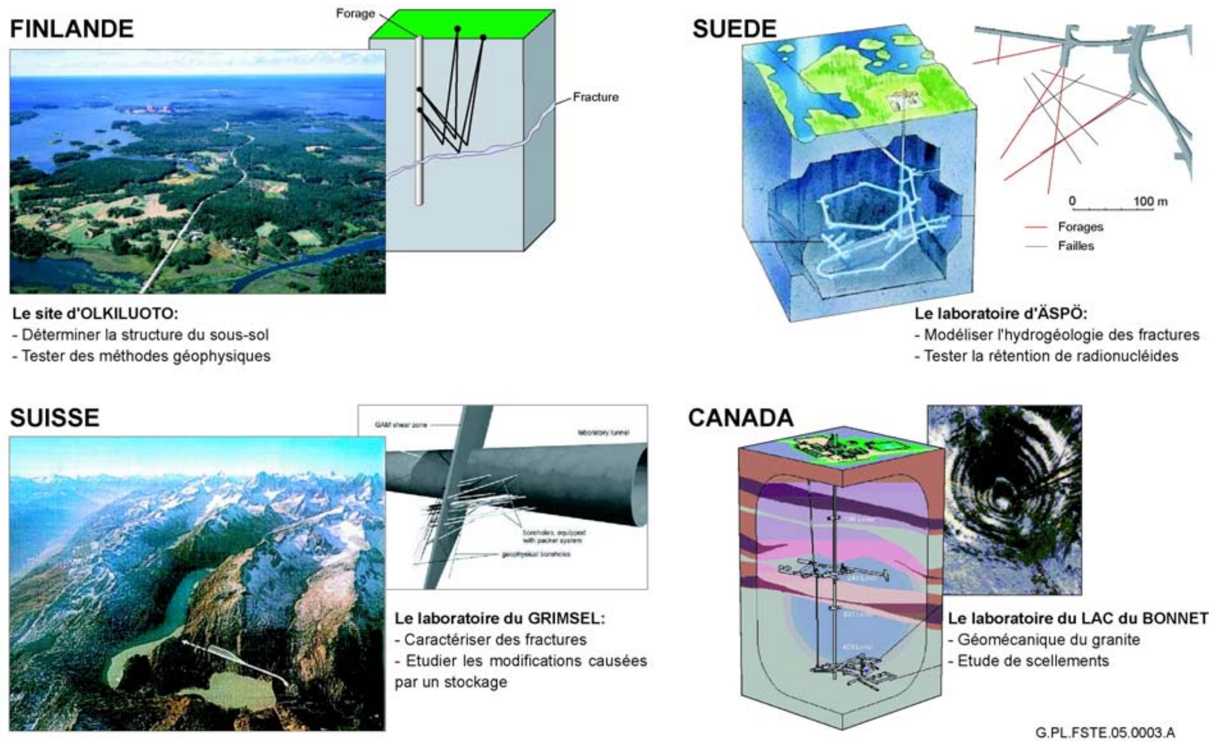


Figure 1.1.1 Granite medium study: international cooperation

The repository design studies have also been founded on demonstration elements acquired in underground laboratories on the installation and behaviour of engineered repository components - seals, backfill, engineered barrier, etc.

Lastly, the study approach has benefited from feedback acquired abroad for the safety analysis of a repository in a granite medium, particularly in Sweden and Finland.

This approach has therefore made the most of the extensive knowledge acquired internationally on the studies into a repository in a granite medium.

Andra has also established national scientific partnerships (CEA, BRGM (French Geological Survey), the Forpro Research Group, part of CNRS (National Centre for Scientific Research) and the *Ecole des Mines* in Paris). Apart from French research teams participating in foreign programmes, this has addressed the need of cautiously transposing results obtained abroad into the French geological context.

1.1.3 The scope of the approach

Lacking a specific study site, the approach adopted, based especially on numerous data acquired internationally, has allowed Andra to ascertain the various aspects to be considered when designing and assessing a repository. It has led to proposals for "generic" repository designs, with the potential to ensure, in the French geological context, the suitability of a repository fulfilling long-term safety objectives

This approach does not however claim to draw the same conclusions as an approach reinforced by surface surveys on a granite site followed by work in an underground laboratory. This work alone can provide sufficient knowledge of the properties of a granite from which may be drawn a fair assessment of repository feasibility.

The specific characteristics of a site would require adjusting the design of the repository components to the properties of the granite studied, adapting its architecture to the massif structure, specifying how it is constructed and operated and assessing accurately the options retained against the long-term safety objectives.

1.2 The Dossier 2005 structure and the position of the volume “Phenomenological evolution of a geological repository”

The Dossier 2005 includes firstly, the presentation, in the form of "reference documents", of the knowledge underlying the design of a repository and its analysis and, secondly, a three-"volume" summary of the design options proposed and the related scientific and safety analyses.

- Knowledge reference documents

Andra has structured the acquisition of knowledge around reference documents. Three are shared with the Dossier Argile :

- repository materials reference documents, grouping data relating to the behaviour of materials (steels, concretes, etc.) other than the rock formation hosting the repository.

- reference documents on the behaviour of the high-level, long-lived waste packages, which summarises the knowledge and models on waste behaviour in a repository environment,

- knowledge reference documents and inventory and dimensioning model, which list all the high-level, long-lived waste produced and yet to be produced by existing nuclear facilities.

A fourth set of reference documents specific to the granite medium assembles the data available on the French granites as a typological analysis.

- Three “tomes”

Three tomes summarise the knowledge acquired from the point of view of each of the areas in the study programme:

- one tome on "**Architecture and management of a geological repository**"
  Andra suggests generic options for repository architectures that are both feasible with respect to expectations, particularly safety and reversibility, and realistic from an industrial viewpoint. Based on available knowledge and technology, the technical options studied, chosen to be as simple and robust as possible, show that solutions do exist for a repository in a granite medium.

These options also constituted the basis of repository safety assessment, especially its performance and evolution within the different timeframes. This assessment is the subject of two other tomes in the Dossier:

- one tome on "**Safety analysis of a geological repository**"
  This volume describes the safety analysis approach to a repository in a granite medium in a generic study context. It presents the corresponding safety assessments in its two qualitative and quantitative parts.

- one tome **"Phenomenological evolution of a geological repository",** the subject of this report

The design and safety assessment of a repository is based on understanding its phenomenological evolution and that of its environment. This understanding must make it ultimately possible to report on the processes which condition and control radionuclide behaviour and migration in the environement after a million years. The purpose of this volume is thus to present the summary of the knowledge acquired in order to describe the phenomena and processes conditioning the evolution of the repository and its environment. It is therefore not a knowledge reference document as such, although it aims at providing a report on knowledge acquired on the granite medium for the understanding and modelling of repository evolution. Neither does it take a stance on repository safety. However, it constitutes an important element for safety assessments by identifying, at the generic phases of studies, uncertainties to be taken into account.

1.3 Tome structure

Without a specific study site, analysis of repository phenomenological evolution is based on design of generic architectures for a reversible disposal system. In its first chapters, this volume presents the main results of this approach leading to proposals for disposal concepts. In chapter 2, this file provides a reminder of generic granite properties and specifies how they are related to the geological background of a granite massif: its origins, formation and evolution over the geological eras. Chapter 3 describes the main waste characteristics incorporated in repository design. It then explains the principles behind repository design for granite medium and describes generic technical options proposed for each type of waste.

Chapter 4 presents the main methodological elements for granite site surveying. The models for the granite site investigated thus describe the initial state of a granite massif before repository construction and operation.

Repository phenomenological evolution is analysed in chapter 5 for the whole disposal duration. It contains a review of the thermal, hydraulic, mechanical and chemical phenomena coming into play in the evolution of the different repository zones and within the various timeframes under consideration. A report is drawn up on this assessment identifying the main phenomena contributing to this evolution, specifying how their consideration is a design element for a reversible disposal system in granite formation.

2 Granite medium

The concept of a deep disposal is based on the idea that there are geological formations able to confine the radioactivity contained in waste packages disposed there over very long periods of time. The geological medium (clay, granite and salt) must confine in the very long term long-lived radionuclides which could be released into the biosphere. It is thus pivotal to the repository system.

Repository design in granite medium is based on the ability to make the most over long periods of time of beneficial properties of the granite and its own characteristics.

Granite properties result from its geological history: its in-depth origins, crystallisation and events which have gradually structured it. This chapter provides a generic description of the major stages in granite geological history. It specifies how the granite acquires over the course of history the main characteristics supporting repository design (see § 2.1).

Compared to this general scheme, French granites have specificities which must be incorporated in design studies. Andra has therefore drawn up a knowledge reference document on French granites which identifies granite characteristics which could affect repository design (Andra, 2005f). On this basis, the chapter presents the outline of the geological context in which the granites were formed and structured and the main characteristics acquired (cf. § 2.2.).

2.1 Granite geological history and acquisition of its main properties for the radioactive waste repository

For the repository study, the word granite designates both a rock and a geological formation. The granite, a geological formation, is usually organised into "massifs"[1].

Thus, the possibility of a repository in granite medium depends on rock properties and characteristics and geological context of the massif studied.

Inset 2.1 ***Granite and commercial "granit"***

The term granite designating a rock came into French in the 17th century from the Italian word granito derived from grano and from the Latin granum, grain. The Latinate word might also have been derived from an old Gaelic term, gwanith faen, which meant a millstone.

The term commercial "granit"(without "e") has a generic meaning of any granular rock, whatever its composition, when it is used for ornamental or architectural purposes (figure 2.1.1). The word "granite" (with "e") designates a plutonic rock composed of quartz, feldspars and micas.

Figure 2.1.1 *Unfinished obelisk in the Assouan granite quarry (Egypt)*

[1] Geological sedimentary formations are usually arranged in superimposed layers (e.g.: the Callovo-Oxfordian clay formation of the Meuse/Haute-Marne site). Magmatic formations, such as granites, often have more volumic geometries (three-dimensional) than planar. For granites, the term massif is generic and is applied to most of the arrangements likely to be encountered.

Whereas sedimentary rocks like the clay formation of Meuse/Haute-Marne originate from the earth's surface, either on the continents or in oceans, magmatic rocks have a deep-rooted origin several hundreds of kilometres below the surface. Volcanic rocks, such as basalt, are solidified when they reach the surface. Plutonic rocks, such as granite, are crystallised at a depth of several kilometres and several tens of kilometres. Granite origins and crystallisation conditions mainly determine *rock* properties and general *granite massif* structure. The history of a granite massif after formation and *deformations* which it undergoes mainly dictates the fracturing organisation.

2.1.1 Geodynamic context

Granite magma can be generated at planet level through several geodynamic mechanisms within tectonic plates or at the limits of their edges: between a continental plate and an oceanic plate and between two continental plates. Within these different geodynamic contexts, the differences in pressure and temperature conditions and in water content of the source material, the more or less significant contribution of the mantle, oceanic crust and continental crust result in magma formation different in composition.

Several arrangements can thus be schematically distinguished (figure 2.1.2).

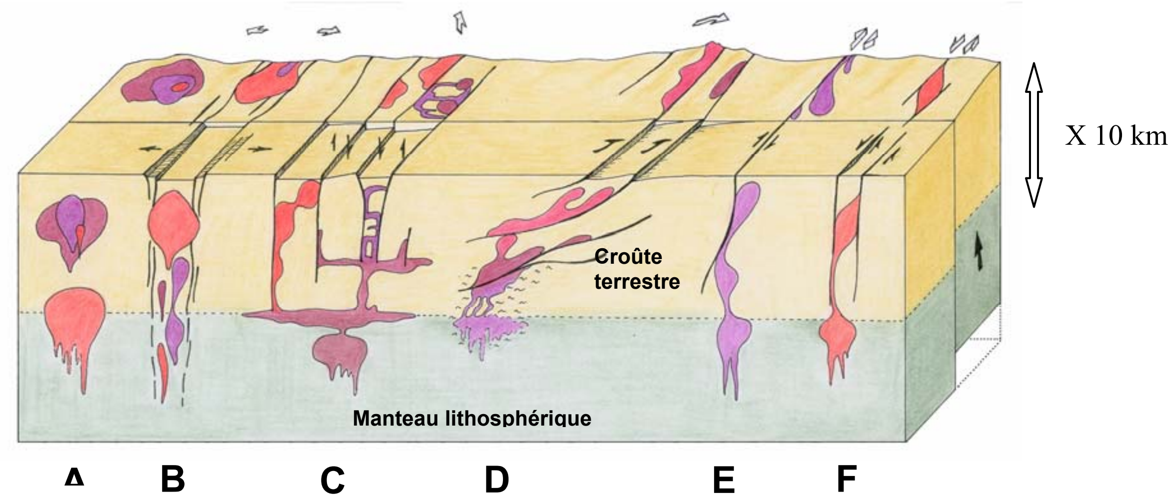


Figure 2.1.2 Different modes of granite intrusion formation (adapted from Clarke., 1992 and Pitcher, 1993) (the block in the background visualises the shape of the outcropping surface after erosion)

Legend of figure 2.1.2:

A *In the absence of strong tectonic stresses, the ascent of magmatic intrusion governed by diapirism due to the effects of contrasts in the density between the magma and the surrounding formations . Ascension ceases with magma crystallisation and density balancing.*

B *Within the context of extended rifting, granite ascent is facilitated by the presence of normal faults at shallow depths of the lithosphere.*

C *Diapiric magma ascent can be slowed down by rheology contrasts on contact of the mantle with the crust and within the crust. A vertical brittle tectonic can then take over as in case B. Higher reservoirs are formed through expansion along the major faults and more or less significant subsidence (cauldron and "sugar-box" shaped subsidence).*

D *Within the orogenesis under overall compression, magma generated in the mantle and at the crust base by partial ablation sees its ascent facilitated by major flat faults and major thrusts which can guide it up to high structural levels where it often forms massifs in large thick sheets.*

E *The existence of major shears causing horizontal movements at the crust can take over from diapiric movements and guide the magma. From this drain, it will spread laterally towards zones subject to lower stresses.*

F *The tectonic play of a shear in the earth's crust can give birth to a relay zone (in "pull apart" style) where a magmatic reservoir will form and crystallise.*

2.1.2 Stages in granite massif history

Four stages characterise the granite massif history: granite magma formation, crystallisation, fracturing stages and massif ascent to the surface. Characteristic durations of these stages vary from several tens to several hundreds of millions of years.

2.1.2.1 Stage 1: Granite magma formation

Granite magma is a viscous set of melted crystals and silicates (temperature of 700-900 °C) which forms depending on the geodynamic context (figure 2.1.2) at a depth of between 2 and 15 km, over a fairly short period of time of between 0.5 and 1 million years (Bonin, 1990).

Magma is brought up by diapirism owing to a lower density than the other components in the earth's crust and due to tectonic pressures related to crust deformations and major fracture zones (figure 2.1.3).

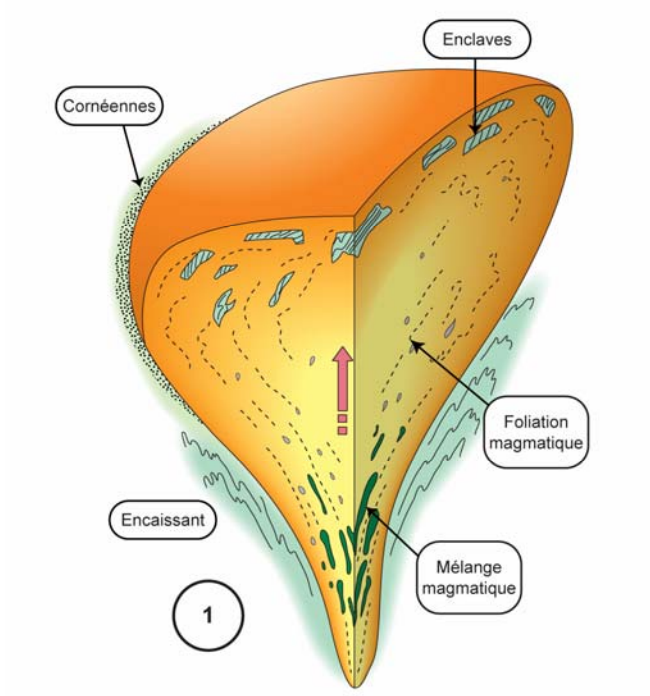


Figure 2.1.3 *Stage of granite magma formation (the figure represents in a simple form the case of "bubble geometry")*

Depending on the geodynamic context, general granite intrusion geometry can be simple or complex and composite (figure 2.1.2). The same granite massif can be made up of an immiscible mixture of several magmas. During its ascent and expansion, intrusion can also insert enclosures of surrounding rocks from the earth's crust and even assimilate them more or less completely.

Dynamics of granite intrusion formation in the earth's crust is often emphasised by distribution of minerals in the granite (its foliation). Granite formation can also cause metamorphic transformations of the surrounding rocks on contact (formations of "hornfels") related to temperatures and pressures coming into play.

The general shape of granite intrusion, its lithological nature and homogeneity thus mainly result from the formation mode of the magma(s) which caused the granite massif. .

2.1.2.2 Stage 2: granite magma solidification and crystallisation

At the same time as its formation, granite magma solidification starts and continues over a few million years. Solidification is at the origin of the granite rock and its characteristic grainy texture. It results from gradual crystallisation of the minerals: micas, feldspars and quartz. Crystallisation temperatures are between 700 and 900 °C, and even more at the local level. Solidification-crystallisation is gradual and fractional. This leads to differentiations between the intrusion core and its edges, especially frequent crystallisation at the top of the intrusion of fine-grained aplitic veins, coarse-grained pegmatite and greisens (figure 2.1.4).

The velocity of temperature and pressure drop governs the number of nuclei of crystal and their potential to increase, which determines rock granularity and inter-granular porosity. In thermo-mechanical terms, magma solidification causes, through thermal retraction, a network of "joints", discontinuities which constitute the first elements in rock fracturing.

Inset 2.2 ***Types of granites and their classification***

Several classifications of granites are based on the link between their composition and their origins for example:

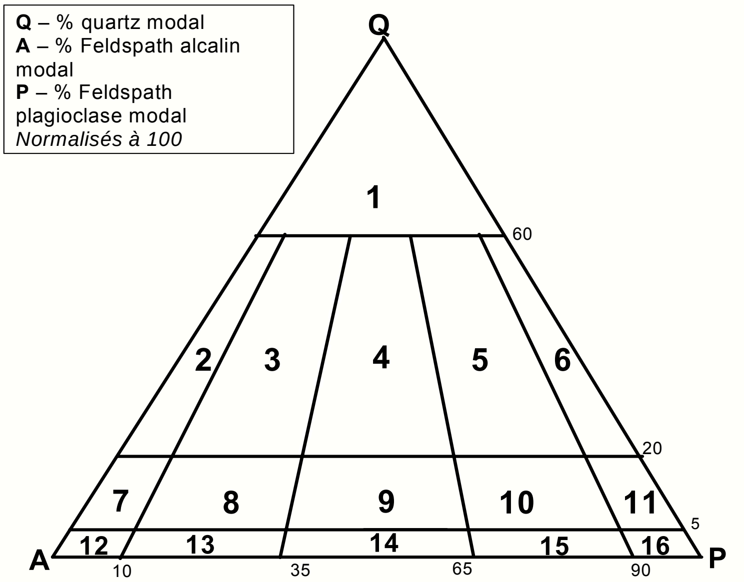
- the **S-I-A-M** classification**,** developed from Chapell and White (1974), classifies granitoids based on the types of source materials with more or less complete melting and whose mixtures are at the origin of magmas (Clarke, 1992). It thus distinguishes granites whose components are of surface origin (**S**ediments for example) at the crust base ("**I**nfracrustal") or in the **M**antle, and those whose origins are not related to orogenesis (**A**norogenic), the case of rift areas and stable cratons;
- The classification of Pearce et al. (1984) discriminates granites within the framework of plate tectonics based on composition of specific trace elements (Rubidium, Yttrium, Niobium and Tantalum), within different geodynamic contexts: anorogenic intra-plate granites, island arc, oceanic ridge granites and collision granites.

Granites are thus classified on the basis of their mineralogical composition: proportion of quartz, sodium-potassium feldspars ("alkali") and calcium-sodium feldspars ("plagioclases").

Streckheisen's classification and nomenclature constitute the international reference adopted by the IUGS (International Union of Geological Sciences) since 1976. The classification is modal, meaning that rock composition is described as a volumic percentage of minerals.

It is based on triangular diagrams of a Quartz-Alkaline-Plagioclase of “Q A P” type for granites (figure below). The term granite is applied to it if the proportion of quartz exceeds 20% and the quantity of alkali feldspar is above 35 %. In an extended usage, the other fields of classification are assimilated if the quartz is of significant proportion.

Classification modale IUGS – Streckeisen et nomenclature des roches plutoniques (1976)



1 – Granitoïdes riches en quartz	9 – Monzonite quartzifère
2 –Granite à feldspaths alcalins	10 – Monzodiorite quartzifère
3 – Granite s.l. [syéno-granite]	11 – Diorite et Gabbro quartzifère
4 – Granite s.l. [monzo-granite]	12 – Syénite à feldspaths alcalins
5 – Granodiorite	13 – Syénite
6 – Tonalite	14 – Monzonite
7 – Syénite quartzifère à feldspaths alcalins	15 – Monzodiorite
8 – Syénite quartzifère	16 – Diorite et Gabbro

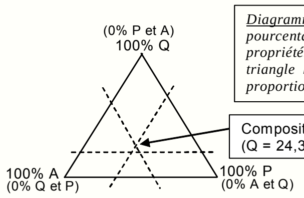


Diagramme triangulaire : chaque côté du triangle représente une échelle de pourcentage entre deux composants représentés par chaque sommet et les propriétés du triangle équilatéral permettent de vérifier qu'en chaque point du triangle les parallèles à un côté recoupent les deux autres pour donner les proportions du système à trois composants.

Composition modale de la roche X normalisée à :
(Q = 24,3%) + (A = 41,4%) + (P = 34,3%) = 100%

La roche est un syénogranite proche d'un monzogranite.

The fluids brought into play during solidification phenomena can also cause rock mineralogical transformation. The hydrothermal fluids involved are partly composed of water from the surface related to geodynamic phenomena which accompany granite genesis and formation (figure 2.1.2) and/or partly mobilised from the crust and the mantle. They can affect the rock as a whole: for example “pervasive” alterations causing mass chloritisation and rubifaction due to iron oxides. They can also cause crystallisation of the specific minerals lining the granite thermal joints (deuteric minerals) such as micas and epidotes (figure 2.1.4).

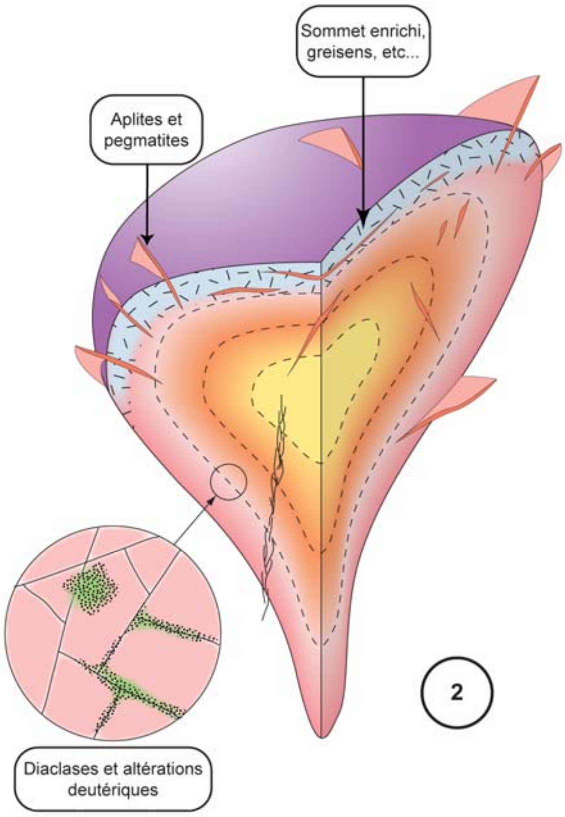


Figure 2.1.4 Magma crystallisation stage

Thus granite magmatic origins, its formation mode and crystallisation determine rock mineralogical composition and texture which especially results in a more or less light colour and a more or less fine grain (figure 2.1.5).

Granite magma solidification is normally accompanied by deformations, resulting from geodynamic stress which affects granite formation. Deformations in the granite are in viscoplastic state. This ductile deformation causes mineral creep (especially concerning quartz and feldspars) and their restructuring in the rock in more or less planar structures of or a more or less continuous nature. These ductile structures can affect granite magma over large-scale stretches and constitute heterogeneity in the massif. They can constitute areas causing massif fracturing and faults at the next stage (inset 2.3).

Inset 2.3 ***Ductile and brittle deformations***

Quartz is the main mineral whose behaviour conditions the appearance of viscoplastic deformations in granite. At a given depth, the brittle type deformation ("breakable") only comes into play if the stress causing it is lower than that necessary for viscoplastic deformation ("ductile"). Brittle/ductile transition for quartz varies around 20 km in depth, depending on the shearing system and the impact of fluids (Ouillon, 1995).

Due to variability in crust composition and spatial heterogeneity of the stresses brought into play in orogenesis, ductile and brittle modes of granite deformation compete over a transition zone of between 10 and 20 km in depth.

Internal structuring of a granite massif, its lithology and the ductile deformation intensity which affects it, thus mainly result from the granite magma solidification stage. Mineralogy and texture of the rocks it is composed of as well as the ensuing properties are mainly acquired at this stage with initial granite fracturing elements being formed.

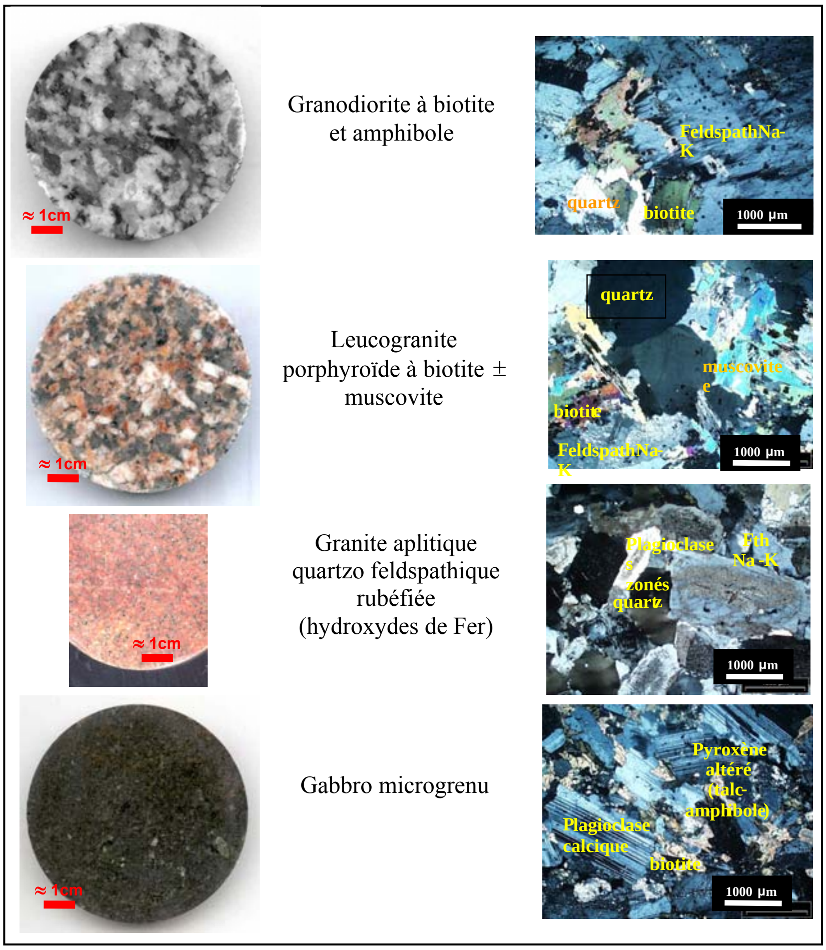


Figure 2.1.5 *Some types of granite (rock samples on the left and microscope pictures on the right)*

2.1.2.3 Stage 3: massif fracturing

After consolidation, granite is subjected to tectonic phases causing massif deformation and the formation of shearing faults of varying geometry and scales. Fracturing organisation depends on the massif geodynamic context and the number of tectonic phases likely to directly affect it. Thus, granite formed late on in the region's geodynamic history is only slightly affected by brittle tectonics, whereas intrusive granite at the initial stages of orogenesis is likely to be affected by several tectonic episodes. Thus, in the same region, granites can be affected to a greater or lesser extent by fracturing depending on their situation.

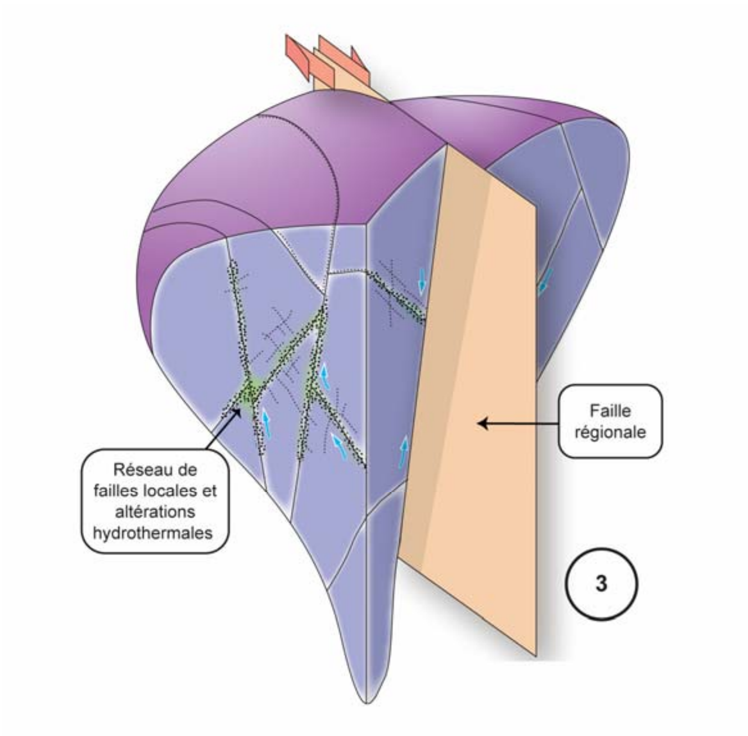


Figure 2.1.6 Massif fracturing stage

Fracturing organisation is formed on several scales: regional faults completely intersect the granite massif, local faults cut the massif up into compartments or blocks (figure 2.1.6).

Granite fracturing is accompanied by hydrothermal fluid circulation in the faults. Temperatures of these fluids depend on their source: from 400 °C for in-depth fluids to 50 °C for fluids partly coming from the surface. The proportion between underground and surface fluids depends on geodynamic context (figure 2.1.2) and depth of granite intrusion. These circulations can alter the rock at the fracture walls. They can result in precipitation of mineral in the fractures, even in clogging them (mainly carbonates, sulphides and iron hydroxides, chlorite and clay minerals).

Volcanic rock veins such as dolerites (or lamprophyres) which are solidified in the fractures attest to extensive tectonic phases post granite solidification.

Granite massif fracturing organisation thus mainly stems from deformations caused during the tectonic phases which affect it after its solidification in the earth's crust. The faults then constitute main locations of water and fluid circulations in granite.

2.1.2.4 Stage 4: granite outcropping and gradual formation of the current hydrogeological system

Solidified and deformed underground, a granite massif appears on the surface due to the general ascent of the portion of the earth's crust where it is formed. This ascent is due to isostatic rebalancing after geodynamic phenomena related to granite formation (figure 2.1.2). The ascent can also be related to large-scale vertical movements connected to plate tectonics. These vertical movements cause recurrent faulting of the major faults in the granite. This recurrent faulting may be significant if other tectonic phenomena, varying in distance, simultaneously affect the region. Apart from this specific impact, recurrent faulting is normally of a lesser degree.

Inset 2.4 ***Isostasy***

Geodynamic phenomena and, especially the formation of mountains chains, cause imbalances in the spread of masses in the earth's basement.

There is in that way a natural tendency towards compensation of these imbalances through vertical movements of the earth's crust and the underlying lithospherical mantle.

When ascent of the crust is sufficient, granite comes to the surface: it *outcrops*. From then on, it is subject to erosion and alteration phenomena caused by atmospheric agents and mainly by water. This results in generalised alteration of the surface part of the granite at a depth of between a few metres and several tens of metres. On the surface, erosion gradually shapes out the hydrographical network leading to current topographical configuration of a granite site (figure 2.1.7). These phenomena are spread between several million years and hundreds of millions of years, depending on the age of the granite and the geodynamic context.

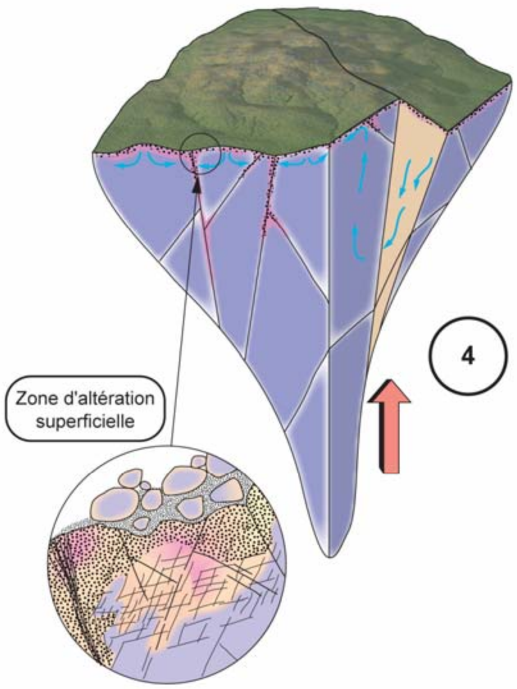


Figure 2.1.7 Ascent of the massif, outcropping, erosion and surface alteration

The altered part on the granite surface and the fracture network enables meteoric water to percolate. This water is mixed with older water drained from the granite during the previous phases, and then replaces it. Chemical composition of the granite water changes. Meteoric water percolation can also cause local modifications in fault mineralogy. However, these modifications are usually subtle and of an extent unrelated to the alterations related to previous hydrothermal circulations, as water temperatures are far lower. Thus the hydrogeological and hydrogeochemical system is gradually brought about evolving right up to the current epoch. This system mainly depends on fracturing organisation which governs the water pathways into the underground granite. It also depends on the site topographical and morphological context, which is the driving force behind water infiltrations and movements in the granite. .

Hydrogeology of a granite massif mainly results from the last stage in the granite geological background: ascent of the crust and tectonic movements fix the characteristics of the granite fault network. Surface erosion phenomena set the morphological and topographical context, which is the driving force behind underground water infiltrations and flows.

2.1.3 Main granite properties for a repository

During its geological history, a granite massif acquires characteristics on which repository design relies. These mainly concern:

- general massif structure: its geometry, depth and homogeneity;
- rock properties: mechanical resistance, thermal conductivity, very low permeability and porosity;
- fracturing organisation and hydraulic and retention characteristics.

2.1.3.1 General massif structure

General granite massif structure results from successive stages of its origins and formation. Its geometry and dimensions are determined by the geodynamic context of initial stages in the granite history. Its current arrangement also results from erosion phenomena brought into play as soon as surface outcropping occurs.

Massif homogeneity is mainly related to its magmatic history : this can be composed of one or several types of magma. Rock veins formed at the end of the crystallisation stage or at a later date also constitute heterogeneity specific to each massif. Repository architectural design must incorporate this heterogeneity when it causes significant mechanical and hydraulic discontinuities. In the general case of the properties of different rock constituents being similar, repository architecture is not restricted by lithological heterogeneity.

2.1.3.2 Granite rock

Rock mechanical and hydraulic properties are related to its mineralogy and texture, resulting from in-depth magma crystallisation. Granite is a mechanically resistant rock. The higher the quartz content, the more thermal conducting it is (inset 2.5). It is also a rock normally of very low permeability and low porosity.

Hydrothermal alteration phenomena which can affect the granite as a whole ("pervasive" alterations) are likely to modify rock diffusion properties. These cause mineral alteration often of a clay nature. However, these modifications are normally not significant and do not restrict general repository architecture.

Inset 2.5 ***Granite rock***

- ✓ **Petrophysics data (Wojkowiak, 1986)**

Volumic weight
Apparent dry density of 25.4 to 29.4 kN/m^3 (2.5 to 2.9 T/m^3).
Real volumic weight of 26.4 to 27.2 kN/m^3 (2.6 to 2.7 T/m^3).

Porosity
Total porosity measured with mercury porosimetry: 0.15 to 2.2 %.
Crystalline matrix porosity is highly dependent on any alteration even a slight one in certain primary minerals (amphibole, biotite, feldspars).

Water permeability
Normally very low and less than 10^{-13} m/s when the rock is unaltered.

Diffusion factors
Normally very low when the rock is not hydro-thermally altered: less than 10^{-12} m^2/s.

Thermal conductivity
This characterises rock ability to transfer heat. This value depends on mineralogy and especially quartz content. The range measured on samples of American granites is between 2.93 and 3.76 W/m.K, whereas the range for French samples is between 2.02 (granodiorite) and 3.98 W/m.K. Thermal conductivity also depends on the temperature rise at which it decreases at a varying pace.

Specific heat (mass)
This measures rock capacity to absorb thermal energy. This is within a range of between and 550 and 1 380 J/kg.K , with an average of around 700 to 900 J/kg.K.

Heat expansion coefficient:
Granite expansion due to heat is controlled by the type and quantity of minerals, rock anisotropy and its state of micro-fracturing. In unfractured granitoids this is measured at between $7.8.10^{-6}$/K and $33.6.10^{-6}$/K.

- ✓ **Mechanical properties**

Mechanical properties of the granite matrix is strictly controlled by primary mineralogy, textural anisotropy and alteration state, water saturation and temperature, etc. For information only, averages and standard deviations at ambient temperature of the main parameters of the various granites (Wojtkowiak, 1986) are:

Elasticity module ....149.9 ± 18.5 GPa
Poisson's coefficient ....0.21 ± 0.08 GPa
Resistance to simple compression ....213.9 ± 68.68 MPa
Resistance to traction ....8.32 ± 3.48 MPa

- ✓ **Granite radioactivity**

Natural granite radioactivity is related to potassium content, with associated gamma radiation at ^{40}K and uranium and thorium content with radiation associated with the respective decay chains of ^{235}U, ^{238}U and ^{232}Th. It thus varies depending on the type of granite (lower for granodiorites, higher for leucogranites). One kilogram of "average" granite has an activity of around 1 000 Bq.

The production of radon, an inert gas, is associated with radioactivity emitted by minerals and it emits alpha particles and causes other solid radioactive descendants.

2.1.3.3 Granite fracturing

Given the low matrix permeability of granite, fractures constitute the only real drains likely to be deployed for fluid circulations. As water circulation is the main element which could result in alteration of the waste and radionuclide release, repository design must incorporate fracture organisation and hydraulic properties, as well as the capacity for radioelement retention.

General fracturing organisation results from the various phases of brittle deformation undergone by the granite during and after crystallisation. Previous ductile deformations corresponding to a viscoplastic state of the granite do not usually cause significant modifications to rock hydraulic properties. Fracturing organisation thus depends on:

- geodynamic context when granite is consolidated (figure 2.1.2);
- time of granite formation and crystallisation in the geodynamic process which gave birth to it. Granite formed at a later date is usually less fractured than granite undergoing all the stages of orogenesis;
- intensity of tectonic phases after crystallisation;
- effects of the ascent of the earth's crust and granite massif outcropping.

Fracturing organisation is thus the consequence of the various phases in the specific history of a granite massif. Fracture hydraulic properties depend on this history. However, fracturing organisation and hydraulic properties are not directly linked and cannot be established without specific examination of the massif studied. Very general rules can be established between fracture size and hydraulic conductivity stating that the largest faults are the main water pathways in the granite. However, they cannot be applied without taking into account fracturing organisation and especially hydraulic connectivity between fractures (section 4.3). The type of fracture minerals and clogging intensity also act on hydraulic and retention properties in a way proper to each type of granite (section 5.6).

2.2 French granites

Within the context of generic granite medium studies, repository design principles are based on general and common granite properties as outlined above. Analysis of the variability of French granite characteristics was subject to a specific review so as to be able to adapt the concepts proposed to these characteristics and carry out the corresponding safety assessments (Andra, 2005f).

The assessment is focused on the Massif Central and the Massif Armoricain, the two largest areas of crystalline basement with outcropping on French territory (figure 2.2.1). Seventy-eight granite areas of more than 20 km2 were considered in the analysis.

This section presents the geodynamic context at the origins of French granites and the main stages in their history. This is reviewed in terms of how this geological history determines their main characteristics

Figure 2.2.1 Granites within the French geological context

2.2.1 Geodynamic context of French granite origin and settling: consequences on their geometry and lithology

In geodynamic terms, French granites were formed within an orogenic context, over the course of two successive orogenic cycles (BRGM-Andra, 1999):

- the Cadomian orogenic cycle (670-540 million years ago);
- the Hercynian cycle (385-250 million years ago).

Cadomian orogenesis, the older cycle, mainly concerns the northern area of the Massif Armoricain. In geodynamic terms, it is interpreted as the result of evolution of an active continental margin, i.e. a continental margin below which an oceanic plate sinks through subduction (figure 2.2.2).

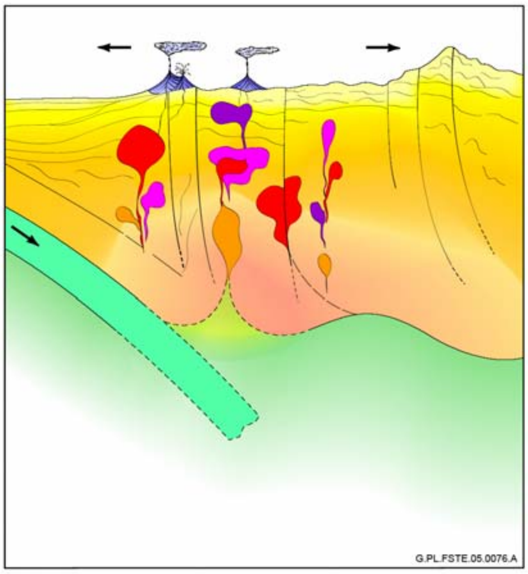


Figure 2.2.2 Diagram of formation of granite massifs on an active continental margin

After consolidation, granites constitute significant components in the Cadomian block in the northern part of the massif Armoricain (figure 2.2.1).

The Hercynian cycle is at the origins of all the other granites in the Massif Central and in the Massif Armoricain. In geodynamic terms, Hercynian orogenesis is interpreted as the result of the collision between two continents: a northern continent where the Cadomian block constitutes a component, a southern continent whose perimeter remains hypothetical. Granites are produced and formed at the various stages of this Hercynian orogenesis: for a minor part of them at the beginning of the collision, for most of them during paroxysm or at the end of the collision and for the remainder after the collision (figure 2.2.3).

a) b)

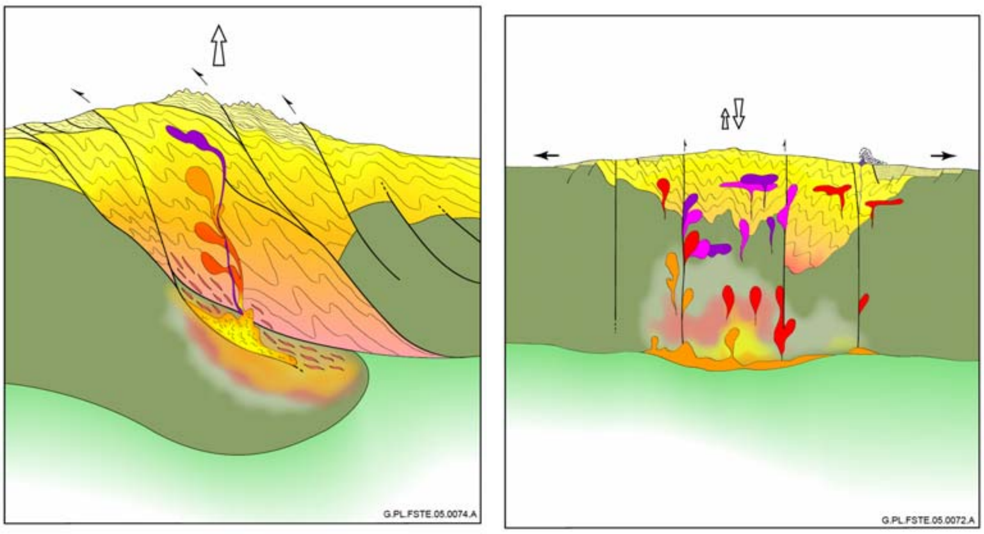


Figure 2.2.3 Diagram of granite massif formation during a continental collision: a) at its paroxysm b) after collision

The type of granite thus varies according to its orogenic situation. Regarding rock mechanical properties, these differences are not significant for repository study, as rock texture ensures great resistance. Differences in mineralogical composition and especially rock quartz content determine rock thermal conductivity and its heat transfer capacity. Significant variability exists between the various types of granite, and this is considered in generic repository design basis for certain types of waste.

Differences in context also result in differences in granite massif geometry. Granites involved in the collision at an earlier stage normally have a more complex geometry than those formed at a later stage. Differences in context also come into play for granite massif lithological homogeneity, either because the same massif is made up of several magmas, or because crust ablation is more or less complete creating the presence of enclaves in the granite of varying size. Lithological homogeneity thus varies significantly according to the granites and their situation. This can also be a determining factor for repository construction if lithological heterogeneity is especially marked and is accompanied by significant variability in mechanical and hydraulic properties

This results in differences in geodynamic situations for the formation and settling of French granites, a significant variability in their geometry. However, the large volume of rock available underground in a granite massif entails that these differences are not very significant for repository architectural design (chapter 3).

2.2.2 Tectonic phases: consequences for granite fracturing

After formation and consolidation, granites in the Massif Central and the Massif Armoricain are subject to tectonic phases which affect the whole Hercynian area:

- at the end of the Hercynian orogenesis (300 to 250 million years ago) and related to crust ascent, the major shearing faults which intersect the basement of the Massif central and the Massif Armoricain take on their definitive pattern. These major shearing faults constitute the main elements in basement fracturing in these regions (figure 2.2.4); they frequently cause a *vertical fracturing organisation*;
- at a later date the Hercynian crust is subjected to a succession of expansion and compression phenomena related to the opening of the Atlantic in the west and Pyrenean and Alpine orogeneses (Brgm-Andra, 1999). Deformation phases correspond to geodynamic stress systems whose orientation varies from one phase to another causing the recurrence or not of Hercynian fractures. In the eastern part of the Massif Central, rifts (“Limagnes”) evidence the size of these deformations which affect granite massifs located at their edge. However, away from these large-sized structures, the intensity of deformations is far lower.

As a general rule, fracturing resulting from Hercynian orogenesis is the main element structuring granites.

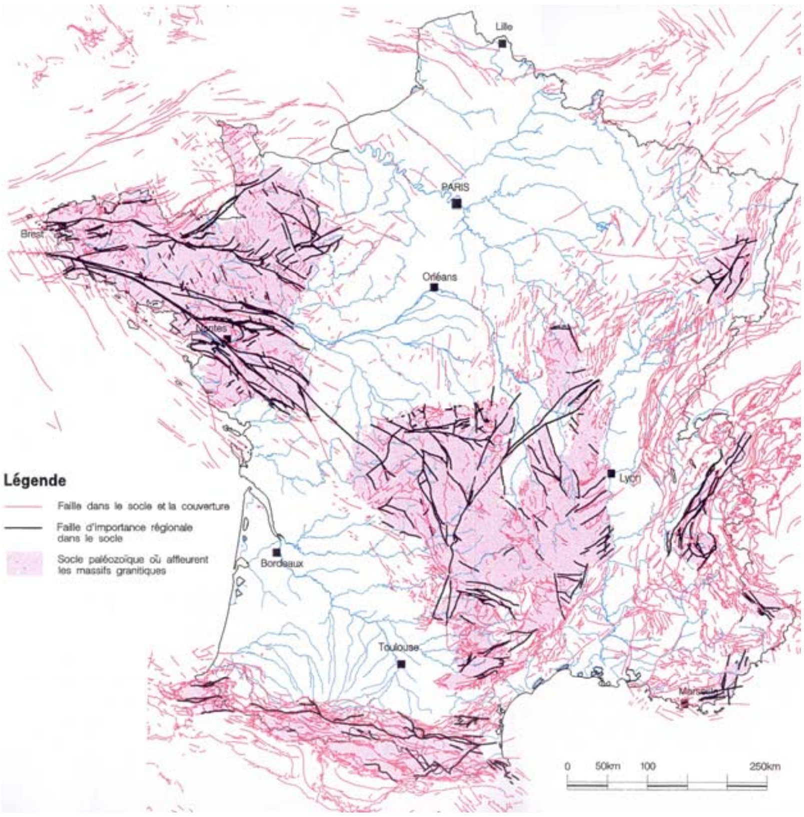


Figure 2.2.4 *Main faults affecting the basement of the Massif central and the Massif Armoricain*

Hydrothermal fluids coming into play during the course of these different tectonic phases modify fracture mineralogy where they circulate, even that of the rock when the circulation is large. Depending on their size and type, the fractures are partially or totally clogged with mineral crystallisation on the fracture planes (figure 2.2.5). These phenomena largely determine fracture hydraulic and retention properties.

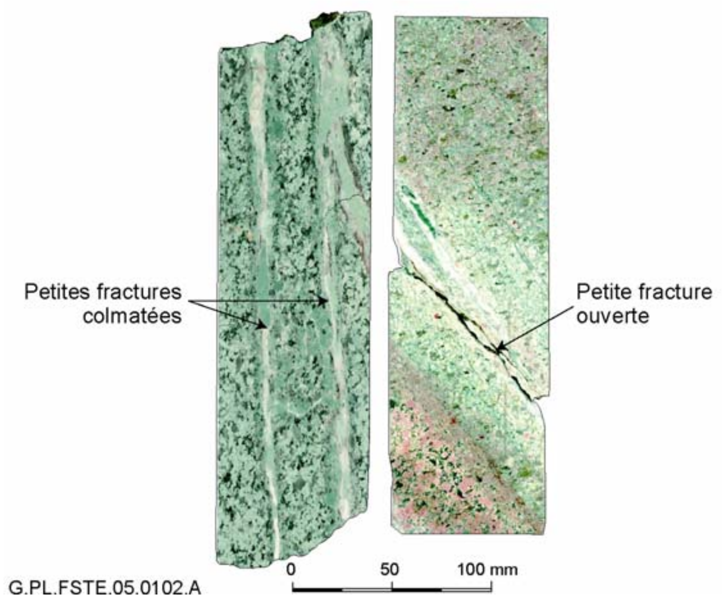


Figure 2.2.5 *Clogging of granite fractures with hydrothermal minerals*

Fracturing of all the granites in the Massif Central and the Massif Armoricain mainly results from Hercynian orogenesis. During later tectonic phases, fault recurrence is usually low and does not cause significant modification of the fracturing system. Fracture hydraulic properties are also mainly the consequence of hydrothermal circulations accompanying these deformation phases.

2.2.3 Granite outcropping and consequences of erosion for hydrogeology

Depending on their geographical situation, French granites were exposed to erosion actions for several million to a few tens of millions of years. The current landscapes have been modelled for around 5 million years with mainly the gradual hollowing out of the hydrographical network.

Landscape formation is connected to that of the current hydrogeological system. The surface is both the place of meteoric water infiltration within the granite and the outlet of water circulating in the granite (springs, rivers, sea, etc).

Topographical and morphological configuration of a granite site is thus a parameter affecting in-depth water circulation. Contrasting topography tends to increase hydraulic gradients and thus circulation flow rates (figure 2.2.6). Granite morphostructural arrangement compared to the surrounding areas also affects water circulations. Analysis of granites in the Massif Central and the Massif Armoricain thus resulted in distinguishing three main morphostructural arrangements (figure 2.2.6):

- granite massifs in topographical depression compared to the surrounding geological formations where water circulations tend to converge on the centre of the granite;
- domed massifs where water infiltrating at the granite top tends to flow towards the surrounding areas;
- sloping massifs where water tends underground to cross the granite towards the surrounding underlying areas.

Each one can correspond to more or less accentuated topographies.

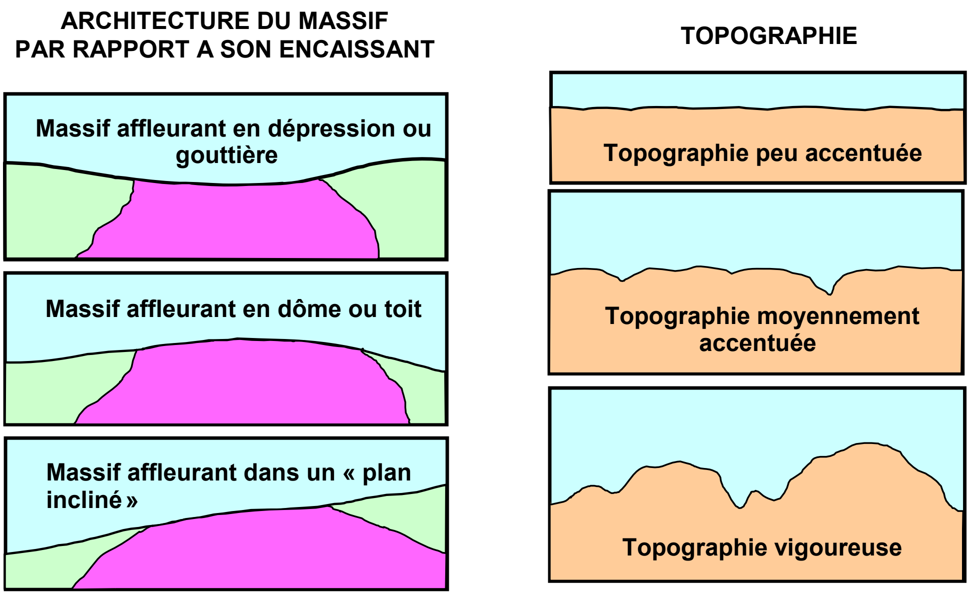


Figure 2.2.6 French granite morphostructural and topographical arrangements

Gradual landscape formation over the past few million years also changes granite water composition. Shaping out of the hydrographical network results in deeper and deeper drainage of granite fractures by surface water.

This gradual modification to the hydraulic system causes the ancient water often more saline to be replaced with more recent meteoric water. This replacement varies in pace and depth depending on granite morphological situation and fracturing organisation (figure 2.2.7).

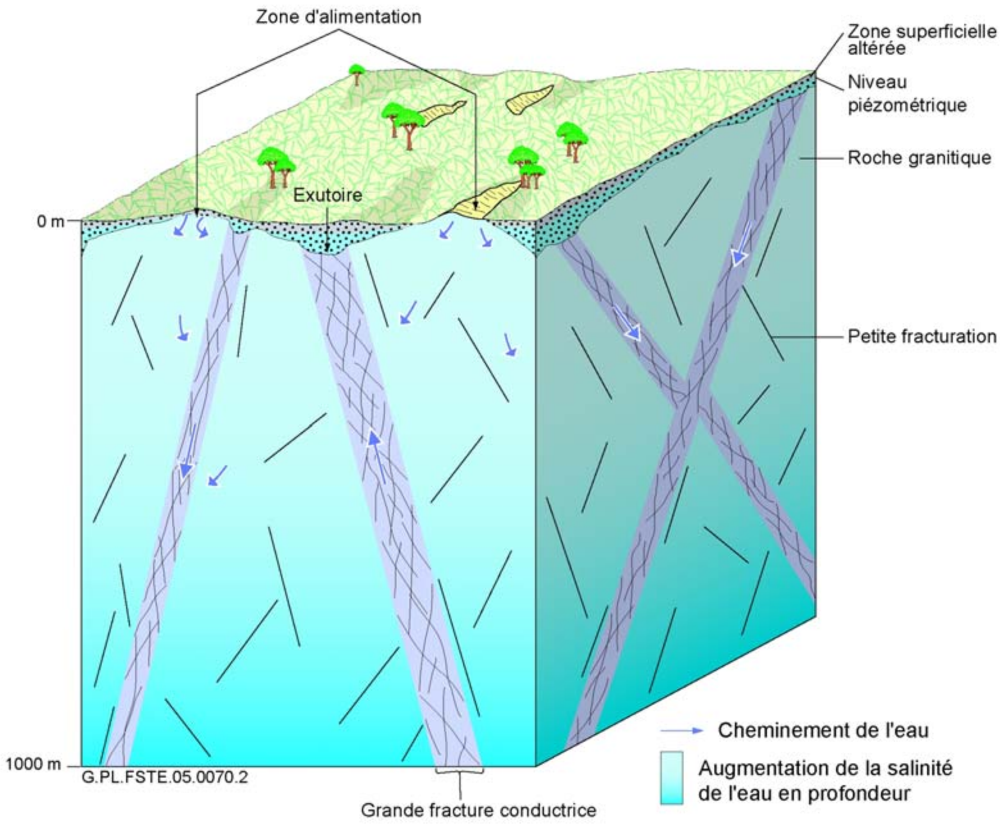


Figure 2.2.7 Granite massif hydrogeology

French granite hydrogeology is very largely dependent on morphological and topographical configuration resulting from erosion phenomena affecting an outcropping massif. Several arrangements can be defined for French granites.

Granite massif hydrogeology thus results from both fracturing organisation and its morphological and topographical configuration.

3 High Level and Long Lived waste and disposal concepts

Along with the properties of a granite site, the inventory and characteristics of the waste to be disposed constitute main entry data for repository design.

This chapter summarises HLLL waste and spent fuel (section 3.1) and describes waste typology. Waste origins, primary packages and quantitative and radiological inventories as well as the main physico-chemical characteristics of the waste or primary packages (thermal release, etc) are presented. In order to do so, the various waste generation scenarios adopted for the study are presented along with their basic hypotheses.

The principles supporting repository design in granite medium are covered in the second part of this chapter (section 3.2). It specifies the functions assigned to the various repository components so that the repository can fulfil its long-term waste confinement objectives.

Repository options proposed for each type of waste is described in section 3.3. They constitute the references for the analysis of long-term repository phenomenological evolution.

3.1 HLLL waste (Andra, 2005b)

High Level and Long Lived waste contains: short- and medium-lived radionuclides but in a high quantity (incurring a high level of activity) and long-lived radionuclides in medium to very high quantities.

The main sectors of activity contributing to the production of this waste are the nuclear power industry (EDF electricity producing reactors, COGEMA's fuel reprocessing plants of The Hague and Marcoule), as well as national research and defence activities (CEA centres). In addition, the operating and maintenance waste from the nuclear reactors and the reprocessing plants are added to the spent fuel reprocessing residues.

The spent fuels unloaded from the EDF reactors are treated in the COGEMA plants of The Hague. Reprocessing aims at separating the uranium and the plutonium, which are not considered as waste, from the waste themselves: fission products, activation products, minor actinides conditioned in the plants of The Hague[2]. In addition to these residues of high activity, there are also essentially metallic materials, fuel assemblies, as well as waste of intermediate activity linked to the operation and maintenance of the reprocessing plants (liquid effluents, etc.). The recovered uranium and plutonium are used in the manufacture of the MOX (uranium oxide and plutonium) and URE (reprocessed uranium) fuels. After utilization in the reactors, the latter are stored.

Nuclear reactor operations also generate intermediate-level waste: this involves devices for starting up and operating the reactors which, after some time in service, are replaced and therefore become waste. This waste is currently stored near the reactors.

The long-lived waste produced by sectors other than electro-nuclear production (research, defence) is normally intermediate-level technological waste: replaced or obsolete parts, contaminated by processed materials and radioactive waste, etc. Note also the existence of a small quantity of spent fuel produced by research or military reactors, for which disposal possibilities are being studied in the case of the waste not being reprocessed.

[2] The UP2-400 (La Hague) and UP1 (Marcoule) plants, today decommissioned, have processed the spent fuel from gas-graphite and fast neutron breeder reactors. The fission products solutions have been conditioned by vitrification. The liquid effluents, on the other hand, have been conditioned in a bitumen matrix at Marcoule.

3.1.1 Main categories of HLLL waste

HLLL waste is composed of two main categories

3.1.1.1 High-level C waste (or vitrified waste)

This waste represents 1% in volume of the radioactive waste and corresponds to the non-reusable materials contained in the solutions resulting from the reprocessing of the spent fuels in the COGEMA plants: fission products, minor actinides, activation products.

Their high b-g activity causes a large thermal release which decreases over time, mainly with the radioactive decay of the intermediate radioactive half-life fission products (Caesium137, strontium90).

They are incorporated today in a matrix made of borosilicate glass (glass R7T7), whose confinement capacity is particularly high and durable (several hundreds of thousands of years) when it is under favourable physico-chemical environmental conditions. The radionuclides are thus spread uniformly in the vitreous matrix. This vitrified waste is poured into stainless steel drums, to make up C waste (vitrified) primary packages.

Inset 3.1	***Radionuclides produced in reactors by fission reaction***
- **the fission products** come directly from the fission of uranium and plutonium atoms: caesium, strontium, iodine, technetium, etc., or from the disintegration of fission fragments. Caesium137 (and its decay element barium137) and strontium90 (and its decay element yttrium90) are the main source of radiation and heat released from the HLLL waste, both high during the first 300 years considering their radioactive half-life of 30 years; - **actinides** are natural or artificial elements with a nucleus counting protons higher than or equal to 89. Four actinides exist in the natural state: actinium, thorium, protactinium, and uranium. The minor actinides (mainly americium, curium, and neptunium) are formed in a reactor by capture of successive neutrons from fuel nuclei. Their radioactivity and their heat rating fall slowly. After the decay of the intermediate radioactive half-life fission products, the waste produces a residual heat release resulting from the activity of américium241, which in turn progressively decreases; - the **activation products** are formed by capture of neutrons mainly in cladding and fuel structure materials. Their radioactivity is significantly lower than that of fission products and minor actinides, but must be taken into account because some of these radionuclides have a long radioactive half-life.	

3.1.1.2 B waste of medium to long life

This comes mainly from nuclear fuel manufacturing and processing plants and research centres. It therefore includes a large variety of items such as structure elements of fuel assemblies (fuel rod claddings called "hulls", endpieces called "end-caps", assembly holding grids, etc.), effluent reprocessing sludge, miscellaneous materials (filters, pumps, etc.). They are for the most part metals, but organic and inorganic compounds are also present (plastics, cellulose, etc.).

They have low or intermediate β-γ activity; consequently, they release no heat or hardly any. However, the quantity of long-lived elements that it contains justifies a very long-term containment, like that for C waste.

Depending on type, it is conditioned in bitumen (sludge from effluent reprocessing), in concrete or by compacting (hulls and end pieces and technological waste). The thus-conditioned waste is placed in concrete or steel drums. These make up the B waste primary packages which are both more numerous and more diverse through their conditioning.

Inset 3.2	***Heat release from waste packages***
The radionuclides contained in the waste emit β, γ and α radiation which is partially or totally slowed down with the waste and/or its conditioning matrices, particularly glass. It therefore loses all or part of its kinetic energy which is transformed into heat. **The amount of heat released by the waste and the waste packages over time therefore depends mainly on the type and quantity of radionuclides they contain and it decreases in proportion to the radioactive decay of these radionuclides.** The heat effect corresponds essentially to radionuclides which are short-lived (cobalt60) or intermediate-lived (caesium137, whose radioactive half-life is 30 years). Thus, the heat released by the waste packages is above all significant during the first tens to a few hundred years maximum after manufacture of the packages. Beyond this period, there are fewer β–γ emitters; the heat released by the packages is then mainly caused by the α emitters, but less heat is emitted.	

3.1.2 Inventory model

3.1.2.1 Surveying the existing and future waste production of the current reactor fleet

- **An inventory model of existing and future waste for the repository studies**

To study the feasibility of a repository, Andra created in close collaboration with waste producers an inventory model of HLLL waste, which takes into account the waste already produced, stored, in a conditioned or unconditioned form, on the production sites, as well as the waste to be produced by current nuclear power facilities. This dimensioning inventory model (MID) provides an envelope of the volume and nature of waste which could be disposed of to allow the study of its feasibility within the dimensioning margins.

It refers to conditioned waste. Knowledge or formulation of hypotheses on the nature and conditioning methods for existing waste which is yet to be conditioned and future waste are required. These hypotheses refer back to the industrial processes currently implemented by the producers: (vitrification, compaction, cementation and bituminisation).

The inventory of existing waste necessitates knowledge of the processes that generate radioactive waste and effluents, the waste production balance figures that each installation regularly produces, the identification of the storage locations for the produced waste and control of their contents.

The inventory model for future productions is based on waste production and conditioning hypotheses, primarily nuclear power plant management scenarios worked out with the waste producers (EDF, CEA, COGEMA).

- **Accounting for spent fuel**

Spent fuels are not considered as waste. However, to explore the specific problematics which they could raise with respect to management techniques, some study scenarios take into account the spent fuels coming from EDF or CEA nuclear reactors under the hypothesis that they were not treated. The spent fuel contains radionuclides involved in fission reactions (plutonium, minor actinides and fission products) and presents high-level activity which means a high exothermicity. This heat release is due to their intermediate-lived fission product content, plutonium and americium (principally released by plutonium decay); these last two elements lead to slower decay over time. Other spent fuel characteristics are: their large dimensions and increased fissile material content (uranium and plutonium) that constitutes a criticality risk.

Inset 3.3	***Spent fuel assemblies***
A spent fuel assembly consists of zirconium alloy rods containing fuel pellets made of uranium oxide (UO_2) or a mixed uranium-plutonium oxide (UO_2-Pu) depending on whether the fuels are UOX or MOX. These rods (4 to 5 m long) are closed at the ends by two welded plugs. Each stack of pellets is held axially by a helical spring at the top. The rods are kept in place by a series of metal grids and a device placed at the top is used for handling the assembly.	

- **Four scenarios to identify orders of magnitude**

Four study scenarios have been defined in collaboration with the producers to distinguish the magnitudes of HLLL waste that will be produced in the future by the current EDF nuclear power plants. It is based on three hypotheses applied across the board to the current nuclear power plants fleet (58 reactors): a cumulated production of electricity of 16000 terawatts/hour (TWh), an average reactor service life of 40 years, an average thermal burnup rate of the unloaded fuels[3]. These hypotheses lead for the existing EDF installed fleet to a total quantity of unloaded fuels of 45 000 metric tonnes of heavy metal (MTHM).

The objective of these scenarios is not to prefigure any industrial scheme, but rather to examine how a repository architecture may be adapted to various managements of the nuclear cycle backend. The principle adopted is to encompass all possible industrial strategies without favouring one over another.

Inset 3.4	***Waste generation scenarios***
-	
• **Scenario S1a** assumed the reprocessing of all the CUs unloaded by the current EDF installed base (45000 MTHM, including 8000 MTHM of UOX1, 20500 MTHM of UOX2, 13000 MTHM of UOX3, 800 MTHM of URE and 2700 MTHM of MOX). • In **scenarios S1b and S1c,** 42300 MTHM of UOX/URE are treated. On the other hand, the spent fuel MOX (2700 MTHM) is assumed to be not treated and the feasibility of its direct disposal is assessed. In scenario S1b, the vitrified waste packages have a heat rating greater than current packages. In scenario S1c, their heat rating is equivalent. • **Scenario S2** was introduced to analyse the feasibility of the direct disposal of the spent fuels UOX and MOX. It is based on the partial reprocessing of the UOX CU spent fuel up to 2010 (8000 MTHM of UOX1 and 8000 MTHM of UOX2), and then on a direct disposal of 29000 MTHM, consisting of 12500 MTHM of UOX2, 14000 MTHM of UOX3, 500 MTHM of URE and 2000 MTHM of MOX.	

3.1.2.2 Reference packages of the inventory model

- **Accounting for the diversity of current and future waste packages under standardised disposal options**

The review of waste and the definition of their conditioning mode lead to *a very wide variety of HLLL waste primary package families (total of 61)*, which differ in terms of radiological content, heat release, physico-chemical nature of their waste or conditioning materials, dimensions and quantities.

To ensure that the disposal studies cover all these package families, the inventory model groups the families into a more limited number of representative "reference packages" in order:

[3] Burnup rates are the following according to nuclear fuel types : URE: 45 GWj/t, UOX1: 33 GWj/t, UOX2: 45 GWj/t, UOX3: : 55 GWj/t, MOX: 48 GWj/t

- to develop the scientific and technical studies while limiting the number of cases to be dealt with specifically but without overlooking the diverse nature of the waste packages,
- to propose a standardisation of the structures and means which would be implemented in a disposal installation.

This approach has led to a disposal design for each of the waste packages dealt with in the inventory.

Each inventory model reference package has characteristics that cover a higher or lower number of primary packages from different families, which simplifies the studies.

Table 3.1 *List of the inventory model's packages grouping all the inventoried families of packages*

Reference packages	Cat.	Lev.1	Lev.2	Lev.3	Titles of the waste grouped together in the reference packages
Activated waste	B	B1			CSD-C containing the activated waste from PWR and NRR reactors
Bituminised waste		B2	B2.1		238 and 245 litre bituminised drums
			B2.2		428 litre bituminised drums
Technological and diverse waste cemented or compacted		B3	B3.1	B3.1.1	1000-litre concrete containers reconditioned or non-reconditioned in metal containers
				B3.1.2	Concrete container (CAC and CBF-C'2) containing miscellaneous technological waste
				B3.1.3	1800-litre concrete containers containing miscellaneous waste
			B3.2	B3.2.1	500-litre concrete containers (sludges and concentrates)
				B3.2.2	1200 litre concrete containers (CBF-C'2) containing CEDRA and AGATE waste
			B3.3	B3.3.1	Standardised containers for compacted waste (CSD-C) containing alpha waste
				B3.3.2	EIP (multipurpose storage) drums containing powdered cemented waste
				B3.3.3	500-litre steel containers containing miscellaneous waste
				B3.3.4	870-litre steel containers containing miscellaneous waste
Structure waste cemented		B4			Drums of cemented hulls and end caps
Structure waste compacted, with or without technological waste		B5	B5.1		CSD-C containing a mixture of hulls, end caps and technological waste (including organic waste)
			B5.2		CSD-C containing a mixture of hulls, end caps and metallic technological waste
			B5.3		CSD-C containing PWR (HAO) cladding waste, without technological waste
			B5.4		CSD-C containers containing magnesian cladding waste
Structure and technological waste placed in drums		B6	B6.1		180-litre steel containers containing AVM operating waste
			B6.2		EIP drums containing metallic structural waste
			B6.3		EIP drums containing magnesium cladding waste
			B6.4		EIP drums containing technological and organic waste
			B6.5		EIP drums containing metallic technological waste
Sources		B7	B7.1		Source holders
			B7.2		CSD-C containing PWR primary and secondary source fuel rods
			B7.3		Multipurpose storage drums containing sealed sources
Radium and americium bearing waste		B8	B8.1		Multipurpose storage drums with radium bearing lead sulphate
			B8.2		870-litre steel containers containing lightning rod heads with radium or americium
			B8.3		EIP drums containing ORUMs (objects containing radium for medical use)
Vitrified waste	C	C0	C0.1		Vitrified PIVER waste
			C0.2		Vitrified UMo waste
			C0.3		Vitrified AVM waste
		C1			"Current thermal" UOX/enriched recycled uranium vitrified waste
		C2			"Future thermal" UOX/enriched recycled uranium vitrified waste
		C3			UOX/MOX vitrified waste
		C4			UOX vitrified waste = Pu
		C4			UOX + Pu vitrified waste
EDF PWR fuels	CU	CU1			Spent UOX and URE PWR fuel
		CU2			Spent MOX PWR fuel
CEA fuels		CU3	CU3.1		UNGG and EL4 spent fuel
			CU3.2		Célestin spent fuel
			CU3.3		Spent fuel from nuclear propulsion reactors

Legend of table 3.1:

• ***At level 1,*** *the main reference packages are differentiated by:*

- the nature of their content (reactor operating waste, effluent reprocessing sludge, technological waste, fuel assembly cladding waste, sources, radium-bearing waste, high-level spent fuel reprocessing waste, spent fuel as appropriate).
- their heat release level (B waste, C waste and SF),
- their conditioning methods (compacting, bituminisation, cementation, vitrification, containerisation). Several vitrified C waste reference packages are defined to separate productions of legacy glass (C0) from current productions (C1) and potential future productions (C2, C3 and C4). This distinction primarily relates to the variation in the chemical composition of the glass, the heat rating and waste package dimensions.

• ***At levels 2 and 3,*** *the reference packages describe the variability of the waste packages in more detail, for the purposes of detailed studies: chemical composition of the waste, presence of organic matter, production of gas, nature and dimensions of the container, etc.*

- **Some characteristics common to all reference packages**

  ✓ **B waste packages**

B waste is combined in several reference packages:

- *B2 reference packages, which represent almost half the volume* of the inventory model for the B waste packages, contain the waste embedded in bitumen matrices. This type of waste does not give off heat. The radiolysis of the constituent organic materials of the bitumen leads to generating hydrogen;

- *B5 reference packages*, which combine fuel assemblies structure waste and are conditioned after compacting in standard compacted waste containers (CSD-C). Most have a low heat release rate (particularly attributable to cobalt60), which rapidly decreases (30 watts during the production of the package, 10 watts after 15 years of cooling). Some B5 packages contain organic and technological waste and can generate hydrogen by radiolysis of the organic materials;

- *B1 reference packages* (operating waste from the EDF pressurised water reactors (PWRs) and deconstruction waste coming from the Superphenix fast neutron reactor 4), which have a low heat rating (20 watts during the production of the package, 3 to 4 watts after 15 years of cooling) and comprise the most highly irradiating B waste (dose rate at a few centimetres from the package on the order of 50 Sv/h during production, 15 Sv/h after 10 years of cooling);

- The other reference packages, B3 (technological and diverse waste cemented), B4 (hull and end-cap waste cemented), B6 (various technological waste), which present a wide variety of waste and conditioning modes.

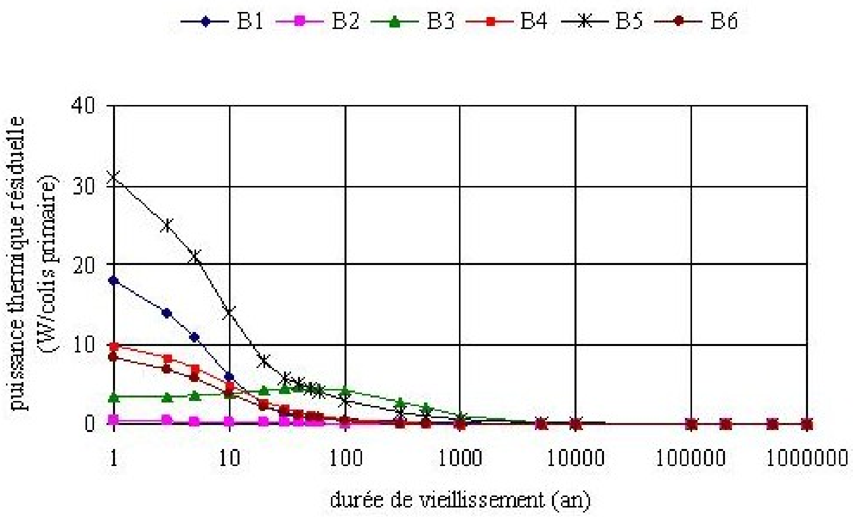


Figure 3.1.1 *Thermal release graphs for reference B waste packages (Andra, 2005b)*

Inset 3.5 ***Gas release by package***
Certain B waste primary packages produce gases such as hydrogen (1-10 litres per annum at atmospheric pressure per waste package) and also carbon dioxide and methane, resulting from the radiolysis of their constituents. These are primarily waste embedded in bitumen or that contain organic matter (cellulose, PVC…). Industrial facilities, be they nuclear or non-nuclear, evacuate these gases by ventilation for safety reasons. Feasibility studies have verified the possibility of implementing these industry-proven methods for the repository operating period. After the repository's closure, would closure be decided within a reversible management context, the radiolytic gases will diffuse into the medium and the structures in a gaseous form and dissolved in water; it was verified that the gases will not eventually create an overpressure which could irreversibly alter the confinement of the waste. Some waste packages may also contain traces of gaseous radionuclides. Their release is very limited and can only lead to very low-level radiological exposure. However, to protect people and the environment, these gases are confined wherever possible in the packages; in case a small portion were released, it would be captured by ventilation.

✓ **C waste packages**

Five C waste reference packages cover the existing and foreseeable families of vitrified waste packages:

- *The C0 reference package groups together the old waste, which release an average heat quantity*: old packages manufactured in the PIVER experimental installation at Marcoule, the "UMo" waste coming from the reprocessing of fuels from the old line of natural uranium graphite gas reactors (UNGG), currently stored at La Hague facility and planned to be vitrified; vitrified waste packages produced in the Marcoule vitrification shop, mainly from UNGG fuels;

- The other C waste packages *are highly exothermal. Reference packages C1 and C2* include the vitrified waste from UOX/URE spent fuel reprocessing currently in production (C1) or that is planned for reprocessing in the short term (C2). Two reference packages *(C3/C4)* are to be added here, which do not correspond to the current practice of reprocessing, but aim at exploring imaginable alternative schemes: the waste packages include more actinides (americium, curium, even plutonium on an exploratory basis) and primarily relate to MOX fuel reprocessing. The resulting waste would be combined with the waste from UOX fuel reprocessing (at the ratio of 15% MOX and 85% UOX). The radiation level varies with the type of waste package and its age. It is in the region of 250 Sv/hr after 60 years of cooling for the most highly irradiative C waste packages.

Inset 3.6 **C waste primary packages**
Vitrified waste is conditioned in CSD-V stainless steel containers (standard vitrified waste container), exactly the same (materials, geometry) for all the packages C0.2, C1 to C4 (height 1340 mm, diameter 430 mm). The container used at the Marcoule vitrification facility (AVM, reference package C0.3) differs from the CSD-V in diameter (500 mm) and height (1,015 mm).
The stainless steel containers of PIVER vitrified waste (reference package C0.1) have the same diameter, but their height varies (575 to 875 mm). These packages weigh less than 130 kg. The weight of the other C waste packages is about 500 kg.

✓ **Spent fuel**

The spent fuels (CU) are not considered to be waste; they were examined, however, as study objects:

- the *fuels coming from the EDF PWR reactor installed base is subdivided into two types*: CU1 for the UOX/URE fuel and CU2 for the MOX fuel, which are distinguished by their geometry, particularly their length. They do not exceed 800 kg in weight. This type of waste, like C waste, releases significant amounts of heat. The higher input by plutonium and americium to this heat release results in *slower decay over time*. Two situations are included for conditioning: on the one hand, fuels could be delivered as they are to a shop where they would be directly conditioned in disposal containers, or, on the other hand, they could have been previously placed in clads, such as considered by the CEA in the study of a long-term storage;

- the fuels coming from national research and defence reactors are grouped together under type CU3: they are small sized and their heat rating is intermediate or low (less than 200 Watts).

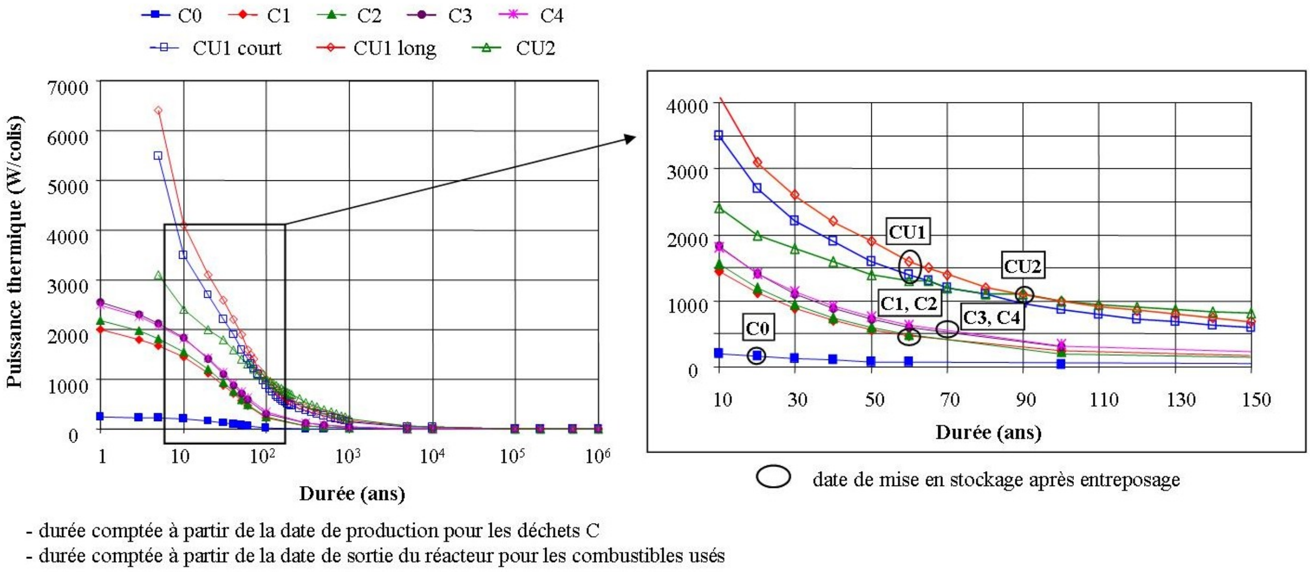


Figure 3.1.2 *Heat release graphs for C waste and spent fuel reference packages (Andra, 2005b)*

- **Quantitative inventories according to the scenarios**

In the above scenarios, quantification of the number of reference packages is based on the inventories and waste production forecasts drawn up by the producers.

Generally high, envelope-type estimates have been adopted. For the waste to be produced, dimensioning margins were added in order to integrate the uncertainties. Furthermore, as a cautious approach, no allowance has been made for potential management possibilities for existing or future waste (particularly part of the bituminised waste) in the event of other disposal solutions.

Table 3.2 *Number and volume of primary packages, for B waste reference packages*

Reference packages	Scenario S1a		Scenario S1b		Scenario S1c		Scenario S2	
	Number	Volume (m^3)	Number	Volume (m^3)	Number	Volume (m^3)	Number	Volume (m^3)
B1	2 560	470	2 560	470	2 560	470	2 560	470
B2	104 990	36 060	104 990	36 060	104 990	36 060	104 990	36 060
B3	32 940	27 260	32 940	27 260	32 940	27 260	30 390	24 540
B4	1 520	2 730	1 520	2 730	1 520	2 730	1 520	2 730
B5	42 600	7 790	39 900	7 300	39 900	7 300	13 600	2 490
B6	10 810	4 580	10 810	4 580	10 810	4 580	10 810	4 580
B7	3 045	1 440	3 045	1 440	3 045	1 440	3 045	1 440
B8	1 350	775	1 350	775	1 350	775	1 350	775
Total	**199 815**	**81 105**	**197 115**	**80 615**	**197 115**	**80 615**	**168 265**	**73 085**

Table 3.3 Number and volume of primary packages, for C waste reference packages

Reference packages	Scenario S1a		Scenario S1b		Scenario S1c		Scenario S2	
	Number	Volume (m^3)	Number	Volume (m^3)	Number	Volume (m^3)	Number	Volume (m^3)
C0	4 120	700	4 120	700	4 120	700	4 120	700
C1	4 640	810	4 640	810	38 350	6 710	4 640	810
C2	990	170	27 460	4 810	0	0	5 920	1 040
C3	13 320	2 330	0	0	0	0	0	0
C4	13 250	2 320	0	0	0	0	0	0
Total	**36 320**	**6 330**	**36 220**	**6 320**	**42 470**	**7 410**	**14 680**	**2 550**

Table 3.4 Number of spent fuel assemblies if needs be

	Production Sites	Number of PWR fuel assemblies			
		Scenario S1a	Scenario S1b	Scenario S1c	Scenario S2
"Short" UOX AFA-2GE assembly, type CU1	EDF	0	0	0	27 200
"Long" UOX AFA-2LE assembly, type CU1		0	0	0	26 800
Total UOX assemblies, type CU1		**0**	**0**	**0**	**54 000**
"Short" MOX AFA-2GE assembly, type CU2	EDF	0	5 400	5 400	4 000
Total MOX assemblies, type CU2		**0**	**5 400**	**5 400**	**4 000**

Furthermore, the number of primary claddings considered for CU3 type fuel, if needs be, is 5,810.

- **Radiological inventory**

The presence of fission or activation products in the waste and also actinides are what constitutes the radiological inventory of the waste packages.

✓ **Fission and activation products**

The *short-lived radionuclides* (less than 6 years), particularly *cobalt60*, and the intermediate-lived radionuclides (between 6 and 30 years), *particularly caesium137 and strontium90, represent a very large part of the activity in activation and fission products. The intermediate-lived activity is present essentially in the C waste*; in the B waste, it is much lower (at least by a factor of 100) and concerns the reference packages covering the fuel assemblies structure waste (B5.1/B5.2, B5.3, B4 and B6.3).

The long-lived activation and fission products (excluding nickel63) *represent by comparison* much lower activities and *are particularly concentrated in the C waste packages*. The B waste packages also contain some of them, but at activity levels of 100 to 1 000 times less. Nickel-63 is a special case with an intermediate radioactive half-life (100 years). It is present at a relatively high activity level in many waste packages. *Its activity is significant in B waste packages, particularly reference packages B1, B4 and B5.*

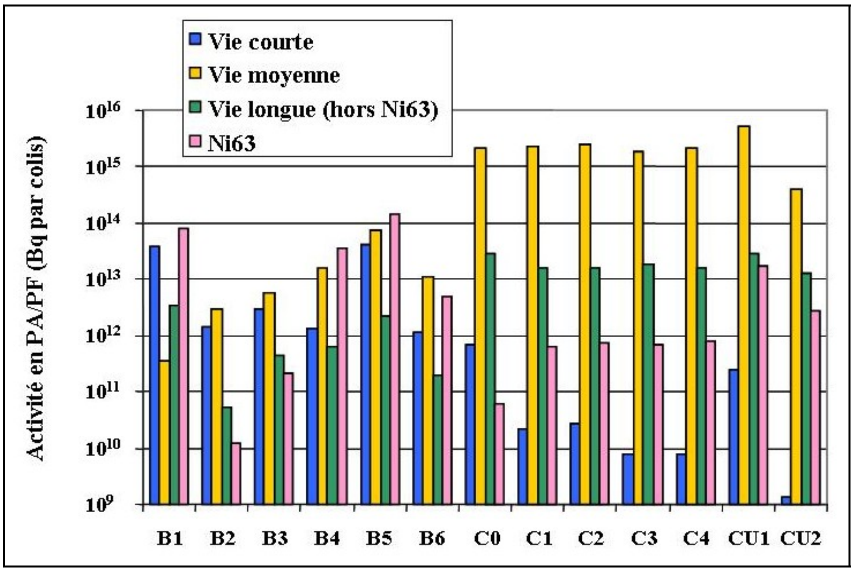


Figure 3.1.3 Distribution of activation and fission products for each type of package

✓ **Actinides**

The reference packages also contain variable quantities of actinides: *the C waste packages concentrate most of the inventory of the actinides* initially contained in the fuels (excluding uranium and plutonium extracted during the reprocessing and present in the form of traces). *However, the actinide content of B waste reference packages is not negligible*: the reference packages B3 and B5 have an intermediate-lived actinide activity level comparable to those of vitrified waste reference packages C1 to C4. The proportion of long-lived actinides is also higher in B3 and B5 waste packages than in the other B waste packages and is similar to the long-lived actinide activity level in reference package C0.

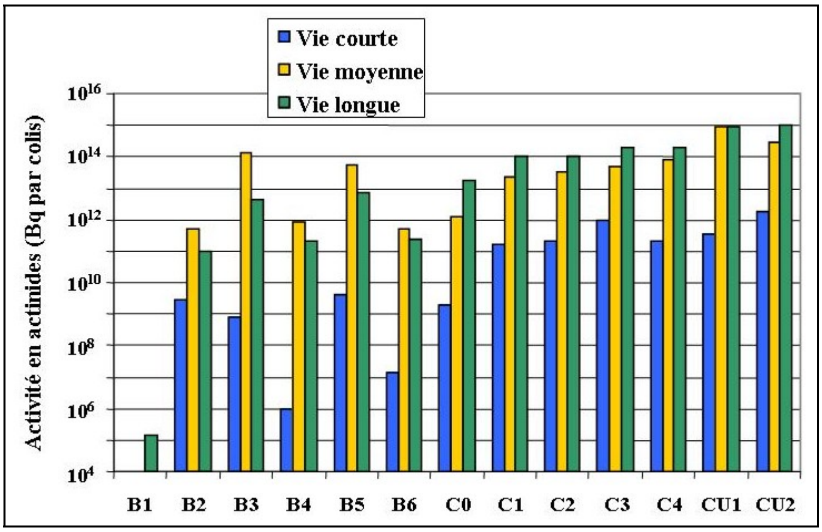


Figure 3.1.4 Distribution of actinides for each reference

For long-lived radionuclides, the total activity of all the waste of the inventory model is 6 10^{+17} becquerels for the activation and fission products (excluding nickel63) and 6 10^{+18} becquerels for the actinides (in case of scenario S1a for the total reprocessing of spent fuel[4]). *Long-lived activity is for*

[4] The S2 scenario leads to similar orders of magnitude: 7 10^{17} Bq for activation and fission products (excluding Ni63) and 1.7 10^{19} Bq for actinides.

the most part concentrated in C waste: 91% of the long-lived activity in activation and fission products is found there in addition to 97% of the long-lived activity in actinides. *Within B waste, the B5 reference packages represent the greatest part of the inventory in long-lived radionuclides*, with approximately 75% of the activation and fission products and 67% of the actinides.

Inset 3.7 **Chemical inventory of the primary waste packages**
The chemical composition of the waste primary packages is highly diverse. The packages can contain metals (such as stainless steels, zircaloys), organic matter (mainly the bitumen of reference packages B2) or glass (C waste). The stainless steels and some of the alloys contain nickel and chrome. B waste, and to a lesser extent C waste, can also contain aluminium or magnesium. One constituent of the glass matrix of the C waste glasses is boron, a chemical element that is toxic when not immobilised. Some B waste contains, in addition, materials composed of elements such as lead and cadmium which are chemically toxic when accessible in the environment.

3.2 Design principle for a repository in granite medium

The repository design study consists of an initial stage of identifying the safety functions to be fulfilled by the repository to achieve the general objectives assigned to it: to host and contain the waste packages in the granite, ensure long-term isolation of waste from man and the environment.

This identification was carried out through a functional analysis, an element of the safety approach implemented by Andra for the geological repository studies and adapted to the generic context of the granite medium studies (Andra 2005c, d, e).

The repository design study then leads to the definition of technical systems based on beneficial properties of the granite medium, including engineered components to ensure waste isolation over long periods of time.

Options proposed are adapted to each category of waste (B and C). Options for spent fuel disposal have also been studied. They fulfil reversibility requirements of the disposal process (Andra, 2005f).

3.2.1 Long-term safety functions of a repository

Firstly, the in-depth repository *protects the waste from erosion phenomena and main human activities* which after hundreds of thousands of years only affect the shallow thickness of the ground.

In this context, controlling dispersion of the radionuclides contained in waste relies on *three major functions* that must be performed by the repository:

- preventing water circulation,

- limiting radionuclides release and immobilising them within the repository,

- delaying and attenuating migration of radionuclides which could have been released by the waste.

Ultimately, these three functions must be passively fulfilled (without human intervention). Some are only implemented at a late stage. For example, the repository's ability to limit radionuclide migration does not become operational until the waste packages begin to release radionuclides. Such functions are said to be *latent* during the period when they are available but not yet operative.

3.2.1.1 Preventing water circulation within the repository

Confinement of radioactivity contained in the packages firstly consists of maintaining it immobilised there. The repository must therefore:

- *limit water renewal around the packages*, which is the main factor liable to alter package envelopes,

- *prevent advective transport* of the radionuclides in order to restrict their possibility of migration only via diffusion, a very slow phenomenon, by limiting both the water flow reaching the repository and *water circulation velocity* between the cells and the water conducting faults of the granite medium.

Inset 3.8 ***Advection and diffusion***

The elements placed in the repository (waste package constituents, construction materials, etc) can eventually dissolve in water. They dissolve very slowly, at rates governed by chemical balances, and depending on the amounts of water percolating in the repository. Movements of an element dissolved in water are governed by two phenomena often occurring together:

- Diffusion: due to the effects of Brownian agitation, the element dissolved migrates from zones where its concentration is greater in the water (near the waste for radionuclides) towards zones where its concentration is low. This phenomenon whose velocity depends on the element considered is always very slow;
- Advection: when the water is itself in circulation, the dissolved element is caught up in the movement. Advection velocity depends on the void spaces geometry and the surrounding hydraulic environment.

Depending on water circulation velocity, the movement caused by advection can be faster than diffusion, or slower and therefore negligible. In this latter case, it is thus said that the predominant transit mode is diffusion. This second situation is desirable for the repository

3.2.1.2 Limiting radionuclides release and immobilising them within the repository

The arrival of water at the waste packages which constitute an initial radionuclide confinement barrier cannot be ultimately ruled out. Under these conditions, the role of the repository is to limit the release of radioelements in the water and immobilise them in the waste or as close as possible.

By creating beneficial physicochemical environmental conditions, repository installations can limit water alteration of the waste containers and, within these containers, of the matrices (glass, bitumen and cement) where the radionuclides are incorporated and which withstand well dissolution (notably the glass).

Once the water has started to alter the waste packages, the role of the repository conditions is to limit the mobility of radioelements likely to be dissolved in the water by creating reducing geochemical conditions (completed with pH control) and even maintain and re-precipitate these radioelements in solid form (only some radioelements, such as iodine 129 and chlorine 36, remain unaffected by these beneficial geochemical conditions).

3.2.1.3 Delaying and attenuating radionuclide migration

One of the repository functions is to delay and disperse the migration of radioelements released by the waste within the space and over time in order to attenuate it:

- migration of radioelements dissolved in the water is controlled by diffusion, dispersion and retention in the granite, the repository host formation,

- dissolving, in water, the radionuclides likely to be released in gaseous form enables these elements to be controlled in a similar way,

- moreover, radioelements migration can be limited within certain repository components (engineered barrier and bentonite seal, etc), and therefore delayed.

3.2.2 General design options for a repository in granite medium (Andra, 2005f)

In order to fulfil ***long-term safety functions***, the design proposed for a repository in granite medium consists of:

- using a variety of technical measures to make the most of the beneficial properties of the granite medium, such as notably its low permeability and mechanical resistance,

- designing engineered repository components (disposal package, engineered barrier, backfill and seal) so that they contribute to safety functions in terms of complementarity or redundancy with the granite medium.

- adopting design options aiming at limiting repository disturbances of the granite medium.

In addition to the long term and operational safety, design must meet the ***reversibility requirement***, closely linked to application of the principle of precaution provided for in the law of 30 December 1991. Beyond the possibility of retrieving emplaced packages (*retrievability*), reversibility is based on a *cautious management* of a possible repository in successive stages, which, given the timeframes under consideration, leaves the options open for future generations.

These principles lead to adopting various technical measures for repository architecture, its design, the choice of materials for engineered components and the disposal processes.

3.2.2.1 Making the most of favourable granite properties

The granite medium is characterised by an extremely low permeability rock, with high capacity for radionuclide retention and mechanically resistant. As granite is intersected with fractures liable to conduct water, making the most of its favourable properties requires adaptation of repository architecture to this fracturing.

- **Architecture with compartmentalization and adapted to granite fracturing**

Repository architecture is organised into different zones by major categories of packages: B waste, C waste and spent fuel. These zones are sufficiently far apart to avoid interaction between different types of waste, particularly from a thermal or chemical viewpoint. Compartmentalization of each repository zone also reduces quantities of waste and radioelements which would be affected in cases of system failure or intrusion.

Apart from these design principles, repository architecture and compartmentalization is dictated by granite fracturing.

✓ **Construction away from faults**

At repository scale, repository zones for the various categories of waste are constructed away from major faults of the granite massif.

Each repository zone is divided into *modules* grouping together a series of cavities (the disposal cells) for the same type of waste. Modules are located in granite blocks not intersected by large- or medium-size faults, considered as significant water conductors.

One of the basic principles of a repository in a granite medium is to *construct disposal cells in rock of very low permeability*. This does not mean that there can be no fracturing whatsoever in the rock but that small-sized fractures which may exist in disposal cell walls, are not or nearly not water conducting. Therefore water flow which might come into contact with packages is very low or even nil.

Disposal cells are of a dead-end type (therefore with only one access to repository drifts), thus limiting possibilities of circulation of water coming from the drifts.

These principles regarding repository site and architecture meet the requirements laid down in The basic safety rule RFS III.2.f, which states:

"Repositories in geological formations must be located in crystalline mediums, within a host-block exempt from major faults, as the latter are likely to be preferential pathways of hydraulic movement. Disposal modules must be emplaced far apart from medium-sized fracturing, although this may be intersected by access structures".

- ✓ **Construction of modules with respect to waste heat transfer**

At the module scale, the principle of adapting architecture to fracturing works differently for each type of waste. Indeed, the footprint required for different types of packages may necessitate implementation of different options (see fig 3.2.1).

The inexistent (or low) thermicity of B waste makes possible a design with compact disposal cells and therefore requiring only a low volume of granite. B waste disposal thus requires a small footprint and adjustment of architecture to granite fracturing is eased. Disposal modules are built so as to avoid fractures likely to cause advective water circulation.

C waste and spent fuel thermal characteristics define disposal module dimensioning and lead to such large footprints that it is not possible to avoid the intersection of a module by a fracture, potentially water conducting[5]. Repository architecture must also be adapted to two levels of fracturing. Size of disposal cells allows them to be built in very low permeability granite rock with minimal fracturing. Modules are installed in granite blocks, avoiding fractures which would let in too much water, the medium-sized fracturing, mentioned in RFS III.2.f. Otherwise, a granite massif is generally a few kilometres thick. The large volume of granite rock available for a repository at depths of between 300 and 1000 metres allows therefore for flexibility in adapting architecture to granite fracturing. General repository architecture can then be designed on one or more levels.

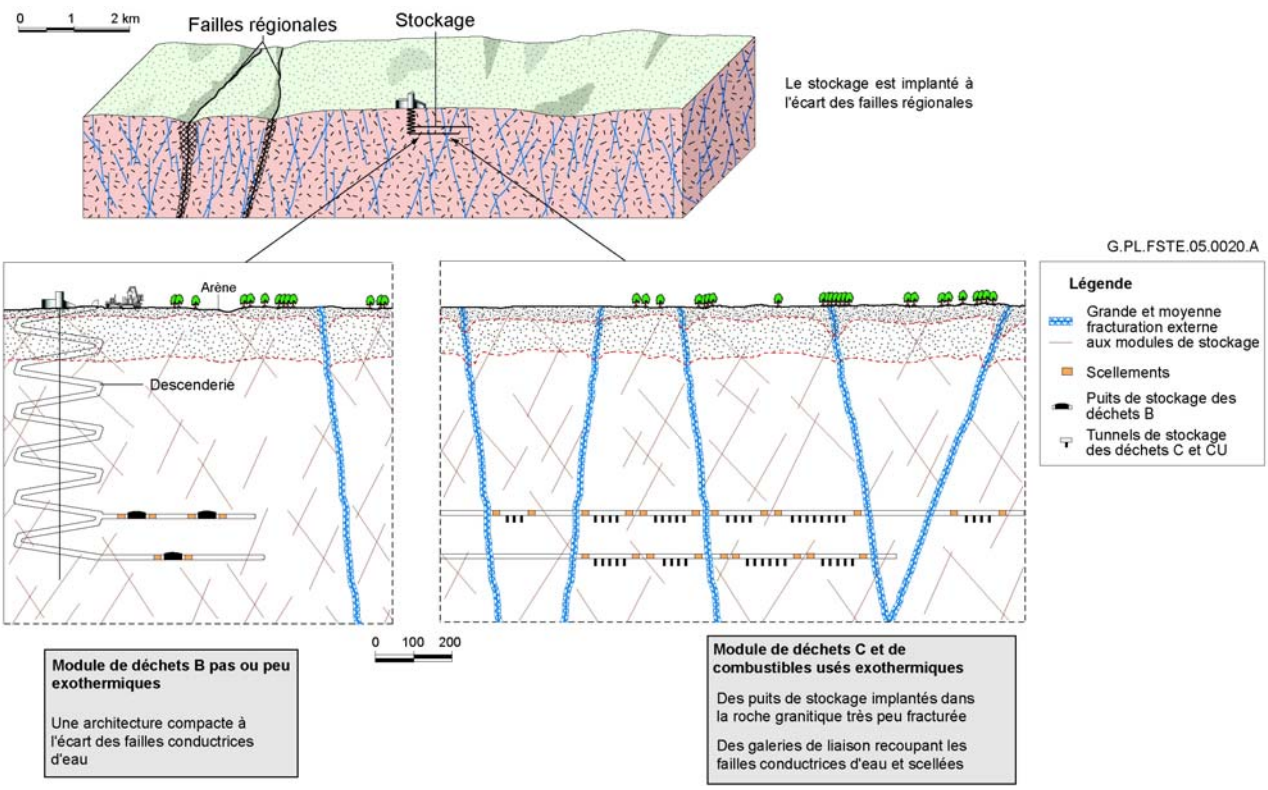


Figure 3.2.1 *Conceptual diagram for the construction of repository structures related to fracturing*

From a functional point of view, such architectural arrangements enable the repository to fulfil a primary objective of preventing advective water flow within the underground installations. As regards

[5] According to waste volume and to their different thermicity, spent fuel disposal is more demanding in terms of footprint than C waste one.

disposal cells, this helps to facilitate a diffusion transfer system. Water flow rates are limited in the module drifts. In addition, the repository is located away from regional faults, safe from major water circulation.

Such architectural arrangements also facilitate other repository functions, limiting radionuclides release by disposal cells and their migration towards the environment.

- **A disposal process enabling "ongoing" surveying and characterising of granite blocks where modules are constructed**

Adapting repository architecture to fracturing means knowing well and accurately the granite-host rock characteristics. The surveying strategy may include several stages:

- surveying and characterising from the surface, or from underground structures (geological medium qualification underground facility), in order to define the granite structure where the repository is to be built. An iterative approach between safety analysis and the various phases of granite site survey, on the surface and then underground, defines criteria for exclusion of faults (or fractures) which may or may not be intersected by repository connecting drifts, access drifts to modules and disposal cells;

- on this basis, the process includes *in situ* characterisation of host-granite blocks for disposal modules before package disposal. This stage of granite "ongoing" characterisation during the staged repository construction finalises module architecture and distribution of disposal cells in the granite according to fracturing.

Such a strategy aims at adapting repository architecture as best as possible to granite fracturing and to ensure that proposed design concepts fulfil their functions effectively as regards control of water circulation in the repository.

3.2.2.2 Design of engineered components, complementary and redundant with the granite medium for long-term safety

At the scale of both the repository as a whole, and the disposal cell, several arrangements are possible to ensure complementarity and redundancy between the granite medium and repository engineered components with respect to long-term safety. They particularly concern repository architecture and choice of materials for engineered components (disposal packages, engineered barriers, backfills and seals).

- **Multiple sealing of underground installations**

Connecting drifts and access drifts to modules and disposal cells are likely to intersect water-conducting fractures. *In order to limit water circulation within the repository, seals are installed at various levels of the underground installations.*

In the case of disposal cells, water may come from drifts serving them. Drifts are likely to be crossed by a more water conducting fractures than the cell wall one. The 'dead-end' architecture of cells, their construction in granite rock of very low permeability, and low permeability 'plugs' at cell heads limit water circulation and aims at establishing a transfer system in the cells governed by diffusion phenomena.

At the repository module scale, water circulation is limited by:

- very low permeability seals installed in drifts to cut off modules from water coming from any possible intersecting faults,

- backfills of sufficiently low permeability in module drifts.

Disposal cell seals and plugs are made of swelling clay (bentonite), which are of very low permeability over long periods of time. Backfills may also incorporate clay materials to ensure sufficiently low permeability.

At the repository scale, connecting drifts between modules as well as structures between the surface and underground are backfilled. Seals are installed in access structures where they intersect water-conducting faults.

- **A physico-chemical environment suitable for waste packages**

Disposal cell design aims at providing a suitable physico-chemical environment for waste and packages in order to control changes in state over time and limit radioelements release.

Such an environment is ensured by the materials used for waste over-packs, the choice of which depends on type, volume, radiological inventory and chemical nature of the waste, as well as by engineered barriers.

For B waste containing metal elements (B1, B3, B4 and B5 reference packages), the aim is to limit corrosion by providing a favourable chemical environment (reducing potential, pH 10 to 12.5), in particular by using concrete for waste over-packs. For bituminised B waste, the aim is to maintain, on the long term, bitumen confinement properties (B2 reference package) by controlling chemical conditions and temperature (between 20 and 30°C).

For C waste and spent fuel, emplacing clay buffers between packages and the granite rock attenuates chemical interaction between packages and water from the granite.

- **Disposal packages which are leak-tight or of very low permeability over a sufficiently long period of time**

In order to ensure complementarity with the geological barrier, primary packages are inserted in additional containers, to constitute disposal packages. A study has been carried out in order to ensure their leak-tightness or very low permeability over sufficiently long periods of time, which depends on types of waste and their radiological inventories.

A concrete disposal package has been chosen for B waste. For some types (B1 and B5 packages, which have major radioactive content and do not release gas), disposal packages have long-term confinement properties (around ten thousand years). This performance is achieved by using a specially adapted concrete mix (with very low permeability and porosity) and a specific design (method of closing). This type of container limits water reaching primary packages as well as radionuclide release for this period of time.

For C waste packages, the aim is to prevent water from coming into contact with the glass for several thousand years. This period concerns the thermal phase (i.e. the period when the temperature at the heart of the glass is over 50°C) during which glass alteration phenomena by water are accelerated. The proposed design is based on a very thick steel container.

For spent fuel, a copper container is proposed, with long term leak-tightness property (up to several hundred thousand years). In contrast to C waste, radionuclides are not trapped in a confinement matrix (a fraction of the radionuclides is released upon contact with water, and the remainder is released as the uranium oxide matrix dissolves). This option is based on the ‘KBS-3’ copper container a concept adopted in Sweden (SKB) and Finland (Posiva). It was adopted by Andra at this generic design phase. Site data would justify revision of this option if adaptation of architecture to granite massif fracturing and engineered structures (backfills and seals) allow sufficiently long transfer time in the geological medium to ensure radioactive decay of radionuclides.

3.2.2.3 Limit granite disturbance caused by the repository

While repository design aims to take account the favourable properties of granite. It should be ensured that repository construction and its long-term evolution do not aversely affect the properties of the granite medium. The various arrangements studied involve structure dimensioning, choice of materials for engineered components and the disposal process.

- **Design basis limiting mechanical and thermal disturbance**

Granite is a mechanically resistant rock. The structures (drifts and cells) are dimensioned to ensure mechanical stability in the long term.

Heat released by C waste (and by spent fuel, if disposed of) causes a temperature rise in the cells and surrounding granite. In order to control the thermal phenomena incurred, the aim is to keep the temperature in the cells lower than 100°C (and therefore in the rock). In practical terms, a maximum temperature of 90°C has been adopted for the hottest point in the swelling clay buffers for C waste cells and at the surface of spent fuel copper containers.

The essential parameters for repository architecture dimensioning in order to limit the temperature are the number of disposal packages per cell and the spacing in between disposal cells. The C waste and spent fuel repository zones footprint is mainly subordinate to these thermal considerations and the thermal power released by the packages when emplaced in the repository.

- **Disposal process limiting hydrogeological and hydrogeochemical disturbance of the host granite massif for underground installations**

Excavation of underground installations drains off the granite water and disturbs initial hydrogeology. As granite is only slightly permeable, this disturbance mainly affects the most water conducting faults and fractures. In order to limit the groundwater draining from the granite and by extension the quantities of pumped water while excavating the underground installations, it can be envisaged to resort to injection techniques for the most water conducting faults and fractures intersected by the structures.

After a transient phase of disturbance related to underground installations excavation, equilibrium between water drainage and re-supply is established within the granite massif.

Appropriate management, depending on the granite hydrogeological context, of repository zones excavation, their operation and then their closure constitutes then a mean of limiting hydrogeological and hydrogeochemical disturbance of the granite.

3.2.3 Adaptation of design arrangements to long-term safety functions

The various options proposed contribute to one and /or the other of the major disposal functions:

- *the function "preventing water circulation in the repository"* is mainly fulfilled by architectural and sealing arrangements. Repository architecture is adapted to granite fracturing,

- *the function "limiting radionuclides release and immobilising them within the repository"* is mainly fulfilled by systems implemented near the packages in order to permanently ensure environmental conditions to waste protection and immobilisation of radionuclides released,

- *the function "delaying and attenuating radionuclides migration"* makes the most of all technical measures adopted within the design options: structure design, choice of structure and package materials.

Table 3.5 Technical measures and long-term safety functions for a repository in granite medium. Contribution of technical measures to the function: XXX: essential; XX: significant; X: accessory

Design principles	Technical measures	Safety functions: Preventing water circulation in the repository	Safety functions: Limiting radionuclides release and immobilising them in the repository	Safety functions: Delaying and attenuating radionuclides migration
Making the most of favourable properties of granite medium	**Architectural** Constructing cells in very low permeability granite rock	XXX	X	XX
	Constructing modules in the "blocks" apart from water conducting faults	XXX	X	XX
	Constructing the repository away from regional faults	XXX	X	XX
	Disposal process Ongoing characterisation of granite "blocks"	XXX	X	XX
Designing engineered components complementary to and redundant with granite medium	**Architectural** Multiple sealing of the structures (cells, modules, drifts, surface-bottom connecting structures)	XXX	XX	XXX
	Materials A physico-chemical environment beneficial to packages and waste: engineered barriers and over-packs adapted to types of waste		XXX	X
	Disposal packages (containers, over-packs, etc) leak-tight or only slightly permeable for sufficiently long periods of time depending on waste type		XXX	XX
Limiting granite disturbance caused by the repository	**Design basis** Structure dimensioning ensuring long-term mechanical stability	XXX		XXX
	Structure thermal dimensioning for control of phenomena induced by structure temperature rise		X	
	Materials Disposal packages and engineered barriers whose alteration does not significantly disturb granite retention properties			XXX
	Disposal process Disposal process managed so as to limit disturbance of granite hydrogeological and hydrogeochemical characteristics	XXXX	XX	XXX

3.2.4 Integrating reversibility (Andra, 2005f)

In addition to operational and long term safety, ***repository design must meet the reversibility requirement***. Reversibility is related to a cautious and staged management of a possible repository which, given the timeframes considered, leaves the options open for future generations.

Reversibility requirement involves, over the course of time, human presence, monitoring and maintenance activity which do not put at stake whatsoever, long term safety, the primary aim of the repository. But rather, based on cautious and gradual management of the disposal process, reversibility can contribute to improving the confidence in long term safety.

Reversibility requirement was at the heart of the analyses carried out for the study of a possible repository in granite medium. The design approach implemented by Andra aimed at proposing generic design options fulfilling this reversibility requirement.

Beyond the ability to retrieve disposed packages (retrievability), reversibility can be defined as the possibility of gradual and flexible management of the repository which leaves future generations free to decide. With this aim in mind, the disposal process can be broken down into a succession of stages to be performed which provides from the construction of the initial modules up to closure of a module or of a repository zone, the possibility of waiting and observation time, before deciding to go on to the next stage or reverse the process. The completion of a stage is not a definitive decision, but a justified choice, based on thorough understanding of scientific, technical, economic, social and environmental parameters and the consequences caused by going from one stage to another.

In this perspective, repository design therefore considers the three aspects of reversibility:

- architectural arrangements beneficial to a gradual repository management,

- technical measures for going backward to the various disposal stages,

- means of observing repository status and its evolution at any time in the process.

3.2.4.1 Repository architectures incorporating and fostering reversibility

Simplicity and robustness of the concepts, durability of materials, modular design: repository architectures proposed by Andra integrate reversibility requirements and facilitate its implementation.

• Simple and robust disposal concepts

Concepts proposed by Andra at this stage of the study are, by principle, simple and robust. Simplicity is based on the concern for technical feasibility and control of performance. Mechanical resistance of granite rock especially allows limiting support systems in structure design. Simplicity of options proposed by Andra facilitates the description of their evolution over time as well as their modelling. Robustness is based on resistance of the concepts in terms of safety and necessary scientific knowledge.

• Durable materials and systems to facilitate potential package retrieval

The aim of facilitating packages retrievability by future generations has led Andra *to give the priority to durable materials for packages and structures* (concrete, steel, etc.), since their good preservation is the basic condition for reversibility. Their durability in a repository environment may be estimated at several centuries.

In addition, several systems participate in facilitating the reversible management of the repository and the possible package retrievability: for example, regrouping the packages in standardised over-packs, identical handling systems for package emplacement and retrieval, handling space in between the packages and/or between the packages and disposal cell walls.

• Modular design of underground installations for flexible management and changes in design

The architectures proposed are of modular design meaning that they enable the repository to be managed in a flexible way for example, construction and operation in stages thus facilitating incorporation of experience feedback.

Each category of package (B, C and CU) is received in an assigned repository zone, constructed, operated and closed independently. Each repository zone is designed to be built and operated gradually as *successive sub-assemblies of disposal cells.* Closure, which is designed in the same way as for operation in a gradual manner, is organised into several stages: closure of cell sub-assemblies, which can be carried out at the same time as the creation of new sub-assemblies, closure of access to this sub-assembly, and then of the repository installations specific to this waste category and lastly of all installations.

As the repository is being developed in stages, new structures can be designed taking advantage of the lessons learnt and knowledge acquired during operation and observation of previous structures, as well as of technical progress carried out otherwise. It is as well possible to incorporate data from social, technical and scientific backgrounds

3.2.4.2 Technical feasibility of reversing the process

Andra has studied the technical feasibility of reversing the process for the various repository stages: technological resources, operating conditions and necessary precautions.

The repository is therefore designed to allow packages to be retrieved in the first stage by simply reversing the process of their emplacement in the cell (as in a storage facility). For later stages, Andra has incorporated arrangements for being able to gain access again to the installations which are closed and install the equipment required to retrieve the packages, would such a decision occur.

3.2.4.3 An observation programme supporting reversible repository management

Keeping options open during the repository process implies knowledge of its evolution and situation at all times: therefore it requires constant observation and implementation of the necessary measurement resources and systems. Andra has studied the possibilities of integrating measuring sensors in the structures without disturbing repository operation and safety.

In addition to the monitoring measures related to operational safety, the role of this observation programme is to check that the repository evolution matches forecasts, to propose, if needed, actions to maintain open the various management options and to compile lessons learnt in order to improve repository design and management. The data thus acquired will contribute to improving modelling and increasing the reliability of forecasts.

3.3 Description of disposal concepts (Andra, 2005f)

Design options described in this section are based on the previously adopted principles. They are mostly based on common granite properties as mentioned in chapter 2. However, they also take into account specificities of granite within the French geological context, especially in terms of general repository architecture. In order to fulfil this purpose, data on French granites was systematically analysed for the identification of the main variability in granite properties and rank them for repository design (Andra, 2005a).

3.3.1 General repository architecture

3.3.1.1 Modular architecture adapted to granite fracturing

The general architecture of the underground installations is adapted to the structure of the surrounding granite. The repository modules are installed in "blocks" of granite apart from water conducting fractures. A buffer zone of several tens of metres (depending on the local characteristics of the granite) is kept between modules and fractures. Distances between modules are generally of the order of hundreds of metres. The general architecture of a repository depends on the distribution of "blocks" in the granite massif hosting the repository.

The repository zones that include the repository modules for the same category of waste (B, C), or spent fuel if the need arises, are distinct.

To prevent interactions, especially chemical interactions, between waste packages of different types, each repository module will only include waste of the same type. For example, B waste containing organic matter are disposed of in dedicated modules.

As a general rule, repository architecture of modular design due to its module separation strengthens safety by limiting the consequences of any failures within the module perimeter.

3.3.1.2 A reference architecture on two levels

A granite massif normally provides a repository with a vast volume of rock at a depth of between 300 and 1,000 metres offering the flexibility to adapt the architecture to granite fracturing.

The analysis of the advantages and constraints of two-level architecture underlines its interest: it reduces repository footprint and facilitates “ongoing” granite surveying which is carried out during disposal in order to localize the modules. A distance of about 100 metres between each level would prevent thermal interaction between C waste and spent fuel repository modules and would ensure compliance with the maximum temperature criteria (90 °C) in the disposal cells.

The network of underground drifts includes a "bundle" of several parallel drifts (3 to 5 depending on the repository zones) to separate throughputs associated with construction activities from those of nuclear operation activities throughout the disposal processes.

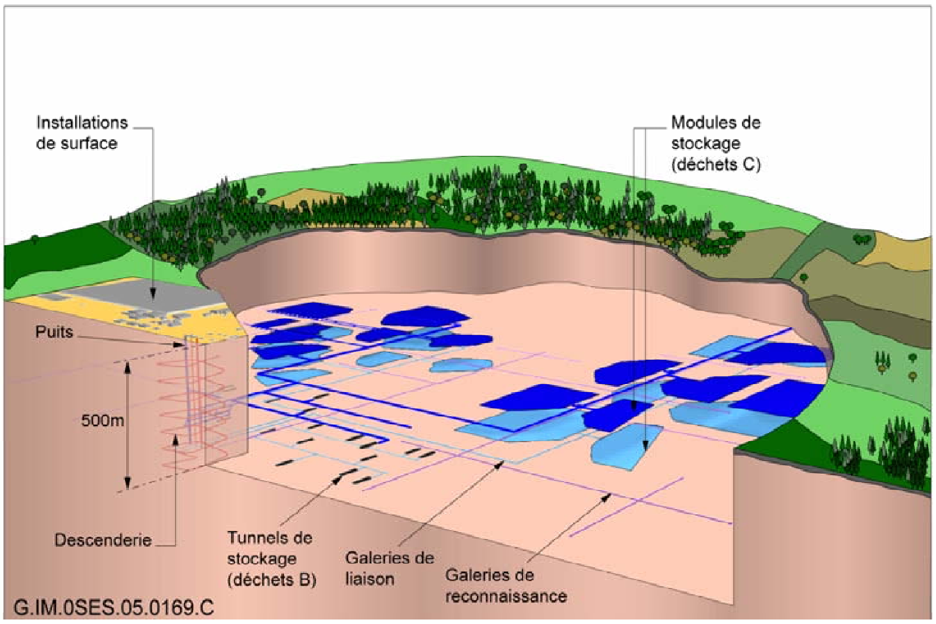


Figure 3.3.1 Overview of a repository in granite medium: surface installations and underground installations on two levels

3.3.1.3 Structures connecting the surface and underground facilities (shafts or ramps) installed in relation to the local hydrogeological context

Shafts or ramps could be envisaged to connect the surface to the underground installations (figure 3.3.1). They are generally designed as a complementary feature in the repository design. For example, in Finland, the "Onkalo" reconnaissance facility, which is likely to become an access to the waste repository, has a ramp as main connecting structure between surface and underground.

The number and the dimensioning of shafts and ramps are adapted to their specific transfer functions and the corresponding throughput rates: the evacuation of the excavated rock, transfer of materials, disposal packages, personnel and ventilation.

In terms of the long-term safety, these structures are installed in relation to the local hydrogeological context to prevent any drainage from the repository toward the surface. The access to the shafts and/or ramps can also be grouped together in the same zone to limit any hydraulic effects between structures and achieve greater control over the hydraulic regime in the repository.

3.3.1.4 A systematic backfilling of structures and multiple seals

The connecting structures between surface and underground and the repository drifts could intercept water conducting fractures. They are therefore backfilled to protect the repository modules from possible water circulation.

Seals installed at key points in the drifts also prevent water arrival that could come from fractures intercepting drifts.

Backfill and seals therefore have complementary and redundant functions in terms of long-term safety. Their detailed specifications depend on the characteristics of the granite site. In the context of such generic granite studies, both systems have been examined and adopted for all the repository zones.

Backfill is systematically proposed in the surface-underground connecting structures and in the repository drifts. Basically, the closer the drifts to the waste, the greater the requirement of the backfill hydraulic performance. In the repository modules, the drifts are backfilled with a low permeability material. Outside repository modules, the permeability of the backfill in the drifts and surface-underground connecting structures is specified in relation to the conductivity of the fractures likely to be intercepted and of the damage to the rock caused by excavation.

Very low permeability and long-lasting seals are systematically planned between the water-conducting fractures and the repository modules installed in very low permeability "blocks" of granite. Depending on the site configuration, seals could be planned in the surface-underground structures or the repository connecting drifts to limit the direct arrival of water coming from the superficial more permeable part of the granite.

3.3.1.5 Adaptation to different site geological configurations

Several components can be adapted to the various configurations of French granite sites.

The repository zones for various waste categories can be distributed at different depths to suit the site thermal conditions. They can be more or less far apart from each other depending on the large-scale fracturing of the site.

The surface-underground connecting structures can be more or less grouped together to variable depending on the distribution of the repository zones and the site hydrogeology. The choice between shafts and ramps for transferring materials and packages can also depend on the site conditions (topography, characteristics of the superficial parts of the granite, etc.).

The number and the distribution of connecting drifts depend on the installation of the various repository zones in the granite and the repository levels depth.

The closing mode for drifts and access structures and especially the respective position of backfills and seals can be adapted to granite massif hydrogeological configurations

3.3.2 B waste disposal

The volume of B waste, about 80,000 m3, entails adopting solutions that can ensure a relatively good compactness of packages in the disposal cell. This limits the number of cells and the volume of rock to be excavated and the number of very low permeability granite blocks needed for installing the disposal tunnels.

Furthermore, the diversity of waste mean that only those waste packages that are compatible with one another can be emplaced in the same cell. This compatibility concerns the chemical nature of the waste, their thermal release and possible gas production.

Several types of grouping are possible:

- disposal cells with waste containing organic compounds or organic matter that are likely to produce complexing species when altered by water.

- bituminised waste (B2) cells.
- disposal cells with waste free from organic matter, but producing hydrogen by radiolysis of the concrete in the cemented primary packages, or packaged in a concrete shell (most B3 and B4 waste),
- disposal cells containing slightly exothermic waste (B1 and B5) free from organic matter and not giving off gas.

Therefore, starting from a standard disposal cell design, the dimensioning and the packaging of the waste are adapted to each of these cell configurations.

3.3.2.1 Concrete disposal packages with confinement properties

The design of the disposal packages is identical to that proposed for the repository in a clay medium.

Operations simplification and package retrievability have led to the design of standardised parallelepiped-shaped concrete packages (figure 3.3.2).

Depending on the initial packaging of the waste, the disposal packages contain 1 to 4 primary packages. They weigh between about 6 and 25 tonnes and their dimensions are between 1.20 and 3 metres. The disposal packages are handled by forklift truck type machine. Their design enables them to withstand dropping when being stacked in several levels in the disposal tunnels.

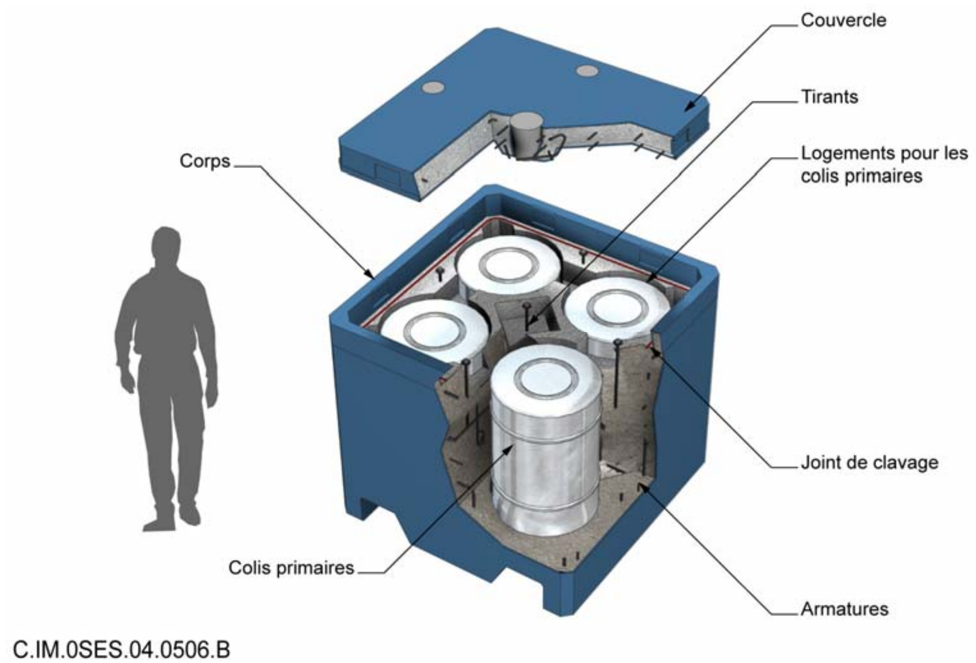


Figure 3.3.2 Standard disposal container

The body and lid are prefabricated (using a moulding technique) in reinforced or fibre concrete, whose formulation is chosen to give them a high performance and long durability.

For waste producing hydrogen, the concrete over-pack is designed to evacuate the gas and prevent any excess gas pressure that could damage the packages.

For the more radioactive waste not giving off gas (B1 and B5 packages), a container, with a reinforced confinement capacity of at least tens of thousands of years, has been studied. This means making the most of the hydraulic and transfer properties of the concrete. This performance requires a very low permeability envelope, a very low diffusion factor at package scale and a long-term mechanical integrity.

These studies are consistent with the ones carried out in Japan for the disposal of the same waste type, produced during spent fuel reprocessing.

Several solutions have been examined: they are based on the use of a single concrete formulation for all the components of the packages, reinforcement through fibres and without metallic rods. Feasibility was achieved through the realisation of demonstrators of such container. The properties in terms of performance are still subject of a test and qualification programme in 2005.

The Japanese agency RWMC has also studied a similar solution and has successfully produced a demonstrator.

These results confirm the possible perspectives for the design of concrete B waste disposal packages having the required hydraulic and transport performances. They demonstrate the possibility of obtaining a long-lasting confinement of about ten thousand years. In a granite medium, this helps to meet the robustness requirements of the repository in terms of long-term safety, for a large number of site configurations in the French geological context.

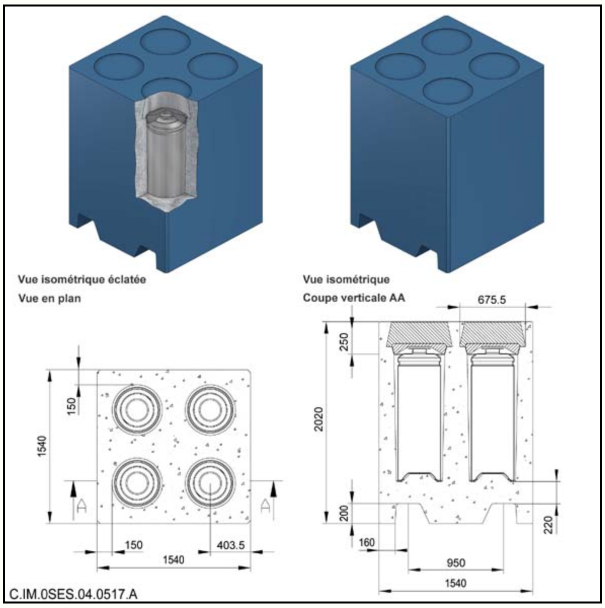
Inset 3.9 ***Containers with a reinforced confinement capacity***

The analysis of the distribution of radiological activity between packages has demonstrated the interest of studying the feasibility of a disposal container with an additional confinement performance for certain packages (B1 and B5.2) which account for a large proportion of the radioactive inventory of B waste for certain radionuclides (niobium 94, zirconium 93, caesium 135, etc.). The container must last for a very long time (at least 10 000 years) and provide mechanical resistance over the same period.
The increased confinement performance makes the most of the concrete hydraulic and transport properties (diffusion, retention) to limit and delay radionuclides migration when released by the primary packages.
The container includes:

- a prefabricated body with 4 housings adapted to the size of the primary packages,
- 4 prefabricated individual plugs that close the housings once the primary packages have been inserted and provide the shuttering before pouring the individual lids,
- 4 concrete lids that are poured above the 4 housings.

The confinement performance is essentially determined by that of the body and by the quality of the binding between the poured lid and the prefabricated body (BHP 90 MPa) concrete with stainless steel fibres and no reinforcing rods.

A demonstrator of such a container has been produced jointly by Andra and the CEA.



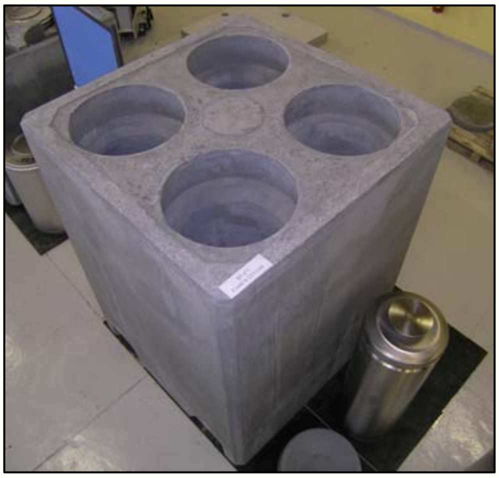


Figure 3.3.3 *B waste disposal container with a reinforced retention capacity*

3.3.2.2 Repository tunnels constructed in granite blocks low in permeability

The solution proposed for the B waste disposal cell is a horizontal tunnel in which are stacked several layers of disposal packages. The tunnels are dead-ended: their end, limited by the granite rock does not open onto a drift. This arrangement reduces water circulation in the disposal cells.

The tunnel lengths, varying from 70 to 200 metres, are adapted on one hand to the characteristics of and inventory of the various types of waste and, on the other hand, to granite fracturing.
Because of the mechanical properties of granite, the tunnels cross section can be quite wide (width of 10 to 20 metres), which contributes to repository compactness.

For the slightly exothermic waste (B1 and B5), the dimensions also takes into account temperature criteria relating to both the control of the long-term behaviour of concrete packages and the behaviour of radionuclides in the cells. The maximum temperature adopted is 70°C (not taking into account heat evacuation through cell ventilating).

The tunnels are about ten metres high; about ten metres wide for slightly exothermic waste (B1, B5) and about twenty metres for non-exothermic waste (B2, B3, …). (figure 3.3.4).

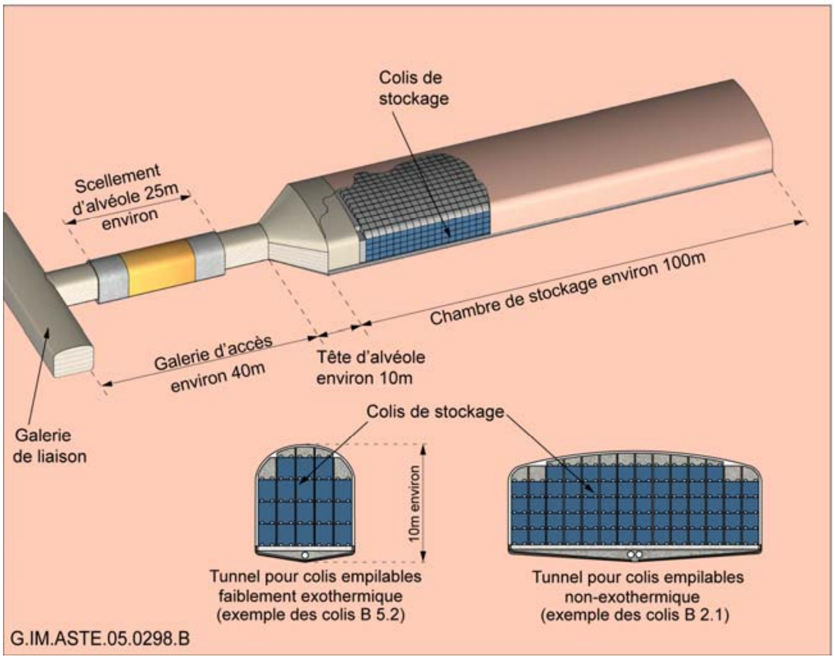


Figure 3.3.4 Repository tunnel for stackable B waste packages

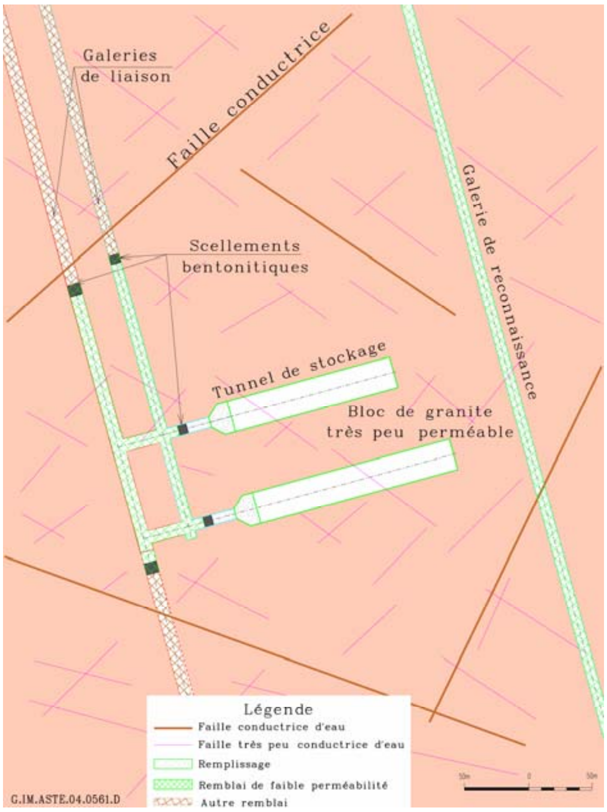
The disposal chamber is an irradiated volume in which the packages are handled by remote-controlled equipment. The head of the cells is equipped with a radiological air-lock (dual-gate system) for handling operations.

If necessary, it is possible to place suitable concrete structures between the packages and the cell roof so as to fill the remaining spaces and protect the upper levels of the stacked packages from any seeping water.

When the cell is closed, the volume occupied by the dual-gate system is backfilled; the access drift is sealed by a very low permeability clay plug.

In terms of general architecture of a repository zone, repository tunnels are constructed in granite low permeability blocks and apart from water conducting faults (figure 3.3.5).

A two-level repository optimises the use of the volume of low permeability rock available between the water conducting faults.



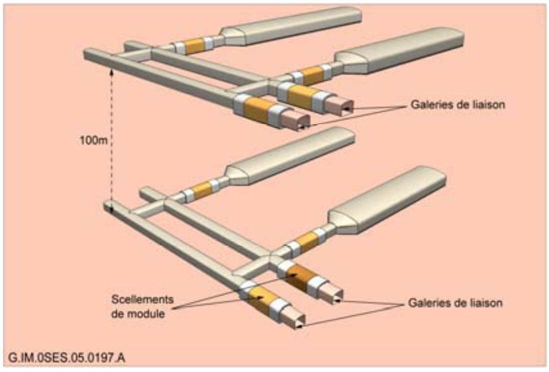


Figure 3.3.5 Principle for constructing B waste repository tunnels

3.3.3 C waste disposal

The design of the C waste repository is determined by their exothermal nature and the nature of their packaging (glass matrix).

The management of C waste heat output is an important design factor for the repository. Controlling the repository behaviour involves taking into account the temperature criteria within the disposal cell (maximum 90°C) and leads to reducing the number of packages per cell and to planning a sufficient distance between each cell.

The waste inventory used for the study led to a rather extensive repository footprint (a few km^2) mostly because of the constraints caused by faults and water conducting fractures in the granite.

Adapting the repository module architecture to granite fracturing is achieved on one hand at the scale of the disposal cells that are located in a slightly fractured granite rock, and on the other hand at the scale of the module that is located apart from water-conducting fractures.

The repository design aims of taking advantage of the glass matrix of C waste to retain the radioactive elements. The aim is to protect the glass from both water and chemical interactions with other components of the repository. The design therefore includes a swelling clay buffer around the packages and an over-pack that remains leak-proof as long as the temperature in the core of the glass remains above 50°C.

3.3.3.1 Disposal package: a carbon steel over-pack

The solution adopted at this stage, for its simplicity and robustness with respect to current knowledge and techniques, is identical to that proposed for the repository in a clay medium. It consists of an individual plain (unalloyed) steel over-pack.

The over-pack consists of a body and a lid made of the same material. A handling system is integrated inside the lid so as reduce the residuals gaps outside the packages (figure 3.3.6).

The container thickness (55 mm) is determined to withstand any corrosion that is likely to occur after package emplacement. It provides sealing and mechanical resistance that lasts for several thousand years (by taking into account a force of about 10 MPa resulting from the water pressure and the swelling of the clay buffer engineered barrier).

The 1.6 metre long over-pack has a diameter of about 55 centimetres.

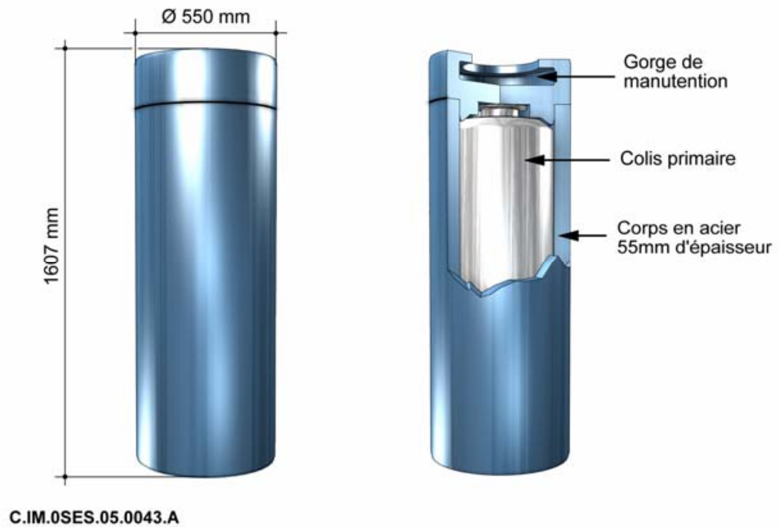


Figure 3.3.6 C waste disposal package (type R7/T7)

Several techniques could be envisaged to manufacture the steel body of the over-pack. All have been tested industrially, in terms of dimensions and steel thicknesses similar to the over-pack ones. Once the primary package has been inserted in the over-pack body, the lid is welded onto the body through the current electron beam method that achieves a full thickness welding and has little effect on the material's properties in terms of corrosion.

3.3.3.2 Disposal cells: small-sized disposal boreholes with clay buffers

The solution proposed for the C waste cell is a borehole (circular pit), of a length limited to about 12 metres and a diameter of less than 2 metres, with a clay buffer interposed between the packages and the rock (figure 3.3.7).

With such a borehole length, their location can be adapted to the small fracturing of the granite for all the configurations of the French context.

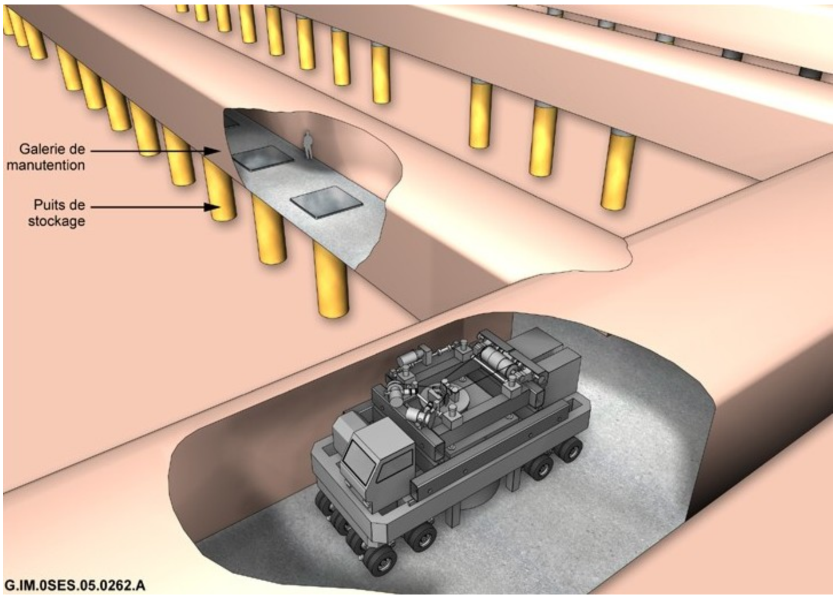
These small diameter boreholes could be drilled by a boring machine.

The number of packages per borehole depends on the heat output of the disposed waste. For moderately exothermic C0 waste, emplacing 5 packages per borehole would comply with the maximum envisaged length and with the criterion of a maximum temperature of 90°C at the hottest point of the engineered barrier. For the more exothermic C1 to C4 waste granites (after a 60 years cooling period of preliminary storage), a design with 2 packages per borehole would comply with this criterion for the large majority of French.

A steel sleeve is interposed between the engineered barrier and the packages to allow them to be emplaced in the boreholes. A gap is left between packages and sleeve in order to make this emplacement operation and the possible retrieval of the packages easier.

The engineered barrier helps to ensure a migration mode for elements dissolved in water by diffusion, even if there are small fractures that slightly conduct water in the borehole walls. The characteristics of the engineered barrier (swelling pressure, density, hydraulic conductivity, thermal properties and plasticity) can be adjusted to the site conditions by means of suitable mineralogical compositions and manufacturing specifications. The swelling clays studied at international level, especially the “MX 80” swelling clay used as a reference in many studies, can be adapted to the configurations of the French context. Its thickness (60 cm) is fixed to take into account possible long-term chemical interactions with the metallic sleeve and the steel over-packs.

The disposal boreholes are dead-ended: there is no access between their bottom and any repository module drift. This arrangement limits the possibilities of water circulating in the boreholes. At the top, they open onto a handling drift designed to ensure package emplacement in the disposal borehole. The handling drift is backfilled with material low in permeability composed of crushed granite and swelling clay (of a proportion of 10 to 30%) (Figure 3.3.7).



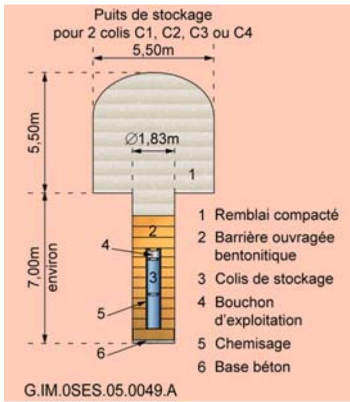


Figure 3.3.7 C waste disposal shaft and handling drift

3.3.3.3 Repository modules constructed away from water conducting faults

In the proposed architecture, the C waste repository zone is divided into several modules composed of parallel handling drifts along which are distributed the disposal boreholes.

In each module, handling drifts spacing is 25 metres to prevent any mechanical interactions. The distance between the disposal boreholes is determined according to thermal criteria, especially a maximum temperature of 90°C at the hottest point in the engineered barriers. For granite with average thermal properties in the French context, this spacing in between disposal boreholes would be about 8 metres.

The handling drifts have a width and a height (5 to 6 metres) sufficient to allow the transfer, the emplacement and possible retrieval of the packages in the disposal boreholes. Interconnecting drifts join each pair of handling drifts to meet the requirements of operational safety. They open onto a bundle of three drifts for the various throughputs between the modules and the access structures.

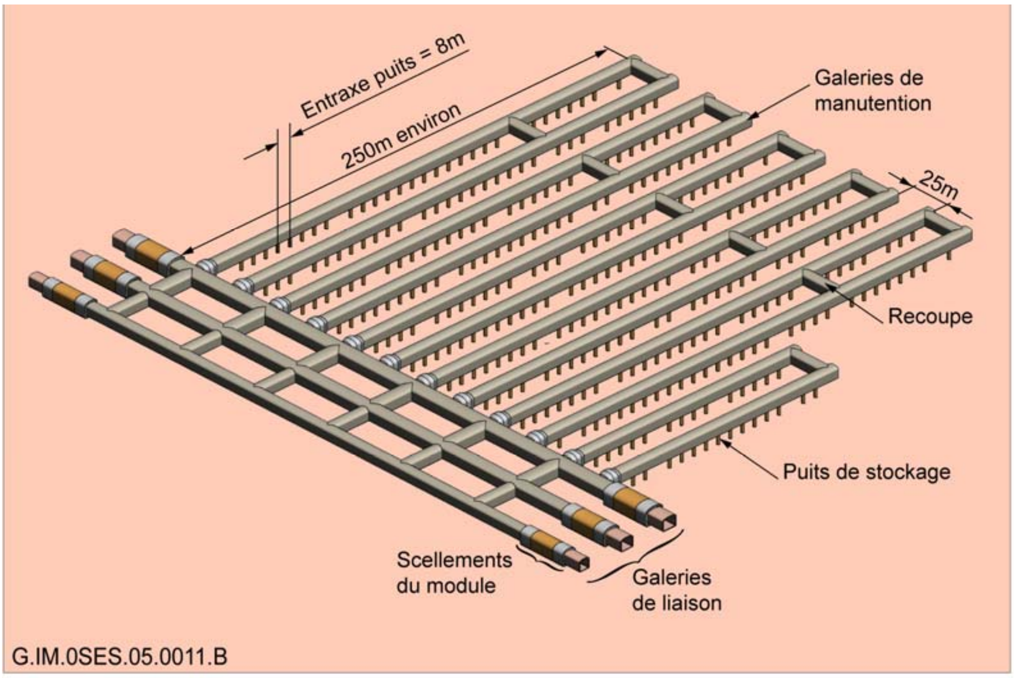


Figure 3.3.8 Standard architecture of a C waste repository

The repository modules are installed in the granite away from faults (in general pluri-hectometric or longer faults) which would conduct significant amount of water and therefore must not be intercepted by connecting drifts. The geometry of this fracturing means that the handling drifts would be about 200 to 250 metres long (figure 3.3.8).

To deal with the waste inventory considered for the study according to the production scenarios (scenario S1a with full recycling or S2 scenario with recycling stopped), 15 to 40 modules are needed, each module containing between 450 and 600 disposal cells. As for B waste, “two-level” architecture reduces the repository footprint and makes granite survey and characterisation easier.

The installation of modules in granite blocks away from any water-conducting fractures does not exclude the presence of small rock fractures within the module. However, these must have a sufficiently low hydraulic conductivity so as not to adversely affect the confinement functions of the various repository components.

Granite surveying and reconnaissance prior to disposal operation aim to check that the cell locations are suited with the fracturing. As a result it may be decided not to locate a certain number of disposal boreholes where the presence of small fractures would present an arrangement and a hydraulic conductivity that could put at stake the required robustness for long-term safety.

3.3.4 Spent fuel disposal

The architecture proposed for the spent fuel disposal is based on the same principles as that of the C waste disposal. The exothermal nature of the packages in practice leads to manage the repository footprint using the same plan with modules installed away from water-conducting faults. The disposal boreholes are distributed along parallel handling drifts about 25 metres apart. The distance between disposal boreholes would be 10 to 15 m.

However, unlike C waste, spent fuel is not confined in a glass matrix: the spent fuel assemblies are therefore likely to release radioelements more quickly in case of water ingress from possible nearby fractures.

In fact, because of the footprint needed for the spent fuel disposal (several km^2), the presence, near the disposal cells, of fractures conducting small quantities of water cannot be ruled out, even though the process of cells location avoids them, as for the C waste case. The disposal packages must therefore be designed so that spent fuel assemblies are protected from water arrival for a sufficiently long time to withstand a possible failure of the drift seal arrangements.

In the context of a study without any specific site, Andra has relied on the experience acquired with the "KBS-3" concept with a long-lasting leak-proof copper container. This concept was adopted in the 1980s by Sweden and became then the common reference for both SKB (Sweden) and Posiva (Finland) for their studies of a repository in a granite medium. Copper is a thermodynamically stable metal in environmental chemical conditions similar to those occurring underground in a granite massif. The repository is designed so that these conditions are maintained for the time scale considered by the safety analyses, i.e. several hundred thousand years (figure 3.3.9).

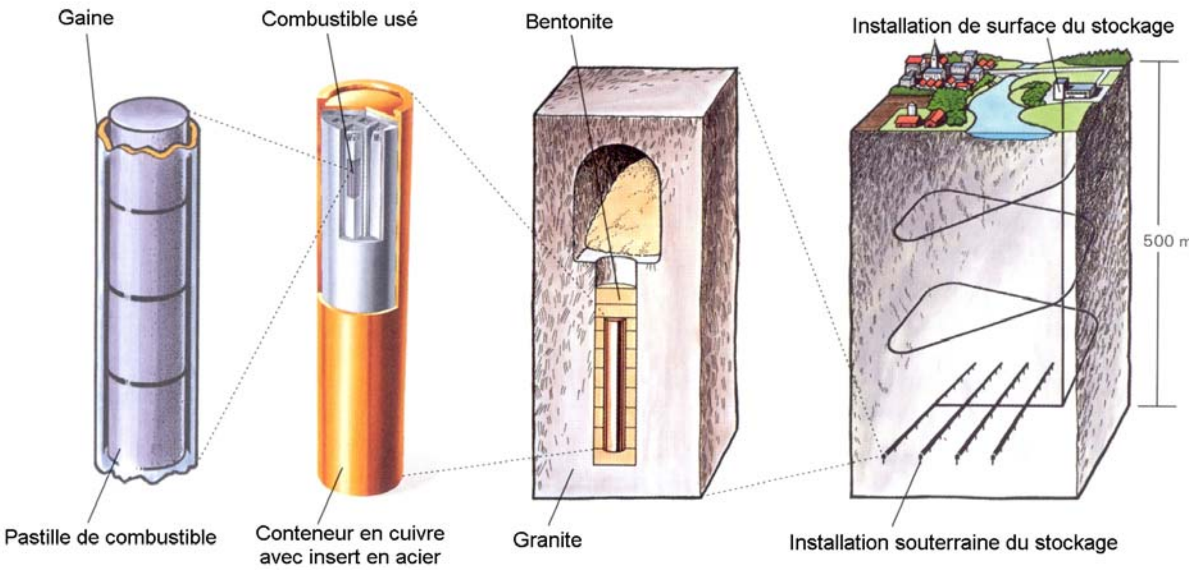


Figure 3.3.9 The Swedish concept KBS-3 for spent fuel (SKB data – 1999a)

Full scale experiments of the main components of this concept are carried out in the Aspö laboratory.

The container durability requirements could be lower in the case of certain granite sites because of their geological nature. The Spanish organisation Enresa is currently studying the possibility of a spent fuel disposal concept with a durable steel container design that would last for a few thousand years.

3.3.4.1 Copper container

The spent fuels container designed by SKB comprises a cylindrical copper shell (envelope) and an internal mechanically resistant cast steel structure (called the "insert") (figure 3.3.10).

Figure 3.3.10 *Concept KBS-3: container with copper envelope and cast iron insert for spent BWR fuel assemblies (source SKB)*

The copper envelope consists of a cylindrical body onto which are welded a bottom and a lid. Its thickness (50 mm) allows the container to withstand a hydrostatic pressure of more than 5 MPa and a swelling pressure of the clay buffer engineered barrier of about 7 MPa. The mechanical strength of the packages is ensured by the deformation of the envelope, which is then pressed against an internal rigid insert, but without degradation of the envelop integrity performance. The feasibility of manufacturing tubes 50 mm thick has been demonstrated by SKB for various metallurgical manufacturing processes: manufacture by extrusion, by drilling and drawing or by forging.

The cast iron insert is dimensioned to achieve, on one hand the container mechanical resistance, but also on the other hand the system non-criticality. It is designed in Sweden to house 12 type BWR spent fuel assemblies or 4 type PWR spent fuel assemblies (analogous to French REP spent fuel). This number is compatible with the maximum temperature criterion of 90°C at the surface of packages in the disposal boreholes after their emplacement.

The transposition to French spent fuel leads to an insert design with housings for four UOX (CU1) assemblies or a single MOX (CU2) assembly. The thickness of the cast iron in between the housings is dimensioned to prevent any risk of criticality.

The container diameter is 1.15 m for CU1 and 0.65 m for CU2. Its length also depends on the fuel type: 4.50 m or 5.25 m.

Welding on of the lid after spent fuel assemblies emplacement has been largely studied by SKB. Various techniques have been tested: electron beams and friction. The tests showed that they are compatible with manufacturing remote-controlled process in nuclear context.

3.3.4.2 Disposal borehole

The design of the disposal boreholes avoids components, especially metal ones, that are likely to chemically interact with the copper container and to adversely affect its leak-tightness function. As for C waste, the swelling clay buffer ensures a hydraulic transfer regime by diffusion in the disposal boreholes even if there are small fractures in their walls. It helps to maintain chemical environmental condition compatible with the copper of the container while providing a chemical buffer to any water coming from the granite and the handling drifts. The bentonite rings around the containers have a thickness of about 35 centimetres.

The reduced dimensions of the disposal boreholes (about 8 m long and less than 2 m in diameter) mean that they can be excavated with a boring machine, as for C waste, thus greatly limiting the damage to the rock wall. The disposal boreholes are dead-ended, opening at their top onto a handling drift allowing the transfer and emplacement of the spent fuel containers. (figure 3.3.11).

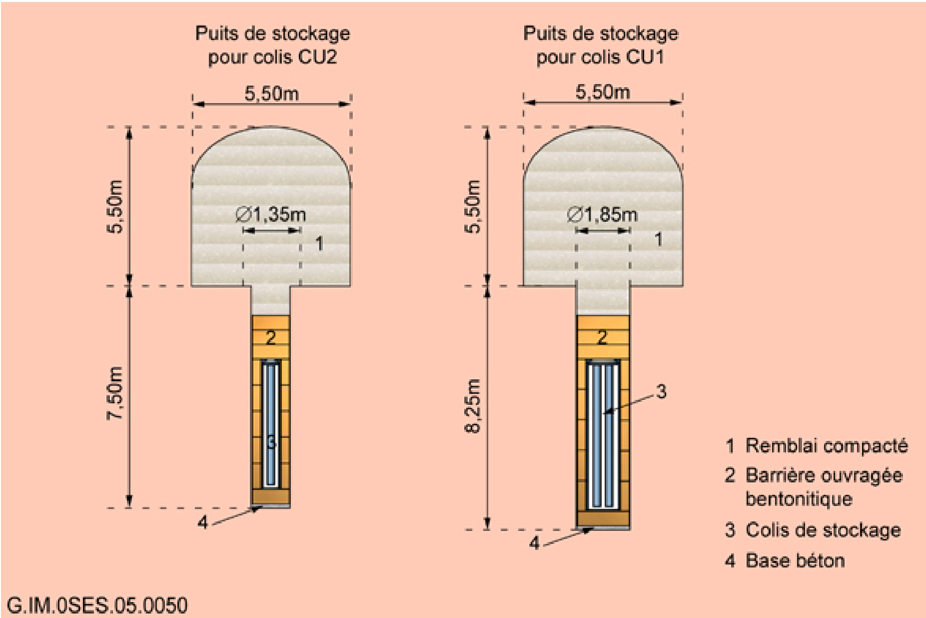


Figure 3.3.11 Spent fuel disposal borehole

4 Granite site surveying, characterisation and modelling

Repository design principles proposed in the previous chapter are based on granite rock properties, mainly its mechanical resistance and its very low permeability, and on the adaptation of repository facility architecture to massif fracturing to protect the installations from water circulations. Thus, the aim of granite site surveying and characterisation is to check that the rock has beneficial mechanical and hydraulic properties over the whole volume of granite concerned by the repository. Their aim is also to determine fracturing and hydrogeological models for the site so as to guarantee appropriateness of repository architecture to its structure.

In addition to objectives related to repository architectural design in granite medium, site surveying and characterisation works also aim, for safety assessment purposes, to evaluate site geodynamic stability and thus any modifications which could affect it in the long term. Safety assessments also involve characterisation of rock radionuclide retention properties and of fractures within the site hydrogeochemical context.

In order to achieve these aims, definition of a survey approach incorporates the methodological constraints related to characterisation of a medium fractured at various scale. It is also based on gradually determining site models at each stage of the works, to ensure through iteration with the design studies and safety assessments, that the technical options proposed are appropriate to the site investigated.

This chapter thus describes the principles of a granite site surveying approach (cf. § 4.1). It presents the means and methods deployed for granite site modelling (cf. § 4.2 to 4.5). This chapter is thus structured to assess the state of knowledge on a granite site after surveying and characterisation works: knowledge of the geological medium which constitutes an essential component for the understanding of long-term repository phenomenological evolution.

4.1 Approach to granite site surveying and characterisation

The site surveying approach is based, in time-phasing terms, on the definition of stages, each of which fulfils its proper objectives, taking into account constraints specific to granite medium characterisation, especially its fracturing.

In terms of methodology, the approach is based on determining site models which are detailed throughout the successive surveying stages by deploying methods and tools appropriate to the stage concerned.

4.1.1 A staged approach

Before repository construction, site surveying consists of two main stages: a site surveying phase from the surface followed by a qualification phase using underground structures. During waste disposal, structure construction is specified with “ongoing” surveying and characterisation works.

4.1.1.1 Surface surveying stage

The purpose of surface surveying is twofold:

- checking general suitability of the site studied for a repository, i.e. absence of redhibitory characteristics. This is assessed against choice of site criteria laid down in the basic safety rule R.F.S III.2.f (inset 4.1);
- specifying, by focussing the works, the part of a granite massif adopted for potential repository construction. Depending on this choice, the works also result in stipulating the underground laboratory site for *in situ* underground characterisation of granite.

-

Inset 4.1 ***Criteria for site choice in RFS.III.2.f***

The essential and significant site choice criteria are set out in section 4.4 of Basic Safety Rule III.2.f.

✓ **Essential criteria**

Stability: "Site stability should be such that any changes in the initial conditions due to geological phenomena which may occur (glaciation, earthquakes and neotectonic movements) will be acceptable in terms of the safety of the repository. In particular, for a period of not less 10,000 years, stability (covering limited and foreseeable evolution) must be demonstrated".

Hydrogeology: "The hydrogeology of the site must be characterised by a very low permeability of the host formation and a low hydraulic head gradient. A low regional hydraulic gradient will also be preferable for the formations surrounding the host formation".

✓ **Significant criteria**

Mechanical and thermal properties: "Studies, particularly with the assistance of modelling the combined effect of the thermal and mechanical phenomena, must be carried out to investigate the influence of the mode and sequence of the emplacement of the waste on mechanical effects in the repository, in particular the previous cooling time and waste density. These specific studies should provide the corresponding physical parameters and accurately determine their influence".

Geochemical properties: "A quantitative description of the geochemical properties of the system must be made by analyzing the transfer conditions of the radionuclides. Mineralogical analyses of host formation materials should be carried out and their geochemical evolution modelled as a function of temperature and irradiation"

A minimum depth must be respected: "The site must be chosen so that the planned depth of the repository guarantees that the isolation performance of the geological barrier is not significantly affected by the erosion phenomena (particularly after a glaciation), by the effects of an earthquake or by "human" intrusion."

Absence of sterilisation of underground resources: "For sub-surface management purposes, the site must be chosen to avoid areas where the known or suspected importance is of an exceptional nature".

In geographic terms, the surfaces concerned can be several hundreds of square kilometres for initial preliminary surveying, and a few tens of square kilometres for the focussing stage (figure 4.1.1).

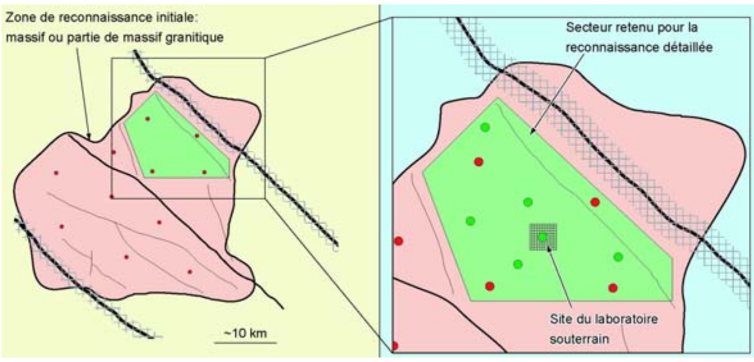


Figure 4.1.1 *The surveying time for the granite massif surface and focussing strategy (the green and red points represent survey boreholes)*

In schematic terms the works consists of geological and geophysical surveys (mainly airborne) and boreholes over a pluri-kilometric to kilometric grid (figure 4.1.2). The geological and geophysical surveys, sampling of rocks and water on the surface and from boreholes (drill cores), hydrogeological and geomechanical measurements in boreholes provide the data required for determining initial site models.

4.1.1.2 Qualification stage using underground facilities

The aim of this stage is to qualify the site which means checking it is appropriate to long-term safety objectives given the repository concepts proposed. It is based on the construction of underground structure ("laboratory"). The studies, works and experiments carried out there aim to refine site modelling. Their main aim is to stipulate the characteristics of granite blocks for construction of repository modules and consequently those of the granite fracturing at this level which cannot be completely carried out only using surface works.

The works mainly consist of (figure 4.1.2):

- monitoring, through geological surveys, geophysical methods and boreholes, the excavation of access structures (shafts and ramps) down to one or two surveying underground levels. This monitoring is accompanied by surface boreholes mainly aiming to record hydrogeological disturbance caused by excavation of the structures;
- surveying, using specific boreholes and drifts, sufficiently large and various volumes in the underground granite to characterise the rock and fracture network on the scale of a repository module. This *in situ* underground characterisation is completed as much as necessary with surface works (geophysical methods and boreholes) to justify its extrapolation to granite volumes compatible with repository dimensions.

This stage consequently includes the detailed specification of the "ongoing" surveying and characterisation methods and tools to be deployed during disposal process in order to specify construction of the repository structures.

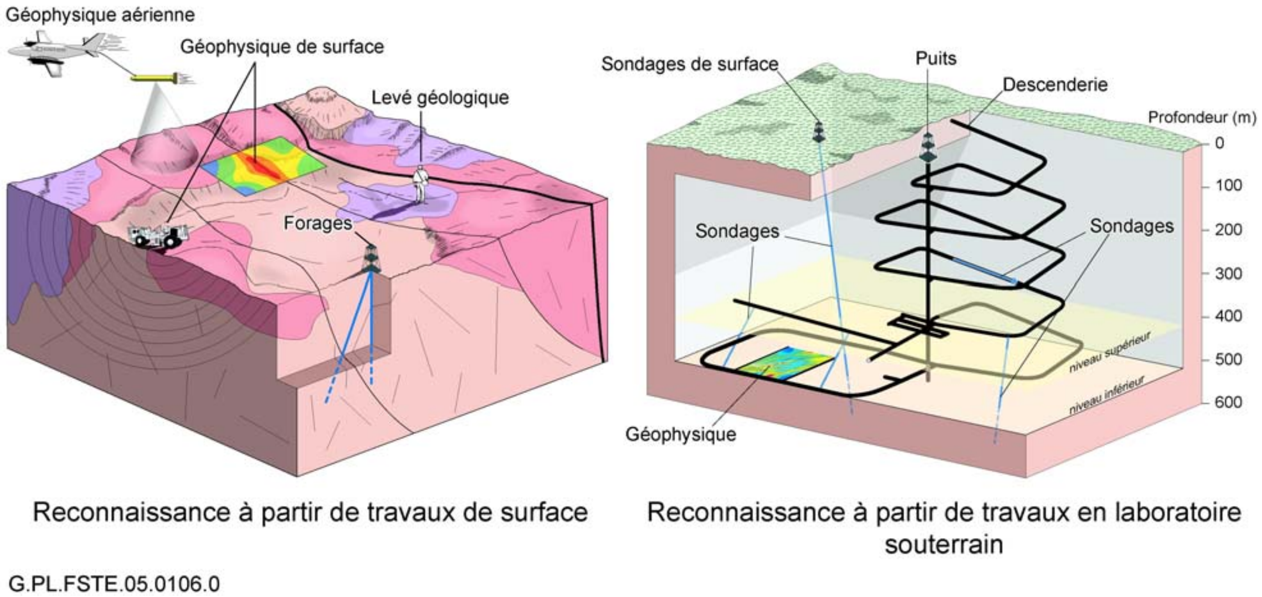


Figure 4.1.2 Main surveying works from the surface and in an underground laboratory

An approach shared at international level

A staged surveying approach is a strategy shared at international level. *In Sweden,* surveying works underway on the Oskarshamn and Forsmark sites are based on the same strategy (Andersson et al., 2003). *In Finland,* ongoing construction of an underground surveying structure on the site of Olkiluoto (ONKALO project) follows on from site characterisation stages using boreholes and geophysical methods from the surface (POSIVA, 2003a).

4.1.1.3 "Ongoing" surveying and characterisation during waste disposal

During waste disposal, "ongoing" surveying and characterisation works are conducted in order to specify repository structures location: B waste disposal tunnels, C waste modules and disposal boreholes (spent fuel if so decided). These works are required as the location of faults and fractures which must not be intersected by the structures cannot be established from the surface by boreholes or geophysical methods with a sufficient level of accuracy, accuracy allowing an optimised and risk-free use of the very low permeability granite blocks where the structures are to be constructed.

The works (boreholes and geophysical methods) are carried out from drifts, which can be specific, especially during initial repository construction phases. They can also be carried out from repository construction drifts as soon as repository construction is sufficiently advanced (figure 4.1.3), benefiting from the two-level architecture.

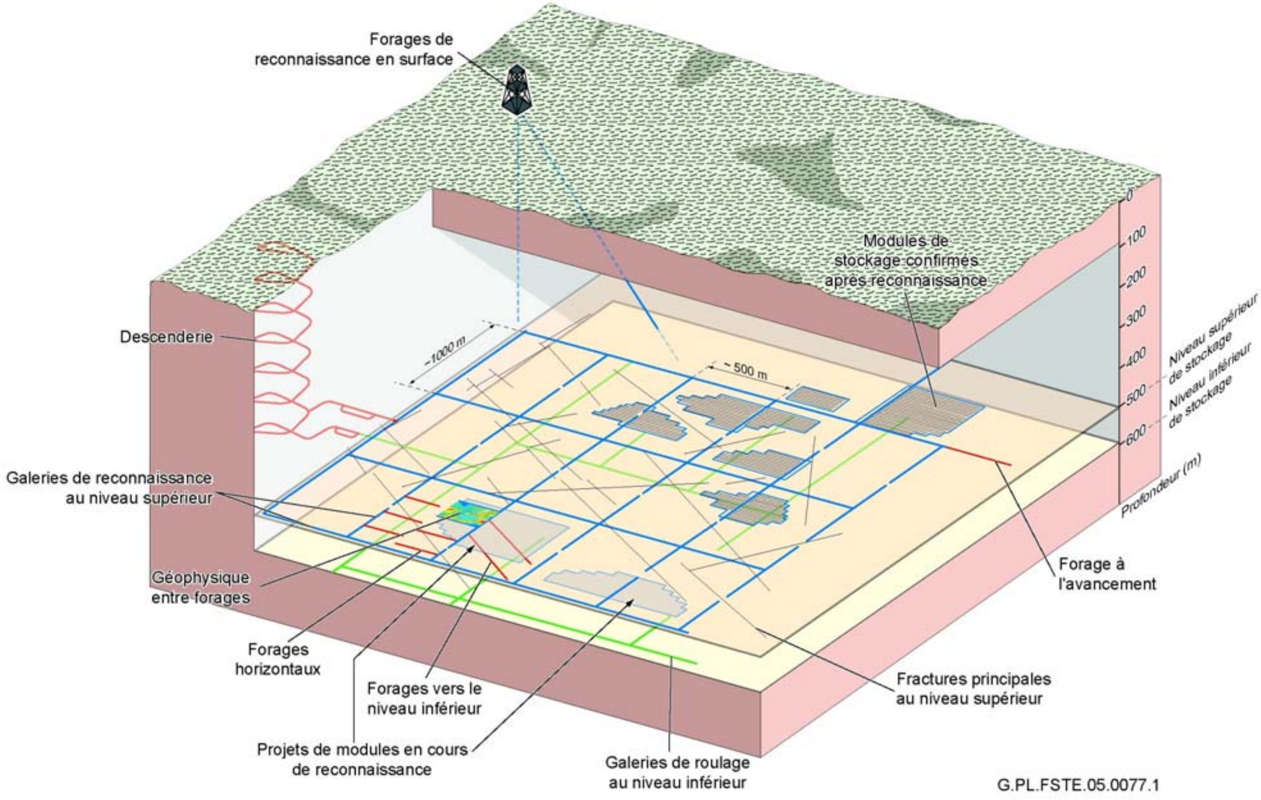


Figure 4.1.3 Functional diagram for advance surveying works

The works strategy is adapted to each type of waste. Works begin with the definition of the repository module limits, followed by checking that repository cell construction is appropriate to granite characteristics (inset 4.2).

Inset 4.2 ***Ongoing granite surveying for construction of disposal boreholes for C waste or spent fuel modules***

During the repository construction stage, the aim of the geological reconnaissance works is to determine where the disposal shafts are to be installed and to check that this siting is in accordance with the fracturing of the granite.

Firstly, boreholes are drilled from a repository drift in the axis of one of the future handling drifts (for example one out of five or ten) along which the disposal boreholes will be distributed. Between these exploration boreholes, geophysical surveys (e.g. seismic tomography) identify traces of any fractures in the granite rock. A diagram of the fracturing network is then produced using the geophysical data, geological surveys and hydrogeological measurement performed in these exploration boreholes. From this diagram, new exploration boreholes are then drilled in the axis of each of the future handling drifts. Their survey includes measurements aiming at testing the hydraulic conductivity of possible fractures. On these bases, it is decided whether or not to excavate the handling drifts.

Secondly, in the handling drifts, a geological survey is performed along the walls to confirm the correctness of the fracturing diagram. The planned locations for the disposal boreholes are then tested by vertical exploration boreholes of a length equivalent to that proposed for the disposal boreholes. Tests of water flow and geological survey of the small fracturing are then conducted to ensure the correct location of the disposal boreholes, i.e. their compliance with the criteria established throughout the study stages prior to the repository construction. If compliance is not confirmed with sufficient confidence, the location will be ruled out. A 10% exclusion rate was considered to be likely in the SKB studies for the design of the KBS-3 spent fuel repository (SKB, 1997a).

After drilling the disposal boreholes, a final check is made on the basis of geological surveys and measurements of possible water flow rates in the disposal boreholes to guarantee their location suitability.

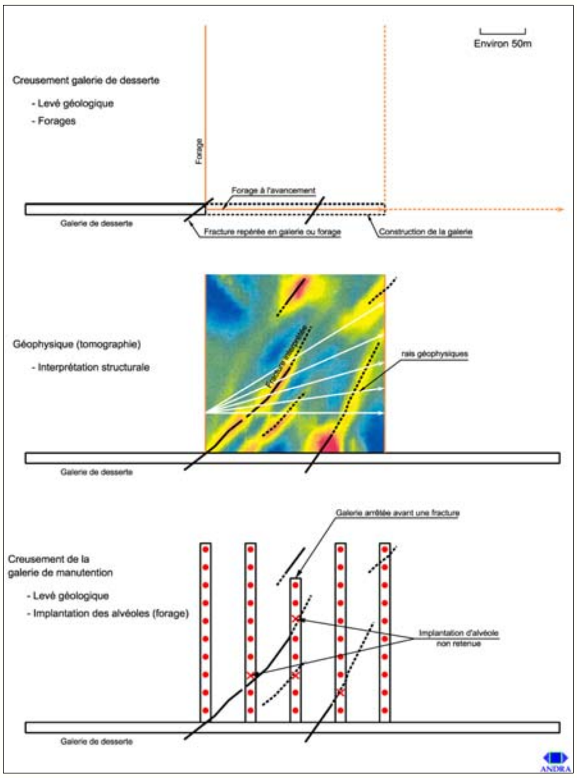


Figure 4.1.4 *Principle of ongoing fracturing characterisation*

4.1.2 Site models

The purpose of the surveying and characterisation process is to compile models used for repository architectural design and safety assessments. In terms of rationale, it is based on the collection of data in the field which are analysed and interpreted to characterise granite geological, hydrogeological, hydrogeochemical, mechanical and transport properties (figure 4.1.5).

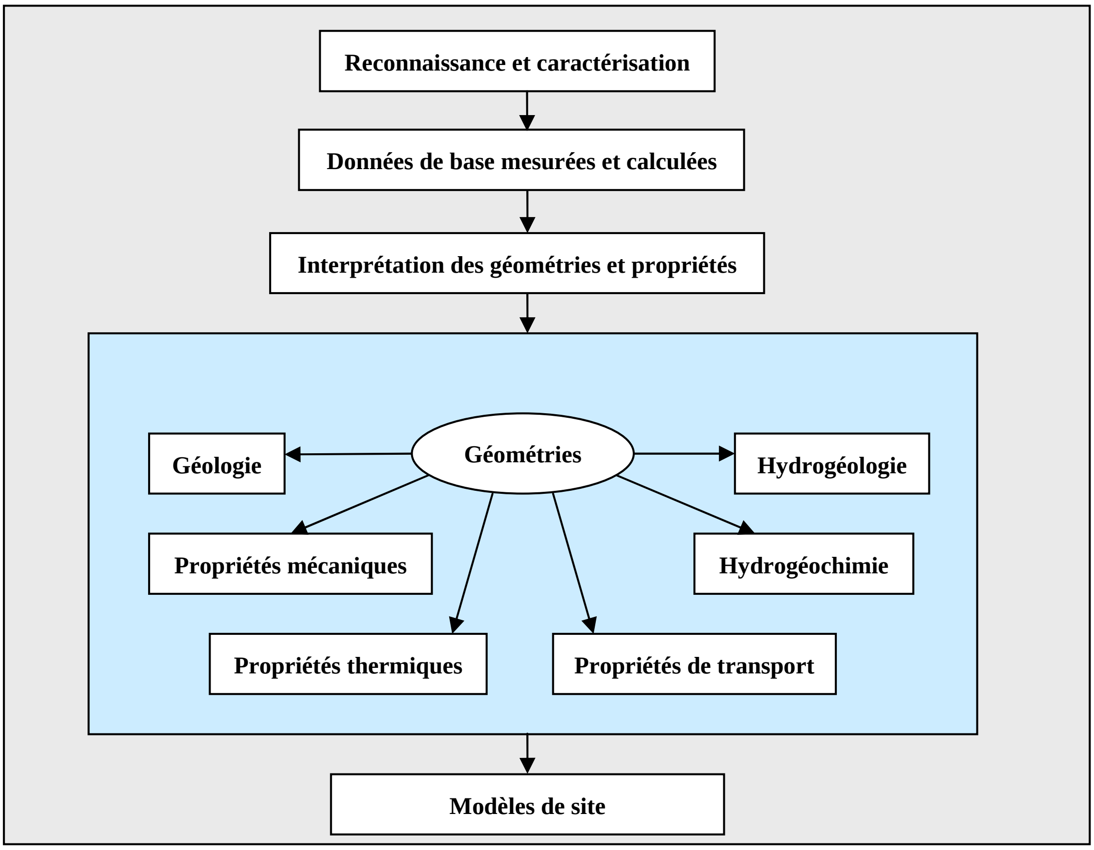


Figure 4.1.5 Strategy for compiling site models

Data integration is based on analysis of consistency between the various disciplines deployed and compiling of models representing the three-dimensional (3D) distribution of site granite properties:

- *Geological models* representing the structure of the granite massif studied and its fracturing;
- *Hydrogeological and hydrogeochemical models*, namely models of underground water circulations and their chemical composition. These models support radionuclide transfer and retention simulations for safety analyses;
- *Geomechanical models* describing site geomechanical context and granite performance in response to disturbance especially of a thermal nature caused by a repository.

The various models compiled do not necessarily concern the same volume of rock: regional geological and hydrogeological model covering several hundreds to thousands of km², model on the repository scale or detailed models on the scale of a repository module or disposal cell.

This modelling process is largely shared at international level (Andersson, 2003).

4.2 Granite site geological modelling

The purpose of site geological modelling is to represent the structure of the granite studied, in 3-D and on different scales.

4.2.1 Geological model components

A granite massif is a composite geological formation, resulting from a geological history in several stages (cf. chapter 2) including:

- Genesis, settling and crystallisation of granite magma at varying depths depending on the type of granite,
- One or several phases of deformation and fracturing during and after granite settling,
- Ascent of the massif and erosion of the overlying formations, leading to granite “outcropping”.

Each phase in this geological history has consequences for granite massif properties, its general structure (3D geometry and homogeneity), its state of deformation and especially its fracturing organisation.

4.2.1.1 Granite massif general structure

General 3D geometry of a granite massif results both from conditions under which the original magma was crystallised and later deformations undergone by the massif (cf. chapter 2).

Several elements ensuing from this history support the 3D representation of the granite geometry:

- General granite contours assessed from geological and geophysical surveys;
- Internal massif structure reconstituted from the distribution of various lithological units and their geometric relations with each other (clean-cut or gradual, twisting or straight contacts, etc); analysis of magmatic fluidity, i.e. mineral orientation and distribution also indicates magma formation and crystallisation mode;
- Veins and enclaves (aplites, pegmatites, etc) evidence granite magma formation mode and its relations with the surrounding terrains: their distribution is indicative of general massif structure, for example differentiations between its core and edges;
- mineralogical modifications due to hydrothermal alterations which accompany the final stages of granite magma settling are often marked by characteristic colours of the rock (iron oxide pigment of haematite type, greenish chloritisation, etc), guidelines for the reconstitution of internal massif structure.

Contacts between elements can constitute local mechanical and hydraulic discontinuities, especially when “brittle” deformations in the granite are large enough to indicate the differences in rheological properties between units. This is the case often observed at the contacts between dolerite veins (rock of low quartz composition and very fine texture, formed during extensive tectonic phases post granite solidification) and granite rock. Examination of these contacts thus constitutes an indicator of the significance of deformations undergone by the massif after solidification.

4.2.1.2 Granite massif fracturing

Granite massif hydraulic properties are directly dependent on its fracturing, as the rocky matrix contributes very little to water flows.

Thus, the aim of the geological model is to represent fracturing organisation: its density, distribution of fractures in the massif and links between them (especially their connection). The geological model thus supports hydrogeological modelling.

During granite crystallisation, thermal reduction causes joints to form constituting initial mechanical discontinuities in the granite. These discontinuities are partially resumed during the fracturing phases which affect the granite after its solidification.

During the granite massif geological history, fracturing phases, "brittle" deformation, normally take over from ductile deformations stages. Going from a system of ductile deformation corresponding to a viscoplastic state of the granite to a system of brittle deformation corresponding to a brittle state of the granite is related to ascent of the granite massif from its original depths to surface. The transition zone is between 20 and 10 kilometres deep, depending on the geodynamic context. Ductile deformations ("mylonites") do not usually involve significant discontinuities in rock mechanical and hydraulic properties which is not the case with fracturing (figure 4.2.1).

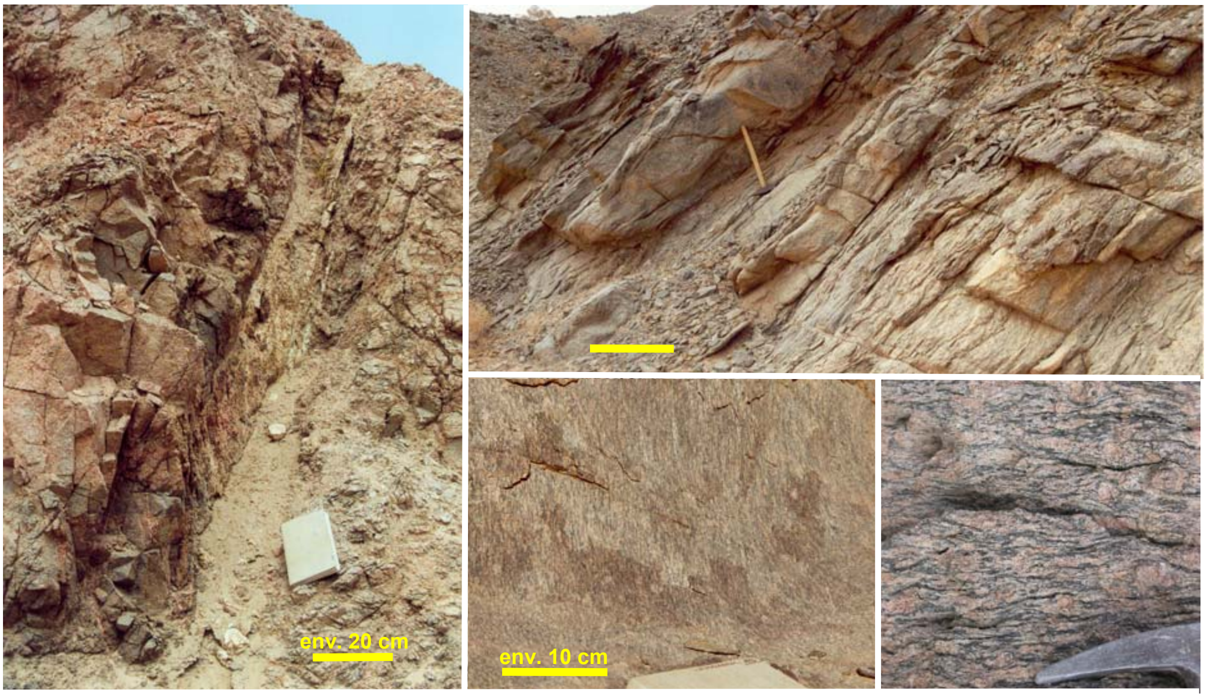


Figure 4.2.1 Granite deformation systems

A: On the left, brittle deformation: fault and clay gouge;
B: Top right, ductile/brittle deformation: fracture schistosity, boudinage and lenticulation;
C: Bottom right, ductile deformation: general aspect of mylonitic foliation and detail of mylonitised granite

- **Fracturing scales**

"Brittle" deformations which affect a massif during tectonic phases synchronous with and post magma crystallisation, cause the creation of fractures on varying scales, from the regional scale involving major faults structuring the earth's crust to micro-fractures on the mineral scale and observed with a microscope (figure 4.2.2).

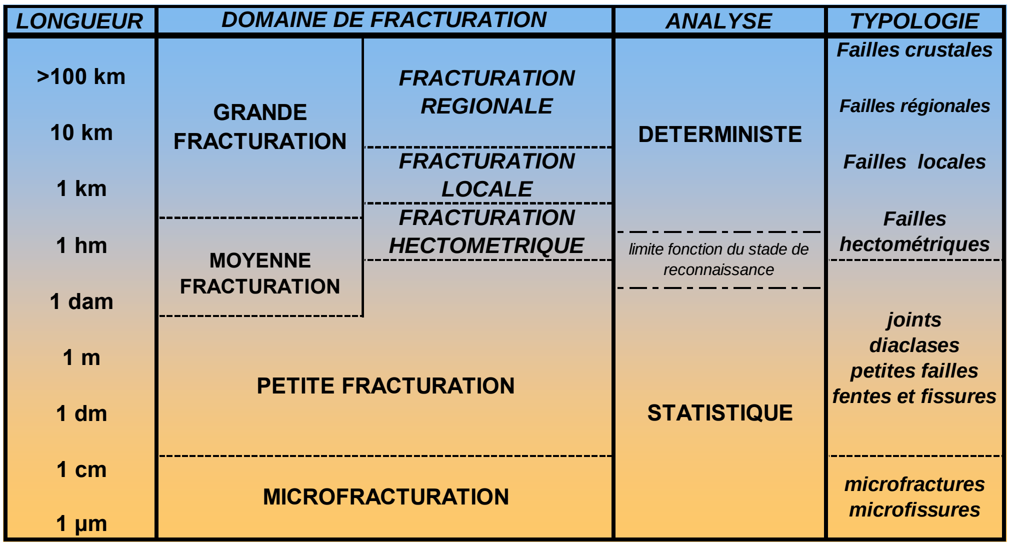


Figure 4.2.2 Fracturing scales

- *small fractures* result from thermal "shrinkage" during magma solidification or subsequent deformation phases. Apart from zones of major granite deformation, they generally conduct very little water. The characterisation and modelling of minor fracturing are based on a statistical approach. Fracturing model input is the systematic geological survey which provides distribution laws of their main characteristics in the granite: size, orientation and dip;

- *large fractures, or faults*, always result from significant deformations in the granite massif during the tectonic phases. They are often a composite of several lower-order fractures. The mode and intensity of the fracture can vary from one point of a massif to another and from one massif to another, which leads to various fracture models dividing the granite massif up into "blocks" of different shapes. In order to detect and model them, large fractures and faults are based on a *deterministic approach* during the exploratory phases: they are generally large enough to be identified one by one and to form the structuring elements of granite modelling.

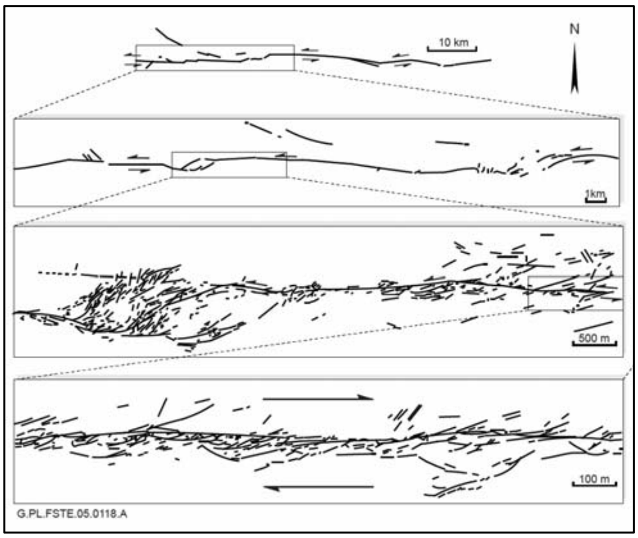


Figure 4.2.3 Diagram of a major fault composed of fractures smaller in size

- *the treatment of "medium" fractures* forms the transition between these scales of fracturing. Its treatment will change as a granite site is surveyed. Treated statistically in the initial stages, it is based on a deterministic approach during phases detailing the structure of the granite on the scale of a repository module. This is particularly the case during the "ongoing" survey work while the repository structures are excavated.

- **Organisation of a fracture network: relations with hydraulic properties**

Fractures are formed according to two main deformation modes (Marre, 1982; Genter et al, 2000): traction ("mode 1") or shearing ("mode 2").

Traction deformation mode involves small-sized fractures, on a metric to pluri-decametric scale. The *joints* related to initial thermal retraction of granite magma belong to this category. This is also the case for small *fissures and joints* appearing through the rock. .

Shearing deformation mode is generalised for all fracturing scales: this is mainly the deformation mode for large-sized fracturing. *Faults* are fractures coming under this deformation mode with relative movement of the parts of the rock that they limit. They result in rock crushing at the edges of the rupture planes.

Hydraulic properties of a fracture network mainly result from fracturing organisation on different scales and deformation mode: internal structure of fractures, their continuity and geometrical relations of fractures amongst each other control hydraulic transmissivity of each fracture in a network and hydraulic connectivity of the fractures amongst each other. They also result from fracture mineralogy: hydrothermal fluid circulations which accompany tectonic phases cause crystallisation of minerals in the fractures and even clogging. Shearing thus frequently results in total argillisation ("clay gouge") along the faults and which is likely to greatly affect fault hydraulic transmissivity.

The 3D geological fracturing model incorporates all geometrical elements, as a support for hydrogeological modelling.

4.2.1.3 Granite evolution from the surface to underground

Appearance of granite on the surface generally poorly reflects its in-depth structure. Granite is subject to atmospheric agents and undergoes supergene alteration which transforms it until it becomes, in temperate climate zones, granitic sand.

In chemical terms, the alteration mainly consists of hydrolysis of most of the silicate minerals except for quartz. The chemical attack gradually transforms the granite into coarse sand, a mixture of quartz, quarry feldspars and altered biotite, clays and iron hydroxides. Very resistant white mica remains unchanged. The alteration preferentially begins with open circulating joints causing a "spheroidal weathering". This opening of joints is due to the general decompression of granite close to the surface. Later mechanical erosion can free up the "spheroids", non-altered surfaces ("elephant's back"), creating gravity scree and rearrange the surface granitic sand (figure 4.2.4).

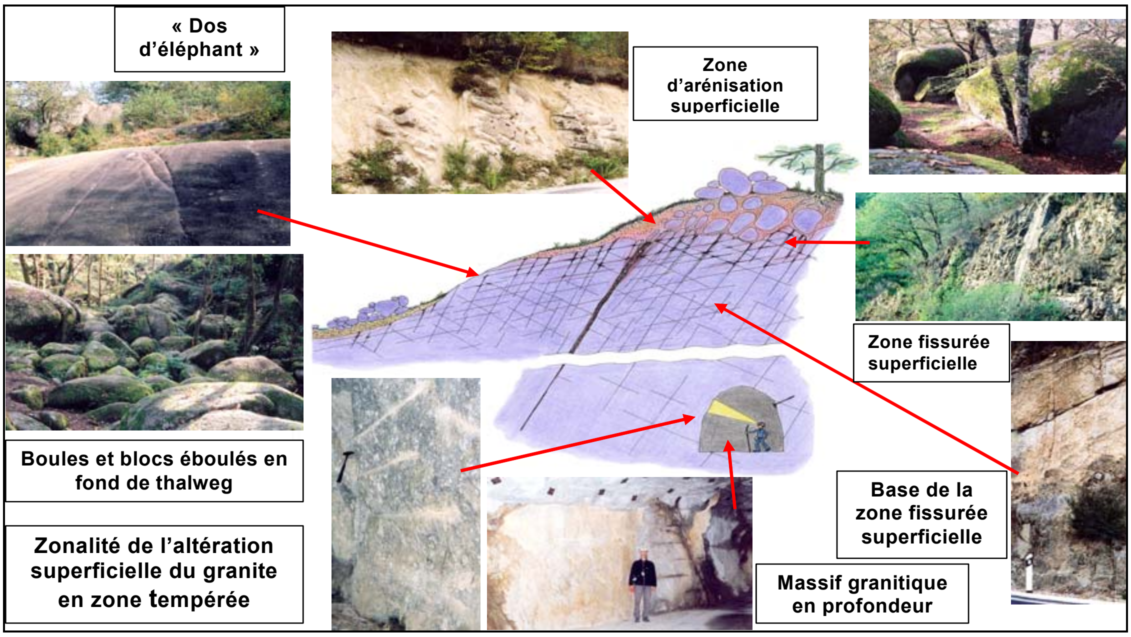


Figure 4.2.4 Granite evolution from the surface to underground

Surface fracturing is thus only slightly representative of what is below as its opening and density are pronounced by alteration. Underground faults are less open and the joints which have no mineralogical filling have contiguous walls.

The geological model includes the representation of the surface granite zone since it constitutes the meteoric water infiltration and transfer zone in the granite from the surface, a significant component of hydrogeological modelling.

4.2.2 Surveying and geological characterisation methods

Most of the methods used for compiling geological models in granite medium are well proven methods, benefiting from a vast amount of experience feedback in the fields of mapping, mining exploration and waste disposal studies. Within the generic study context, Andra has drawn up an inventory of methods tried and has tested, though international cooperation, more recently developed geophysical methods (Leutsch Y., 2004). This section summarises the main elements.

Surveying works deploy the following elements in a complementary and specific manner at each stage of surface and underground surveying:

- Geological surveys as part of the direct observation of granite in surface outcrops, in core samples and rock "cuttings" in boreholes and underground structure walls;
- Geophysical surveys, the aim of which is to provide images of the basement on different scales.

4.2.2.1 Geological surveys

- **Geological surface mapping**

Geological surface mapping of a granite massif is the most commonly used method for initial site surveying. Drawing up regional geological maps and making geological cross sections on the regional and investigated site scales are supports for compiling 3D geological models. It is based on identification and delimitation of lithological units which make up a massif and the surrounding geological formations as well as the survey and analysis of heterogeneity, fracturing and alterations affecting the granite.

Mapping is based on existing data: geological maps already made on different scales, aerial photos, satellite images and digital terrain models. The latter are mainly used as a support for compiling preliminary models of granite structuring, to be validated by geological field surveys, geophysical methods and/or boreholes

- **Geological surveys in boreholes**

Boreholes constitute a means of investigation used throughout the various site surveying and characterisation phases. The coring technique provides directly samples (cores) used for lithology and fracturing analysis. Destructive drilling techniques provide rock "cuttings". Optical imaging techniques provide, whatever drilling technique, pictures of the borehole walls completing core and rock cutting surveys. Geophysical measurements in boreholes complete rock petrophysics characterisation: resistivity, gamma-spectrometry, gamma-density, caliper and possibly magnetometry.

Lithological survey provides the inventory of the various units making up granite and studies their geometrical and chronological relations (figure 4.2.5). Structural survey consists of the inventory of fractures and systematic reading of their thickness, orientation, dips and filling minerals. It identifies the main characteristics of large-sized faults. The data collected is also used as a basis for statistical processing for determining laws of distribution which support small-sized granite fracturing models, support for hydrogeological modelling (cf. section 4.3).

Studies of samples in laboratories complete the geological characterisation in petrographical mineralogical, petro-geochemical, geochronological and geomechanical terms as well as composition of alterations and characterisation of fracture mineralisation.

Figure 4.2.5 On the left: geological survey of core samples. On the right: geological survey of an underground drift wall

- **Geological surveys of underground structures**

Geological surveys of underground structures provide access to continuous observations at decametric to pluri-hectometric scales, which could not be achieved by drilling borehole (figure 4.2.5).

They specify the relation of lithological units to each other. They also specify fracturing organisation, especially geometrical relations between fractures differing in orientation, dip and size (figure 4.2.6).

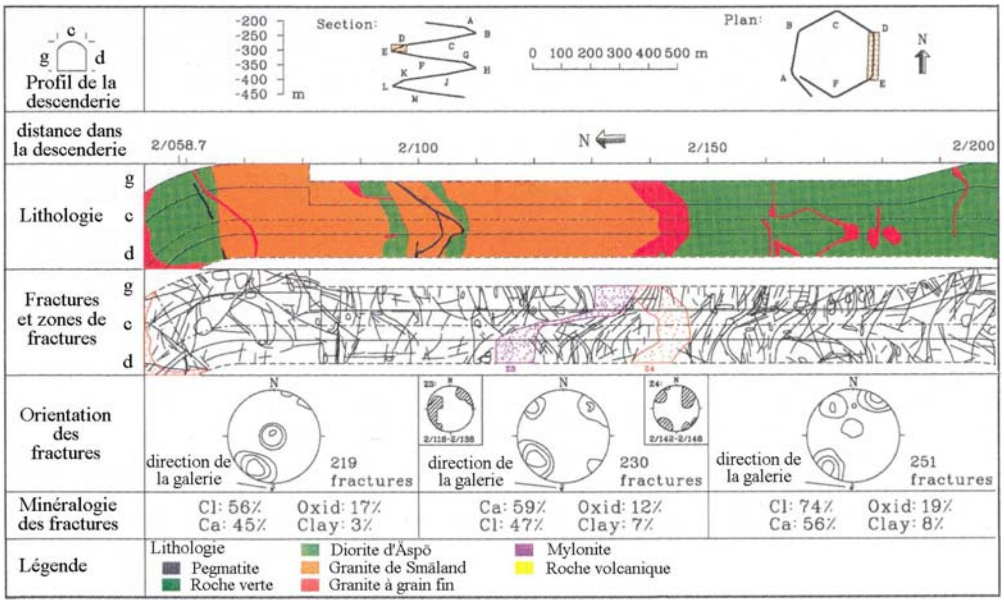


Figure 4.2.6 *Example of geological survey carried out in the ramp of the Äspö laboratory in Sweden, describing relations between the various lithological units and fracturing organisation (from report SKB ICR 95-02)*

4.2.2.2 Geophysical methods

Airborne geophysical methods often form, along with surface mapping, the initial tools used in site surveying. They are based on measuring the various granite properties: magnetic properties, electrical conductivity and radioactivity.

These methods, whose main ones combine into a single flight, aeromagnetism, electromagnetism and radiometry measurements can be used to cover large areas quickly and homogenously, and are input to the geological interpretations on regional and local scales.

Surface geophysical surveys are conducted less extensively to detect variations in rock type and medium heterogeneities: presence of homogenous “blocks” and of fractures.

Underground geophysical methods, generally more complex to implement than on the surface, are effective when conducted in between drifts and/or boreholes. They specify distribution and relations between lithological units and between fractures on the local scale.

These methods complement each other: they are based on different properties of the rock and fractures and involve different scales of investigation. Interpretation of data is based on the comparison of data collected by various methods during successive surveying stages

- **Airborne geophysical methods**

Airborne geophysical methods are tools for quick and easy implementation of geological surveying of large regions. They enable a large area to be covered homogenously in a short space of time. Moreover, the possibility of combining, in one single airborne survey, aeromagnetism, electromagnetism, gamma spectrometry and VLF-EM measurements is another advantage of airborne methods: this thus provides several physics parameters of the ground measured at the same time according to one single flight plan, in order to achieve a multi-parameter mapping of regional geology.

Airborne magnetometry constitutes a lithological mapping tool as it can differentiate the rocks according to variations in their magnetic properties (magnetic susceptibility and/or natural remnant magnetism) related to their mineralogical composition. It also provides mapping of major structural discontinuities**.**

Airborne radiometry (gamma spectrometry) can differentiate the rocks from their concentration in natural radioelements in the potassium (K), uranium (U) and thorium (Th) family. This is deduced from the measurement of the natural gamma radiation spectrum using on an on-board detector in a helicopter or airplane. Gamma spectrometry is a good geological mapping tool but has a low depth of investigation.

Airborne VLF measures variations in the VLF (Very Low Frequency) magnetic field emitted by military radio stations of very low frequency, located very far away from the study area and used for communication with submarines.

The aim is to locate conducting bodies or structures, which cause sporadic anomaly in the VLF magnetic field, by producing a map of variations in the total VLF field, expressed as a percentage compared to the primary horizontal field which is taken as a reference.

The method helps to provide a good mapping of linear conductors, as are for instance regional and local scale faults, even if the environment is very resistant. It is however very directional and sensitive to interferences constituted by artificial conductors but checking the interpretation with frequency electromagnetism resolves these issues (figure 4.2.7).

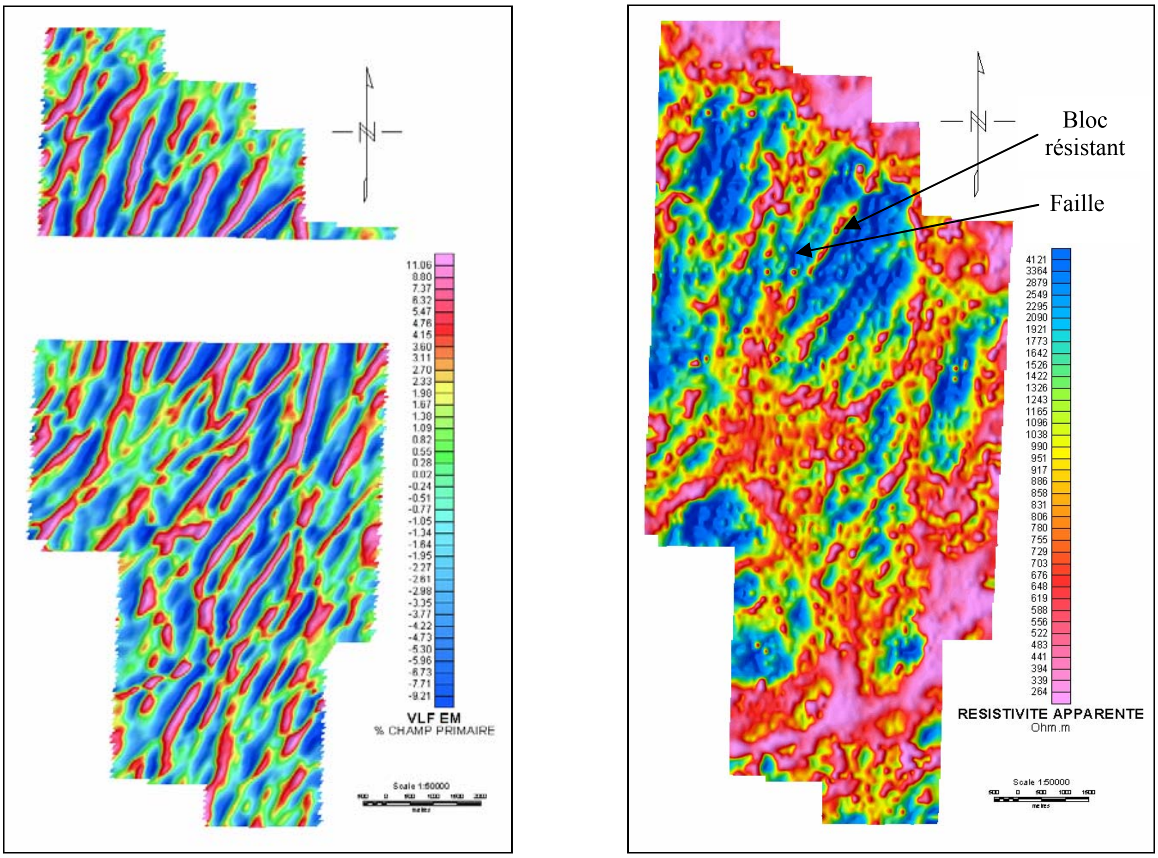


Figure 4.2.7 *Maps illustrating airborne l VLF and electromagnetism methods of outcropping granite characterisation (COGEMA document). The map on the left highlights the directional effect of VLF, compared to the interpretation of frequency electromagnetism data on the right. The non-informed band corresponds to interruption in the VLF signal*

Frequency electromagnetism based on mapping of the apparent resistivity of the ground mainly aims to identify major fracturing on regional and local scale.

It also describes the limits of granite intrusions with the metamorphic surroundings, various enclaves, fracturing corridors and also the areas virtually unaffected by tectonics (also called “blocks”), away from major fracturing corridors (figure 4.2.8)

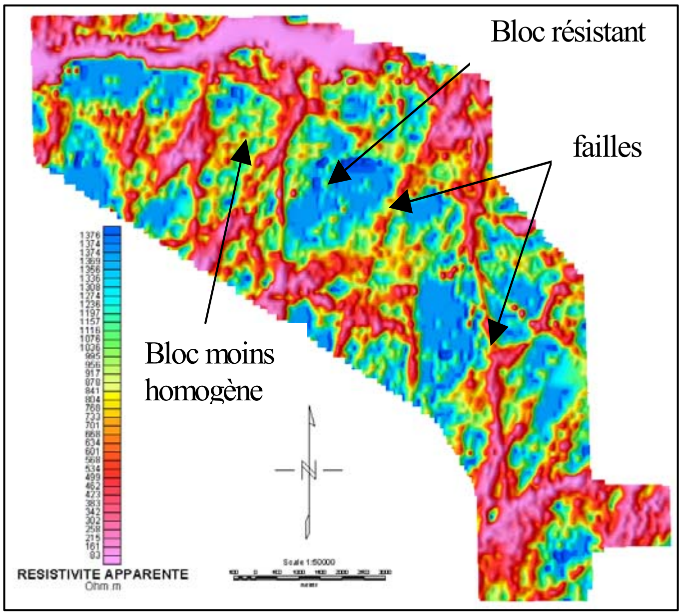


Figure 4.2.8 *Airborne map of resistivity showing granite massif split into blocks caused by faults (COGEMA data)*

- **Surface geophysical methods**

Surface geophysical methods complete geological mapping and provide access to information of a lower scale than that detected by airborne methods. They especially aim to detect fracturing of a minimum hectometric to pluri-hectometric size. They are not very effective for characterising small-sized fracturing. As a general rule, their implementation combines several methods so as to make more robust the geological interpretation of geophysical structures detected.

✓ **Gravimetric methods**

The aim of **gravimetry** is to measure anomalies in the earth’s gravity related to distribution of rocks of different densities in the crust. In the granite massif studies, the method is often used to specify its underground base (several kilometres to ten kilometres). It is also indicative of the deepest major structures which affect a granite massif.

✓ **Electrical and electromagnetic methods**

Electrical methods are widely proven for granite massif surveying. They are based on variations in electrical resistivity of granite rocks. They are very effective tools for mapping hectometric to pluri-hectometric faults which affect the upper part of a massif. This provides right from the initial phases a general model of major fracturing organisation of a massif (figure 4.2.9).

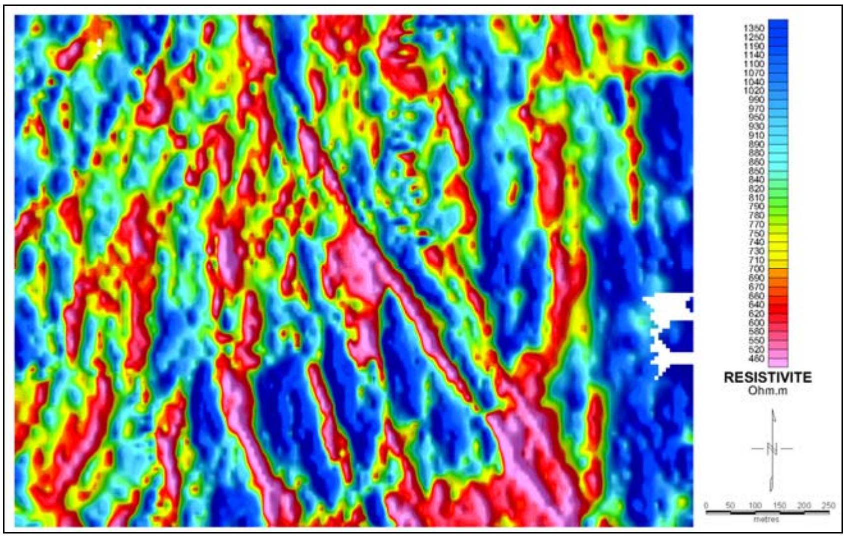


Figure 4.2.9 *Example of an apparent resistivity map in the granite context (system rectangle) (document COGEMA). Conducting alignments, in red or purple on the map, correspond to pluri-hectometric faults.*

However, electrical methods have a limited investigation depth (a few tens of metres). Coupling electrical methods to the **multi-frequency electro-magnetic method** which was developed in Finland provides investigation depths exceeding several hundreds of metres. This technique was tested at Olkiluoto in Finland with cooperation from POSIVA. Tests have demonstrated method feasibility (inset 4.3).

Inset 4.3 ***Andra-POSIVA cooperation: joint acquisition and interpretation of electrical and electromagnetic data***

This works combining conventional electrical survey measurements with multi-frequency electromagnetism measurements was carried out to explore the 0-500 metre depth range. The electromagnetic measurements were carried out over a 3,400 m long line across the Olkiluoto island using both in line array and broadside array configurations for the transmitter-receiver stations (figure 4.2.10). To best cover the 0-500 m range, various transmitter-receiver spacings were adopted: 200, 500 and 800 m.

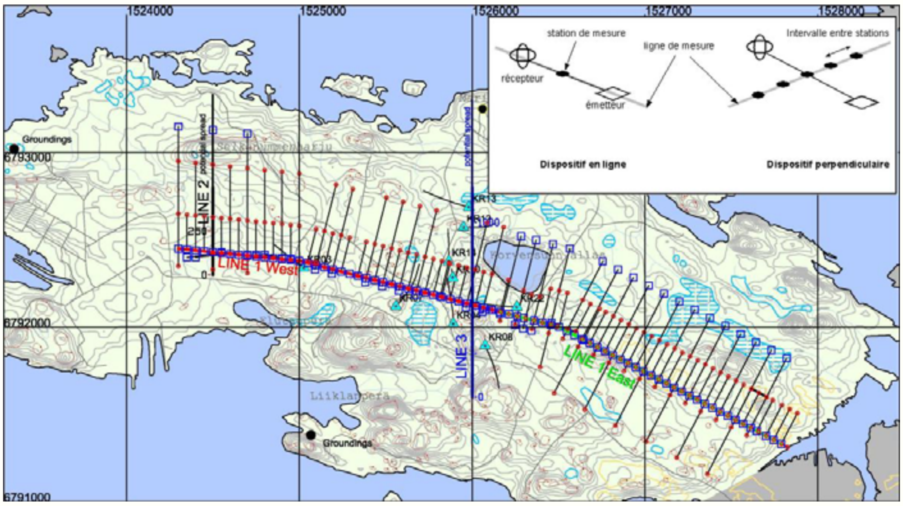


Figure 4.2.10 *Olkiluoto (Finland) : location of electrical (LINE 1 West, LINE 1 East, LINE 2, LINE 3) and electromagnetic measurement lines (in line array: blue square with 200 m station spacing ,broadside array : red with 200 m, and 500 m spacing, light blue with 800 m spacing) (kilometric grid). Inset,the measurement system*

The electrical and electromagnetic data underwent specific processing operations and were interpreted, first separately and then jointly. The final stage of interpretation integrated the borehole resistivity logs and the comparison of the electrical and electromagnetic measurements with the results of previous geological and geophysical surveys. A composite vertical cross section of the main line is shown in figure 4.2.11.

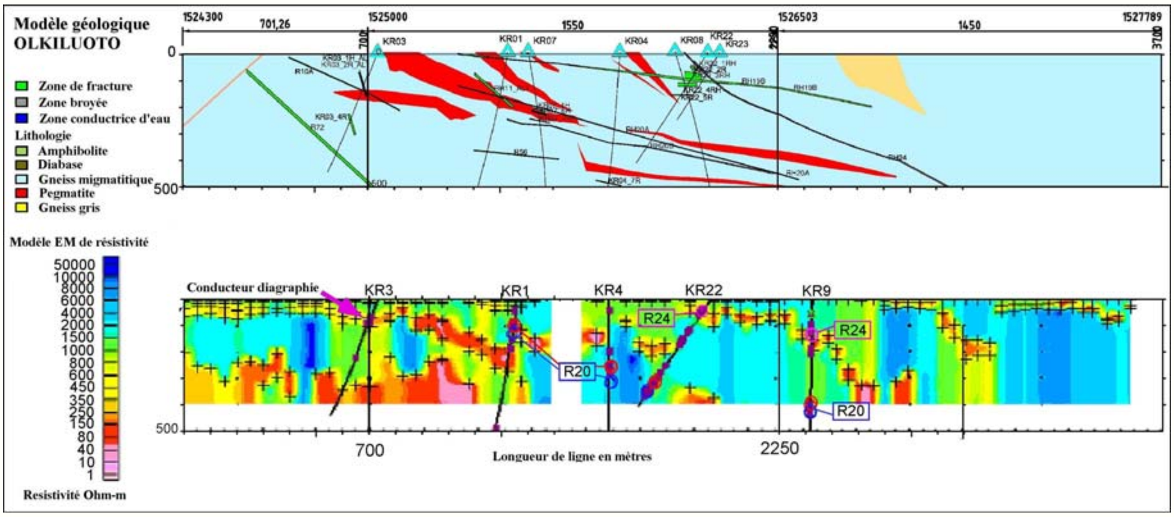


Figure 4.2.11 *Olkiluoto (Finland): geological cross section and resistivity of an electromagnetic profile (200 m between the transmitter and receiver, perpendicular to the line*)

The combined use of these two techniques can be transposed to French granite massifs and provides good mapping of the 0-500 m depth range volume of rock. Electromagnetic multi-frequency survey locates horizontal or low dip faults fairly accurately and assesses their continuity over a large depth range. Electrical measurements show good resolution up to 150-200 metres, and are notably applicable when characterising the altered upper zone of granites, generally encountered in the French case (Heikkenen et al., 2004).

✓ **Seismic methods**

2D and 3D seismic reflection, mainly used for oil exploration in sedimentary basins, is not current for deep surveying of crystalline massifs. In this case it encounters several problems:

- Internal organisation of crystalline massifs does not show a geometry as suitable to seismic reflection as sedimentary basins;
- There is usually no sharp contrast in acoustic impedance within the crystalline components or compared to the surrounding formations;
- They often show vertical to subvertical tectonic structuring which is not suited to seismic surface methods. The areas likely to constitute good seismic reflectors are often not in a beneficial geometrical position;
- Pluri-kilometric to decimetric fracturing causes dispersion of seismic waves underground.

Seismic methods can therefore only be used for the definition of deep granite intrusion geometry along with their relations with the surrounding formations and for the search for horizontal and sub-horizontal structuring within massifs and especially planar low dipping fault.

Seismic refraction defines the geometry and depth of underground layers and interfaces between mediums of different velocities: for example definition of the thickness of the surface alteration zone. In Sweden and Finland, it is used to determine the thickness of the ice cap. However, it is normally difficult to use in the granite medium.

Seismic techniques adapted to granite have been developed over the past decades either in the mining sector or for repository studies. Andra has cooperated with POSIVA to test these methods in Finland.

The **seismic tomography** principle is based on analysis of seismic wave propagation time between borehole/borehole, drift/drift and drift/borehole. It provides the distribution of wave velocities in the granite investigated, image of the distribution of the various rock components and fractures. This method has been tested in Olkiluoto (Finland), in cooperation with POSIVA (inset). Test results have confirmed that this method is appropriate to granite characterisation objectives and its applicability to various geological contexts

Inset 4.4 ***Andra-POSIVA cooperation: acquisition and interpretation of seismic data from boreholes***

Two seismic techniques were implemented:

- *The walk away VSP* (WVSP), or vertical multi offset seismic profile, consists of using receivers lowered down in a borehole to record seismic waves sent by a source displaced at a regular pace along a line at surface;
- *Seismic tomography* consists of using receivers placed in a borehole to measure seismic waves caused by a source moved at a regular pace in another borehole, nearby.

✓ **WVSP measurements**

The seismic source consists of a modified hydraulic rock breaker, controlled by a computer, mounted on a mechanical digger (figure 4.2.12). The receiver chain is made of eight "triaxial" geophones equipped with anchoring arms. The distance between geophones is five meters.

Figure 4.2.12 *Olkiluoto (Finland): seismic source*

The number and position of the receivers were determined to identify faults or contacts between rocks of different kinds at various depths. They were chosen according to the orientation and dip of these geological objects off which the seismic waves are reflected. A total of four boreholes were used in this way and the sources were displaced along three lines.

Measurement processing and interpretation identified around twenty reflectors -mainly contacts between rocks of different kinds or fractures- which were then integrated in a consistent geological model (figure 4-.2.13). This technique, tested in Finland, is applicable to all granite environments (Enescu et al. 2004).

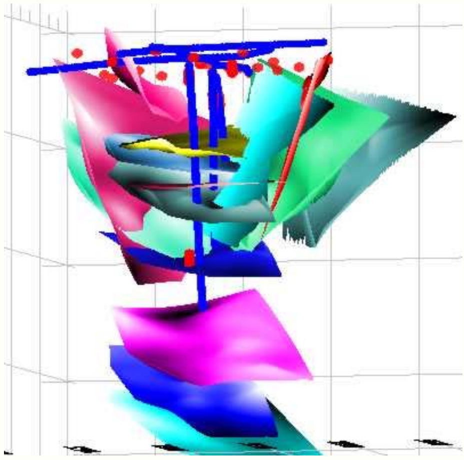


Figure 4.2.13 Olkiluoto (Finland): 3D interpretation of WVSP reflecto

✓ **Tomography measurements**

Measurements were taken between two deep boreholes at a distance ranging from approximately 250 metres near the surface to 150 metres underground.

The piezoelectric seismic source produces high-frequency signals with significant penetration in the medium, from tens to hundreds of metres. It was displaced every two metres. The receivers consisted of a chain of 30 piezoelectric sensors two metres apart.

After processing the data, the seismic wave velocity tomogram was compared with the borehole data to identify the continuity or discontinuity of the faults detected between boreholes (figure 4.2.13).

The tests showed that the technique can be used for borehole distances of up to some 250 metres, which would lead to optimise the number of boreholes to be drilled from underground structures.

- **Underground geophysics**

Geophysical techniques for fracturing detection, excluding measurements in boreholes, have a more restricted usage underground than on the surface. However, some of them can be used underground together with geological surveys and boreholes: radar and seismic methods, reflection and transmission (tomography) in between boreholes or between boreholes and drifts.

Radar tomography is implemented underground either by using devices identical to those used on the surface between the drifts with specific instrumentation between boreholes. Several tests have been carried out mainly in the Grimsel laboratory in Switzerland. They provided good characterisation of the different lithologies of granite rock and their homogeneity. Interpretation of fracturing requires appropriate processing. Investigation depths can vary from fifteen metres (Olkiluoto) to a hundred metres.

Seismic tomography methods tested in Finland (inset 4.4) are applicable underground from boreholes.

These two methods are thus complementary for characterisation of underground granite blocks.

4.2.2.3 The place of methods at different stages of granite site surveying

The geological and geophysical methods presented above are implemented at each stage of site surveying and characterisation so that their complementarity can fulfil the objectives of each stage in compliance with the general rationale of the modelling process.

Based on experience feedback acquired in France and abroad during the past few decades, a standard system for the place of the various methods during the successive stages has been established (table 4-1). This system is to be adapted to the specificities of the site investigated to ensure data collection consistent with the process for compiling a geological model

Table 4.1 Summary of the methods for data acquisition used at the various stages for construction of the geological model

Main models / **Stages**	**Methods**		
	Surface surveying stage	**Underground laboratory stage**	**Repository stage**
Geological: **Lithological**	Geological mapping and photo-imaging (satellite, aerial and digital terrain model) Airborne geophysics: -Magnetism -Electromagnetism -VLF -Radar -Gamma spectrometry -Transient electromagnetism -Surface geophysics: -Gravimetry -Electrical methods -Electromagnetism -VLF -Seismic refraction -2D seismic reflection -Vertical seismic profile -Seismic tomography -Magnetometry Lithological surveys in boreholes and photo-imaging in boreholes + sampling Borehole geophysics: logging	Detailed geological mapping + trenches and shallow boreholes Surface geophysics: -Electrical methods -Electromagnetism -VLF -2D seismic reflection -Vertical seismic profile -Seismic tomography -Radar tomography Lithological surveys in boreholes and photo-imaging in boreholes + sampling Lithological surveys in drifts Borehole geophysics: logging Geophysics in between boreholes -Seismic tomography -Radar tomography	Lithological surveys in boreholes Lithological surveys in drifts Lithological surveys in disposal cells Geophysics between boreholes -Seismic tomography - Radar tomography
Structural (Fracturing)	Geological mapping Airborne geophysics Surface geophysics Structural surveys in cored boreholes Non-cored boreholes Borehole geophysics: logging, radar	Geological mapping Structural surveys in boreholes and photo-imaging Structural surveys in drifts Geophysics in between boreholes -Seismic tomography -Radar tomography	Structural surveys in boreholes Structural surveys in drifts Structural surveys of disposal cells Borehole geophysics Geophysics in between boreholes -Seismic tomography -Radar tomography

4.2.3 Geological models: data integration, identification of uncertainties and visualisation

The process for compiling 3D geological models after geological and geophysical data collection on different scales consists of comparing them and ensuring consistency of model components.

This integration phase consists of:

- Reconstitution of the geological history of the studied granite massif ;
- Identification of uncertainties of various model parameters.

Once this integration has been carried out, geological models are established in the form of 3D images, mainly using data processing tools. They are support for constructing other site hydrogeological, hydrogeochemical and mechanical models.

4.2.3.1 Reconstitution of the geological history of the studied granite massif

Understanding the significance of the various rock units or fractures composing the geological model of a granite massif implies relocating them in the history of the granite from its genesis to the current period.

The questions most often examined concern the mineralogical and chemical composition of the rocks indicating the origin of the magmas. Interpretation requires age measurements or isotopic geochemical analyses, for example, to distinguish between magma families.

Analysis of the fractures and the various tectonic phases which gave rise to them is also an important area of study in understanding the history of the granite. Understanding how the fractures formed and to which episodes in the history of the granite their minerals relate, can provide a basis to carry out extrapolation, at the relevant scale, from field data collected in observation points or particular measurements: rock outcrops on the surface, boreholes and underground geological surveys.

Understanding fracture clogging by minerals resulting from the ancient circulation of hydrothermal fluids is therefore a point which is systematically studied while exploring granite massifs. Evaluating the effect of the extent and chronology of this type of phenomena is important in appraising granite rock permeability. Through the results of the work on the Hercynian granites of France (particularly, the work carried out by the FORPRO research group at the CNRS), were specified in more details the chronology and extent of the hydrothermal circulation phenomena observed in the west of both the Massif Central and the Armorican Massif. Thus leading to the establishment of a general framework of this type of study for a particular site (inset 4.5).

Inset 4.5 Percolation of fluids in Hercynian granites (Cathelineau et al. 2005)

1) Hercynian granites in the west of the Massif central and the Massif Armoricain after their formation have experienced a succession of geological and geodynamic events associated with fluid circulation episodes:

- Emersion of the crystalline basement at Permotrias with the development of peneplanation and penetration, locally deep, of oxidising alterations along the fractured zones;
- Transgression of the liassic sea and the opening of the Atlantic ocean;
- Development of carbonate marine platforms at the Dogger and at the Malm;
- Episodes of marine regression at the lower Cretaceous followed, after the Biscay gulf rifting by the return of the sea at the upper Cretaceous;
- Generalised regression of the sea at the Tertiary, with development of supergene alterations of tropical type at the Palaeocene and Eocene;
- Localised marine incursions at the Miocene (“mer des faluns”) and then at the Pliocene (“Loire gulf”).

2) Different methods have been used to trace the various episodes of fluid circulations in the granites and mainly: dating of minerals (and especially of neoformed adularia feldspars), fission traces for the identification of short-term thermal incursions, analysis of fluid inclusions (mainly to trace halogen elements such as chlorine which are excellent markers of fluid origins), isotopic analyses of oxygen and of carbon ($\delta^{18}O$ and $\delta^{13}C$) silicates and carbonates and partially strontium.

3) In methodological terms, the study confirms the question of finding the trace, based on mineralogy, of the latest geological circulation episodes. However, method complementarity has allowed tracing circulation episodes during the Hercynian and those during the Mesozoïc era related to the opening of the Atlantic ocean and the Bay of Biscay. This provides knowledge on the whole fluid circulation history whose heritage can be currently found in the composition of water percolating in Hercynian granites.

4.2.3.2 Identification of uncertainties

Geological model construction incorporates uncertainties which must be reduced during the successive surveying and characterisation stages. Included in the latter, during "ongoing" characterisation, still remain inaccuracies, notably related to the statistical processing of small-sized fracturing and, which must be identified to ensure sufficient robustness of the models and of their incorporation in disposal cell siting rationale.

The fault location is often surrounded by uncertainty due to its rarely simple and rather often composite geometry. Underground fault location is naturally more precise if it is determined from deep rather than shallow boreholes (figure 4.2.14)

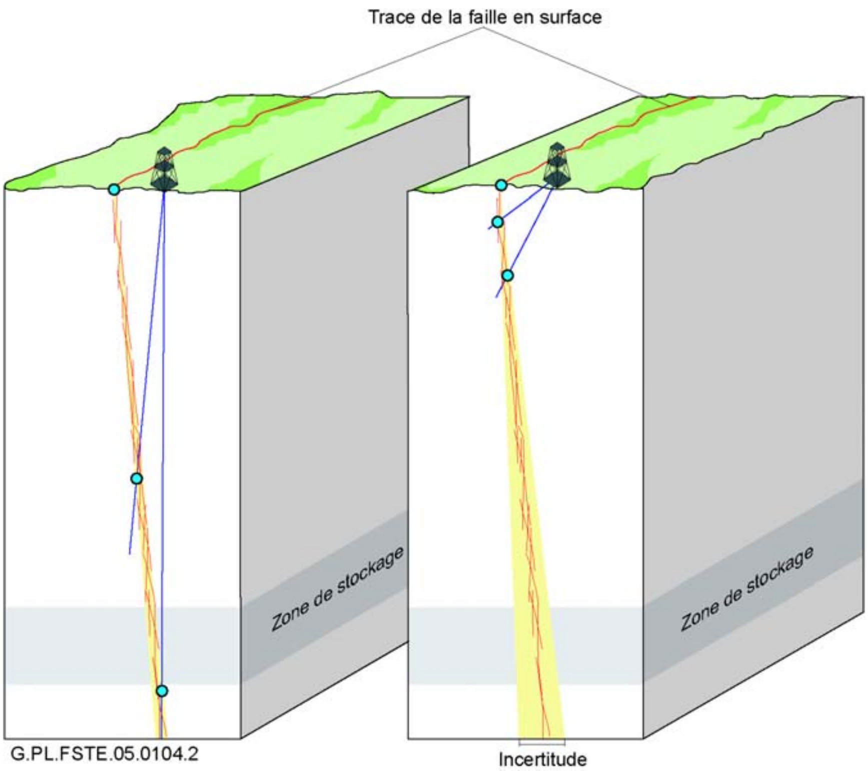


Figure 4.2.14 *Uncertainty surrounding the fault trace according to borehole data: a) from deep boreholes b) from shallow boreholes*

Therefore, consistency of observations and of models compiled on different scales is a key element for interpreting ground data and their integration in a 3D model.

Lastly, the understanding of the geological objects making up the model, i.e the consistency of their integration in granite geological history is indicative of the model robustness. It is based on fundamental and specific studies often involving works beyond the perimeter of the studied repository site.

4.2.3.3 3D modelling and visualisation tools

Data acquired during surveying and characterisation stages is validated and integrated in a *database*. This involves direct measurements and calculated data. They are normally localised in 3D, like for example rock or fluid samples from a borehole and physics and geophysical measurements *in situ*.

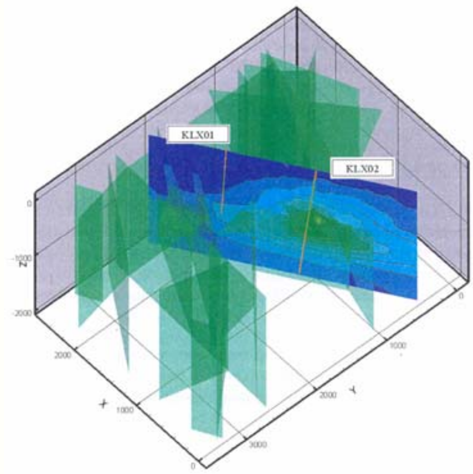
Data 3D visualisation is essential for the construction of geological models which are the backbone of the integrated models covering the various disciplines, first and foremost for the geometry of the geological structures.

Visualisation tools must provide 3D representation of the various elements of the geological model, lithology and fractures. They must additionally manage the location and results of samples, boreholes and geophysical measurements or interpretations. They must also incorporate topography in the form of digital terrain models, images, satellite or aerial photographs. Such tools provide user-friendly access to 3D models and enable them to be shared across various disciplines: geology, hydrogeology, geomechanics, geochemistry, etc.

Until quite recently, this 3D visualisation was based on vertical cross sections in two directions, and plans at various depths. Today, computing provides interpolation and visualisation tools for the construction of true three-dimensional models.

Inset 4.6 ***Visualisation tools***

SKB developed a so-called RVS system (*Rock Visualisation System*) for visualisation of specific faults and cross sections (Munier et al, 2003). POSIVA has an equivalent system which has been supplemented by a mining visualisation tool for the structures observed in the Onkalo underground facility at Olkiluoto. In France, Andra has adopted visualisation tools from the oil industry ("GOCAD") for the representation of the Charroux-Civray granite massif (Vienne) (figure 4.2.15).



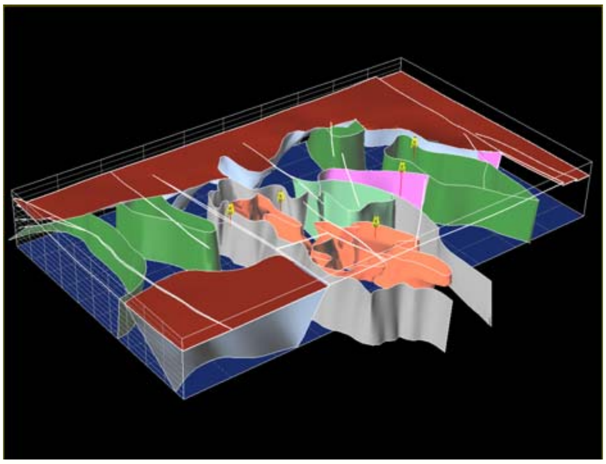


Figure 4.2.15 *Examples of visualisation of geological models: on the left, example of visualisation of faults and planes of cross sections in the "Rock Visualisation System" developed by SKB (Sweden); on the right: visualisation of granite limits using the "Gocad" system*

4.3 Hydrogeological and hydro-geochemical modelling

The purpose of hydrogeological modelling is twofold: it is the support for radionuclide transfer simulations for long-term safety assessments and contributes to evaluating transient water flows likely to be produced during repository excavation and operation.

Hydro-geochemical models complete hydrogeological modelling for the understanding of current and past hydrogeological water flows in the granite massif. They as well provide support to the radionuclide transfer simulations.

4.3.1 Issues related to hydro-geological modelling in a fractured medium

Hydrogeological and transfer models for granite are complex. This complexity stems from the representation of a fractured medium and the consideration of large scales of time and space in the studies of a repository.

The water flows to be considered are low-flux and slow in terms of their kinetics. They are essentially linked to fractures, the distribution of which in the granite does not follow a single and simple law.

The methods used have undergone major developments in recent decades. The progress made in the oil industry has in particular been behind the methods and tools which could be adapted to the granite medium and the repository studies.

Around ten years ago, many radionuclide transfer simulations were conducted on the basis of major simplifications of the fractured granite medium consisting of processing it digitally as the equivalent of a porous medium. In this method of processing, the simulations introduce the largest faults and the role of the small sized fractures is processed by the allocation of hydraulic parameters weighted to the mass of granite.

For about ten years, progress mainly due to computing developments has allowed to explicitly process fractures in increasingly larger volumes of granite. This progress reduces the simplifications to be incorporated in granite representation. They are now regularly integrated into the models and simulations carried performed on an international level, relying on the complementarity of the two representations of granite: equivalent porous medium and medium explicitly represented with fracturing (inset 4.7).

Inset 4.7 ***Hydrogeological models in a "continuous porous medium" and in "fracture networks"***

Hydrogeological modelling of a fractured granite massif must deal with two major contradictory requirements:

- firstly, it must take into consideration a complex network of fractures, down to the smallest fractures liable to be intercepted by a repository component, in order to appraise correctly the flows occurring there,
- and secondly, it is vital to extend modelling over large enough spaces to ensure that all factors determining underground flows are taken into account: topography, surface hydrographic system often beyond the limits of the granite massif, hydraulic characteristics of the altered superficial parts of the granite massif, etc.

As it is not yet possible with current computing resources to use a fracture network model over the whole of the considerable volume that would need to be discretised on the small fracture scale, the solution involves the integration, on various scales, of "porous equivalent" models and models representing explicitly the fracture networks.

• "Equivalent porous medium" models

In a continuous porous medium model, flows are assumed to use the whole volume of rock available and comply macroscopically with Darcy's law. Water flows depend directly on the permeability of the medium. This model, valid for porous media, can be used for fractured rocks over a certain volume which depends on the geometric and hydraulic characteristics of the fracture networks in question.

For example, the generic exercises "Everest" and "SPA" to simulate radionuclide transfer in a granite medium were conducted, with the support of the European Union, on the basis of such assumptions (European commission, 1997 and 2000).

On a regional scale, i.e. over areas exceeding a hundred square kilometres and terrain several kilometres thick (schematically 15kmx15kmx3000m), hydrogeological modelling is still based on such simplifications. Faults are taken into consideration in the model through the attribution of "equivalent" hydraulic properties to parts or the whole of the modelled volume.

• Models explicitly taking account of fractures

Several types of modelling take a fracture network explicitly into account. Discrete fracture network (DFN) models, the most widely used, consider a medium in which, in steady state, only fractures play a part in the advective flow. The flow is thus restricted by the dimension of the fractures, especially thickness and width. The geometry of each fracture is defined, enabling the hydraulic connectivity of the network to be determined. Hydraulic transmissivity parameter is attributed to each fracture and then hydraulic heads and flows can be calculated at any point of the network.

The field of application of DFN models is more specifically hydrogeological modelling and transfer simulations on

the scale of a repository module (approximate volume: 500 m x 500 m x 300 m). With DFN modelling, all fractures extending up to approximately 5 m can be integrated.
• Integration of models of various scales and various types
Modelling scales must fit consistently with the various types of models. With today's computer tools, models performed at various scale can be integrated by successive iterations, and the consistency of the parameters on various scales can be achieved from the regional scale to the repository module and disposal cell scale.

However, this does not lift all of the difficulties inherent in the models to be produced. The various issues to be considered relate to the characterisation and the data to be gathered, and also to data processing and the problem of the corresponding digital simulation. Ultimately, it is a matter of controlling the simplifications which must be introduced throughout the modelling process; in other words, understanding their full meaning, both in terms of the elementary phenomena considered and of their integration into the models and simulations.

In the absence of a specific study site, Andra's work consisted of dealing with each stage in the modelling process and checking that the methods, techniques and digital tools developed abroad would be applicable to the study of a site in French granite. It means:

- checking that the different hydrogeological parameters required for modelling can be determined for any given site based on land measurements and laboratory analyses;
- testing, during the final modelling and digital simulation stages, that the integration methods are consistent with the scales of time and space considered and justifying the corresponding simplifications.

As a result of these studies, it was possible to conclude that each stage in the modelling process, from the feedback received, could be applied on a French site. The realism of the models and simulations is sufficiently preserved by the simplifications introduced cautiously throughout the calculation process.

4.3.2 On-site collection of hydrogeological and hydro-geochemical data

Boreholes are the most commonly used means for underground hydrogeological or hydrogeochemical survey and characterisation work in a granite massif. At each stage in the exploratory process, from the surface or underground, the borehole techniques – coring or drilling – are adapted to the aims of hydrogeological or hydrogeochemical characterisation. There is a considerable amount of feedback in this area providing a very comprehensive range of tested techniques and tools suited to numerous contexts.

4.3.2.1 Hydro-geological data

The main parameters collected on site are: granite hydraulic conductivity, mainly that of the fractures, hydraulic connectivity of the fractures and hydraulic heads (piezometry) in the granite. These parameters are mainly determined by borehole measurements. Other specific site data can be collected from the surface, mainly concerning the hydrographical context: flow rates of springs and rivers and rainfall.

- **Fracture hydraulic transmissivity and rock permeability**

Transmissivity, expressed in m²/s, is the hydraulic parameter which characterises fracture capacity to transmit water flows. It is generally determined by hydraulic tests in boreholes testing one or several fractures by water drawdown or, on the other hand, by water overpressure.

Another commonly used parameter is **hydraulic conductivity**, corresponding to transmissivity of fractures related to a metre of bored formation (i.e. the equivalent of one transmissivity per metre, expressed as rock permeability in m/s).

Various techniques are used depending on the extent of the hydraulic transmissivity of the fractures:

- for large fractures where transmissivity is significant, conventional hydrogeological techniques (pumping, current flow meter logging, etc.) are adapted to determine the hydraulic characteristics of the granite;
- if transmissivity is lower, the "fluid logging" technique based on the detection of differences in electrical conductivity, and therefore salinity, is quite suited to locating low flow-rate fractures;
- if transmissivity is very low (as in the case of small fractures), the fluid logging technique is combined with differential flow logging in the borehole similar to the technique developed in Finland and used systematically in exploratory boreholes;
- finally, tests between fixed packers can be used for accurate characterisation of the granite rock, very few permeable by nature, and small fractures where transmissivity is very low.

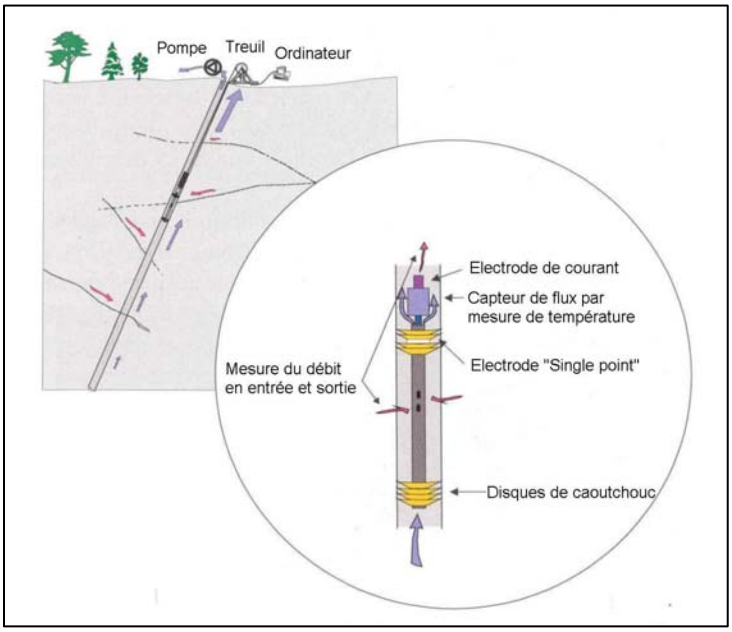


Figure 4.3.1 Principle of the probe "POSIVA Flow Log" (differential flow measurement) developed in Finland

Major fault transmissivity is normally above 10-7 m2/s, whereas small-sized fracture transmissivity is lower than 10-9 m2/s and can be very low (< 10-10 m2/s).

Examples of measurements made in Sweden (POSIVA flow log technique) and in France (measurements with packers) are given in figure 4.3.2. It also illustrates the connection with the density of fractures intersected by the borehole.

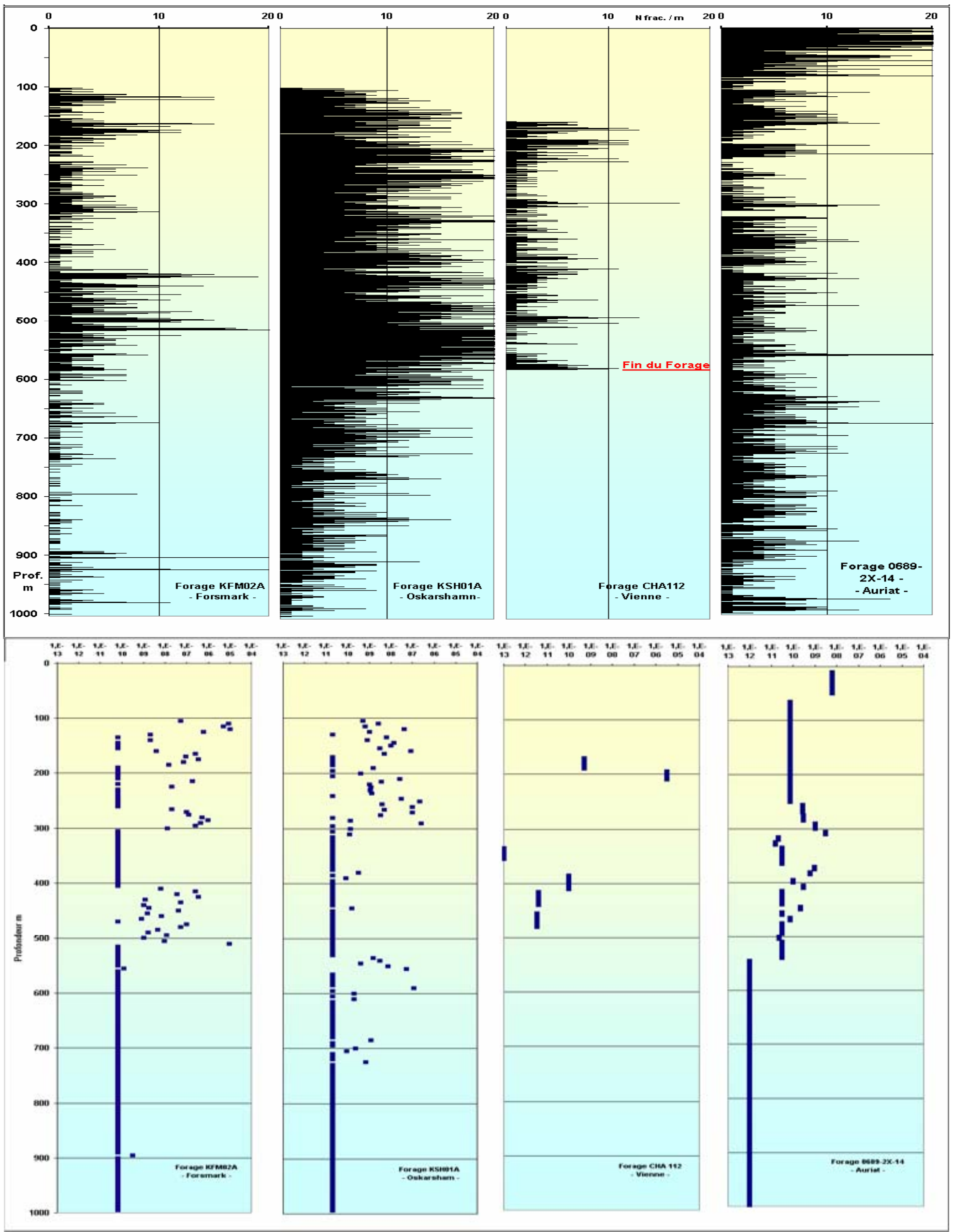


Figure 4.3.2 *Measurements of fracture hydraulic conductivity. a) at the bottom: measurements of hydraulic conductivity in boreholes, in Sweden (according to SKB, 2004b,c) and in France; b) at the top: fracturing density*

- **Fracture hydraulic connectivity**

Hydraulic connectivity between the fractures is another significant parameter which directly affects assessment of overall permeability in a granite massif and in a portion of the rock volume. It can be assessed by testing hydraulic interference in between boreholes. This type of test particularly concerns large fractures (figure 4.3.3).

Other measurements can be carried out using equipment measuring the water pressure within the same borehole, which is separated into measurement chambers by packers. Through this technique, the water pressure of a specific fracture or fracture zone can be measured and the connectivity between fractures or groups of fractures can be evaluated.

The developments in these techniques, especially for oil exploration, provide a complementary set of tools able to characterise the connectivity of a network of fractures on various scales: from tens to several hundred metres.

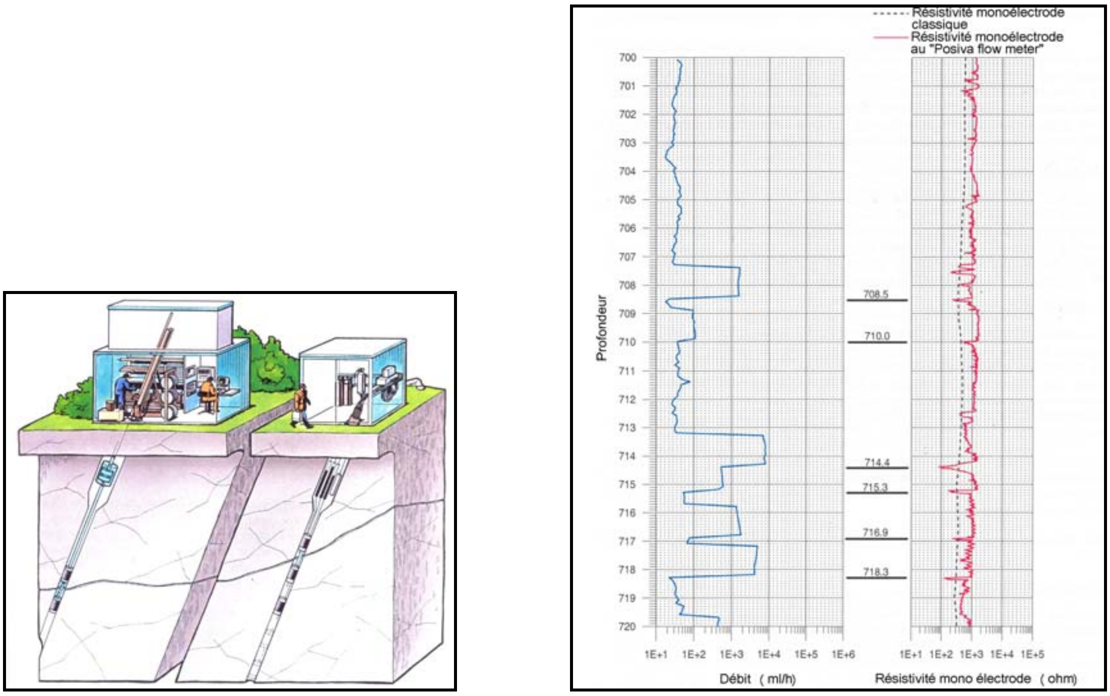


Figure 4.3.3 *Hydraulic measurements in boreholes a) on the left: functional diagram of a hydraulic interference test for studying fracture connectivity between two boreholes (SKB data) b). On the right: continuous measurements in boreholes showing relations between flow rate and electrical conductivity to determine the precise position of water conducting faults (POSIVA data)*

- **Piezometric measurements and monitoring**

A third set of information concerns hydraulic head gradients, the driving force behind massif water flows. They are determined on one hand from topographical data and on the other hand from piezometric measurements in boreholes. Recording these measurements can be prolonged throughout the various surveying stages and during waste disposal.

4.3.2.2 Hydro-geochemical data

Granite massif water composition is determined by water sampling in the boreholes avoiding contamination of the samples from water used for drilling the boreholes.

Various techniques have gradually been developed to meet the requirements of the chemical or isotopic analyses to be conducted. Depending on the water production detected by hydrogeological measurements, fluid samples can be taken directly from the water produced at the wellhead, or underground using sealed bottles or continuous sampling techniques (figure 4.3.4).

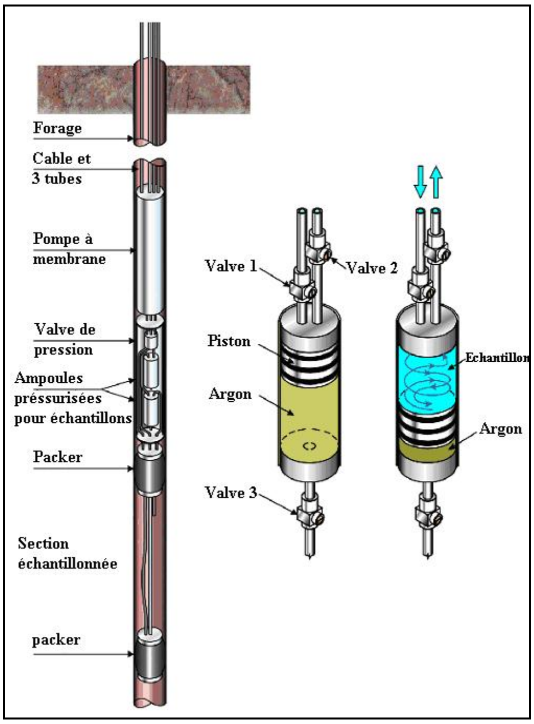


Figure 4.3.4 *PAVE fluid sampling system in boreholes developed in Finland (POSIVA, 2003b)*

4.3.2.3 Transfer and retention parameters

The diffusion properties of the granite rock are established during exploratory work on a granite massif by samples taken from cored boreholes and underground drifts, as well as from surface outcrops if suitable with respect to alteration conditions.

Retention properties are linked to the mineralogical characterisation of the rock and fractures as well as to the intimate geometry of the voids and porous volumes. The values of the associated parameters are established from measurements on granite samples. Tracer tests between boreholes are conducted *in situ* to verify the consistency of measurements on the samples with extrapolated values, in relation with geological variability, on the scale of a large fracture.

- **Analyses and measurements of granite samples**

The diffusion coefficients of granite have been measured on several types of granite in France and abroad. They are generally performed by testing the diffusion kinetics of tritiated water through a few centimetre thick slice of granite. This method was used by the CEA in the course of the works carried out by Andra from 1994 to 1996 on the Charroux-Civray granite massif.

As this massif is composed of several types of granite, extensive sampling of various types of rock was possible. The diffusion coefficients measured were generally very low with values most often below $10^{-13}m^2/s$. When the granite massif was subjected to major hydrothermal alterations during its geological history, the values could increase by a factor of 10 or 100.

- **Tracer tests in between boreholes**

In granite, tracer tests consist of injecting a mixture of tracers at a precise point of a fracture and observing the restitution, at a certain distance, in the same fracture or in another connected fracture. Providing that a sufficiently accurate geological and hydraulic characterisation of the fracture network has been completed beforehand, this type of test can be used to assess the delay on radionuclide transfer compared with water circulation.

A major experimental programme was conducted on such tracer techniques at the Äspö laboratory in Sweden. They led to the development of a conceptual model of transport in a fractured medium and the quantification of differential delays between radionuclides. (chapter 5.6)

4.3.2.4 The place of different methods at the various granite site surveying stages

Hydrogeological and hydro-geochemical data collection throughout the successive surveying stages is related to geological data collection. Control of relations between fracturing organisation and hydraulic parameters (transmissivity and connectivity) is ensured by systematic borehole measurements.

As for geological and geophysical methods, a reference system of the hydrogeological and hydro-geochemical data collection process can be determined (table 4.2), to be adapted to site specific configurations.

Table 4.2 Summary of data acquisition methods used at the various stages for compiling hydro-geological and hydro-geo-chemical models

Main models Stages	Methods		
	Surface surveying stage	Underground laboratory stage	Disposal stage
Hydrogeological	Surface hydrogeological inventory: -hydrographical network -piezometric level -spring flow rates -meteorology Borehole testing: -pumping tests -flow logging -injection tests -interference tests -monitoring	Borehole testing: -pumping tests -flow logging -injection tests -interference tests	Borehole testing: -pumping tests -flow logging -injection tests -interference tests
Hydro-geochemical	Free water sampling on surface or in boreholes during tests Geochemical logging Complete water characterisation (mobile geochemical unit) Monitoring	Sampling during tests Complete water characterisation (mobile geo-chemical unit) Tracer tests Monitoring	Geochemical logging Tracer tests Monitoring

4.3.3 Hydrogeological and hydro-geochemical modelling

The vast amount of experience feedback acquired over the past few decades, mainly abroad, provides methods for integrating site surveying data in safety analyses and design studies. They are based on a complete modelling process, from acquisition of geological data to radionuclide transfer simulation and on all the scientific knowledge contributing to understanding granite massif hydrogeology. Among these data, hydro-geochemistry constitutes a natural complement to hydrogeological modelling for understanding water flows in granite and its environment.

4.3.3.1 A modelling process explicitly incorporating granite fracturing data

The issues relating to the integration of site data into safety assessments, through hydrogeological modelling and radionuclide transfer simulations, concern the following main aspects:

- integration of the various scales of space into the geological and hydrogeological models;
- input of the variability in the transport properties of the fractures within a granite massif;
- input of the various phenomena involved in radionuclide transfer and retention in a granite massif fracture network;
- integration of the various phenomena over large time scales.

These topics have been covered in numerous studies and applications, especially in the scope of the "Äspö Task Force" project, conducted in the context of an international cooperation agreement and based on the Swedish laboratory data (Dershowitz, 2003).

The various methods studied answer the questions raised and integrate site data into the various scales of time and space to be considered in the models. The methods are based on the explicit input of granite fracturing data collected at a site. Due to the development of methods of modelling a granite medium as "fracture networks", site data can indeed be introduced into the modelling process without drastic simplification from the earliest stages of simulation. The simplifications form part of a gradual, iterative process designed to compare site data and modelling results throughout the stages of the site surveying (inset 4.8).

Inset 4.8 ***Modelling process and site data***

In a generic study context, Andra has carried out modelling exercises supported by knowledge acquired in the international framework and field data collected in France, especially at the Vienne site (1994-1996) studied by Andra (Joubert 1998) or the Auriat site (Creuse) studied by the CEA (1980-1981). This has resulted in a typical outline of the modelling process to be adopted throughout the various exploratory stages of a site.

On both regional and granite massif scales, geological models represent the structure of a granite massif in its geological context. The models identify the various lithological units composing a granite massif and its surrounding formations. Major fracturing – regional or "local" faults – modelled by a deterministic approach, i.e. by establishing 3D geometry on the basis of geological surface mapping, geophysical surveys and boreholes drilled during exploratory work. Hydrogeological models in a "continuous porous medium" are established by integrating hydrogeological measurements from boreholes as for instance pressure measurement, permeability, etc (figure 4.3.5).

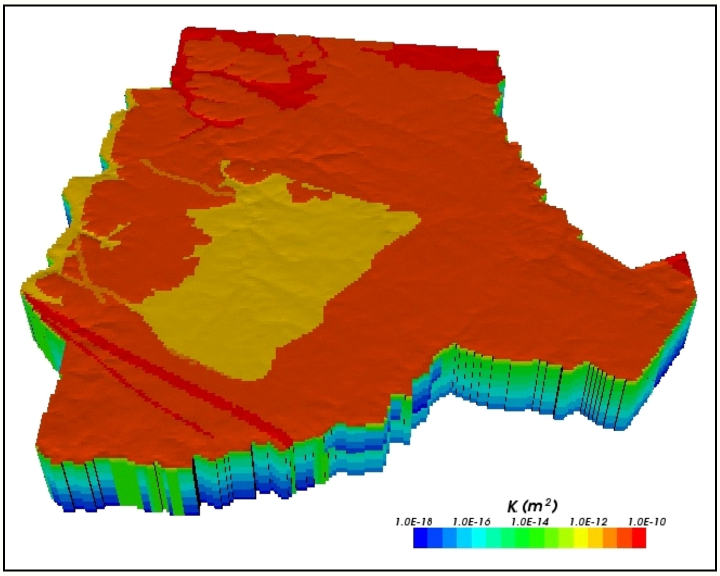


Figure 4.3.5 *Example of a regional hydro-geological model: permeability evolution versus depth*

On the scale of the repository module, geological models include explicitly (fracture network DFN type model) small fractures, characterised either from surface surveys or by underground structures (figure 4.3.6)

Fracturing geometry and distribution in a granite massif are processed in a probabilistic manner on the basis of site data. Processing groups the fractures into "fractures families" with specific geological, hydrogeological and transport properties. Distribution laws, validated by inversion methods and by comparison with site data, deal with variability in the properties of fractures in granite on the scale of one or more repository modules in a probabilistic manner.

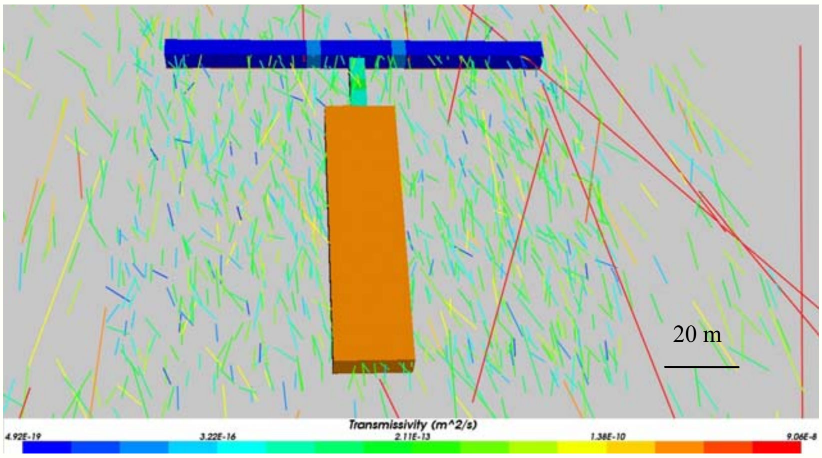


Figure 4.3.6 *Example of a fracturing model on the repository module scale: the disposal tunnel (B waste) is constructed away from fractures with transmissivity between 10-6 and 10-7 m2/s. It intersects small-sized fractures with very low transmissivity (< 10-10 m2/s)*

The various **integration methods** ensure the continuity and provide a link on both regional (equivalent porous medium model) and repository module (DFN type model) scales.

From a hydrogeological viewpoint, water flux balances and continuity in the distribution of hydraulic head gradients between the various modelling scales are the main elements ensuring that the various modelling scales are consistent with each other.

4.3.3.2 Hydro-geo-chemical input

The composition of granite water reflects the chemical exchanges between the water and the granite rocks and fractures, and therefore the water circulations within the granite. Understanding and modelling these exchanges is a way of reconstructing their pathways.

The increase in water salinity with depth, often observed in granite environments, reflects the exchanges between deep, more ancient water of a granite massif and the more recent shallower water. Isotopic evolutions in the composition of the water show the same tendency (Buschaert, 2004)

Successfully developed in Fenno-Scandinavia and Canada, methods of modelling exchanges between waters of different origins allow reconstructing the evolution in the chemical composition of granite water and its present-day distribution in a massif. Applicable in the French context, these methods provide elements required to validate hydrogeological and transport models to be produced on a site scale and over long periods.

Inset 4.9 ***Granite site hydro-geochemical modelling: example of Äspö in Sweden***

The geological and hydrogeological history of the Äspö region is dominated by quaternary glacial episodes which have controlled the paleogeography of the site with the presence, then the melting, of an icecap. There has been a succession of coastal sea and lake situations. The water circulating deep underground in the granite is therefore the result of a mixture of seawater, brackish water, water from melting ice and recent meteoric water (figure 4.3.7).

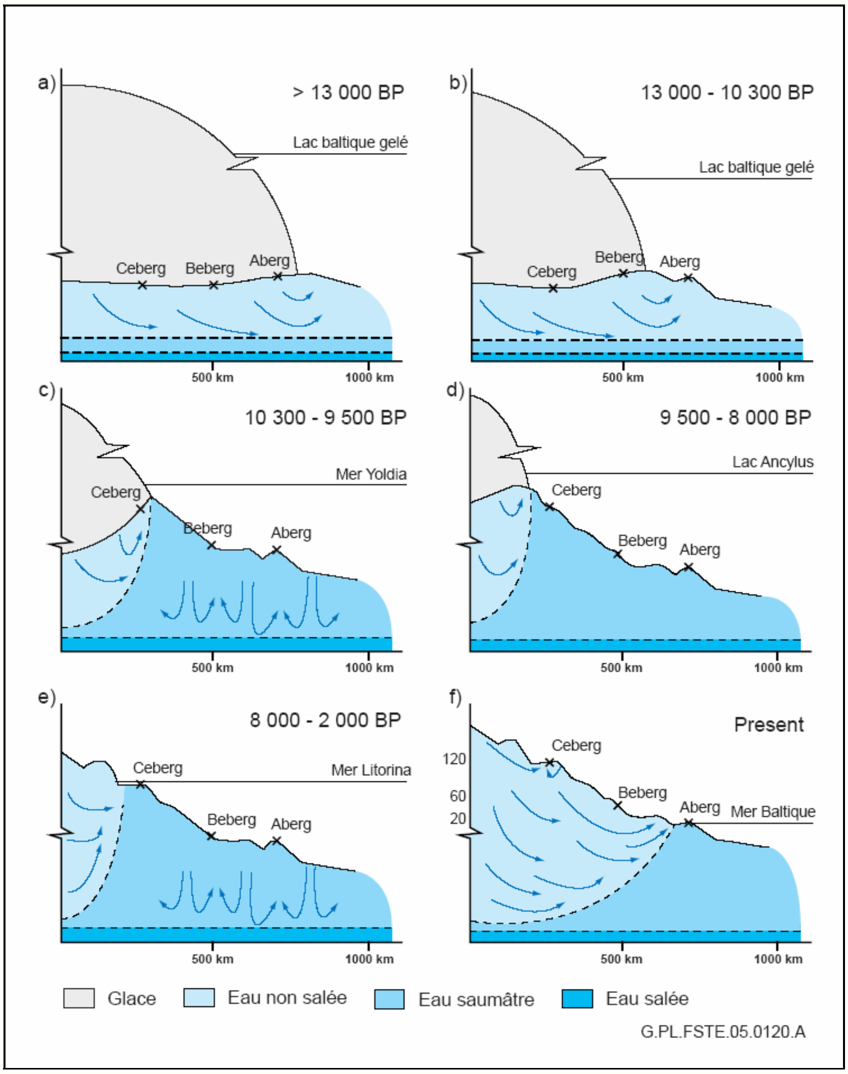


Figure 4.3.7 *Conceptual post-glaciation scenario for evolution in the south of Sweden (according to SKB data). Aberg corresponds to the Äspö site, "Beberg" and "Ceberg" to two more northern sites. On the abscissa, distance between sites; on the ordinate, altitude (ice exceeds 3,000 m at maximum)*

From the hydrogeochemical modelling methods developed from this paleogeographic outline, the evolution in the composition of waters of various origins and their current distribution in the granite massif was reconstructed. The model applied is the M3 model (for Multivariate Mixing and Mass balance calculations, Laaksoharju & Skarman, 1995).

It is based on the observation that chemical composition of water is the result of potential mixtures between previously identified water masses, taking into account water/rock interaction. It thus differs from other more standard models which are more based on reactions than on mixtures to determine water evolution.

In Äspö, the five types of water identified are: meteoric water, glacial water, brine considered as older than 1.5 million years, marine water and sediment poral water. Calculations of mass balances are used to test the deviation for certain elements between values measured and values previously calculated with mixture equations. The model is highly dependent on the choice of extreme waters. However, uncertainties are estimated at less than 10% by varying the extreme poles in the probable ranges. It is also worth mentioning that no time constraint has been incorporated in the modelling (Laaksoharju et al., 1998). A representation mode illustrates the proportion of different types of water in the granite (figure 4.3.8).

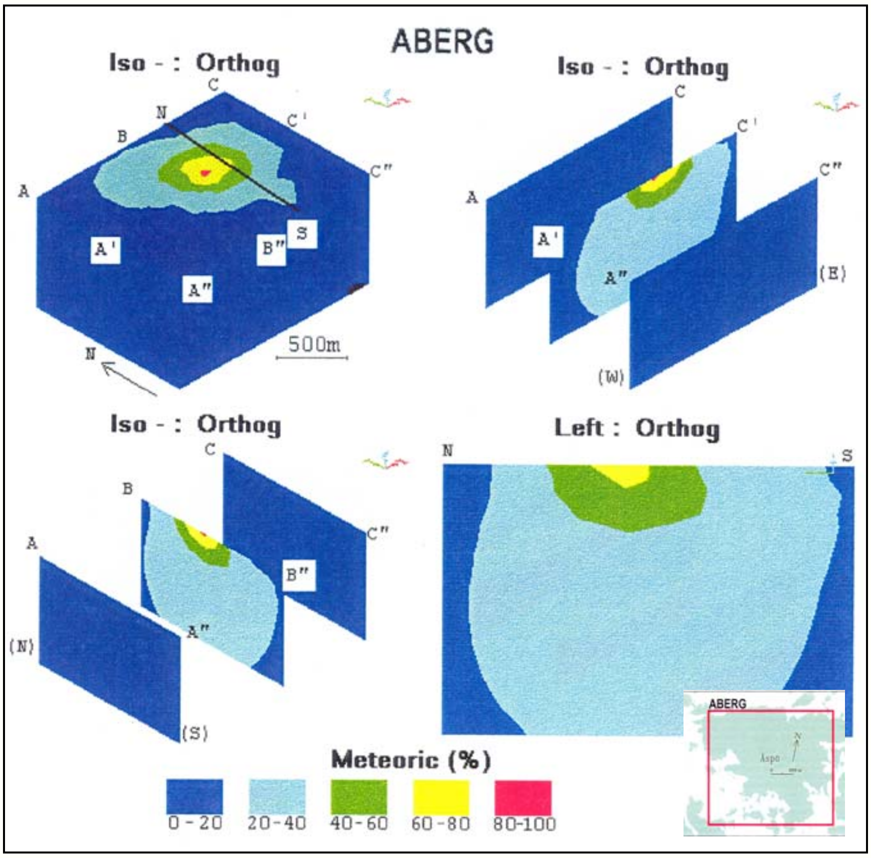


Figure 4.3.8 *Äspö site hydro-geo-chemical modelling: distribution, according to the proportion of meteoric water in the granite basement (taken from Laaksoharju et al., 1998)*

The example of the Äspö site study demonstrates complementarity of hydro-geochemical modelling and hydrogeological modelling. It acts mainly as an element of validation of the granite hydraulic properties on the site scale and of hydrogeological modelling on large timescales.

4.4 Geomechanical and thermal modelling

The considerable feedback relating to underground excavations in granite shows the feasibility of large and stable deep structures.

However, the construction of stable structures does not automatically mean the absence of any damage to the granite walls due to their excavation. Neither does it explain how would be the mechanical behaviour of the granite in the environment of a repository in response notably to thermal stress.

This, therefore, involves collecting mechanical and thermal data throughout the successive surveying stages to characterise a granite massif in view of the perturbations likely to be undergone by it during the various repository phases: excavations and thermal perturbations (see chapter 5).

4.4.1 Collection of granite site thermal and mechanical characteristics

4.4.1.1 Geo-mechanical data

The mechanical characterisation of a granite massif traditionally comprises two parts:

- characterisation of the mechanical properties of the rock, including the fracturing that may affect it;
- measurement of the underground natural mechanical constraints.

● **In situ and samples measurements**

Granite is a mechanically resistant rock. Appraising granite mechanical resistance due either to compression or tension constraints is carried out through current tests on borehole cores during the first surveying stages, then later, *in situ*, underground. Nevertheless, on larger scale, mechanical behaviour of granite massif rock will mainly depend on its fracturing.

Repository structures are to be located in rock with little fracturing; however, fracturing is characterised to ensure that it is not liable to weaken the rock around the structures. The “surface rugosity” of the fracture and the nature of the minerals contained in it are to be considered.

Fracture strength is assessed by shear tests according to specific and proven experimental methods (figure 4.4.1).

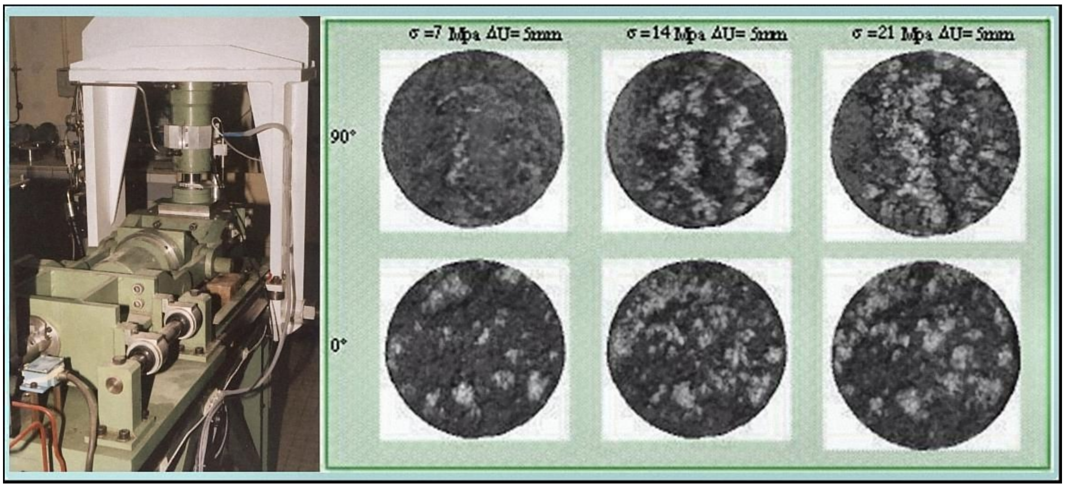


Figure 4.4.1 Machine for shearing tests on granite fracture samples and photos of fracture surfaces after shearing (5 mm) (Riss et al, 1997)

The numerous tests performed on samples have provided a basis for the development of laws relating to the mechanical behaviour of the fractures according to their geometric and mineralogical characteristics. As per today, full-scale *in situ* experiments are necessary to adjust the various coefficients used in the models on the scale of the studied structures. These were notably performed in the Swedish and Canadian underground laboratories.

- **Natural underground stress in a granite massif**

The mechanical stress state prevalent underground in granite massif results from the weight of the overlying formations and stress of a geodynamic origin.

Structure sizing depends on the anisotropy of underground horizontal or vertical stresses. High stress anisotropy has, for example, been observed underground at the Lac du Bonnet laboratory in Canada (Martin and al., 2005). This corresponds to a quite specific situation: at this point, the granite massif below 300 m is not fractured and the tectonic stresses, undergone over its history, could not have not been released. The behaviour of drifts under such a configuration has been tested and their geometry adjusted. Mechanical models representing the behaviour granite rupture under such conditions have been finalised.

In the French tectonic context, the ratio between major horizontal stress and vertical stress is estimated at between 1 and 2 (Virlogeux D., 2002). This shows a low anisotropy of underground stress and the construction of underground structures should be rather straightforward. This assessment cannot be generalised, however, and must be validated by *in situ* stress measurements for each site.

In addition to geological surveys, mainly the fracturing ones, likely to provide information on the state of granite massif stresses, various techniques of *in situ* stress measurement are available and complementary (inset 4.10).

Inset 4.10 ***Stress measurements***

Three main types of techniques are implemented for stress measurement in an underground granite massif:

- identification of borehole wall break-outs and measurement of the damage dimensions and orientations using a caliper. Differences with respect to the nominal diameter of the borehole can determine horizontal stress in the basement;
- the overcoring technique consists of measuring the excavation-related deformations in an initial borehole. Then a second borehole is cored around the first one and the elastic deformation in response to stress release is measured in three directions (figure 4.4.2);

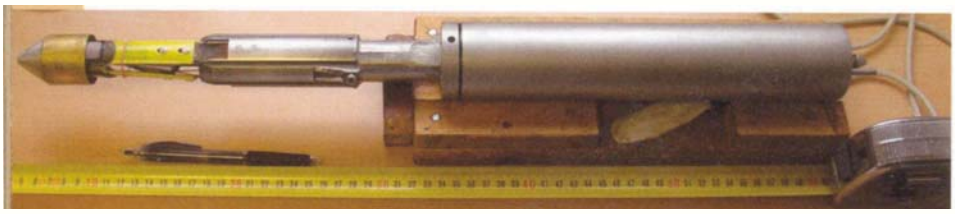


Figure 4.4.2 Stress measuring probe for overcoring (SKB picture)

- the stress measuring method so called HTPF (Hydraulic Tests on Pre-existing Fractures) requires, as for conventional hydraulic fracturing hydraulic tests, to be conducted on portions of the borehole. The zones are identified in advance, either in sound rock or with a single fracture. Water injection tests measure the normal stress borne by the artificial fracture created by injection or by the natural fracture opened by injection. The test finishes with determination of the dip and azimuth of the fracture tested. A minimum of ten measurements is required to determine the stress field (Cornet et al, 1992).

These types of test have been conducted in France and other countries. They enabled to adapt measurement techniques and identify uncertainties linked to the inclusion of fractures initially existing in the rock in the processing and interpretation of the data.

4.4.1.2 Collection of thermal parameters

Thermal parameters to be collected on a site involve, on the one hand, granite rock properties and, on the other hand, temperature distribution in the massif, mainly the foreseeable temperature at repository depth.

- **Rock thermal characteristics**

Rock thermal conductivity, thermal capacity and expansion coefficients are determined on rock samples taken from boreholes (cores) and *in situ* from drift walls in underground structures.

- **Temperature distribution in the granite massif**

Temperatures are measured in boreholes and, therefore, it is granite water temperature that is determined. These measurements are very precise (1/10th, even 1/100th of a Celsius degree). They are normally associated with hydrogeological measurements.

4.4.2 Modelling of granite massif mechanical behaviour

Mechanical behaviour simulation of a fractured granite massif, affected by mechanical and thermal perturbations, is based on models specific to both rock matrix behaviour in continuous medium and fracture's one as discreet element. Looking for effective solutions covering all rock massif behavioural aspects is still subject to development and validation work (Stephansson et al, 2003).

Issues to be resolved are related on one hand to the different fracturing scales and families to be considered and on the other hand to complex relations between mechanical deformations of fractures and their hydraulic properties.

Therefore, simulation objective is to check that the studied deformation domains are of small amplitude, without any major consequence to massif mechanical, hydraulic and thermal properties.

For design purposes, dimensioning is carried out with margins of precaution and ensures deformations to be kept in the domain of small ones. Arrangements proposed for a repository in terms of seals and swelling clay buffers are also a means of limiting deformations in repository structures subject to mechanical and thermal perturbations.

- **Coupled hydro-mechanical and thermo-hydro-mechanical models**

The hydraulic properties of fractures, notably small fractures, depend on the stress state of the massif. The hydraulic transmissivity of the fractures is sensitive to normal stress exerted on the fracture planes. A local modification of the stress system is therefore liable to change the hydraulic properties. This may be due to repository structure excavation or to the heating of the massif linked to the disposal of exothermic waste.

The simulation of the modifications to the hydraulic properties of a fracture network is complex from a theoretical point of view and in terms of experimental validation. However, the various experiments conducted in France and abroad have identified the important parameters to be integrated into the simulations: geometry and mechanical properties of the fractures linked to the fracture planes rugosity, the filling minerals kinds, their hydraulic or mechanical openings, etc. Various behaviour laws have been proposed and digital models established.

International exercises carried out on this theme, such as the Decovalex or Benchpar projects (Stephanson and al., 2003) which are notably based on the results of experiments in the Kamaïshi mine in Japan, have concluded that mechanical models can provide the order of magnitude of the changes to the stress state and movements along the fractures of fractured granite. This defines the deformation regime and domain to be integrated into the safety analyses and the design of repository architectures.

4.5 Long-term geological evolution of a site: geoprospective

On the scale of several hundred thousand years, a granite massif and its environment are liable to undergo changes linked to internal (tectonic movements, earthquakes and volcanism) or external geodynamic phenomena (climate changes and surface erosion phenomena). The purpose of the studies is therefore to identify the phenomena that may be involved in the various timescales to be considered in the evolution of a repository.

4.5.1 French granite geodynamic context

4.5.1.1 Internal geodynamic phenomena

In terms of internal geodynamics and plate tectonics, the granite regions of the Massif Central and the Armorican Massif are situated away from active zones. They are therefore characterised by deformations of very low amplitude, even on the scale of several hundred thousand years. Vertical ground movements are very weak and seismic activity is low.

A geodynamic context showing very little activity does not equate to the total absence of any **seismic** manifestation, in other words earthquakes.

Assessing the “seismic hazard” in France has been addressed by numerous studies, which are the basis of the seismotectonic zoning of the country. For disposal studies, the assessment of the seismic hazard pools together the data recorded regularly over decades (“instrumental seismicity”), the results of research over the historical periods (“historical seismicity”) and the paleoseismic field studies aimed at detecting the trace of strong earthquakes from ancient times (thousands to hundreds of thousand years) in order to evaluate their intensity and possible recurrence. In this evaluation, the granite massifs of the Massif Central and the Armorican Massif are located in zones of low to moderate seismicity. The long-term evolution of seismicity is in relation with plate tectonics kinetics. With no foreseeable change on the scale of several hundred thousand years, no significant evolution in the seismicity level is to be considered for the future.

Volcanic formations exist in the central and eastern parts of the Massif Central. Geologically, volcanic activity reached a peak some 20 million years ago. Volcanism was still active locally in the quaternary period (2 million years). While the actual cause of this volcanism is debated in scientific circles, it appears that the eruption points remain confined to precisely identified regions: the Chaîne des Puys, and the Ardèche volcanoes for the geologically most recent events (less than 100,000 years ago). Bearing in mind the very slow dynamics of these mechanisms, it is accepted that the creation of new volcanic regions on the scale of the next million years can be ruled out.

All in all, considering the slow geodynamic evolution of the granite regions considered in the French geological context, the consequences on a granite site are limited. For the granite massifs as a whole, no evolution is foreseeable on a ten thousand year scale.

On the scale of a hundred or several hundred thousand years, the geodynamic context of the considered regions (Massif Central and Armorican Massif) indicates that a very slight evolution in a granite site is foreseeable for the majority of the granite massifs: indeed, underground stress changes are too slight to cause any changes to the hydraulic properties of the faults and fractures.

Particular situations linked to the proximity of major seismic faults (such as along the South Armorican shear zone) or volcanic activity (Massif Central), may need further assessments specific to a few granite massifs.

Beyond the period of a few hundred thousand years, the consideration of the geodynamic evolution cannot simply be based on general factors. It must be specifically studied for each considered massif. However, a repository site located away from the major regional accidents or the few zones of potential volcanic activity (and thereby complying with the recommendations of the Basic Safety Rule RFS III.2.f) would most probably be subjected to slight local modifications on the timescales considered.

4.5.1.2 External geodynamic phenomena: erosion and climatic changes

Erosion is, in the long term, the main factor liable to alter the environmental conditions of a repository site. This erosion is primarily caused by the hydrographic network: streams, rivers, brooks, etc. It is the result of both ground movements and climate change.

Assessments made in various regions have led to generally similar estimates of the order *of 5 to 20 metres maximum per 100,000 years* for river valleys to be incised. Erosion rates on plateaux are much lower. These erosion phenomena, especially valley carving, are liable to change underground hydrogeological gradients and the pathways of the hydrogeological flows toward modified surface outlets. In connection with the recurrence of glacial climates, the formation of permafrost in the upper and surface layers of the granite massif can also temporarily modify water infiltrations and their migration within the massif.

Generally, the changes foreseeable on a scale of ten thousand years are very slight for all granite massifs in France, with no significant impact for a deep geological repository

On a scale *of a hundred or several hundred thousand years*, foreseeable climate change may, at certain sites, modify the water infiltration fluxes into the massif and the hydraulic gradients. This would notably be the case of coastal sites liable to be affected from a hydrogeological point of view by sea regression in glacial periods. It may also be the case of some Massif Central sites with rather deep permafrost (200 to 300 metres).

Beyond a period of a few hundred thousand years, the changes to be taken into consideration and their corresponding uncertainties may be greater, especially with regard to flow pathways between underground and surface. They concern particular situations such as that of the granite massifs of the Massif Central which drain towards the Mediterranean and which are liable to be affected in the very long term by more intense erosion phenomena than those on the Atlantic side. Such situations should be examined on a specific basis to check whether foreseeable evolutions are likely to put at stake the environmental conditions favourable to a deep geological repository.

Evolution is related to internal geodynamic phenomena, related to plate tectonics and external geodynamics mainly related to climatic changes.

Within the context of the Massif Central and the Massif Armoricain , the main consequences of long-term site geological evolution affect the hydrogeology due to:

- Erosion likely to modify topography, especially the hydrographical system;
- Transient occurrence of periglacial climates causing frost in the basement and potential modification of water infiltrations and surface outlets.

4.5.2 Geoprospective

In terms of the approach, site evolution over the coming hundreds of thousands of years is assessed using extrapolation to the next million years of the geological history over the past ten million years. This period includes the quaternary history (i.e. 2 million years) characterised by formation of the current climatic system.

Analysis methods (Brulhet, 2005) are therefore those for geology with specific review of:

- Hydrographical system evolution mainly based on analysis of alluvial terraces, which evidence the gradual incision of river valleys over the past several million years;
- Periglacial and locally glacial formations, indicators of the effects of climatic changes;
- Paleoseismicity: mainly the identification of “recent” faults affecting quaternary sediments;
- Vertical ground movements on the scale of the past few million years involving specific study of plio-quaternary formations and use of specific dating methods which are very often of a complementary nature.

Methods and techniques developed over several decades are applicable to configurations likely to be encountered on a granite site in France

4.6 Conclusions

- **A staged approach, adapted to the iterative repository design process**

The proposed approach of granite site surveying and characterisation is a conventional approach largely shared at international level for repository studies. Successive surveying stages lead to gradually specify geological, hydrogeological, hydro-geochemical and geomechanical models of the site investigated in iteration of the repository design and safety studies.

- **Proven methods adaptable to the various configurations of French granites**

Construction of geological, hydro-geological, hydro-geo-chemical and mechanical models is based on proven methods both on the surface and underground:

- Geological modelling is based on methods benefiting from a vast amount of experience feedback in the mining sector. Geophysical methods are especially adapted to repository studies in slightly fractured granite environments, mainly using tomographic methods successfully tested in Finland;
- Hydrogeological modelling in fractured medium has been subject to significant developments over the past few decades for explicit incorporation of granite fractures in simulations (DFN type model). This progress has facilitated links between granite site modelling and characterisation and the possibility of discriminating types of fractures and their distribution within a granite massif;
- Hydro-geochemical modelling is based on identification of the various origins of underground granite waters. Reconstitutions made in Sweden and Canada show that the methods developed are applicable to the French context. They are an element of hydro-geological modelling validation in the long term;
- Geo-mechanical data mainly stress measurements and thermal, of temperature, is collected according to conventional methods. Coupled hydro-mechanical and thermo-hydro-mechanical modelling has been subject to significant programmes at international level. These projects lead to identify uncertainties surrounding fracture network behaviour, then to be integrated in repository thermal dimensioning.

The general approach is based on increasingly thorough understanding of granite massif geology. Reconstitution of geological history is indicative of the consistency of the various models compiled, mainly concerning the links between granite facture geological and hydrogeological models. Studies conducted in France and abroad show the current feasibility of history reconstitutions for later and older periods alike. Hydrogeological measurements, mainly piezometric, constitute a permanent element for site characterisation and then monitoring during repository operation. They are based on techniques quite appropriate to disposal studies and suited to the various configurations of French granites.

- **Identification and gradual reduction of uncertainties surrounding fracture network characterisation**

Characterisation of a fracture network in granite medium is a key element for site surveying. The approach is based on deterministic identification of large-sized fractures, i.e. identification of each large-sized fracture likely to conduct water and to affect repository architectural design. It is completed by systematic review of small-sized fracturing in boreholes and in underground drifts on one hand for statistical integration of small-sized fracturing in safety calculations and on the other hand to adapt repository cell construction to this small-sized fracturing if deemed necessary in terms of safety.

The fracturing modelling approach is adapted to staged surveying strategy: it is mainly based on consistency of models compiled on different scales (regional, repository, module and cell). At each stage, it can identify uncertainties surrounding fracture location and hydraulic properties and integrate them in repository architectural design (“buffer space” definition) and by iteration in the safety analyses.

5 Repository phenomenological evolution

A repository is a complex system involving multiple components (packages, buffers and the geological medium), which is subject to a range of often coupled thermal, hydraulic, chemical and mechanical phenomena. The repository's components evolve over time as a result of these phenomena (which do not all share the same kinetics).

In order to ascertain this complexity, Andra has broken down the repository's evolution into a series of situations, each corresponding to the phenomenological state of a part of the repository or its environment at a particular point in the repository life cycle; these situations reflect the thermal, hydraulic, mechanical, chemical and radiological phenomena at work, and account for the sequencing and coupling of said phenomena. The analysis concerns not only the repository construction and operating period of one or more centuries, but also the post-closure period, which has a timescale of one million years.

The set formed by these situations, known as the Phenomenological Analysis of Repository Situations (PARS) defines the complete, continuous phenomenological evolution of the repository and its geological environment. The PARS provides the framework for analysing radionuclide release and transfer phenomena that must be taken into account in the long-term safety assessments.

This chapter draws on this analysis, and summarises its main elements. It provides an overview of repository phenomenological evolution in granite medium and examines the main phenomena brought into play in each repository zone.

5.1 Overview of repository evolution in granite medium

Among the proposed design provisions, separating the repository into distinct zones and modules means a phenomenological evolution specific to each individual area of the repository. The influence of the various thermal, mechanical and chemical phenomena at work is mainly limited to the perimeters of the various repository modules.

From a hydraulic viewpoint, excavating the connecting structures (which link the repository to the surface) as well as the drifts and underground structures, leads to drain water throughout the repository operation phase. This drainage must be considered on the scale of the repository as a whole. However, when the repository is closed, the structures are separated by seals and backfill, allowing each module to evolve independently.

The compartmentalisation of the proposed architectural structures helps to simplify the analysis. It can be used to describe the evolution of the repository general infrastructure (shafts, ramps, connecting drifts, etc.) and the evolution of each zone (B, C and spent fuel) separately. Other provisions also help to simplify the phenomena to be analysed:

- The small number of engineered components in the disposal cells limits the interfaces between different materials, thereby restricting the scope for interactions,

- The size of the structures ensures that they remain mechanically stable over the long term, thanks to the great mechanical strength of granite. The "mechanical" component is not, therefore, a driver for the evolution of a repository in a granite medium.

- The thermal dimensioning and technical provisions restrict the temperature to domains in which the phenomenon description and modelling processes are well understood. Thus, respecting a maximum temperature of 90°C at all points in the rock was adopted as a dimensioning criterion for the disposal zones containing exothermic packages.

5.1.1 Repository infrastructures evolution (shafts, ramps, connecting shifts, etc

- **Short hydraulic transient and very gradual chemical changes over the long term**

During repository construction and operation, the infrastructure (shafts, ramp and module connecting drifts) leads to drain the granite groundwater via the intersected water-conducting fractures. This drainage continues until the repository is closed. Excavation works lead to a rapid decrease in the hydraulic head in the main faults across which the intersecting structures as these faults drain most of the granite's water deep underground. The hydraulic head in the smaller fractures then also gradually decreases, after a delay that depends on the fracture interconnection.

After structures closure, underground structures gradually fill in with water and the granite hydraulic head builds up. After a few months, large faults reach hydraulic head levels similar to those existing before excavation. After a time dependent on the way the granite is fractured, the same occurs with smaller faults of lower hydraulic transmissivity.

The largely impermeable seals that divide up the infrastructure render the resaturation processes for the different areas of the repository mutually independent. Accordingly, structures become saturated after a period determined by the density and hydraulic properties of the fractures that they traverse and by the permeability of the backfill put in place. Generally speaking, these periods are of the order of ten years to a few decades. Such periods are short in relation to the timescales of several hundred thousands of years that are considered in the analysis. The disturbance to the hydraulic state of the granite massif caused by the hydraulic head loss and restoration process is a very short-lived transient. At the scale of the granite massif, the hydraulic situation returns to a state similar to the situation prevailing prior to construction of the repository.

Similarly, water drainage caused by the presence of the repository can lead to transient disturbances in the distribution of granite groundwater chemical composition. In particular, the original water stratification (The deeper the groundwater, the more saline) may be modified during the repository's operating phase. The return to the initial conditions occurs over longer period (measured in millennia) than the restoration of hydraulic head one.

When structures are saturated, the water movements in the connecting drifts are essentially dependent on the low permeability of the backfill and the fractures intersected by the drifts.

After drift closure and resaturation, chemical exchanges take place between granite groundwater and the backfill. For a short transient period, the slightly oxidising environment (ventilation air and possible arrival of water from upper parts of the granite) becomes anoxic then reducing. Over the long term, as backfills are largely composed of crushed granite rock (> 70 %), water tends to be in equilibrium with the rock and chemical exchanges are limited.

To sum up, phenomenological evolution of infrastructures (shafts, ramps, connecting drifts, etc.), depicted in the chronogram below, is characterised by a very short transient period for recovery of hydraulic head in the repository. They evolve very little in the long term as a result of granite mechanical stability along with correlative absence of metal supporting structures, backfill composition very close to granite and very low kinetics of underground water movement.

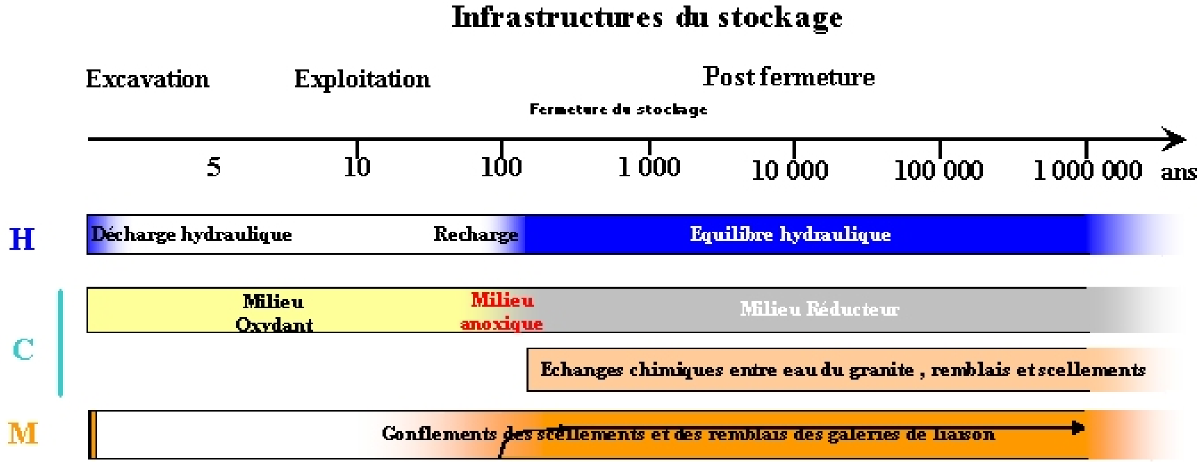


Figure 5.1.1 Chronogram of phenomena occurring in repository infrastructures

5.1.2 B waste repository module

- **Very gradual chemical changes governed by cement-based environment of waste packages**

By design, the tunnels and drifts in a B waste repository module are located in very low permeability blocks and only very slightly fractured granite. Accordingly, during the module construction and operation, the phenomenological evolution of the disposal tunnels consists only in a very slight drainage of granite groundwater via the small fractures in the tunnel walls. The water is removed by the effects of the ventilation flow or by a dedicated extraction system. Any alteration to the concrete disposal containers is restricted to the superficial and negligible effects of ventilation. Any radiolysis gases (e.g. hydrogen) released by certain packages (e.g. B2 bituminised waste) are removed by the ventilation flow and therefore do not affect the evolution of the packages themselves. Stacking slightly exothermic B1 or B5 waste increases the temperature, but the tunnels are dimensioned to not exceed 70°C even if their ventilation system ceases to operate once packages are emplaced. Peak temperatures are reached within a few years. With the other B waste types, which are non-exothermic, there is no significant temperature increase.

After disposal tunnels closure, ventilation and pumping systems are stopped, entailing disposal tunnels resaturation. The resaturation kinetic depends on the density of the small fractures in the tunnel walls. The process may take anything from a decade to a few centuries, or even a thousand years with certain fracturing configurations. Water gradually fills the tunnels from the base upwards.

After resaturation, there is no longer any difference in hydraulic head between the disposal tunnels and the surrounding granite. Consequently, any water movements are very limited, resulting in a primarily diffusive transfer regime.

In this context, disposal tunnel evolution is essentially linked to the slow chemical evolution of the stacked concrete disposal packages. From a mechanical viewpoint, over the very long term (between tens and hundreds of thousands of years), the degradation of the disposal packages can lead to a loss of cohesion of the stacks, causing their rearrangement in the disposal tunnels. However, any alteration of the disposal packages has little effect on the nature of the chemical environment in the cells, which is essentially characterised by a reducing, strongly alkaline atmosphere (with the pH decreasing from 12.5 to 10 over the aforementioned timescales), which would tend to immobilise most of the radionuclides in the tunnels.

Assessment of alkaline disturbance in the tunnel granite walls and the swelling clay cell seals, caused by water in the concrete, has shown that it has little effect on development of environmental conditions in repository tunnels

Production of gas from packages can also disturb the repository tunnel phenomenological evolution in the long term: production of hydrogen by radiolysis of some types of waste (bituminous sludges), or, more importantly, through corrosion of steel (mainly containers). Models of the aftermath of such gases have established that they have little effect on conditions of radionuclide release and retention by the granite.

To sum up, evolution of a B waste repository tunnel, as depicted in the chronogram below, is essentially determined by the persistence of the cement-based environment of disposal packages throughout repository lifetime, which ensures conditions beneficial to radionuclide immobilisation over very long periods.

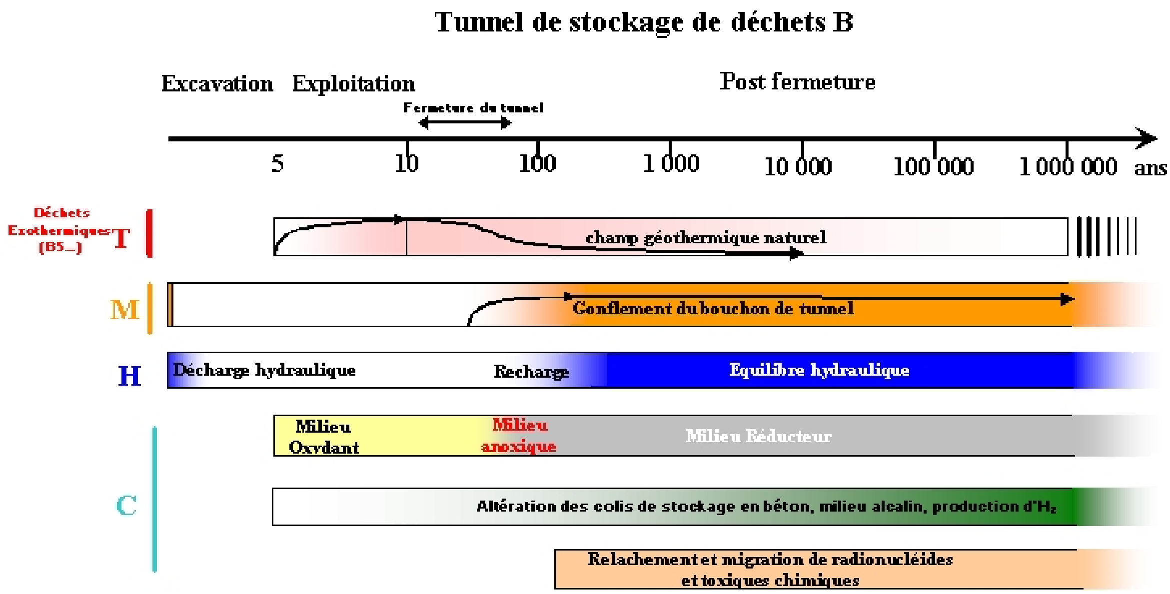


Figure 5.1.2 *Chronogram of phenomena occurring in a B waste repository*

5.1.3 C waste repository module

● **A thermal phase and very slow chemical changes, buffered by swelling clay buffers**

Once closed, the repository modules gradually resaturate. Water from granite fractures gradually saturates the backfill in the handling drifts and the plugs and swelling clay buffers in the disposal boreholes along the handling drifts. Disposal borehole resaturation may take anything from a decade to a few centuries or longer, depending on the hydraulic properties of the granite fractures. By design, the disposal boreholes are located in unfractured or only slightly-fractured granite rock.

The transient phenomenon wherein the bentonite rings around the steel over-packs swell is also affected by the heat emitted by C waste packages. Numerous studies and experimental programs in underground laboratories have addressed the coupling between thermal phenomena and buffer resaturation.

This research has yielded a thorough understanding of the occurring phenomena and has achieved a good control of modelling swelling, pressurisation and behaviour of swelling clay structures when subjected to thermal loads. In this respect, thermally dimensioning structures such that the temperature in disposal boreholes is limited to 90°C means simulations simplification and robustness. In particular, this guarantees that the swelling pressure of the plug and engineered barriers reaches an appropriate level (from 5 to 7 MPa) to ensure structure mechanical stability in the long term.

After disposal boreholes resaturation and cell plug and bentonite buffer swelling, water flows through the disposal boreholes are very limited and are determined by very slow diffusive transfers. In the disposal boreholes, the temperature reaches its peak (limited to 90°C by design) a few decades after closure, and then gradually dedreases until reaching a level similar to the natural geothermal temperatures, after a few thousand years (with C waste).

In this configuration, the evolution of the disposal boreholes is limited to the very slow chemical exchanges between the water, the disposal packages and the bentonite buffer.

- **Steel over-pack and sleeve in C waste disposal boreholes**

With C waste, the disposal package is a 55 mm thick steel over-pack. A 25 mm thick steel sleeve is placed between the packages and the clay buffer. The steel over-pack and sleeve may be corroded, first by the partially oxidizing medium present during disposal borehole resaturation, then by the reducing medium generated by granite groundwater. Oxidizing alteration is minimised by the cell plug and the bentonite buffer. Over the long term, steel corrosion in reducing medium with hydrogen production is the main factor in over-pack and sleeve alteration.

Any reaction between alteration products (iron oxides) and the bentonite in a buffer can alter the buffer's swelling properties. However, since the depth to which the buffer is affected is a rather small fraction of its total thickness (60 cm), the swelling properties are not significantly affected.

Steel over-packs corrode in a reducing medium at a very slow rate, which preserves its leak-tightness for several thousand years. Consequently, by the time water comes into contact with the waste glass matrix, the temperature at the centre of the package will be below 50°C, reducing the glass leaching rate and therefore the radionuclides release rate.

From a mechanical perspective, the long-term degradation of the over-pack causes a gradual readjustment of the swelling buffer and the internal layout of the disposal boreholes. This does not affect the glass packages chemical environment. Any radionuclide release occurs in a reducing medium, with a diffusive transfer regime controlled by the clay buffers, which participates to radionuclides immobilisation in the disposal boreholes.

To sum up, evolution in C waste disposal boreholes, depicted in the chronogram below, is characterised during the thermal phase by a gradual swelling of the plugs and buffers around disposal packages, bringing about slow diffusive transfer. Once swollen, the, swelling clay buffers provide a long-term physicochemical environment of the disposal packages , that helps to preserve the leak-tightness of the disposal packages and immobilise any released radionuclides.

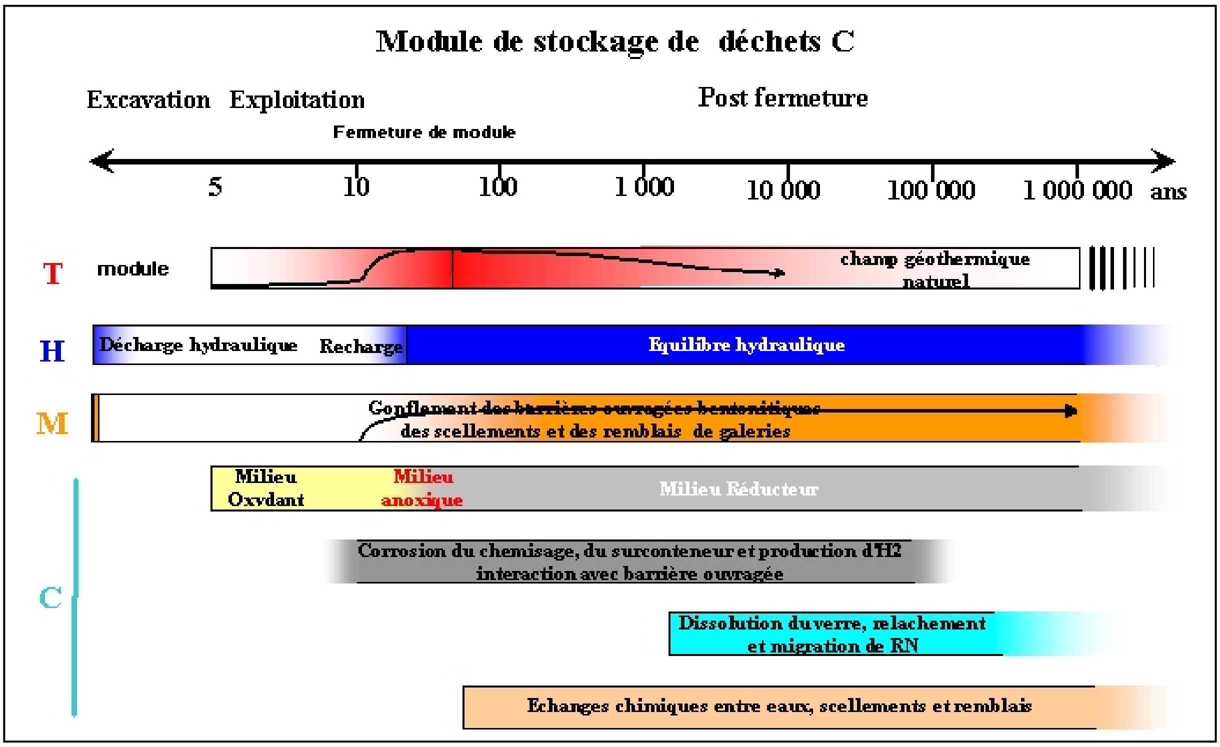


Figure 5.1.3 Chronogram of phenomena occurring in a C waste repository

5.1.4 Spent fuel disposal concept, using a copper container

The spent fuel disposal concept is based on the tightness of a copper container with a service life longer than several hundred thousand years. This tightness is dependent on maintaining a physicochemical environment in the disposal boreholes that preserves the thermodynamic stability of the copper. Accordingly, the design precludes the presence of steel components in the disposal boreholes in order to prevent any interaction between different metals. Furthermore, the buffers and disposal borehole plugs in contact with the containers following resaturation provide a reducing chemical environment that helps to preserve copper stability. The buffer bentonite acts as a filter against any elements liable to modify the container environment. The absence of any significant alteration of the copper container, thermodynamically stable over the long term, prevents the formation of corrosion products liable to affect the swelling performance of part of the buffers so that the bentonite rings thickness around containers can be set at 35 cm.

In conclusion, long-term disposal borehole evolution (figure 5.1.4) comes down to engineered barrier response to external changes in the repository related to site geodynamic development. Within the French geodynamic context, foreseeable changes over several hundred thousand years are very slight and not capable of producing any significant change in the physico-chemical environment of a copper container.

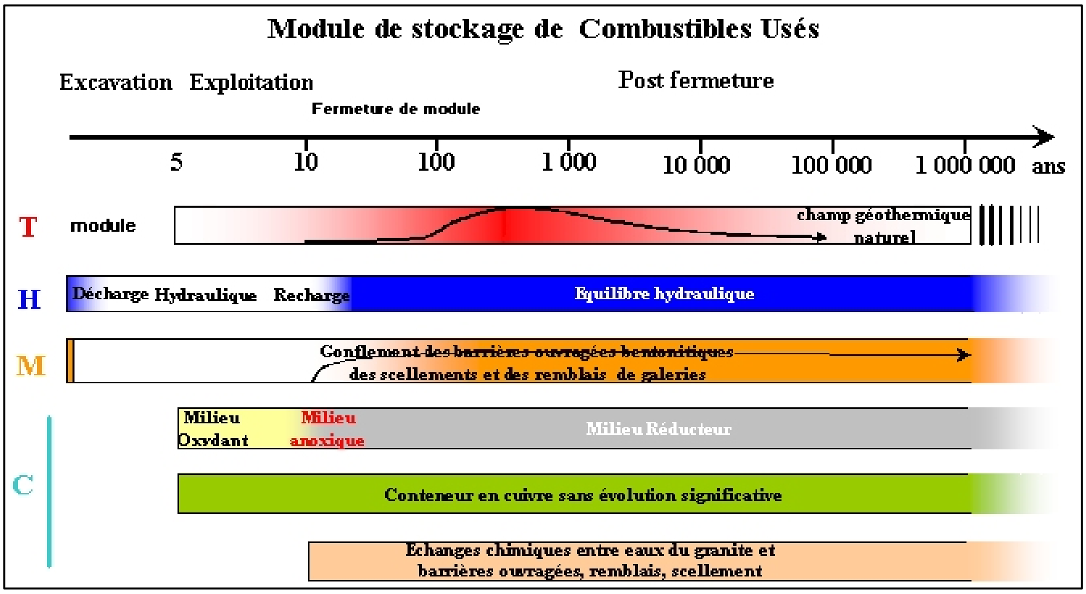


Figure 5.1.4 Chronogram of phenomena occurring in a spent fuel repository

5.2 Repository infrastructures

Phenomena occurring during the evolution of repository infrastructures are mainly related to:

- Transitory hydrogeological and hydrogeo-chemical disturbance in the granite massif, linked to structure excavation and then closure;
- Resaturation of structure backfills and seals, phenomena which determine structure configuration;
- Their slow chemical evolution in the long term.

5.2.1 Hydrogeological evolution

Excavation of structures within a granite massif entails water drainage that will last as long as structures remain open. Such drainage has two consequences:

- It brings about an overall decrease of the piezometric level in the granite massif;
- It causes arrival of water in structures, which must be drained off.

After structure closure, the granite recovers its hydraulic head, and hydrogeological conditions return to their approximate initial state.

5.2.1.1 Hydrogeological evolution during the repository excavation-operation phase

- **Granite piezometric level**

The natural piezometric level in granite massifs is generally at shallow depths in the sandy regolith or in the weathered surface horizon (less than 100 m deep). Therefore, most underground repository structures are located considerably below the initial piezometric level (inset 5.1).

Inset 5.1 **Piezometric level in a fractured medium**

For granite, a fractured medium, the concept of piezometric level is less simple than it is for permeable, porous mediums. Two neighbouring fractures may have different hydraulic potentials if they are not directly connected. The resulting piezometric surface is discontinuous and compartmented into areas with different potentials. On the repository scale, however, the concept of piezometric level is applicable to the description of granite massif hydrogeology.

Three categories of factors are involved in modification of piezometric level and determination of drainage rate and consequent drawdown.

i) External factors related to granite massif topography and environment: local topography, hydrological context, surface hydrogeology, granular disintegration, changes in surface horizons and possibilities of re-supply from surrounding formations.

These parameters determine conditions at the limits of the massif and natural resources available to replace the water drained off.

ii) Characteristic internal factors of the granite massif: fracture density and distribution, fracture openness and transmissivity, fracture interconnectivity and evolution of hydraulic properties versus depth.

These parameters determine hydraulic transfer capacities of the fracture network from the surface, from adjacent formations, or deeper parts of the granite massif, to excavations.

iii) Factors related to the repository itself: general repository architecture, development and relative positioning of excavations, possible grouting of highly transmissive fractures, and phasing of construction work.

These factors continuously determine potential effectiveness of the excavation network drainage system.

All the above factors interact and, for each succeeding geometrical configuration, aim to establish a ***hydrodynamic equilibrium*** between drainage and drawdown. Depending on relative importance of the various factors and the duration of a given geometrical configuration, hydraulic equilibrium may or may not be reached.

- **Different piezometric situations possible in the massif**

Depending on the various factors listed above, three major piezometric situations can be found in the granite massif: high piezometry, depleted piezometry, and intermediate piezometry.

i) With high piezometry, piezometric level should stabilise at an intermediate point between its initial level and that of the shallowest part of the excavated structure (excluding tunnels and ramps) (figures 5.2.1 and 5.2.2). In such a case, drainage rate would be lower than possibilities of re-supplying from the granite massif.

Two configurations can lead to a hydraulic system of this kind: a massif with major re-supply possibilities (extended drainage basin or areas of free water), and/or a massif with low transmissivity, limiting transfer capacity to excavations.

With a highly re-supplied massif, drainage in the excavated structure aims towards a rate mainly determined by transmissivity of fractures intercepted. Piezometry in the massif stabilises at a level of balance between drainage rate in the drifts and supply of water filtering into it. With drift pressure equal to atmospheric pressure, hydraulic potential in the massif increases rapidly moving away from the walls and approaching fractures connected with the rest of the massif.

Such a configuration may be found in coastal massifs re-supplied by the sea. This is the case, for instance, for the Aspö laboratory massif in Sweden, in which transmissivity is nonetheless quite high.

At the centre of the terminal spiral of the ramp, which ends 450 m below ground level, piezometric level tends to stabilise at around the 60 m mark (Vidstrand, 2003).

Such a situation is also possible in the case of a massif of low transmissivity or in which transmissivity decreases rapidly versus depth. Even with more limited re-supply possibilities, a low underground drainage may lead to piezometric stabilisation at a high level.

ii) With ***depleted piezometry***, the exact opposite of the preceding situation, piezometric level is drawn down as far as the slab of the deepest excavations. The piezometric surface follows the lower envelope of the excavations and joins up laterally with the initial piezometric surface (figures 5.2.1 and 5.2.2).

In this situation, possibilities of re-supply from the massif are lower than the rate liable to transit through the fracture network to the drainage system. The situation may result from topographical configurations and hydrological surface situations unfavourable to deep infiltration (small drainage basin, absence of connected free water, lateral drainage of groundwater, etc.), and/or relatively high transmissivity of certain intercepted fractures (independent from transmissivity of zones selected for module construction).

Drainage rate diminishes progressively as piezometric level decreases, finally stabilising at a rate close to incoming flow available when drawdown reaches the base of excavated structures and the water mass corresponding to the storage coefficient of the massif has been consumed. With the exception of possible higher massif levels, all massif fractures are dewatered above the repository and part of the flow to the drifts comes from percolation in unsaturated zones.

This configuration might, for example, be found in continental massifs with "dome topography", where lateral drainage of meteoric water is easy. All things being equal, this situation is also the most probable one in the case of large-footprint repositories for which relative inflow from neighbouring areas of supply diminishes.

iii) In an ***intermediate piezometric situation***, some repository components are dewatered while others are still below the average piezometric surface (figures 5.2.1 and 5.2.2).

In a permanent regime, and for stabilised extension of drained structures, this particular case would correspond to a transfer rate to excavations slightly lower than the potential for supply from the massif.

This situation can also occur during a transient phase ending with a type 2 situation (when excavations progress rapidly, for example) or with a type 1 situation (following module closure, for example). Such transient regimes will probably occur as each module opening or closing induce a period of hydraulic rebalancing.

The relative positioning of components being excavated in relation to the already open caverns is a determining factor here. The various configurations possible can be illustrated by two extreme situations:

- Structure in the centre of an already depleted zone, or a structure shallower than surrounding open structures: excavation in an already dewatered massif;
- Structure outlying or deeper than surrounding structures: excavation in an initially watered massif.

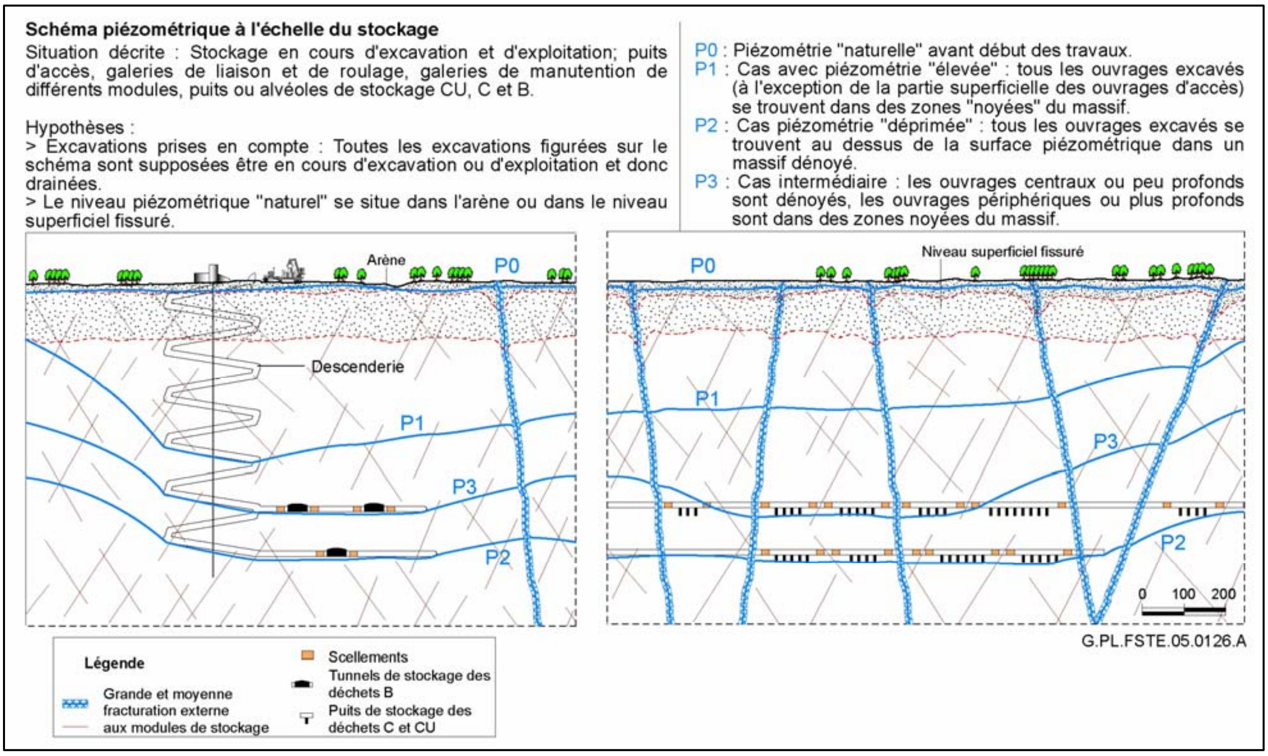


Figure 5.2.1 *Schematic cross-section showing three theoretical piezometric configurations on the repository scale*

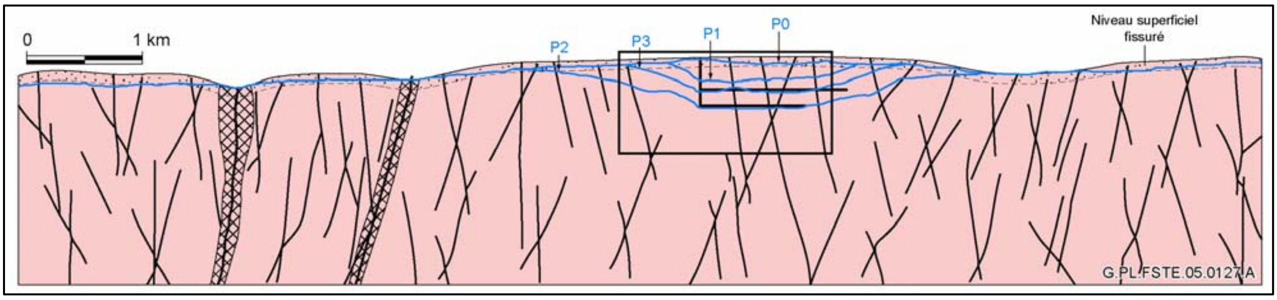


Figure 5.2.2 *Schematic cross-section showing three theoretical piezometric configurations on the massif scale*

- **Drainage rates**

Volumes of water drained by the repository and pumped out during repository operation depend on all of the above parameters for disturbance of piezometric level.

Assessment of pumping rates can therefore only be carried out for a specific site configuration and stage of repository infrastructure development.

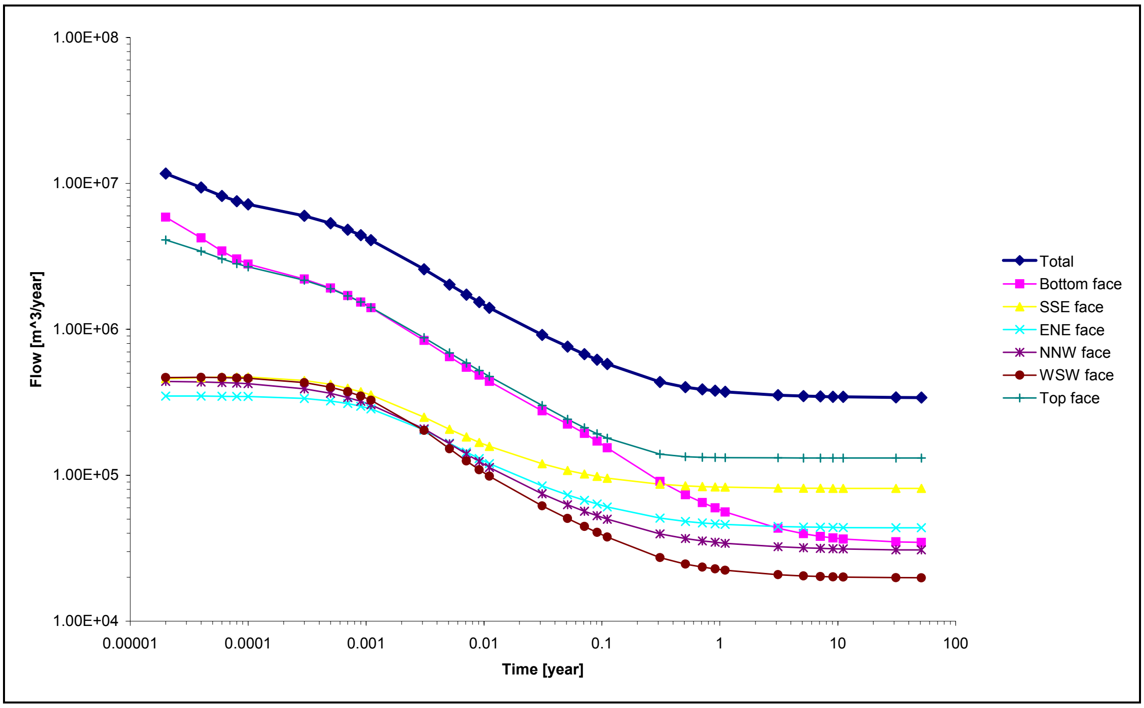


Figure 5.2.3 Evolution of water flow rates brought into play on the repository scale

On an exploratory basis, a digital simulation of drainage rate evolution in a repository located at a depth of 500 m was carried out using a site geological model representative of French granite massifs. Modelling, in equivalent porous mediums (average permeability of granite 10^{-9} m/s) assumes an "instantaneous" excavation at time "zero". Water flow rates were assessed on the 6 faces of the parallelepiped depicting repository volume. Total flow rate stabilised after about a year, at a level of around a few tens m3/h (figure 5.2.3). Maintenance of open infrastructures over periods of a century to several centuries would not drainage rates to be pumped out.

Drainage evolution during excavation of the Aspö laboratory ramp constitutes a concrete reference for a granite site where supply is largely coming from the Baltic Sea, and where fracturing is highly transmissive (SKB, 2002). The ramp, 3600 m long in total, has an average slope of 12.8%. Pumping rates reached 120 m^3/h at the end of ramp excavation. Two of the 21 water collection points showed rates of 24 and 27 m^3/h respectively. Corresponding fracture zones accounted for over 40% of the water flow rate.

- **Role of water arrival treatment**

When there is significant water arrival during excavation, it is possible to limit its flow rate by locally plugging faults through injection, usually of a cement grout. Such techniques reduce incoming water flow. This punctual measure, however, does not ultimately change the total volume of water produced by excavating repository underground facilities. It aims to even out transient high flow rate phenomena for operational purposes.

5.2.1.2 Hydrogeological development after repository closure

After repository closure, underground facilities are saturated with water from granite fractures. In phenomenological terms, it is generally underground water of the granite massif that is the main contributor.

Taking into account repository compartmentalisation by very low permeability seals, each section of a drift or access structures (shafts and ramps) has its own kinetics for hydraulic head built-up. It depends upon the transmissivity of granite fractures in structure walls. Resaturation of infrastructures with water takes several years.

Return to a balanced hydraulic system in the granite massif can take longer, depending on site-specific hydrogeological context. Inversely to the phenomenon of a generalised drawdown in hydraulic head during the excavation phase, return to a water circulation system approximating the initial situation occurs firstly in the connecting faults with the greatest transmissivity.

5.2.2 Hydrogeochemical evolution

During structure excavation, the hydraulic drawdown in the granite massif leads to movement of granite groundwater towards the repository, firstly through the most transmissive faults. The volume of water collected in underground structures is replaced in the massif by equivalent amounts of water. When there is little variation in chemical composition of water in a granite massif, in particular versus depth, such movement causes only minor disturbance in massif hydrogeochemistry.

Where water salinity increases considerably versus depth, significant modification of water stratification can occur in the massif around the repository location. This point has been examined by POSIVA in Finland, within the context of the ONKALO project, an underground facility for characterising the Olkiluoto site selected for a repository (POSIVA, 2003b). Simulations carried out to assess hydrogeochemical disturbances brought about by excavation of the structure show possible modification of water salinity in its lower parts of the underground facility following an upward movement of the deepest groundwater (this phenomenon is known as ‘upcoming’) (figure 5.2.4). They also demonstrate effectiveness of local grouting of the most transmissive faults at points where they are intersected by the ramp to even out such disturbances.

Like hydrogeological disturbances, hydrogeochemical disturbances in the granite massif are transient. After repository closure, massif water circulation returns to something like its initial state. Simulations carried out in Finland assess the return to original conditions at a few hundred years.

Transposing these analyses to the French context depends on chemical composition of water and its distribution in the granite massif. These disturbances are insignificant except in the case of highly saline, underground ‘stratified’ water. Within the French context, this is does not generally occur, due to the largely continental location of granite massifs. This point would need to be examined appropriately for particular locations (coastal, for example) of specific granite sites.

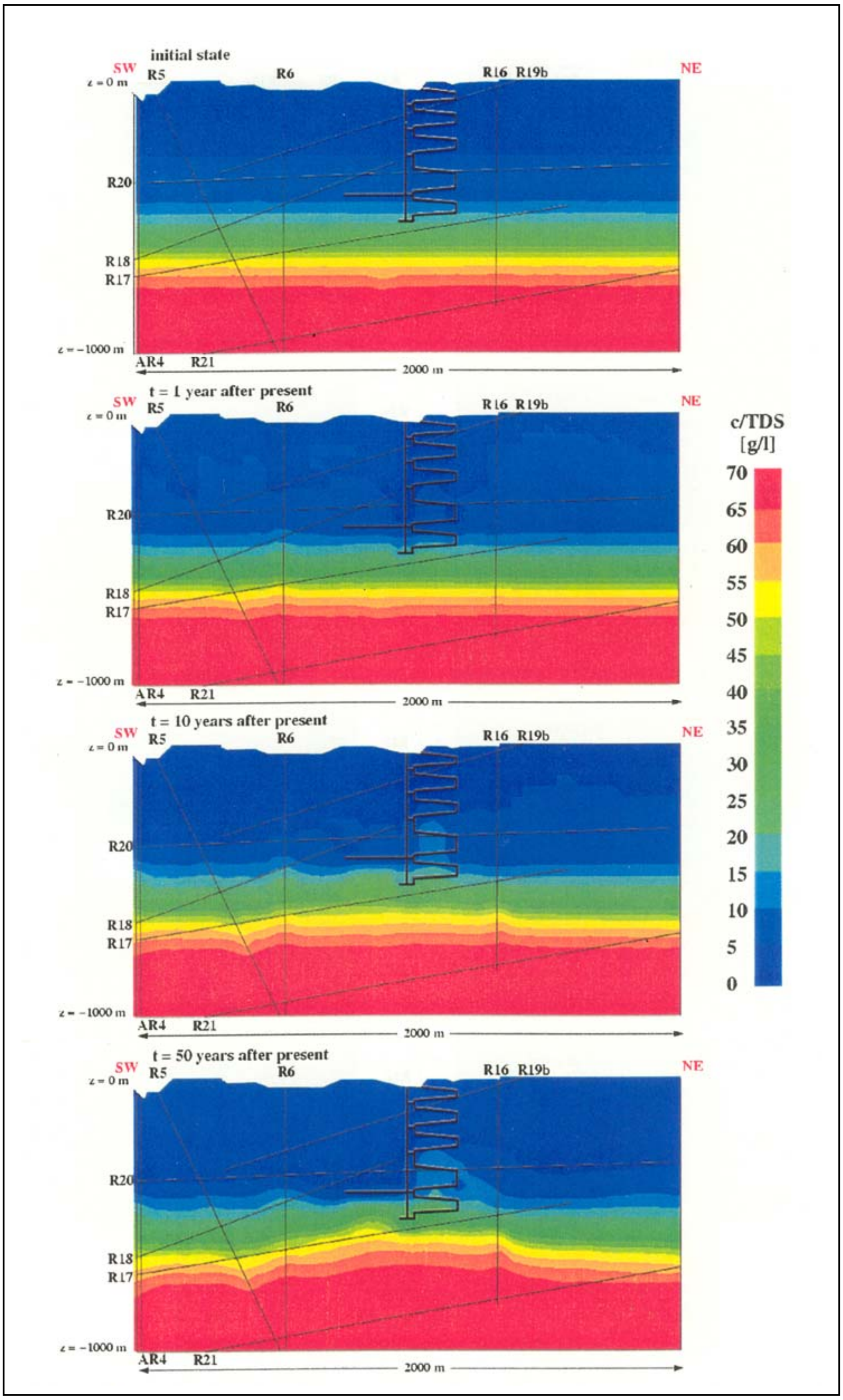


Figure 5.2.4 *Onkalo (Finland). Transitory hydro-geochemical disturbances related to excavation of an underground facility (POSIVA data, 2003b). Water stratification, increasingly saline versus depth (> 65 g/l at 1,000 m), is disturbed at structure level: salt water "upcoming"*

5.2.3 Mechanical consequences of structure excavation

Excavating drifts and access structures (shafts and ramps) in granite results in granite deformations taking two forms:

- Excavation causes modification of the natural stress fields in granite and possibility of local stress concentrations in structure walls;
- There is direct damage to the rock related to excavation methods

5.2.3.1 Granite reaction to stress field

Given granite rock mechanical resistance, the granite stress field is not usually able to create general mechanical instability of deep repository structures. However, depending on natural stress field anisotropy, local instabilities, of varying extent, can be caused by structure excavation. The example of the drift excavated at 420 metres in depth in the Canadian Lac du Bonnet laboratory illustrates granite response when excavating a drift in a highly anisotropic stress field (ratio between maximum to minimum stresses above 5) (figure 5.2.5; Martin et al., 2004).

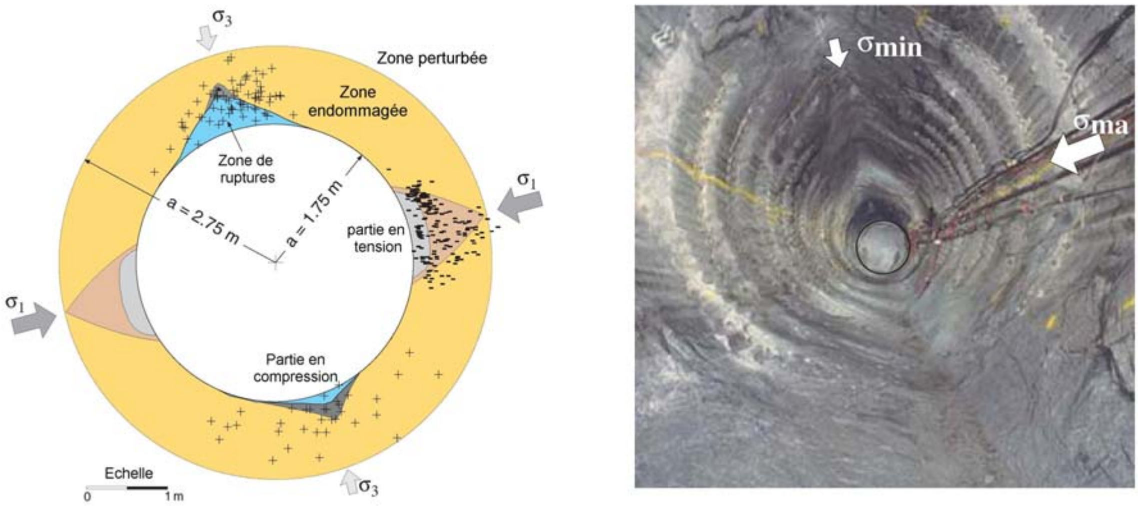


Figure 5.2.5 Lac du Bonnet underground laboratory in Canada: damage to granite in a circular drift wall subjected to a highly anisotropic stress field

In the case of a stress field of low or average anisotropy as foreseeable in the French context (Virlogeux, 2002), i.e. a ratio between maximum and minimum stresses approaching or less than 2, granite rock mechanical resistance results in damage to the wall being limited and related to local stress concentrations, for example at the drift intersection. Granite fracture distribution and mechanical properties then govern directly granite response to these local stress configurations, which need to be specifically examined and treated. For example, excavation can cause instability of granite rock "dihedrons" at the drift roof and walls. These local instabilities are subject to modelling and conventional treatment in the field of underground civil engineering (Martin et al., 2004).

5.2.3.2 Damage related to operating methods

Experiments carried out in laboratories in Canada ("Room 209" and "Mine by experiment», Martin et al., 1997; "TSX", Chandler et al., 2002), Sweden ("ZEDEX», Olsson et al, 1996), Finland ("Olkiluoto Research Tunnel") and Japan ("Kamaïshi mine") have examined the significance of excavation methods, using explosives or not, for damage to structure wall granite. These experiments show that for all methods damage is slight (damage depth of less than 1 m). They demonstrate the possibility of performing excavations minimising the damage by using boring methods without explosives. This can be the case for drifts by using "Tunnel Boring Machines" (TBM). Thus in Sweden, the "ZEDEX" experiment in the Äspö laboratory showed damage to granite on one hand in the case TBM excavation and on the other hand when using explosives (figure 5.2.6).

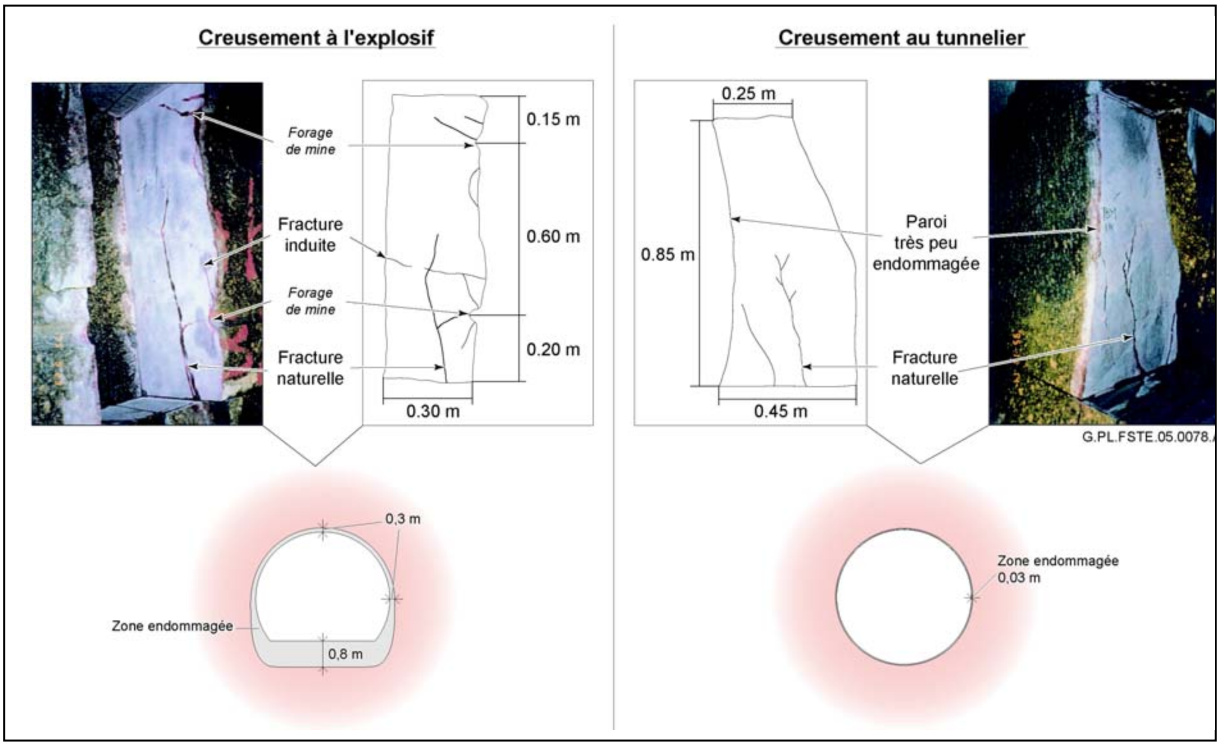


Figure 5.2.6 Damage to drift wall ("ZEDEX" experiment)

Damage observed in the case of excavating with explosives is of a few decimetres deep in the drift wall, whereas it is a few centimetres deep with a tunnel-boring machine. Around the damaged zone, there is stress redistribution with possibilities of elastic movements especially in the fractures ("disturbed zone"). The movement amplitude is, however, too small to cause significant changes to fracture network configuration and to medium permeability

5.2.3.3 Damaged zone hydraulic properties

- **Case of drift excavation exclusively by boring method**

In the case of drifts excavated using tunnel boring type methods, the very slight thickness of the damaged zone does not cause any significant modification of structure wall granite. The damaged zone thus has very little effect on water flows transiting through a backfilled and sealed drift, as the quality of interface with the backfill is the predominant factor.

- **Case of drift excavation using drill and blast method**

In the case of excavation with explosives, fractures incurred by blasting in drift walls can be hydraulically transmissive. Measurements made in the Canadian Lac du Bonnet laboratory within the framework of the "TSX" seal experiment show that fracture transmissivity decreases over around one metre with the distance from the wall (Chandler et al., 2002) (figure 5.2.7).

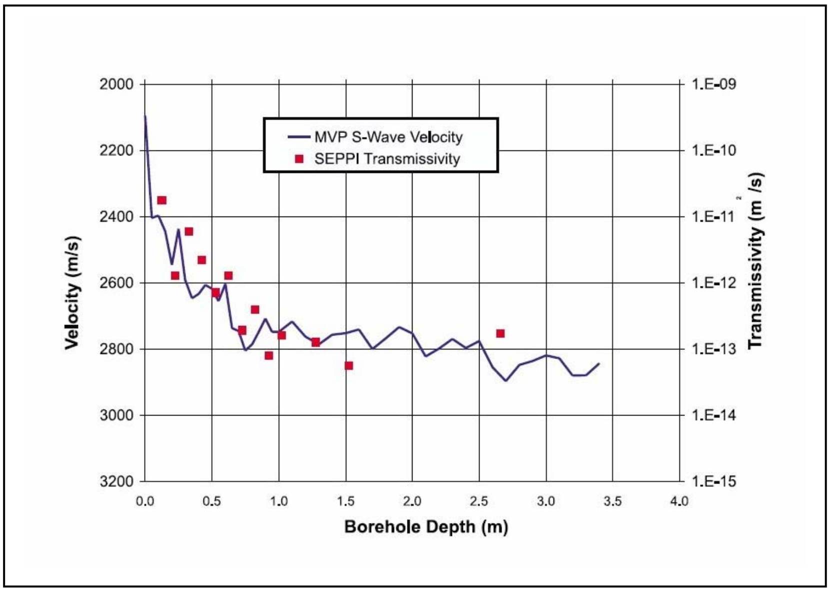


Figure 5.2.7 *"TSX" experiment in Lac du Bonnet laboratory (Canada). Transmissivity evolution in the damaged zone versus depth (drill and blast method) (it should be pointed out that there is good correlation between acoustic measurements and transmissivity ones)*

However, connectivity of fractures generated by two successive blasts is low. With the conventional drill and blast method, two successive blasts outlines are not coaxial which results in poor fracture zone continuity (figure 5.2.8).

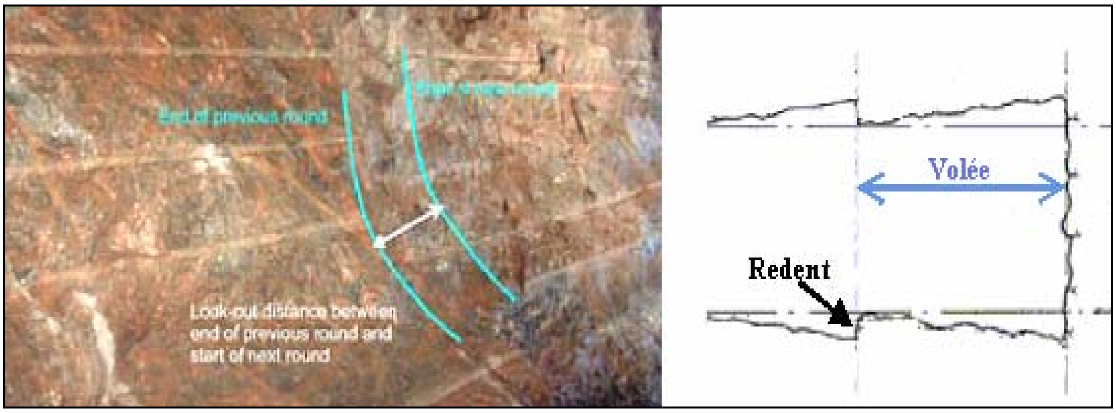


Figure 5.2.8 *Organisation of drift excavation with drill and blast method*

Low hydraulic connectivity between fractures related to two successive blasts was mainly demonstrated by experiments in the Canadian Lac du Bonnet laboratory (Martin et al. 1996).

5.2.4 Evolution of drift backfills and seals

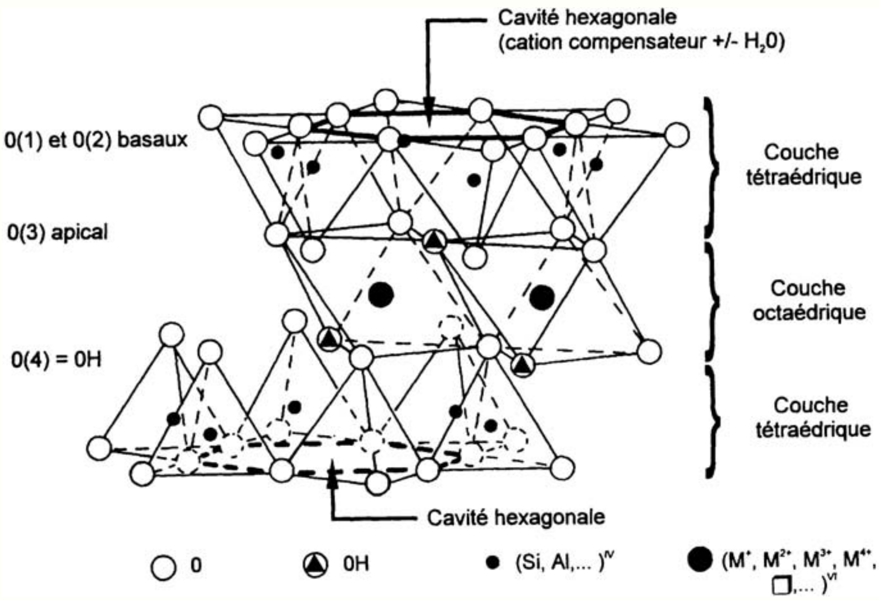
The role of backfills and seals placed in drifts is to limit water movements in the repository after closure. Their design is based on bentonite, swelling clay, as a complete component of the seal cores or as a partial component of backfills (inset 5.2). MX 80 type bentonite is the bentonite tested in the Äspö laboratory and taken as a reference in Andra studies. Other bentonites have also been tested in underground laboratories in Switzerland and Canada.

Inset 5.2 ***Swelling clays (Andra 2005l)***

- ✓ Swelling clay-based minerals

Swelling clays mainly consist of 'swelling' argillaceous minerals (**smectites**) and 'secondary' minerals (carbonates, quartz, feldspars, pyrite, oxyhydroxides). The smectites (and other argillaceous minerals) belong to the phyllosilicates group. They are present in the form of very small crystals (a few microns at the most) appearing in all “surface” domains (alterites, soils, sediments) or “subsurface” domains (diagenesis, hydrothermal alterations). The crystals (or crystallites) result from the stacking of sheets that adhere to one another to form polycrystalline particles. At larger scale, the crystals or polycrystalline particles (possibly but not necessarily associated with secondary minerals) form aggregates. The assembled aggregates and possible secondary minerals form the swelling clays.

Each sheet consists of a stack of two base layers: a) the tetrahedric layer formed by tetrahedrons SiO_4^{4-} or AlO_4^{5-} constituting a two-dimensional array, and b) the octahedric layer formed by two octahedrons in a hexagonal symmetrical array (see figure below)



Three-dimensional representation of 2:1 smectite type clay (sheet composed of 2 tetrahedral layers surrounding 1 octahedral level) (Petit et al., 1999, d'après Grim, 1968)

✓ **Specific characteristic of smectites: charge deficit and interfoliar swelling**

The crystalline structure of swelling minerals corresponds to 2:1 layers (TOT) (see figure below). Cationic substitutions may occur in the tetrahedric layer ($Si^{4+} \rightarrow Al^{3+}$) and in the octahedric layer ($R^{3+} \rightarrow R^{2+}$), creating a deficit of positive charges in the 2:1 sheet. This deficit is compensated by the addition of a cationic interfoliar layer in the crystalline structure. The number of interfoliar cations depends on their valency and the value of the interfoliar charge. For the smectites, this charge may vary between 0.30 and 0.65 for a composition of $O_{10}(OH)_2$ type, thereby modifying the chemical and physical properties of the sheets. The cations are weakly fixed in the interfoliar space. They are completely exchangeable, and polar molecules such as water may penetrate this space, conferring the expansion capacity of the sheets (swelling) through adsorption of the polar molecules. This expansion is proportional to the number of water layers (0 to 3). This number mainly depends on the type of interfoliar cation and the partial pressure (P/P_0) of the water. The maximum hydration of the smectites becomes infinite pour Na^+ and Li^+ and corresponds to 3 layers of water for Ca^{2+}, Mg^{2+} and Ba^{2+}. Potassium allows 2 layers of water in montmorillonites (octahedric charge) and only 1 layer in other smectites.

✓ **Swelling pressure and low water permeability**

During water adsorption, a diffuse distribution of cations is formed around the sheets, particularly a forced concentration of ions creating a so-called 'ionic atmosphere'. Since the positive charges of the cations and the negative charges of the layers are physically separated, the system can be considered as a dual electric layer similar to an osmometre with a semi-permeable membrane consisting of an argillaceous sheet. There is therefore an osmotic pressure gradient in the inter-sheet space, which produces a repulsion force. At the scale of the swelling clay, the various repulsion forces observed in the sheets are transmitted to the particles and then to the aggregates, thereby determining the swelling pressure. If deformation is prevented, for a given interfoliar cation, the swelling pressure will increase proportionately to clay density. This close relationship between water and sheets (and with the aggregates in general) is also a cause of the low permeability of the swelling clays ($\leq 10^{-11}$ $m.s^{-1}$).

✓ **The case of MX 80 adopted for repository studies**

MX80 is the methodological swelling clay selected by Andra to conduct the repository feasibility studies. It is natural clay found in Wyoming (USA). It consists of approximately 80% smectite, 20% secondary minerals (quartz et cristobalite, sodiocalcic feldspars (plagioclases), potassic feldspars (microcline or sanidine), biotite – phlogopite, carbonates such as calcite and ankerite, sodiocalcic phosphate of buchwaldite type, pyrite and hematite) and minerals in trace quantities (titanium (0.1%) and zirconium, sulphates such as anhydrite, and barytine-celestine).

The X-ray diffraction analysis shows that the smectite contains no interstratified elements. It consists of a low charge montmorillonite with a structural formula per half-mesh:

$(Si_{3.98}Al_{0.02})(Al_{1.55}Fe^{3+}_{0.09}Fe^{2+}_{0.08}Mg_{0.28})O_{10}(OH)_2Na_{0.18}Ca_{0.10}$, with mixed Na(2/3)-Ca(1/3) interfoliar lining

The argillaceous fraction (< 2 µm) represents 84.6% of the total mass, which is close to the smectite content. This fraction contains traces of quartz and biotite, whereas the sand and silt fractions are enriched with secondary minerals. The cationic exchange capacity, determined for a purified fraction, is 87.5 meq/100g. The specific surface is estimated at approximately 30 $m^2.g^{-1}$, which is relatively high, especially considering that bentonite only consists of approximately 80% montmorillonite.

✓ Formation for use in the repository

Once extracted and treated (grinding, crushing, drying), the MX80 clay appears in the form of a grey powder with larger particles. In order to be used as a repository material, this powder is then compacted using various techniques to obtain objects of various shapes and sizes, i.e., bricks, tores and granulates (pellets). It can as well be mixed with other crushed materials (such as granite). This compaction eliminates the macroporosity (diameter > 50 nm) without modifying mesopores distribution. At millimetric scale, the pore network remains completely connected. Dry density is above 1.6 $g.cm^{-3}$ for a water saturation degree generally between 70% and 90%. This compaction then gives the MX80 clay, strong swelling and low permeability properties (cf.figure 5.2.9) required for the hydraulic closure structures of the repository (disposal cell plugs, drift and access shaft seals).

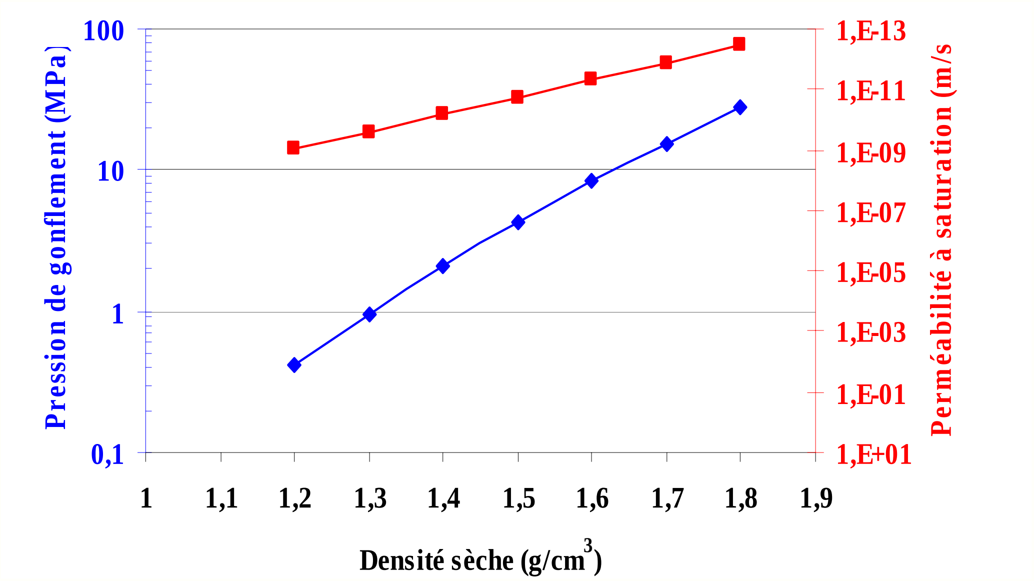


Figure 5.2.9 Swelling pressure and water permeability versus dry density for MX80 swelling clay

Due to bentonite swelling properties, backfill and seal evolution is characterised by two successive stages: structure resaturation and swelling followed by slow chemical evolution in the long-term.

5.2.4.1 Resaturation/swelling phase

- **Backfills**

i) Repository drift backfill design has been studied in Sweden within the framework of KBS-3 spent fuel disposal and constitutes support for analyses of backfill phenomenological evolution. It is planned to use backfills composed of 15 to 30% bentonite and crushed granite with low granulometry. They are placed and compacted in successive inclined layers to ensure continuous contact with granite wall and roof (figure 5.2.10).

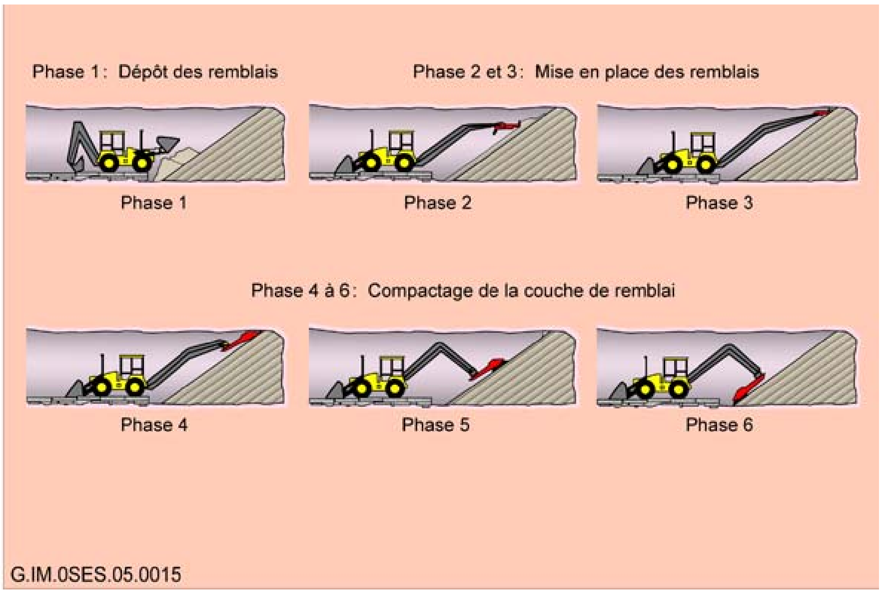


Figure 5.2.10 Low permeability backfill emplacement (SKB)

Backfill hydraulic properties once in place depend on several factors (Gunnarsson, 2004):

- Backfill hydraulic conductivity greatly depends on its dry density. This conductivity decreases by around 20 times when dry density increases by 10%, hence the significance of compaction quality;
- It also depends on the proportion of bentonite. This decreases by one order of magnitude when the proportion of bentonite increases by 10%;
- Water salinity also acts on backfill hydraulic properties.

Taking into account the various factors, SKB has designed and emplaced backfills with material physical properties (density and water content) resulting in hydraulic conductivity approaching 10^{-10} m/s. For example, a sample of the various backfill layers placed in the "Prototype repository" experiment[6] gives values of dry densities above 1.6 kg/m^3 and water content of between 12 and 13%: these characteristics are appropriate to the objective aimed at in terms of low permeability.

ii) Backfill resaturation is related to water coming from granite fractures in drift walls. Swelling is governed by water suction by the bentonite. When water reaches the bentonite, suction pressure is high. Throughout backfill saturation, suction pressure decreases, whereas swelling inceases up to filling any existing voids, mainly at the drift roof, i.e. between the backfill and rock. Then hydration and swelling occur at constant volume and develop, within the backfill, a mechanical pressure which is homogenised and becomes isotropic at saturation. This "swelling pressure", whose value depends on the proportion of bentonite, is applied to the granite drift wall (and for handling drifts at the top of the buffer in the disposal borehole) (Pusch, 2003).

This evolution was monitored in the "Backfill and Plug" experiment conducted by SKB in the Äspö laboratory. This experiment tests backfill performance as it is reloaded hydraulically (figure 5.2.11).

[6] The "Prototype repository" experiment aims at testing, *in situ*, in the Äspö laboratory, the KBS-3 spent fuel disposal concept.

Suction pressure stabilisation (around 1 MPa) corresponds to complete backfill saturation. After hydraulic loading, suction pressure is stabilised in about one year,. After resaturation, backfill swelling pressure is exerted on drift walls. It can be estimated[7] at between 0.2 and 0.4 MPa.

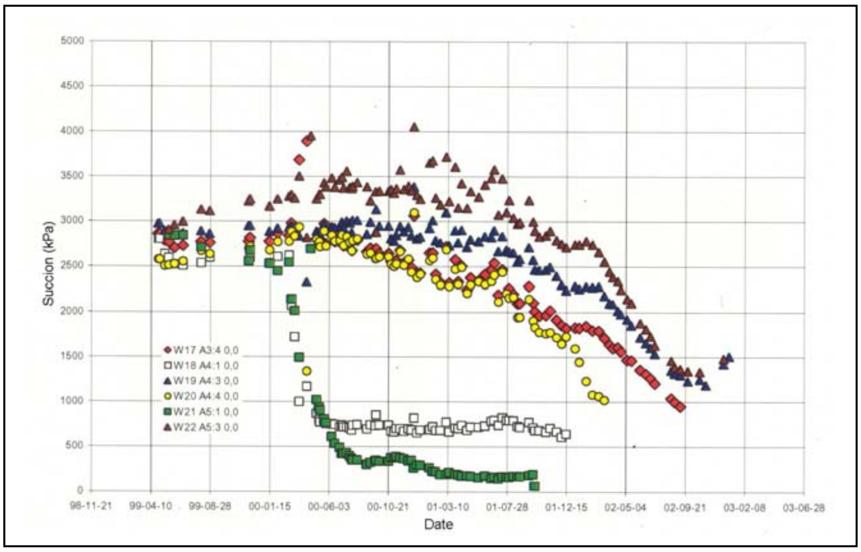


Figure 5.2.11 *Changes in suction pressure in the different inclined backfill layers ("Backfill and Plug" experiment in the Äspö laboratory in Sweden)*

- **Seals**

A seal is composed of a swelling bentonite core and concrete abutments. Clay core length is between ten and fifteen metres i.e. one to twice the drift diameter.

As regards its emplacement, the clay core is anchored in the rock beyond the damaged zone to ensure continuous contact between the bentonite and sound (unaltered) granite rock. It is composed of various joining elements, for example blocks arranged as in the case of the "TSX" experiment conducted in the Lac du Bonnet underground laboratory in Canada (inset 5.3)

After drift backfilling and sealing, water comes into contact with the swelling clay core, either directly through granite fractures in drift walls, or indirectly through concrete abutments. Water suction by the bentonite leads to it swelling.

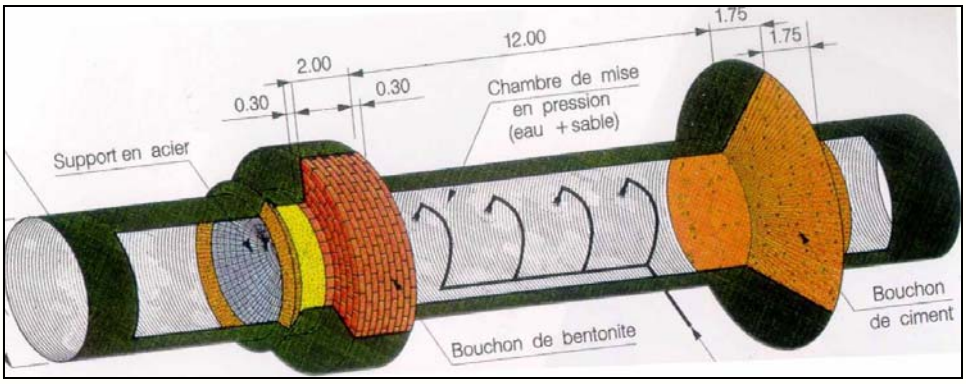
Resaturation progresses from water arrival zone on the bentonite core edge towards the bentonite core centre. This bentonite resaturation and gradual swelling result in:

- The disappearance of discontinuities between the various elements constituting the seals, for example blocks, as in the case of the "TSX" experiment;
- Densification at the clay core centre especially in the whole central part of the seal, as shown when dismantling of the "TSX" experiment.

[7] Ongoing experiment started in 1999

Inset 5.3 ***The "TSX" seal experiment conducted in the Lac du Bonnet laboratory in Canada (Chandler et al., 2002***

A full-scale seal experiment was conducted from 1997 to 2005 at the -420 metre level in the Canadian Lac du Bonnet laboratory. The experiment simultaneously tested two types of seals: a concrete seal and a swelling clay one (mixture of Kunigel bentonite (70%) and sand (30%)). The swelling pressure of swelling clay is around 1 MPa (far lower than the MX 80 one).



The various experimental phases were the following: seals construction (1998), hydraulic loading and performance tests (1999-2002), thermal test (2003-2004), dismantling (2004-2005).

The experiment provided an assessment of bentonite seal hydraulic performance (a very low permeability of close to or lower than 10^{-11} m/s. It informed about the conceptual model for bentonite core saturation. It confirmed that the leak rate is mainly concentrated at the interface between clay and granite rock. Progress venues were identified to improve this interface, mainly by modifying the anchoring key construction technology.

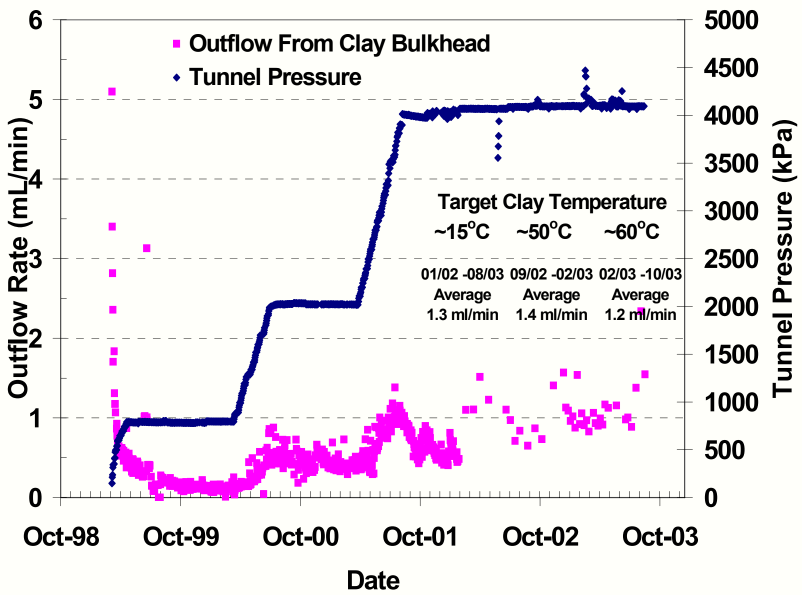


Figure 5.2.12 *"TSX" experiment: water flow through the swelling clay seal (around 1 ml/min under hydraulic head of 4MPa)*

5.2.4.2 Long-term chemical changes

After bentonite resaturation and swelling, there are no longer any mechanical changes in the backfills and seals. Long-term evolution is determined by chemical exchanges with granite water.

- **Backfills**

Backfills are largely composed of crushed granite (> 70%). Therefore, water coming from granite fractures tends to be in chemical equilibrium with backfill granite components and chemical exchanges are thus very limited.

Water exchanges with the bentonite result in ionic exchanges of Na^+/Ca^{2+} and $Na^+/^+K^+$ type. Bentonite smectite can be transformed into illite, a non-swelling clay material by a dissolution/precipitation phenomenon depending on the reaction:

$$\text{Smectite} + K^+ + Al^{3+} \Rightarrow \text{Illite} + SiO_2$$

Significant backfill illitisation can occur only under two conditions:

- Sufficient availability of potassium in solution;
- Temperatures above the temperatures prevailing in repository drifts.

Thus, illitisation does not alter backfill transfer properties, nor does it significantly reduce swelling pressure.

- **Seals**

After seal resaturation, water migrates by diffusion in the clay core (figure 5.2.13). In the long term, concrete abutment alteration increases medium alkalinity, which is likely to affect clay core swelling properties.

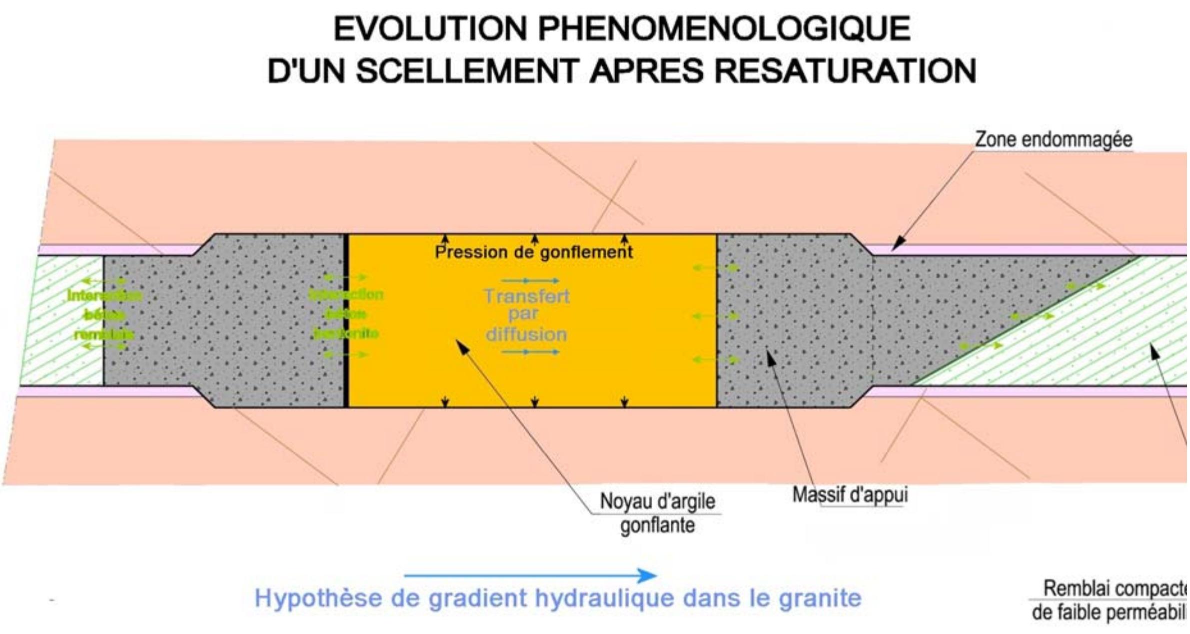


Figure 5.2.13 Phenomenological evolution of a seal after resaturation

- **Alkaline disturbance of swelling clay**

Alkaline disturbance has been the subject of numerous studies, mainly within the framework of the ECOCLAY project (inset 5.4).

In order to assess the extent over time of alkaline disturbance in the clay core, transport geochemistry coupled modelling in 1D was carried out within the framework of the ECOCLAY project based on the following hypotheses:

- Temperature is adopted at a constant of 25 C;
- Approximation of the local balance, therefore keeping low flows of elements transported in solution, compared to geochemical flows of dissolved and precipitated elements;
- The penalising hypothesis of an infinite source of fluid with pH = 12.5 throughout. Indeed, fluid pH decreases with concrete hydrolysis. After dissolving of the portlandite, calcium silicate hydrates buffer the pH at 11 (Bourbon, 2005);
- Transport in the bentonite considered as purely diffusive and unidirectional;
- The same effective diffusion coefficient applied to all dissolved species, as measured in the bentonite for tritiated water: coefficient taken as a constant throughout with a probable value of 1 10^{-11} $m^2.s^{-1}$ (Giffault, 2005).

Extent of alkaline disturbance is given by the position of the smectite dissolution front, defined by a loss of 5% of the inventory initially present in the clay material. According to this definition and the hypotheses mentioned, modelling results, illustrated in figure 5.2.14, represent a foreseeable extent of the alkaline disturbance:

- 0.6 m thick, of which 0.2 m is remineralised after 100,000 years;
- 1.8 m thick, of which 0.6 m is remineralised after 1,000,000 years..

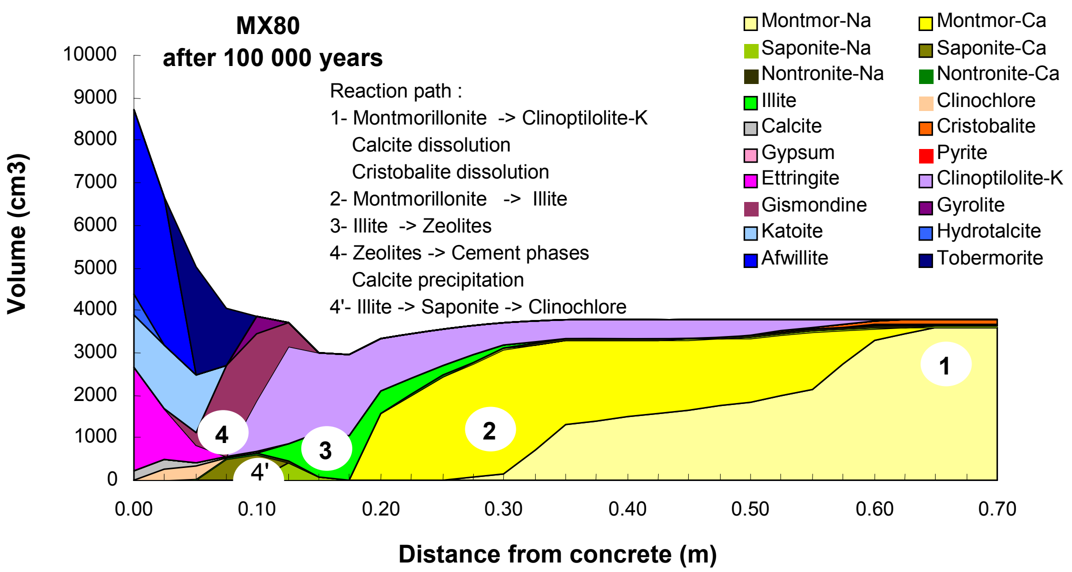


Figure 5.2.14 Mineralogical composition of bentonite MX80 after 100,000 years of interaction at 25°C with a cement-based fluid of constant composition

The extent encompasses, from the concrete bentonite interface and for a third of its depth, a highly remineralised zone, mainly composed of cement-based phases. The other two-thirds of the extent, within the seal core, still contain 80% in volume of the initial bentonite. The high pH of interstitial water and mineralogical transformations coincide, so that beyond the extent (a few tens of centimetres) in the sound (unaltered) material, pH remains that of the granite water in equilibrium with the clay (figure 5.2.15).

In conclusion, given seal dimensions (above ten metres), alkaline disturbance is not able to modify long-term seal performance.

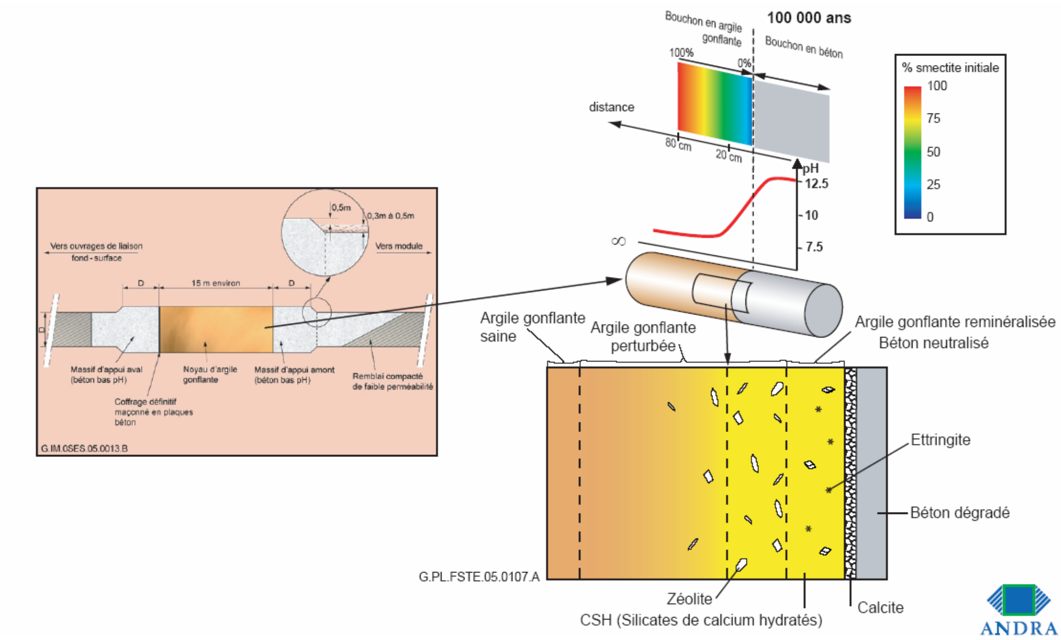


Figure 5.2.15 *Long-term alkaline disturbance of a seal*

Inset 5.4 ***Alkaline disturbance in clay***

✓ Introduction

Alkaline disturbance of the clays by cement-based fluids has been under extensive research both in France and overseas for several years, mainly regarding the study of geological repositories. Following a parallel approach, this research combines experiments performed in both surface and underground research laboratories, the study of natural analogues, particularly at the Maqarin and Khushaym Matruck sites (Jordan) and model exercises (Jacquot & Michau, 2005).). The research was conducted as part of the European ECOCLAY I and II bringing together international agencies and university or national research laboratories (ENRESA, NAGRA, PSI, SCK-CEN, AB SKB, BRGM, etc.), and as part of the CNRS/Andra research group (FORPRO… (Andra, 2005i)). For argillaceous rocks, we particularly benefit from the underground experiments conducted at Mount Terri (Adler, 2001 ; Andra, 2005i). Therefore, the main reactive mechanisms of alkaline disturbance and mineralogical evolutions are well known (Chermak, 1992a ; Chermak, 1992b ; De Windt *et al.*, 2004 ; Gaucher *et al.*, 2004 ; Hlavacek M., 1995 ; Jacquot & Michau, 2005 ; Mosser-Ruck & Cathelineau, 2004 ; Savage *et al.*, 2002 ; Taubald *et al.*, 2000 ; Vieillard *et al.*, 2004).

✓ The Reactive Process

The cement-based and argillaceous materials have different thermodynamic stabilities. Alkaline disturbance in clays in a broad sense (swelling clays and argillites) develops either when in contact with a cement-based fluid or during percolation by a cement-based fluid. This latter fluid results from the degradation of cement-based materials which essentially leads to the release of hydroxyl ions and alkaline/alkaline-earth cations. These elements react with the argillaceous phases either via ion exchange processes with the clay surfaces, or via dissolution/precipitation processes. The exchange of ions in clays mainly occurs for Na, Ca and Sr ions. This instantaneous process helps to reduce the pH and concentrations of alkaline or alkaline-earth elements in clay interstitial fluids thereby buffering the alkaline disturbance in the clays.

The concurrent dissolution/precipitation processes for the exchange of ions principally involves the dissolution of the argillaceous phases (smectites, etc.) and certain accessory minerals such as quartz, and the precipitation of secondary cement-based phases such as CSH (calcium silicate hydrate), CASH (calcium alumino-silicate hydrate) and zeolites as well (De Windt *et al.*, 2004 ; Jacquot & Michau, 2005). The CSH and CASH phases evolve toward zeolites in time.

✓ Alkaline disturbance extent (time-space) and organisation

Assuming a diffusive transfer of solutes, the alkaline disturbance advances in fronts along two successive zones; firstly, a highly remineralized zone in contact with the cement-based water or concrete (disappearance of argillaceous minerals, precipitation of cement-based minerals), then beyond a slightly disturbed zone (partial dissolution of the argillaceous minerals, 5 % maximum dissolution of the smectites). The pH decreases strongly in the remineralized zone, then gradually tends toward the argillites initial pH (7.5) (Jacquot & Michau, 2005).

✓ **Front progression kinetics**

The advance rate of the alkaline disturbance (i.e. fronts) through the clays depends on their diffusion properties. In addition, it tends to decrease over time because of the clogging occurring at the interface between the cement-based and argillaceous materials through the formation of the remineralized zone.

Recent models show the effects of the couplings of reactions on porosity and diffusion. Codes such as Phreeqc or Hightec provide an assessment of the orders of magnitude of the alkaline disturbance extent (Jacquot & Michau, 2005).

5.3 B waste repository zone

Design of the repository for all the different types of B waste is based on the same architectural principles: disposal tunnels for concrete packages stacked on several levels. Long-term phenomenological evolution is mostly determined by the cement-based nature of the disposal packages.

However, there are differences between the various type of waste due to its thermicity and chemical nature. Therefore this section summarises general evolution in the B waste disposal tunnels and describes the most specific aspects of changes to certain packages: slightly exothermic waste of type B1 and B5 and bituminised waste of type B2 (cf. chapter 3).

5.3.1 Thermal evolution: case of slightly exothermic waste (B1 and B5)

B waste primary packages release very little or no heat, except for B1, B4, B5 and B6 primary packages whose heat release is between a few watts and a few tens of watts when produced but declines within a few tens of years.

Taking the hypothesis of package emplacement in a disposal tunnel after 15 years storage, temperature evolution in a tunnel for B5 waste disposal packages was simulated (Andra, 2005k) (figure 5.3.1). The disposal tunnels and their spacing are dimensioned so that maximum temperature of the concrete disposal package does not exceed 70 °C in the centre of the stacks, without taking into account beneficial effects of ventilation.

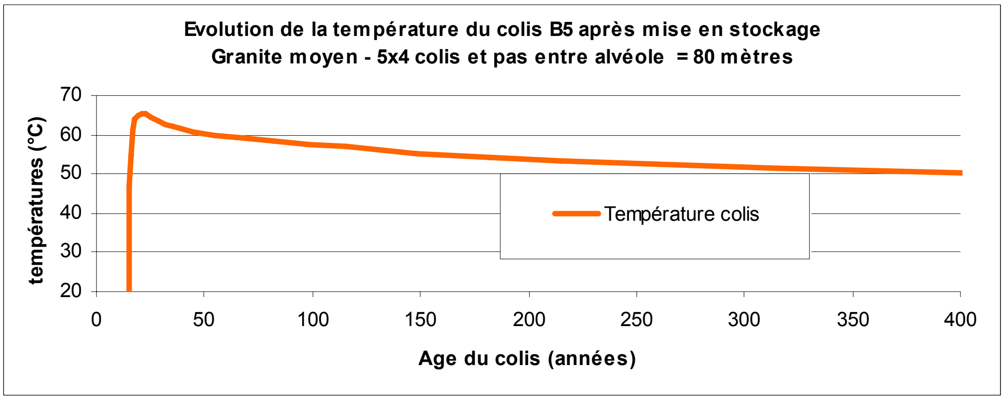


Figure 5.3.1 Temperature evolution in B5 packages after disposal (without consideration of ventilation)

During disposal tunnel operation, ventilation air removes, through convection, 80 to 90% of the heat released by all the packages. Thermal load within the disposal cells and in the granite wall is thus limited: whereas the temperature reaches 50 °C in cell walls in the absence of ventilation, it does not exceed 30-35 °C when the ventilation is running. At the end of 10 years ventilation, and once ventilation is stopped, temperature increases and the thermal load is virtually equivalent to that obtained with disposal packages which would have been preliminary stored for a period equivalent to the ventilation one.

Inset 5.5 ***Hypotheses for thermal modelling of the repository in granite medium***

In the absence of a study site, calculations have been carried out for 3 reference granites (table T1) corresponding to an average reference granite, a so called "cold" granite and a so called "hot" granite. The parameters which vary are initial temperatures of the granite massif at 500 metres of depth and granite rock thermal conductivity. The range of values considered was determined from analysis of French granite typology. The differences between granite massifs are related to variations in earth thermal flux, depending on the type of lithosphere and the mineralogical nature of granites (especially granites varying in quartz content).

Table 5.1 *Thermal characteristics of the massif types*

	Temperature at - 500 m (T °C)	λ (W.m-1.K-1)
Average reference granite	25°C	3,3
Cold granite	18°C	3,5
Hot granite	28°C	2,5

At this stage, it still remains to set the hypothesis for fracturing and module dimensions. This is why the calculations were made for the case of a module of infinite dimensions, resulting in an overestimation of temperatures in repository modules compared to modelling with finite dimensions. The digital model represents a section of the drift and of the surrounding massif. The massif is modelled in one single geological layer with the same thermal characteristics. The various clearances separating the packages from drift walls are also represented.

Thermal exchanges are carried out through:

- Conduction for all the materials in direct contact;
- Radiation in all the clearance spaces and in the air exhaust duct

Calculations were carried out without cooling ventilation and by considering simultaneous emplacement of packages after storage.

5.3.2 Hydraulic evolution in the disposal tunnels

5.3.2.1 Before disposal tunnels closure

During the operating phase, disposal tunnels cause potential drainage of water through small fractures in the tunnel granite walls. Disposal tunnels are constructed by design in only low permeability granite blocks. Thus, the water flow rates to be considered are slight. The water is removed either by only the ventilation in the tunnels, or by a technical measure implemented for this purpose.

The consequences of this drainage on the granite and especially piezometry depend on the location of B waste tunnels in repository architecture. Tunnel effects can in fact be evened out or even cancelled by those of the underlying infrastructure. On the other hand, a disposal tunnel and the corresponding access drifts can have a more significant impact if they represent a low point in repository architecture.

Piezometric disturbance development is similar to that described for the more general case of repository infrastructures (cf. § 5.2.1.1): after the excavation phase, water flow rates likely to be drained off from the disposal tunnels and access drifts tend to decrease and stabilise for as long as repository architectural configuration is not modified, for example, according to the hypothesis where disposal tunnels are kept open for reversibility purposes.

5.3.2.2 After disposal tunnels closure

After sealing a disposal tunnel, water coming from small fractures in the wall granite accumulates on tunnels floor and then gradually fills up all tunnels. The duration of flooding and complete saturation of the disposal tunnels depends on transmissivity of the small-sized fracturing in the wall. It also depends on the way in which tunnel closure phase fits in with the more general closure process for the B waste repository zone. Depending on the different hypotheses taken, the time required to reach tunnel hydraulic balance with the granite can also vary between a few tens of years and several thousands of years (Golder, 2005). During this period water flows converge on the granite towards the disposal tunnel.

After disposal tunnel saturation and hydraulic rebalancing with the granite massif, water flows transiting in the tunnel depend on several factors: hydraulic transmissivity of granite fractures, hydraulic head gradients at repository depth, tunnel orientation and hydraulic properties of the concrete disposal packages stacked in the tunnels.

Depending on these different factors, water flows likely to transit in a B waste disposal tunnel can vary between a few tens of litres and a maximum of several m^3 per year (inset 5.6). In the case of small non-transmissive fracturing in tunnel walls, water flows coming directly from the granite can be nil. Exchanges are then carried out through the disposal tunnel seal made of swelling clay.

Inset 5.6 ***Assessment of water flows transiting in the B waste disposal tunnels***

Without a specific study site, water flows transiting in waste B disposal tunnels have been simulated using site geological models representative of granite configurations within the French context. The simulations were carried out using DFN models.
From a conceptual viewpoint, simulations show that the notion of flows transiting in a disposal tunnel is not simple, given the possibilities of water intake and outlet through the various small-sized granite fractures and the role of the excavation damaged zone ("EDZ") which constitutes a possible short-circuit between fractures.

The simulation carried out involves the case of granite where small-sized fracturing is slightly transmissive but not nil. B waste disposal tunnels are constructed in a granite block away from fractures of transmissivity above 10^{-7} m^2/s. Flows calculated are very slight: between tens and hundreds of litres per year for volumes of disposal tunnels of 10,000 and 20,000 m^3. The impact of hydraulic properties of concrete disposal packages has also been assessed: the case of a 15 cm concrete envelope with specific hydraulic performance (conductivity of 2.10^{-13} m/s) and the case of a concrete envelope without reinforced hydraulic performance (or at the end of 10,000 years of alteration of a hydraulically effective concrete container) (conductivity of 10^{-8} m/s). The results show that water flow increases by around factor 5 in the case of containers without reinforced hydraulic performance.

5.3.3 Chemical evolution in disposal tunnels

5.3.3.1 Before disposal tunnels closure

During the operating phase, the main phenomenon likely to modify tunnel state is alteration of the disposal packages due to ventilation (moderate) under conditions of temperatures which can exceed 40° C in the case of slightly exothermic B1 and B5 waste.

As a general rule, ventilation (moderate about a few m3/s) results in renewal of atmospheric air in the tunnels. It can thus be considered that the rate of carbon dioxide gas and that of humidity (20% < H < 70%) are generally constant during the whole operating phase, even longer if it is decided to keep the ventilation running after disposal package emplacement and before tunnel backfilling and sealing.

Under these conditions, the main phenomenon likely to act on disposal package evolution is the phenomenon of concrete carbonation related to diffusion of carbon dioxide gas in cement-based materials (Bourbon, 2005).

- **Concrete carbonation phenomenon in disposal packages**

CO_2 diffusion in the porous volume of package concrete and its reaction with the hydrates of which it is composed results in neutralisation of the various hydrated cement bases.

The carbon dioxide thus reacts and dissolves in an alkaline solution depending on the reaction:

$$CO_2(g) + 2\ OH^- \leftrightarrow CO_3^{2-} + H_2O$$

Its dissolution neutralises alkaline compounds in aqueous phase in the concrete. In schematic terms, the neutralisation phenomenon can be represented by the following reaction:

$$Ca(OH)_2 + CO_3^{2-} \leftrightarrow CaCO_3$$

This leads to gradual decrease of concrete interstitial water pH due to the disappearance of portlandite and calcium silicate hydrates (CSH).

As the reaction is limited by the transfer of CO_2 in the porous medium, the spatial extent of atmospheric carbonation depends on the degree of concrete saturation. Moreover, alteration is propagated in fronts inside cement-based materials and carbonation processes cause, below the reaction front, on the one hand, reduction in porosity (clogging) by the precipitation of calcite and, on the other hand, rise in the degree of saturation (water formation by carbonation. The combination of these two phenomena thus greatly slows down propagation kinetics by limiting the transfer of carbonate dioxide within the material resulting in the precipitation of calcium carbonate.

In the same way, alteration of metal parts, mainly reinforcing bars in disposal packages, is very slight during the operating phase. The use of stainless steel for the fibres limits their alteration. Moreover the relative humidity (less than 50%) does contribute as well.

In the case of B5.2 waste disposal packages (hulls and end-caps without any organic components), the concrete proposed for the package envelope is a low permeability and low porosity one (Andra, 2005f); under these conditions, the carbonation phenomenon is very superficial.

In conclusion, on the scale of a few tens of years, the atmospheric carbonation phenomenon cannot significantly affect concrete package properties. If ventilation is prolonged beyond a hundred years to a few hundred years (200 to 300 years), alteration propagation kinetics is too low to adversely affect the mechanical stability of disposal packages stacked in the tunnels and thus their potential retrieval with the same means used for their emplacement, if this is so decided.

5.3.3.2 After disposal tunnels closure

Two phenomena cause this alteration: hydrolysis and carbonation of concrete once resaturated. The water is the water coming either from slightly conducting small-sized fractures in tunnels walls or from access drifts through the tunnel seals.

In addition, the waste itself can cause a chemical attack on repository containers, mainly due to organic materials, such as bitumen in B2 reference packages.

- **Concrete hydrolysis**

The arrival of water in contact with disposal package concrete kicks off their hydrolysis which only becomes significant after their complete resaturation. This hydrolysis corresponds to successive dissolution of their various minerals: alkaline and alkaline-earth oxides and portlandite ($Ca(OH)_2$) followed by the CSH (calcium silicate hydrates). Then these hydrolysis processes are maintained by granite water percolation in B waste structures.

These dissolution processes diffuse in fronts towards the inside of disposal packages from their surface in contact with water. This dissolution is broken down into 4 successive phases characterised by pH and stability conditions of the various mineral phases. The concrete is thus characterised in a simplified manner by conditions known as "sound", followed by "altered", "degraded" and finally "neutralised" (Bourbon, 2005). These 4 phases are preceded by the initial transient condition of the concrete known as fresh (figure 5.3.2):

- Fresh cement is characterised by the presence of alkaline and alkaline-earth oxides. The pH of interstitial solutions is above 13. The bases resulting from hydration of these oxides are firstly neutralised by percolating water;
- After this initial transient condition, the cement is called "sound". It keeps this state as long as not all of the portlandite has been dissolved. The pH of interstitial solutions is then reduced to around 12.5;
- Following on from portlandite dissolution, altered concrete is degraded by CSH dissolution-precipitation with reduction in the calcium/silicon (C/S) ratio and release of calcium hydroxide. The pH drops from 12.5 to 10.5 approximately corresponding to pH at which the tobermorite is stable;
- Tobermorite decalcification corresponds to degraded cement conditions. The pH remains stable at 10.5;
- Beyond this point, the cement is considered neutralised, which is the final stage of degradation at which it is regarded as comparable to a consolidated granular material.

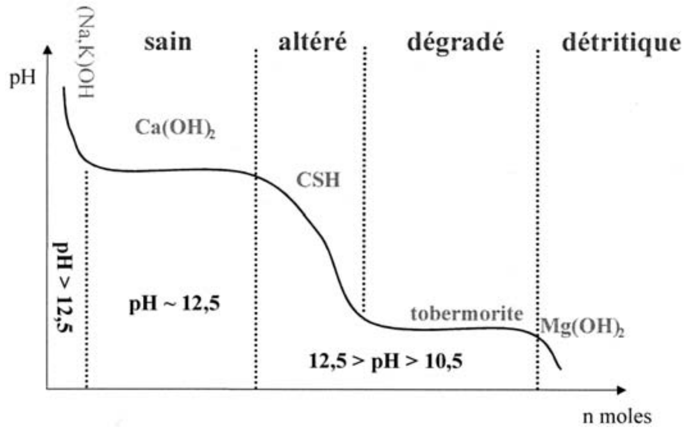


Figure 5.3.2 Concrete alteration stages in a B waste repository

- **Water carbonation in a saturated disposal package concrete**

Water carbonation processes in a water saturated medium are similar to those described for atmospheric carbonation. Carbonation corresponds to the formation of a calcified zone on the surface part of packages in contact with water.

Disturbance progression kinetics in disposal packages is controlled by the diffusive transport properties of the cement-based material. This results in gradual clogging of the porosity, which modifies the diffusive properties of the material. Mainly for standard containers, they become significantly lower that those of sound material and slow down the hydrolysis processes.

Two zones with modified transfer properties succeed each other from the package surface: carbonated zone with permeability likely to be reduced compared to that of sound concrete and hydrolysed zone with increased permeability.

In conclusion, the antagonism of hydration and carbonation phenomena along with low volumes of water transiting in disposal tunnels after closure (from a few tens of litres to a few m3/year for tunnel volumes of several thousand m3) entail a very low concrete degradation kinetics.

It is not able to adversely affect mechanical stability of the package stacks before several thousands of years for standard packages without reinforced hydraulic performance (B2) and ten thousand years for packages with reinforced hydraulic performance (B5.2). In chemical terms, the slow evolution in pH, from 12.5 to around 10.5 does not significantly modify chemical conditions for radionuclide release and retention in disposal tunnels (see § 5.3.4).

- **Production of hydrogen gas and its transfer**

B waste package disposal results in production of hydrogen gas due to:

- Bitumen radiolysis in the B2 waste matrix;
- Corrosion in anoxic environment of waste drum envelopes and of steel waste itself.

Bitumen radiolysis is the prevailing phenomenon for B2 waste for the first few thousand years. Corrosion of compaction drums is the cause of most of the hydrogen produced by B5 waste for the first few hundred years. In the long term, hydrogen production is mainly related to steel corrosion.

The hydrogen is removed by dissolution-diffusion in the water transiting in disposal tunnels. However, given the low water flows coming into play, there could be[8], in certain configurations, formation of a gaseous phase followed by an increasing pressure in disposal tunnels. Above a pressure exceeding hydrostatic pressure (around 5 MPa for a repository depth of 500 m), the hydrogen gas penetrates small-sized granite fractures in the tunnels walls. Absence of small-sized conducting fractures in the wall causes a very slight replacement of water in disposal tunnels. In a biphasic water-gas transfer regime through the seal, the gas migrates through the swelling clay seal without significantly modifying the rate of bentonite saturation.

5.3.4 Radionuclides release by disposal packages, their transfer and retention in disposal tunnels and near-field granite

Radionuclides release by disposal packages can take two forms. It can take place in gaseous form during disposal operations in the tunnels. The release mode involves the part of volatile radionuclides contained in disposal packages. After tunnel closure, radionuclides are mainly released in soluble form, on contact with water coming from the granite.

5.3.4.1 Volatile radionuclides release before disposal tunnels closure

During the operating phase, ventilation results in the chemical degradation of disposal packages being negligible. There is thus no radionuclide release due to disposal package alteration. However, internal

8 Since a detailed assessment of gas production in B waste disposal tunnels has not been carried out within the framework of generic granite studies, analysis is based on studies conducted for the case of a clay medium.

irradiation of packages containing organic matter can result in release of gases taking volatile radionuclides along. This is mainly the case of bituminised waste.

- **Phenomena of radio-oxidation and radiolysis of organic waste**

Bituminised sludge waste packages evolve through oxidation and/or radiolysis due to the effects of irradiation in their mass by embedded radioactive salts.

Given the duration of the ventilation phase of B waste cells, bitumen radio-oxidation affects a limited thickness of the packages, on the centimetric scale, from the package surface. It causes formation of oxygenated organic species and a decreased bitumen viscosity.

Irradiation under non-saturated conditions without oxygen mainly results in production of hydrogen by radiolysis of the bitumen matrix. Other gases, such as CH_4, C_2H_6 and C_2H_2 are also produced but in small quantity. Hydrogen production within the bitumen matrix causes the embedding matrix to swell. Firstly, hydrogen is removed by diffusion. Secondly, when hydrogen content exceeds its solubility threshold, a gas bubble is formed which migrates outside the package (Andra, 2005i).

Around 1 to 2 litres of hydrogen are produced per package per year between 10 and 100 years after production resulting in maximum swelling of the embedding matrix after around fifty years.

- **Radionuclides release**

Radioelements which can be released, all at least partially, in volatile form in repository operating conditions are 3H, 14C, 39Ar, 85Kr and 129I.

Out of these elements, 3H, 39Ar, 85Kr have short or medium half-lives (12.3 years, 269 years and 10.7 years respectively). Therefore, if they cannot be promptly released in the disposal cells, their radioactivity becomes negligible.

In the case of bituminised sludges, (B2 reference package), these radioactive gases are transported according to two processes: if hydrogen bubbles are formed, the radioactive gases migrate along with these, otherwise they are diffused within the embedding matrix (cf. § 5.3.4.2).

Thus, as long as ventilation and consequently the low rate of air humidity are maintained in disposal tunnels, volatile radionuclides release is slight.

5.3.4.2 Release of radionuclides and toxic chemicals from B waste after closing of disposal tunnels

Release of radionuclides and toxic chemicals by B waste packages is mainly controlled by primary packages degradation due to the effects of water from disposal tunnel resaturation.

In practical terms, after closure, water is gradually accumulated in the lower part of disposal tunnels. The first packages likely to release radionuclides and toxic chemicals are therefore those placed in the lower parts of the stacks of packages.

The degradation mode depends on the type of waste and their nature: B2 bituminised waste, hulls and end-caps (B4 and B5) and other materials.

- **Bituminised sludges**

Radionuclides are located in soluble salts and slightly soluble salts called (so called “insoluble”) embedded in the bitumen matrix. However, radionuclides location and speciation in bituminised sludge waste packages are complex. Consequently, it is difficult to precisely determine the remobilisation mechanisms of these species.

In the case of radionuclides sorbed on their surface, they are available right from water arrival at their contact. In the case of radionuclides associated with insoluble salts (corresponding to the majority of cases) and occluded, they are released depending on dissolution of the latter and on their solubility throughout slow degradation of the bitumen matrix. Sorbed radionuclides on the surface are thus released in solution as soon as water saturates the bitumen matrix surface and starts its degradation.

Degradation of bituminised sludges in aqueous solution corresponds to adsorption of the water on the surface of the bitumen matrix. Then, the water penetration front in the bitumen matrix diffuses little by little inside and results in solubilisation of soluble and insoluble salts (figure 5.3.3) and release of associated radionuclides. A robust and encompassing assessment results in duration of release of salts of around 10,000 years.

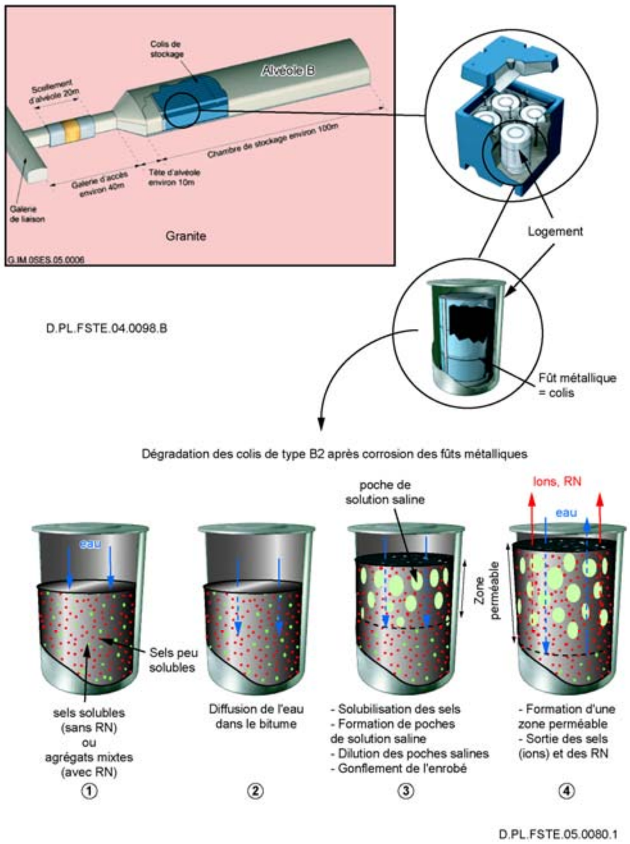


Figure 5.3.3 Diagram of the various stages of bituminised sludge degradation

- **Cladding waste**

Hulls and end-caps are mainly constituted of stainless steel (and inconel) and zircaloy.

When water reaches the waste, radionuclide release involves radioelements located on the surface of metal materials (contamination, residues, etc) and in their mass (activation products, etc).

Radionuclides located on the surface are released by the dissolution/precipitation process as soon as water reaches the surface. For other radionuclides located in the mass of materials, their release is governed by degradation of the material which acts as a confinement matrix.

Thus, corrosion of stainless steel and inconel mainly occurs due to corrosion of the metal and dissolution of the passivating oxide. Cement-based water which reaches the disposal packages is high in pH (around 12.5). Under these pH conditions, corrosion rate is around 1.10^{-4} µm per year. It is likely to change only with a decreased pH (about 10) related to gradual alteration of container concrete. However, these pH values are only reached by degraded concrete (Bourbon, 2005) and this does occur, in the centre of the disposal cells, only after several thousands to tens of thousands of years. Impact of pH change on the steel corrosion rate does not significantly affect radionuclide release.

For the zircaloy, must be considered, on one hand, its corrosion and, on the other one, dissolution of zirconium oxide and radionuclide migration within zirconia. Generally, zircaloy corrosion kinetics is slow, between 1.10^{-4} µm and 2.10^{-3} µm per year. In the event of an oxidising transient due to radiolysis (irradiating packages), it is relatively short in duration (see below) and does not affect radionuclides release.

- **Other types of waste**

The variety of waste types means several possibilities in terms of the radionuclides release process.

Phenomena described for metals in the hulls and end-caps waste are those which govern radionuclide release by other types of metal: release of activation products by gradual corrosion of the metal matrix which contains them and release, through water leaching when in contact, of contamination products located on the surface of metals, notably on the surface of steel in technological waste.

For other materials (glass, radium- and americium-bearing waste, sealed sources, etc), release of surface products also occurs through water leaching when in contact. Release is far slower in the case of radionuclides associated with cladding in various materials

5.3.4.3 Radionuclides transfer and retention in disposal tunnels and near-field granite

After their release by primary package waste, transfer of radionuclides in disposal tunnels is mainly controlled by:

- The hydraulic system, small-sized fracturing in tunnel wall granite and hydraulic properties of concrete packages (cf. § 5.3.2);
- Phenomena of radionuclide retention by concrete disposal packages, depending on the chemical environment of disposal tunnels.

- **Hydraulic regime**

From a hydraulic viewpoint, the principle of disposal tunnels construction only in very slightly fractured granite blocks means that there is slow water replacement in disposal tunnels.

- **Chemical conditions for retention**

From a chemical viewpoint, granite ground water is quickly buffered, in the disposal tunnels, by the waste packages concrete. Thus, water arriving at the contact of the primary waste packages is cementitious water with a pH of 12.5. Since chemical degradation of the waste concrete containers is a slow process, water composition, when close to the waste packages (pH, major elements), remains globally the same along the release process of all the radionuclides in the disposal tunnels and similar to interstitial water composition of a sound concrete.

Redox conditions in disposal tunnels can be locally affected by the presence, on the one hand of irradiating waste and, on the other hand, of waste charged with nitrates (B2) and likely to cause a modification in redox conditions in the vicinity of certain waste packages. However, the irradiating nature of B waste is only significant for B1, B5 and B6 reference packages and is over after 500 years. Thus, water radiolysis processes are slight ones.

As a general rule, redox conditions in disposal tunnels are determined by granite groundwater properties and very often buffered by iron-bearing minerals of the granite and in its fractures (Puigdomenech et al, 2001). Groundwater promptly becomes anoxic after disposal tunnels closure and then reducing.

- **Retention of different radionuclides by disposal package concrete**

Radionuclides released by B waste end up in a highly alkaline, reducing cement-based medium. The behaviour of radionuclides released in this medium characterises radionuclide families depending on their solubility and retention (Giffaut, 2005).

Certain organic components in B waste are likely to modify radionuclide retention by package concrete: carboxylic acids (formic and acetic acids), tributyl phosphate (TBP) from B2 bituminised waste, iso-saccharinic acid from B3 and B5.1 waste, organic adjuvants in concrete. Concerning this point, data indicates that radionuclide retention is probably not affected by these different organic components even if the effects of synergy between the different organic ligands of various types have not yet been assessed.

Under reducing cement-based conditions thus defined in B waste tunnels, three radionuclides are considered as mobile: chlorine, iodine and technetium (inset 5.7).

Other elements have low to very low solubility and/or high sorption in cement-based phases: caesium, selenium, uranium, trivalent lanthanides, thorium, neptunium, plutonium and americium (inset 5.7).

Inset 5.7 ***Radionuclide solubility and sorption in cement-based materials***

The solubility of radionuclides is evaluated on the basis of equilibrium calculations (using the Andra thermodynamic database: Thermochimie v.5) compared with data from literature and/or dedicated direct measurements. Sorption is assessed on the basis of measurements of test specimens from batches or on column, and on literature (Andra, 2005j ; Giffaut, 2005).

The Kd sorption model expresses relations between radionuclide concentration in water and radionuclide concentration in solids (cement-based material). In schematic terms, the following components can be differentiated (Giffaut, 2005):

✓ **Elements called "mobile" in cement-based medium such as Cl, I and Tc**

- *Chlorine*, iodine and, in some conditions, technetium are elements of infinite solubility, but the latter two have sorption properties that are not nil in cement-based phases.
- *Iodine* fixation by cement-based phases is weak (replacement of the sulphates with monosulphoaluminates, affinity for the CSH, etc.): Kd ~ 10^{-3} $m^3.kg^{-1}$ (Giffaut, 2005 ; Nagra, 1999a).

The behaviour of *technetium* depends on the redox conditions. In fact, two states of oxidation can coexist: Tc^{IV} and Tc^{VII}. Tc^{VII} has an infinite solubility and almost nil retention. At the very basic pH imposed by the stages of degradation of the concrete (sound concrete and altered concrete), the reducing conditions of the cement-based materials considered alone (~ -310 mV) are at the limit of the domain of stability between the two states of oxidation of the technetium (-350 mV to pH = 12).

Inside the disposal cells, because of the large quantities of steel waste and the formation of hydrogen during their corrosion in reducing conditions, it is probable that the conditions are significantly more anoxic. So, technetium solubility is limited by the precipitation of TcO_2,nH_2O (~ 10^{-7} $mol.L^{-1}$). The sorption of the Tc^{IV} is average for cement-based materials (~ 2 $m^3.kg^{-1}$)

✓ **Other elements with low to very low solubility and/or (high) sorption in cement-based phases**

- *Caesium* has infinite solubility in cement-based media, but it presents an affinity that is not negligible for CSH phases of the cement-based materials with a Kd of the order of 10^{-2} $m^3.kg^{-1}$.
- *Selenium* is stable in its +IV oxidation level in B waste disposal cell conditions. In spite of its negative charge, the ion SeO_3^{2-} has a certain affinity for CSH surfaces (Kd of the order of 0.1 $m^3.kg^{-1}$). In addition, the portlandite has a high capacity to fix Se^{+IV} probably because of the stability of the solid $CaSeO_3$ (~ 10^{-5} $mol.L^{-1}$) and a tendency to form a solid solution with ettringite.
- *Uranium* is very sensitive to redox conditions. Its behaviour varies considerably between +IV and +VI oxidation states. The alkaline conditions of the B waste disposal cells seem to stabilise the +IV oxidation state. However, determining the solid phase controlling the solubility of the uranium in these conditions is complex, between uraninite (UO_2,xH_2O) and schoepite ($UO_2(OH)_2,H_2O$), passing through the formation of calcic phases such as uranophane ($Ca[(UO_2)(SiO_3OH)]_2,5H_2O$) depending on redox conditions. Calcosilicate phases are probably favoured in the cement-based environment of the disposal cells. The solubility of uranium is of the order of 10^{-6} $mol.L^{-1}$. With regard to sorption processes, these are important on cement-based phases (~50 $m^3.kg^{-1}$).
- The solubility of *trivalent lanthanides* (Sm, Eu, Tb, Ho) in cement-based environment is governed by the processes of incorporation and coprecipitation with calcic solids (calcium phosphates, calcite, Portlandite, etc.) which leads to a very low solubility (~ 10^{-10} $mol.L^{-1}$). As regards their sorption capacity, these elements

have a considerable affinity for cement-based phases, CSH in particular (~ 100 $m^3.kg^{-1}$). Irreversible sorption processes are also foreseeable, limiting these elements mobility even more.

- *Thorium* has very low mobility in B waste disposal cell conditions. Its solubility is in fact very weak (~ 10^{-11} - ~ 10^{-10} $mol.L^{-1}$) and its affinity for the mineral phases is very high (~ 20 $m^3.kg^{-1}$).
- *Neptunium* and *plutonium* are stabilised in a reducing cement-based medium at +IV oxidation level. Their solubility is governed by phases NpO_2,xH_2O and PuO_2,xH_2O which leads to low contents (respectively ~ 5 10^{-9} $mol.L^{-1}$ and ~ 10^{-9} $mol.L^{-1)}$. Neptunium sorption on cement-based phases has not been studied. By analogy, however, its behaviour can be assumed as similar to the plutonium one. They therefore have significant retention on cement-based phases of the order of ~ 20 $m^3.kg^{-1}$.
- *Americium* is stable with a valence of +III and behaves like the lanthanides, and europium in particular which is an analogue. Its solubility is, therefore, of the order of ~ 10^{-10} $mol.L^{-1}$. However, its sorption on cement-based phases appears to be lower than europium one (~ 30 $m^3.kg^{-1}$).

Table 5.2 Summary of solubility and retention of certain radionuclides of interest in a sound to altered cement-based medium

Element	Solubility ($mol.l^{-1}$)	Kd ($m^3.kg^{-1}$)
Cl^{-I}	Infinite	0
I^{-I}	Infinite	~ 10^{-3}
Cs^{I}	Infinite	~ 10^{-2}
Tc^{IV} / Tc^{VII}	~ 10^{-7} / Infinite	~ 2 / 0
C^{IV}	~ 10^{-5} - ~ 10^{-6}	~ 1
Ni^{II}	~ $2{\cdot}10^{-7}$	~ 2
Se^{-IV}	~ 10^{-5}	~ 10^{-1}
Zr^{IV}	~ 10^{-8}	~ 40
Nb^{V}	~ $\cdot 10^{-9}$	~ 100
U^{VI}	~ 10^{-6}	~ 50
Sm^{III}	~ 10^{-10}	~ 100
Eu^{III}	~ 10^{-10}	~ 100
Tb^{III}	~ 10^{-10}	~ 100
Ho^{III}	~ 10^{-10}	~ 100
Th^{IV}	~ 10^{-11} - ~ 10^{-10}	~ 20
Np^{IV}	~ $5{\cdot}10^{-9}$	~ 20
Pu^{IV}	~ 10^{-9}	~ 20
Am^{III}	~ 10^{-10}	~ 30

- **Radionuclides transfer and retention in small-sized fractures of wall granite**

Radionuclides released by the packages migrate either towards slightly water conducting small-sized fractures in tunnel granite walls or towards the seal placed in the disposal tunnel head.

✓ **Clogging of small-sized fractures in tunnel granite walls by mineral precipitation**

Possibilities of transfer towards small-sized granite fractures depend on their actual conductivity at the time of radionuclides release by disposal packages. High alkalinity of the medium and disposal packages degradation cause precipitation of minerals along the fractures in tunnel walls, thus reducing their conductivity. Modelling carried out within the framework of the "HPF" experiment in the Grimsel laboratory demonstrates that tobermorite (CSH), prehnite (CASH) and mesolite (Na-Ca zeolite) (Mäder et al., 2004) precipitate. Effectiveness of this phenomenon depends on the exact chemical composition of granite groundwater and mainly its natural CO_2 pressure which can vary from one site configuration to another one (Buschaert, 2005). This matter is thus to be specifically assessed on the site studied. It is worth mentioning that this results in reduction in water flows (already low by design) which can circulate in the tunnels, further contributing to slowing down degradation phenomena of disposal packages.

✓ **Independent pathways of gases and water in fractures**

Hydrogen produced by B waste packages may increase gas pressure in disposal tunnels followed by migration of these gases to small-sized granite fractures. Hydrogen does not significantly modify the mode of radionuclide transfer to small-sized fractures. The hydrogen pathway in fractures, in a biphasic flow system, tends to be independent of that of water and solutes without significantly modifying fracture retention properties. This phenomenology has mainly been identified by the "GAM" experimental programme in the Grimsel laboratory (Garcia et al, 2002). The mode of radionuclides transfer and retention in granite fractures in disposal tunnel walls is thus similar to that acting throughout the whole granite massif (cf. section 5.6).

- **Radionuclides transfer and retention in seals**

Mobile radionuclides are transferred through disposal tunnel seals by diffusion. Radionuclide retention depends on their type. This retention is expressed by a factor of delay related to the partition of an element between the solid phase and water phase (inset 5.8).

Inset 5.8 *Description of solute retention and transport in porous medium*

The equation usually used to describe the transport of an inert solute in a porous medium is the advection-dispersion equation.

$$\frac{\partial \omega C_e}{\partial t} = -div(F)$$

Where: ω: porosity (-)
C_e: concentration of the solute in water ($kg.m^{-3}$)
div(F): divergence of the advective and diffusive flows ($kg.m^{-3}.s^{-1}$)

When the solute transported by water interacts with the porous matrix, the total concentration of the solute is distributed between the liquid phase, C_e and the solid phase, C_s, and the advection-dispersion equation becomes:

$$\frac{\partial \omega C_e}{\partial t} + \rho_d \frac{\partial C_s}{\partial t} = -div(F)$$

Where: ρ_d: dry density of the porous medium ($kg.m^{-3}$)
C_s: solute concentration in the solid ($kg.kg^{-1}$)

Several sorption models can be used to link the concentration in the liquid phase and the concentration in the existing solid phase. The Kd model expresses a linear relationship between these two magnitudes, valid at equilibrium in a range of concentrations and in given physical and chemical conditions.

$$C_s = K_d C_e$$

The advection-dispersion equation can be re-written showing a delay coefficient (or factor) R as follows:

$$R\frac{\partial \omega C_e}{\partial t} = -div(F) \quad where \quad R = 1 + \frac{\rho_d K_d}{\omega}$$

This delay factor shows that the solute is displaced less quickly than the water. When Kd is nil, the delay coefficient is equal to 1 and the transport equation is reduced to that of an inert solute.

If the linear relationship defining Kd is as valid in the case of sorption as in the case of desorption, the process is reversible and the total mass of solute is found *in fine* in solution, after temporarily passing through the solid phase. The delay coefficient, R, therefore implies slower transport than in the absence of sorption. The velocity diminution factor is equal to the delay coefficient, hence its name. The delay factor therefore also implies a reduction, by this same factor, of the maximum concentration in solution compared with a non-sorbed solute (see diagram).

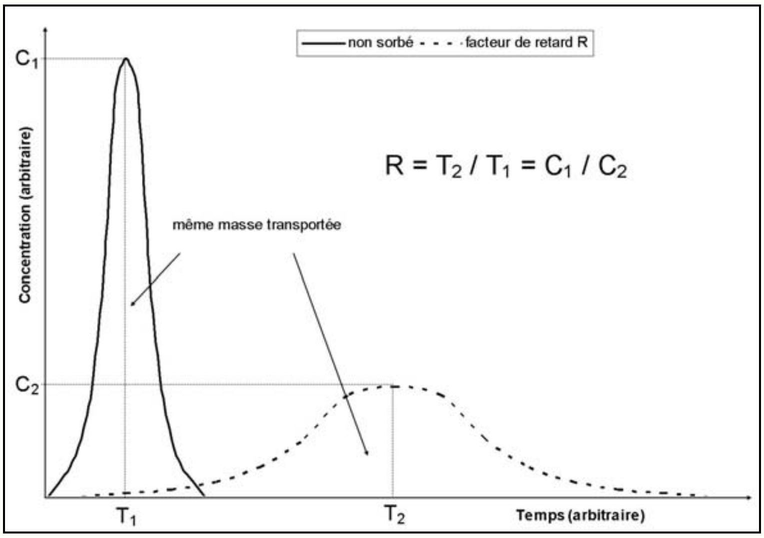


Diagram showing the differences between a peak concentration for a non-sorbed solute and a sorbed solute for the same abscissa during advective/dispersive transport downstream from a dirac of the stable tracer injection and for a sorption assumed to be linear and totally reversible.

Some elements are called “mobile”: chlorine, iodine, carbon and boron which have high solubility and low retention.

Other elements have (very) low solubility and/or high retention on clay surfaces: caesium, selenium, trivalent lanthanides, plutonium, uranium and americium (inset 5.9).

It is possible to increase caesium retention capacity of seals (and engineered barriers) in swelling clay by incorporating specific minerals especially zeolites. At this generic stage of studies, these options have not been incorporated in Kd distribution coefficients presented below.

Inset 5.9 ***Radionuclide retention properties (solubility and sorption) in swelling clay***

Radionuclides solubilities in swelling clay are widely dealt with in international literature. They are and have been the subject of numerous European (TRANCOM II, RADWASTOM 3C, NFS-2, …) and national research programmes (GdR Practis, etc.). The solubility data used by Andra are taken from these numerous programmes, as well as from specific Andra research work performed by groups of laboratories. Schematically, we can differentiate between (Giffaut & Coelho, 2005):

So-called mobile elements such as Cl, I, C and B that have a high solubility and a low retention

Chlorine and *iodine* have infinite solubility and no (or very poor) retention on clay. *Carbon* solubility is not nil but this element presents no sorption property on clay. *Boron* is usually considered a mobile element (infinite solubility and poor retention between 2 and $5 \cdot 10^{-3}$ $m^3.kg^{-1}$).

Other elements, with a (very) low solubility and/or high retention on clay surfaces

- *Caesium* (Cs^+) has an infinite solubility in clay media but is adsorbed on clay surfaces at two surface sites: an ion exchange site and a silanol site. A model is used to evaluate a partition constant in these conditions (~ 0.1 $m^3.kg^{-1}$).
- *Selenium* has a very low solubility, of the order $5 \cdot 10^{-10}$ – 10^{-14} $mol.L^{-1}$, on account of its aptitude to co-precipitate with pyrite (Inset 10.11). In these very reducing conditions, it is probable that selenium would be in its -II oxidation level. Its sorption on clay in this form is low, of the order of 10^{-3} $m^3.kg^{-1}$.
- The behaviour in solution of the *trivalent lanthanides* (samarium, holmium and terbium) is similar overall for all these elements. Their solubility, governed by co-precipitation processes, is very low (~ 10^{-12} $mol.L^{-1}$) (Inset 10.11). A sorption model is developed based on the sorption studies on clay of these elements, and europium in particular. An average value on the domain of interest of the exchange constant is thus evaluated (~ 12 $m^3.kg^{-1}$).
- The solubility of *plutonium* is approximately $2 \cdot 10^{-7}$ $mol.L^{-1}$ in the very reducing conditions of the spent fuel disposal cells (Inset 10.11); it reduces to approximately 4 10^{-9} $mol.L^{-1}$ if conditions become less reducing (Eh > -200 mV) or more basic (pH > 7.5). Experimental studies indicate retention of plutonium IV of approximately 1 $m^3.kg^{-1}$. No data is available for plutonium III, but its sorption is probably similar to trivalent actinides one such as americium.
- The solubility of *uranium* IV is of the order of $5 \cdot 10^{-8}$ $mol.L^{-1}$ (Inset 10.11). A surface complexing model has been developed to reproduce the high retention observed, of the order of 100$m^3.kg^{-1}$.
- *Americium* with a valence of +III is stable in spent fuel disposal cell conditions and has a solubility close to 10^{-10} $mol.L^{-1}$ (Inset 10.11). Americium sorption on clay is considered similar to europium one (~ 12 $m^3.kg^{-1}$).

Table 5.3 *Summary of solubility and retention of certain radionuclides of interest in the seals and engineered barriers made of swelling clay*

Element	Solubility ($mol.l^{-1}$)	Kd ($m^3.kg^{-1}$)
Cl^{-I}	Infinite	0
B^{III}	Infinite	$\sim 10^{-3}$
I^{-I}	Infinite	0
Cs^{I}	Infinite	$\sim 10^{-1}$
Tc^{IV}	$\sim 4 \cdot 10^{-9}$	~ 30
C^{IV}	$\sim 5 \cdot 10^{-5}$	0
Ni^{II}	10^{-5} - 10^{-6}	$\sim 5 \cdot 10^{-1}$
Se^{-II}	$5 \cdot 10^{-10}$ - 10^{-14}	$\sim 10^{-3}$
Zr^{IV}	10^{-11} - $3 \cdot 10^{-6}$	> 100
Nb^{V}	$< 5 \cdot 10^{-7}$	~ 10
U^{IV}	$\sim 5 \cdot 10^{-8}$	~ 100
Sm^{III}	$\sim 10^{-12}$	~ 12
Eu^{III}	$\sim 10^{-12}$	~ 12
Tb^{III}	$\sim 10^{-12}$	~ 12
Ho^{III}	$\sim 10^{-12}$	~ 12
Th^{IV}	$\sim 10^{-9}$	~ 3
Np^{IV}	$\sim 4 \cdot 10^{-9}$	~ 1
Pu^{IV} / Pu^{III}	$2 \cdot 10^{-7}$ - $4 \cdot 10^{-9}$	~ 1
Am^{III}	$\sim 10^{-10}$	~ 12

5.4 C waste repository zone

Evolution of C waste repository modules is mainly marked by internal evolution in the vertical and small-sized disposal boreholes which contain a reduced number of over-packs (2 in the case of C1 to C4 waste and 5 in the case of C0 waste).

This internal evolution is mainly related to that of clay buffers placed between the package/sleeve and granite rock. The issues concerning this evolution thus involve swelling phenomenology of engineered barriers during the resaturation phase in a thermal environment and long-term evolution of the system mainly related to corrosion of metal components

5.4.1 Mechanical consequences of disposal borehole excavation

The response of granite to drift excavation is described in paragraph 5.2.2.1. This description applies to all handling drifts along which C waste disposal boreholes are located.

Disposal boreholes are excavated using a full-section boring machine, applying techniques that have already been tested *in situ* at Äspö and Olkiluoto in Finland. With these excavation techniques, damage to disposal borehole walls is very slight. Analyses based on various characterizing methods of excavation-induced fissures (Autio, 1997) indicate that, by applying such excavation techniques, resulting fissures and "cracks" are only about one centimetre deep (figure 5.4.1).

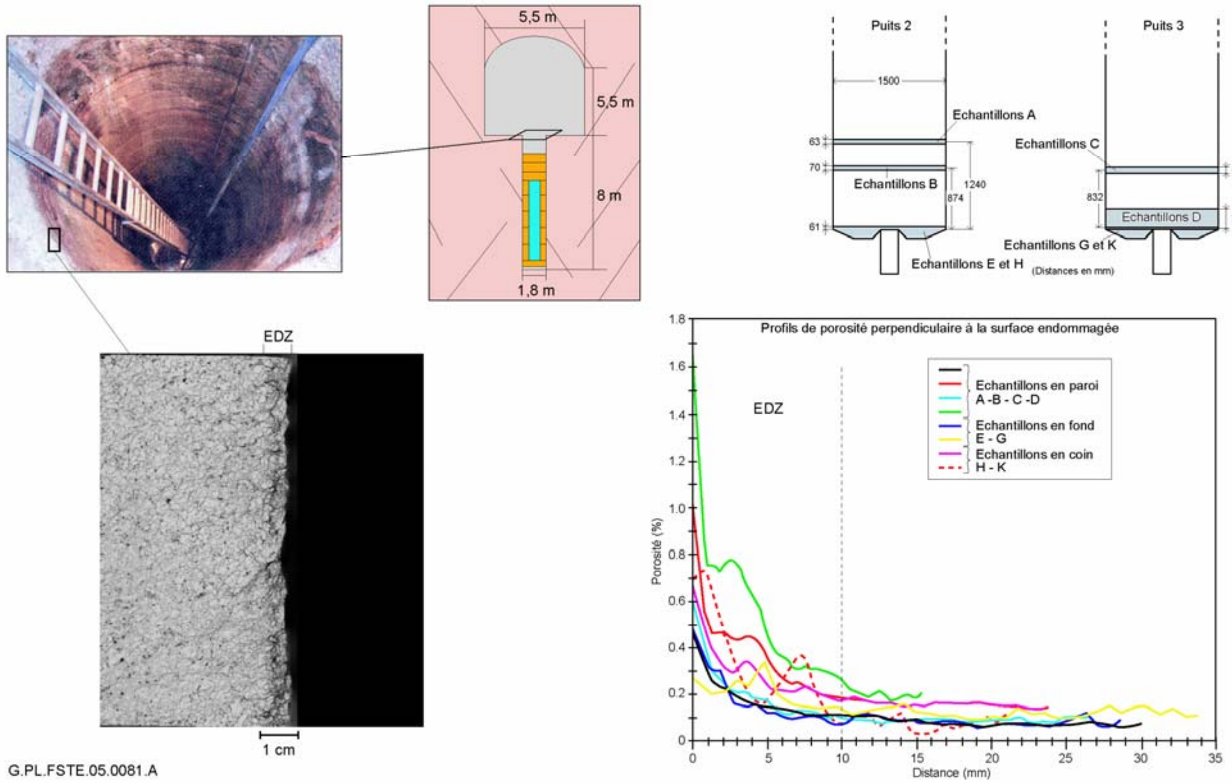


Figure 5.4.1 *Minimal damage to the granite wall of a disposal borehole excavated by boring. (POSIVA data – University of Helsinki). Left: Image of the excavated wall: The excavation damaged zone (EDZ) is very thin (1 cm). Bottom right: Evolution of rock porosity versus depth, granite porosity increases around the thickness of the EDZ (1 cm): location of samples*

Depending on existing stress field, junctions between disposal boreholes and handling drifts may constitute a weak point in terms of mechanical stability. For example, at Äspö, computations indicate that tangential ("circumferential") stress at these junctions reaches 150 to 180 MPa, which is only slightly below rock compression resistance. Emplacing a swelling clay plug and fitting a "collar" backfilled with material partially composed of swelling clay and located at the top of the boreholes, protect against disturbances at borehole-drift junction.

5.4.2 Clay buffer evolution in disposal boreholes: strong THM coupling

Emplacing bentonite rings, then packages and cell plugs leads to a certain number of thermo-hydro-mechanical (THM) coupled phenomena related, on one hand, to bentonite (swelling clay) properties and, on the other, to package thermicity. These phenomena still go on after handling drifts backfill and closure.

5.4.2.1 Clay buffer[9] swelling (bentonite engineered barrier)

As soon as water coming from small-sized fractures in the disposal borehole wall is available, bentonite tends to swell through suction. This suction phenomenon is related to bentonite composition, which largely consists of smectites (inset 5.1).

[9] In this paragraph, the term "buffer" refers to both i) the clay rings placed between the rock and the over-pack and ii) the cylindrical borehole plug placed above the over-pack.

- **Swelling phenomenology**

Once water is present around engineered barriers, it is absorbed by the bentonite and distributed throughout as per the suction gradient (Pusch, 2003).

Resaturation affects bentonite rheology, giving it a certain degree of plasticity and causing it to swell. The combination of these two properties is the most immediate cause of clay buffer swelling. In the bentonite, this swelling phenomenon corresponds to smectite sheets expansion (on the scale of about ten angstroms) and void spaces reduction in between bentonite particles (on the scale of a few tens to a few hundred microns).

The role of these phenomena on two scales, has been demonstrated through numerous laboratory tests using bentonite samples of various dimensions (figure 5.4.2) (ENRESA, 2002).

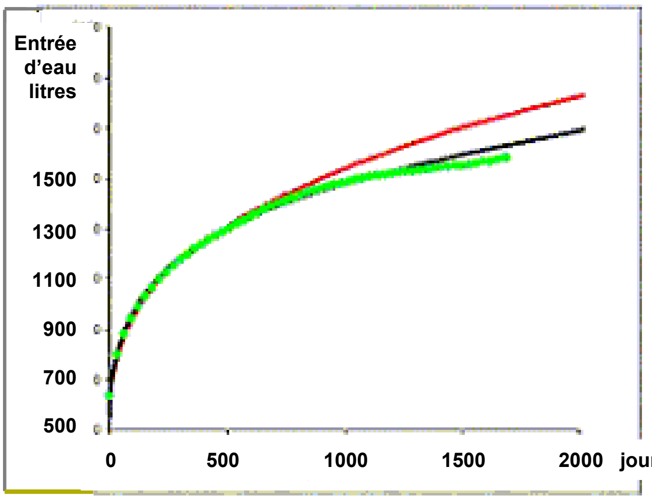


Figure 5.4.2 Evolution of water flows entering a full-scale mock-up of clay buffer constructed at the Polytechnic University of Catalonia.
After 900 days, the water flow measured in (green) deviates from the forecast one by modelling (in red).
Taking into account the rearrangement of bentonite structure (in black) provides a good fit between experiment and modelling.

On the disposal borehole scale, bentonite swelling tends to fill the designed clearances between the buffer and the rock as well as between the buffer and the steel sleeve. Water coming from small-sized fractures in the granite wall firstly interacts with the outer part of the buffer (figure 5.4.3). C waste packages which release heat in the inner part of the buffer tend, on the other hand, to slow down progression of the bentonite resaturation front.

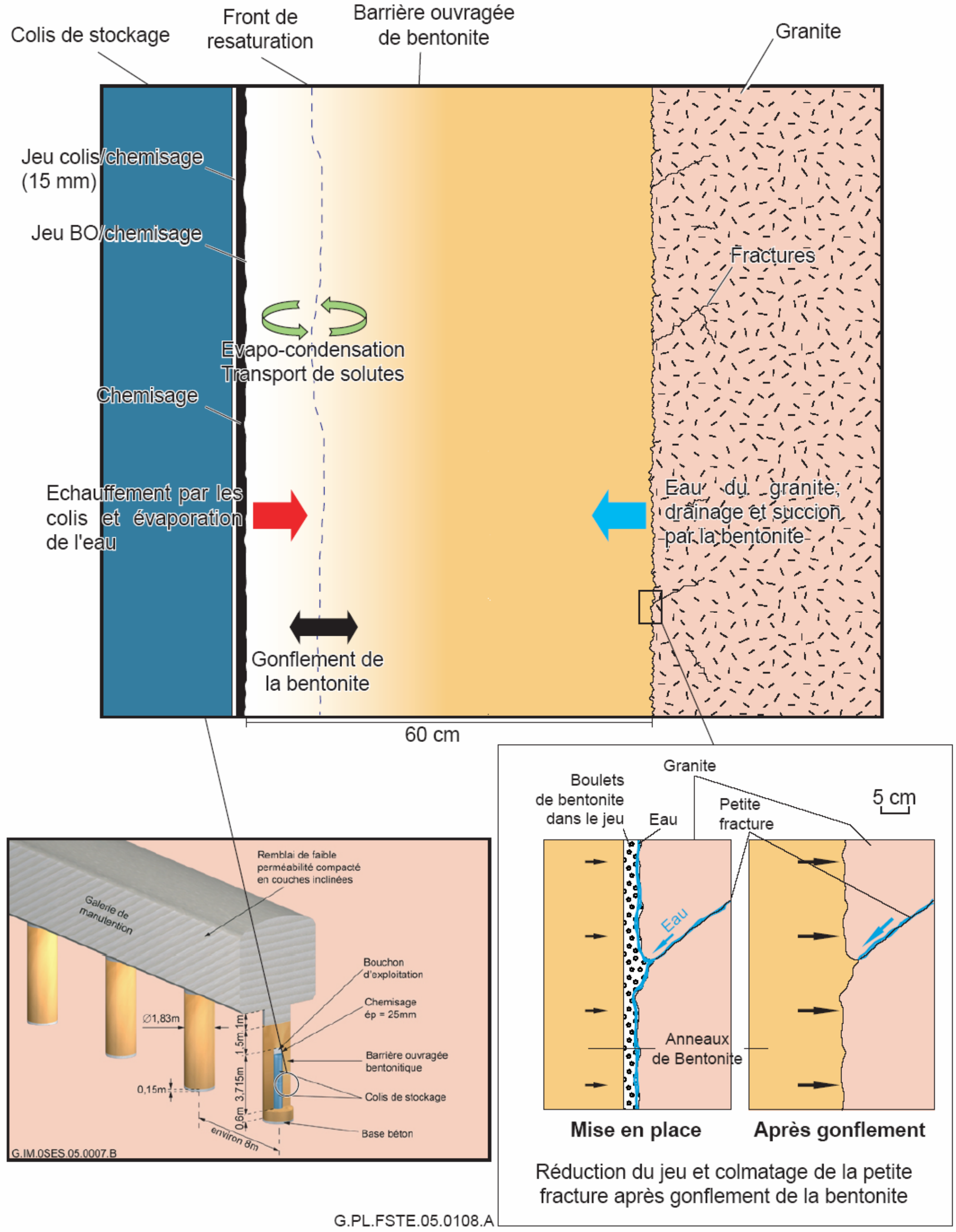


Figure 5.4.3 Model of swelling of a swelling clay buffer in a C waste disposal borehole

Ultimately, the buffer fills all the void spaces between the borehole components. Once all voids have been filled, hydration and swelling take place at constant volume and develop, within the buffer, a mechanical pressure which is homogenised and becomes virtually isotropic (SKB, 2004a).

- **Clay buffer swelling kinetics**

The model of buffer swelling proposed above shows that buffer saturation kinetics depends partly on bentonite water supply depending on the geological situation of the disposal borehole compared to granite fracturing and partly on the heat rating emitted by C waste packages.

✓ **Variability in cell geological situations**

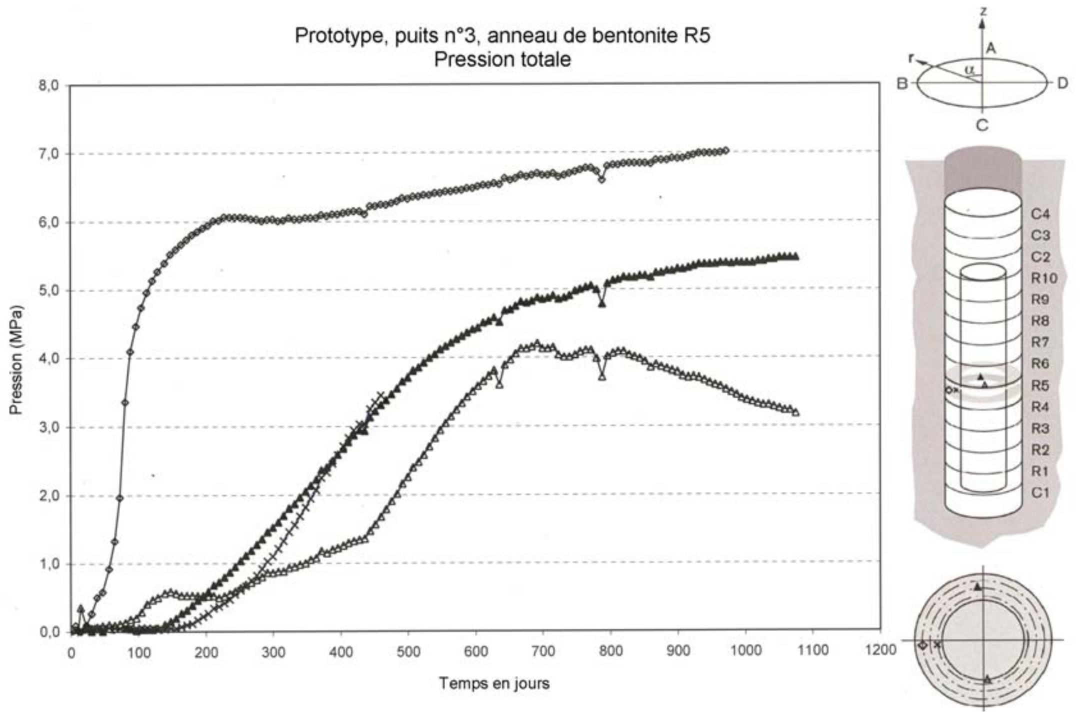
Absence of water conducting fractures in disposal borehole walls or weak transmissivity of such fractures can lead to very slow kinetics of buffer saturation and swelling.

This is demonstrated by comparison of two disposal boreholes with clay buffers (bentonite MX 80) tested in the "Prototype repository" laboratory experiment conducted by SKB at Äspö in Sweden (figure 5.4.4) (Johannesson et al., 2005).

In one borehole (n° 3), the buffer is supplied with water from conducting fractures in the wall; within a year, the pressure reaches 6 MPa on the external edge of the buffer.

In another borehole (n°1), 12 metres away, water supply is very low; after more than two years, swelling is limited to a fraction of the bentonite closest to the rock. There is no pressure increase in the borehole. In this case, buffer saturation is expected to occur ultimately (tens to hundreds of years) by water from the overlying handling drift backfill.

This illustrates the difference between situations that may be encountered inside a C waste disposal module in terms of kinetics of buffer resaturation and swelling.



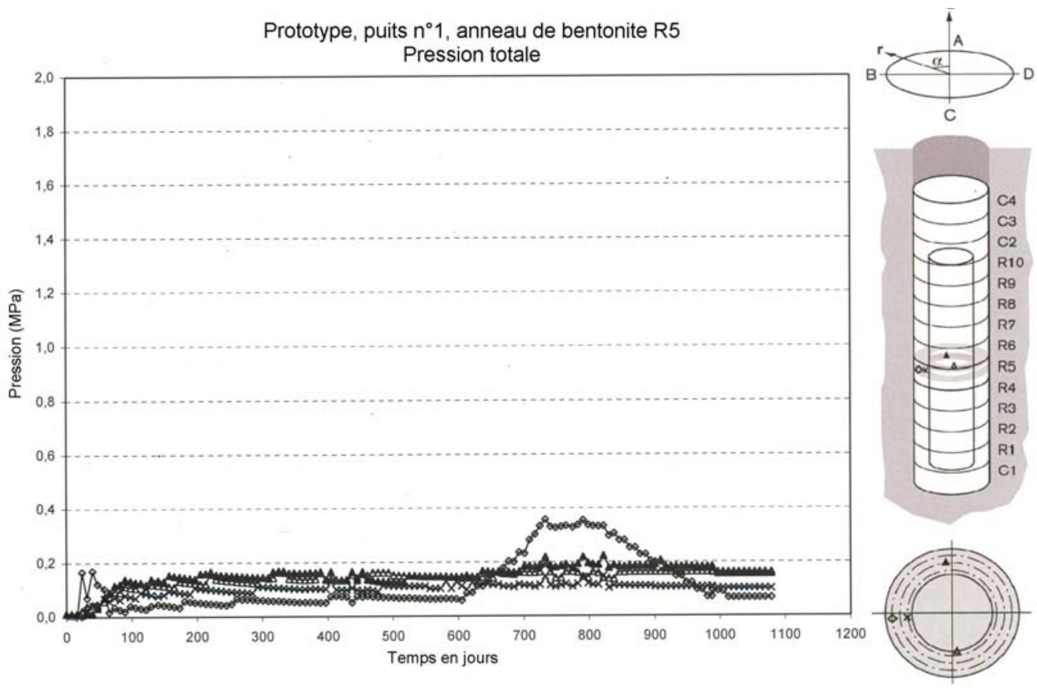


Figure 5.4.4 *Comparison of evolution of total pressure in two disposal boreholes: a) Top: Case of a borehole where buffer swelling is not limited by granite water supply. b) Bottom: Case of a shaft where the swelling is significantly delayed by very weak granite groundwater supply. ("Prototype repository" laboratory experiment at Äspö in Sweden)*

✓ **The role of temperature**

Heat release from C waste disposal packages controls buffer swelling. In phenomenological terms, the heat tends to desaturate the bentonite on the buffer inner face, thus delaying its swelling. This is demonstrated by all the experiments conducted *in situ* and on laboratory mock-ups. These models reproduce buffer swelling as well as the evolution of saturation over time, taking into consideration these phenomena in the internal part of the buffer. For example, this is illustrated by the distribution of buffer water content tested over 5 years by ENRESA *in situ* at the Grimsel laboratory in Switzerland (Villar et al, 2005) (figure 5.4.5). Consequently, bentonite density decreases as water content increases.

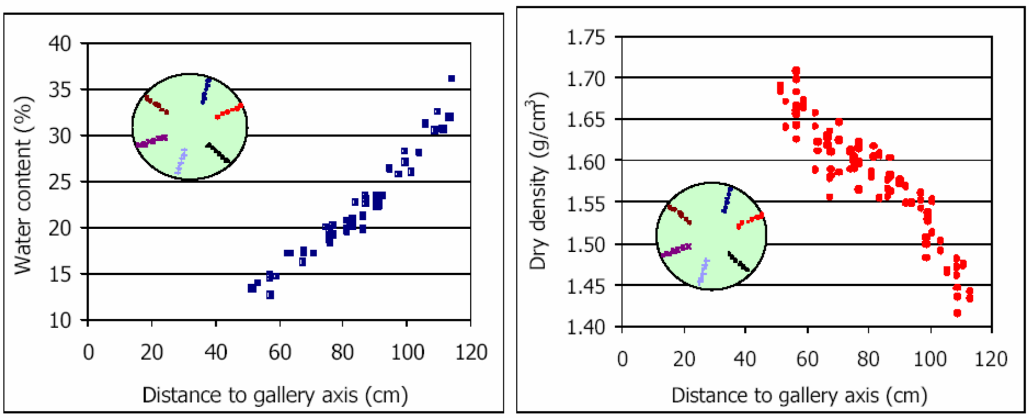


Figure 5.4.5 *Evolution of water content and bentonite density versus distance from the heat source (data from the FEBEX experiment conducted by ENRESA at the Grimsel laboratory*

Bentonite desaturation is all the more significant as package heat rating is high and as temperature on the inner face of engineered barriers increases. This involves an increase in bentonite thermal gradients as shown in the “TBT” laboratory experiment conducted by Andra at the Äspö laboratory in Sweden (figure 5.4.6) (Sandén et al, 2005, Hökmark et al, 2005).

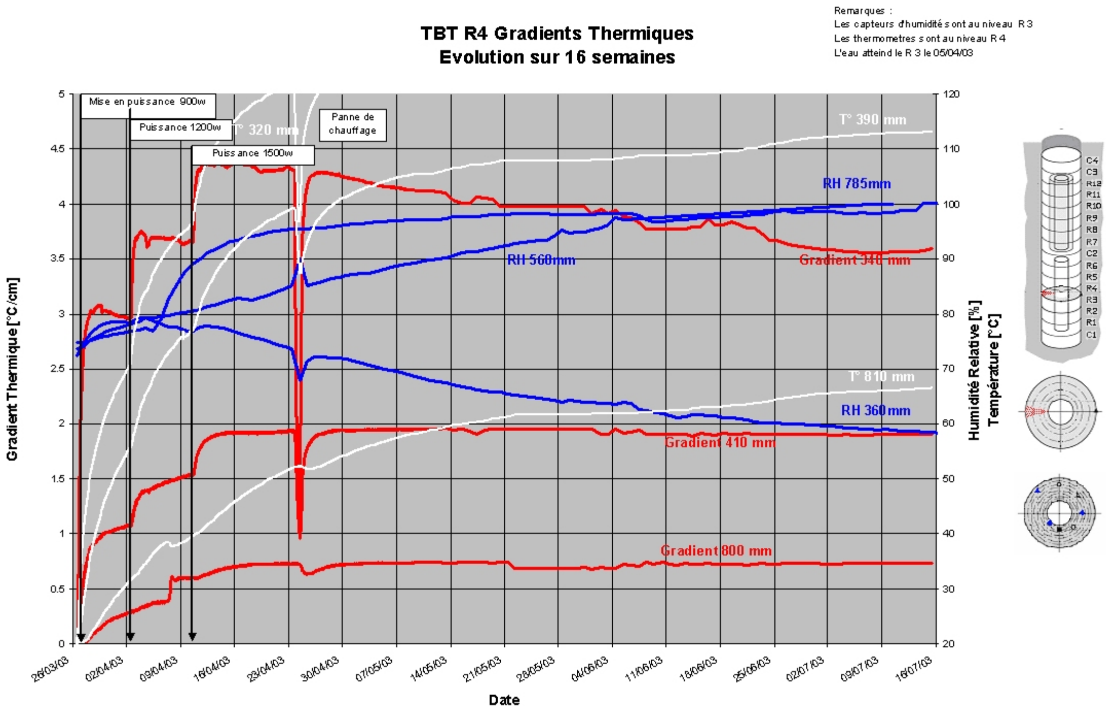


Figure 5.4.6 *Evolution of thermal gradient, bentonite water content and temperature through a swelling engineered barrier (“TBT” laboratory experiment at Äspö, testing engineered barrier temperature in excess of 100°C on its inner face.)*

5.4.2.2 Bentonite interaction with granite rock

Bentonite buffer resaturation causes it welling. Swelling pressure is thus applied to the granite wall. This rock-buffer interaction will occur early in the resaturation phenomenon since the resaturation “front” tends to develop from the water-producing rock towards the heated container.

During the resaturation phase, bentonite buffer develop swelling pressure of around 7Mpa, a weak enough value to avoid rock damage. Indeed, granite elastic deformation that may be due to swelling is very slight, given the strong elasticity module of the rock.

In addition, bentonite swelling will cause a close contact between granite rock and buffer. Observations made in reduced-scale boreholes at the Stripa laboratory (Gray, 1993) indicate that bentonite penetrates the small-sized fractures in disposal borehole walls (figure 5.4.7).

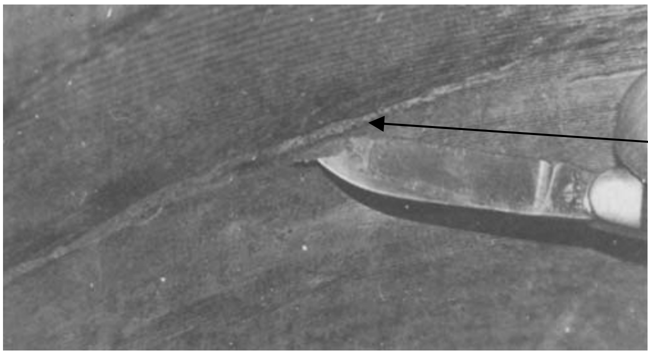


Figure 5.4.7 Photograph illustrating close interaction between swelling clay buffer and granite fracture (taken from Gray, 1993)

5.4.2.3 Hydro-mechanical interaction between bentonite plugs and drift backfills

According with C waste disposal concepts, the handling drift backfill is in direct contact with the bentonite plug in disposal boreholes. During resaturation, cell plug swelling as backfill swelling, can cause vertical displacement of this contact. It may also, given differences in backfill and plug density, lead to a relative loss in plug density. Displacements are counterbalanced by rock wall friction. Overall, when plug swelling pressure equals the sum of backfill pressure and rock friction forces, there is equilibrium and movement stops.

Reduced-scale model tests made at the Stripa laboratory in Sweden (Gray, 1993) have provided an initial evaluation of movement towards the high point of contact from 4 to 7 cm and this result is being currently checked at the Äspö laboratory.

5.4.2.4 Conclusions: sound understanding of the swelling phenomenon of swelling clay buffer under thermal condition

Data collected in underground laboratories and from mock-ups highlight the robustness of modelling based on experiments for temperatures less than or close to 100°C. Experiments have identified all phenomena coming in to play during bentonite swelling; modelling reproduces the various stages of swelling and distribution of resaturation phenomena along buffer thickness.

5.4.3 Thermal changes

C waste repository modules are designed to guarantee maximum temperatures lower than 90°C at the hottest point of the buffer. For granite with average thermal properties (inset 5.5), this corresponds to a 8 m pitch between boreholes for a 25 m pitch between handling drifts (as pitch between drifts is determined to limit any mechanical interaction between drifts). This dimensioning results in the absence of thermal interactions between disposal boreholes.

After waste package disposal, temperature rapidly rises in the disposal borehole and reaches the maximum after a few years. The temperature in the disposal borehole rock wall reaches its maximum (around 50 °C in the case of C2 waste taken as a reference in the calculations) after between ten and twenty years. Between two disposal boreholes and two handling drifts, rock temperature reaches its maximum after about one hundred years.

Temperature then decreases relatively quickly in the borehole during the first hundred years of disposal, then at a slower pace to become less than 50°C after a few hundred years. Figure 5.4.8 illustrates these thermal changes in a C2 waste repository module based on the hypothesis of a 60 year prior storage (Andra 2005k).

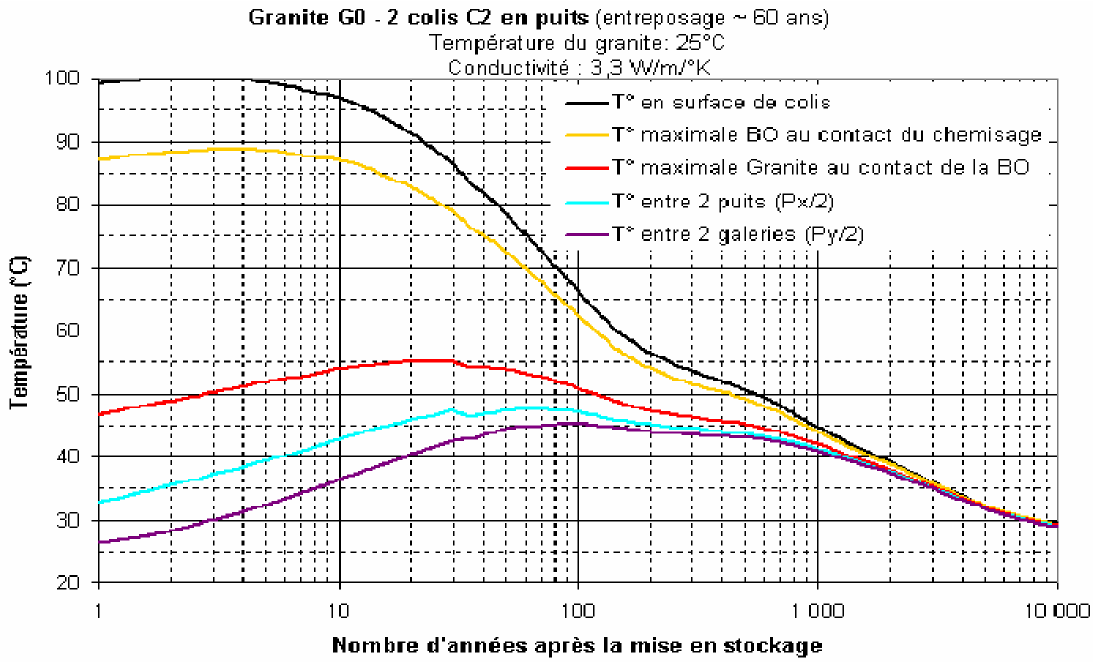


Figure 5.4.8 Thermal changes in a C2 waste disposal borehole

5.4.4 Long-term chemical evolution in a disposal borehole

Resaturation of swelling clay buffers and their swelling are accompanied by chemical exchanges between the bentonite and granite groundwater. Granite groundwater comes into contact with the steel sleeve and over-pack after complete resaturation of the engineered barriers (an average of tens of years depending on the geological configuration of disposal boreholes). Interactions between granite groundwater and these steel components thus mainly determine chemical changes in the disposal borehole.

5.4.4.1 Water transfers in disposal boreholes

After complete resaturation of the disposal borehole and swelling of the bentonite engineered barrier, the transport regime in the borehole is dominated by diffusion phenomena in the clay buffer engineered barrier.

The water flow likely to be exchanged between the disposal boreholes and granite mainly depends on “contacts” between “stagnant” water in the buffer and “circulating” water in the “small-sized” fractures in the wall.

In these fractures, the hydraulic regime is controlled byt he hydraulic properties of small-sized fractures, which can be intersected by boreholes, their potential connection and the general hydrogeological context of the site in terms of hydraulic head gradients.

Estimation of the water flow-rate around the disposal boreholes based on fracturing models (Golder, 2005) varies between 0.5 l/year to 200 l/year. The very low water flow-rate exchanged between the buffer and the neighbouring rock is evaluated at between 0.2 and 5 litres per year (for a total volume of disposal borehole of between 100 and 200 m^3).

5.4.4.2 Corrosion of the steel over-pack

After the thermal phase, chemical conditions in disposal boreholes become again reducing ones. Under these conditions, steel is generally corroded according to the reaction:

$$Fe + H_2O, Fe_3\,O_4 + 4\,H_2$$

Steel corrosion thus consumes water and causes hydrogen production. The corrosion mechanism to be considered is generalised corrosion which eventually causes the loss of over-pack confinement. Generalised corrosion kinetics is estimated between 0.1 and a few µm/year (Andra, 2005l) depending on temperature.

The over-pack is dimensioned to ensure sustainability and leak-tightness at least during the thermal period of the repository (a thousand years). At the generic stage of the studies, the proposed dimension (55 mm) fulfils this objective by taking into account, on the one hand, corrosion of the over-pack in the oxidising environment during the initial repository stages and, on the other hand, loss of mechanical resistance due to generalised corrosion in reducing environment during the following stages (figure 5.4.9).

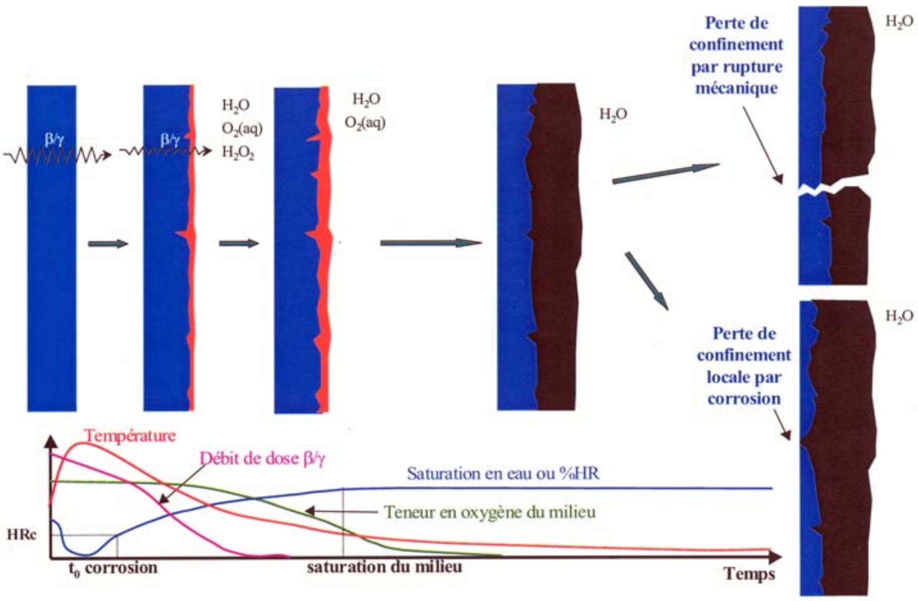


Figure 5.4.9 *Schematic model of corrosion evolution and loss of leak-tightness of a C waste over-pack*

Loss of over-pack leak-tightness leads to the contact between granite groundwater and glass packages and to the beginning of radionuclides release due to glass dissolution (cf. § 5.4.5).

Steel corrosion products, lower in density than the steel, tend to expand. Buffer swelling pressure can also rise slightly due to densification. After over-pack rupture, corrosion products and buffer bentonite fill up the void spaces existing between the glass packages and over-pack.

- **Iron-bentonite interactions**

Products from corrosion of the steel sleeve and over-pack will interact with the bentonite and tend to modify chemical and mineralogical composition of the swelling clay buffer. This interaction is characterised in the bentonite by processes of ion exchanges and dissolution/precipitation (Andra, 2005a). It progresses in a concentric front from the bentonite/sleeve interface. It results in the formation of an initial highly re-mineralised zone of centimetric thickness, mainly constituted of iron chlorite and ankerite, then of a second zone slightly more disturbed by iron enrichment of the remaining smectite and formation of secondary minerals.

Disturbance continues until the metal components have been completely corroded, which means for several tens of thousands of years. However, the higher the temperature, the more intense the disturbance. It thus mainly develops when both temperature and saturation beneficial conditions are met, which means for hundreds to a few thousand years. It develops more slowly after the thermal transient.

The limited extent of both the remineralised zone and the slightly disturbed zone does not modify hydraulic, retention and swelling properties of the clay buffer for duration of several hundreds of thousands years.

- **Hydrogen produced by corrosion**

Corrosion of the steel sleeve and over-pack causes hydrogen production. Related to corrosion kinetics, the flow[10] of hydrogen is at a maximum during the thermal transient. Hydrogen gas migrates with water towards the small-sized granite fractures by diffusion through the bentonite, for as long as the pressure does not cause formation of a distinct gaseous phase. If corrosion rate is sufficient, a specific gaseous phase is eventually formed between the over-packs and the clay buffer engineered barrier. Gas pressure rises and gas migrates through the bentonite. Several mechanisms are described for this transfer (inset 5.10). For foreseeable gas productions in C waste disposal boreholes, the transfer mechanism is a biphasic flow which jointly moves water and gas. When it leaves the bentonite, the gas migrates, on the one hand, towards the handling drift backfill, high in porosity (30%) offering gas a large expansion volume and, on the other hand, for gas pressures higher than the hydrostatic pressure (around 5MPa), into small-sized fractures. In small-sized granite fractures, gas also migrates according to a biphasic system, which does not modify radionuclides retention properties of the rock at the fracture planes (Garcia et al, 2002).

Inset 5.10 ***Conceptual model of gas transport in dense clay mediums***

The current conceptual model developed to represent gas transport in dense, initially saturated, swelling clays (and deep clays), comprises 4 successive phases, each one corresponding to a specific mechanism (Talandier, 2005). The sequence of these mechanisms depends on the gas pressure and flow:

- The first mechanism is **gas dissolution** in water, and its **transport by advection - dispersion and/or diffusion** in dissolved state (diagram A, below).

This mechanism is not conducive to transporting significant amounts of gas as the diffusion coefficients of dissolved gases in clay and clay permeability are low. Therefore the second mechanism is triggered as soon as the gas flux exceeds the capabilities related to dissolution and dissolved gas transport.

- The second mechanism is **two-phase flow** (diagram B, below). The flux of gas produced remains in gaseous form and migrates into the porosity following a Darcy type flow, partially desaturating the environment depending on the gas pressure reached.

This transfer mechanism is independent of the mechanical stress field applied to clay. Clay porosity is not modified as the gas flows through. As the term two-phase indicates, this mechanism brings water and gas into joint motion. Thus water permeability and gas permeability (in the Darcy sense) are defined according to the degree of saturation of the clay.

- The third mechanism initiates if the flux of gas production cannot be evacuated by the first two mechanisms. Gas migration is thus coupled to mechanical behaviour. More to the point it depends on the contact forces between the solids of the clay skeleton. Gas pressure builds up until it locally overcomes the contact forces (cohesion), it "expands" the porosity and the gas can then migrate onwards in the larger porosity domain that it has created (diagram C, below) At the microscopic scale, this porosity expansion is equivalent to the formation of localised **microfissures**. Given the low viscosity of the gases and their low affinity to solids (as compared to water ones), this microfissuring-based transfer mechanism enables large amounts of gas to migrate even though only locally occurring microfissures are involved.

During this purely mechanical mechanism and in contrast with a biphasic transfer, water is not displaced ahead of the gas penetration front. Strictly speaking the Darcy type flow concept is no longer applicable.

If the gas pressure drops, the microfissures cannot be kept open. The microporosity initially created contracts mechanically and the water can *in fine* reoccupy the entire porosity. When combined with clay minerals swelling near the microfissures, it leads to clay self-healing according to water flow in a fully re-saturated clay. The argilite regains its initial water permeability.

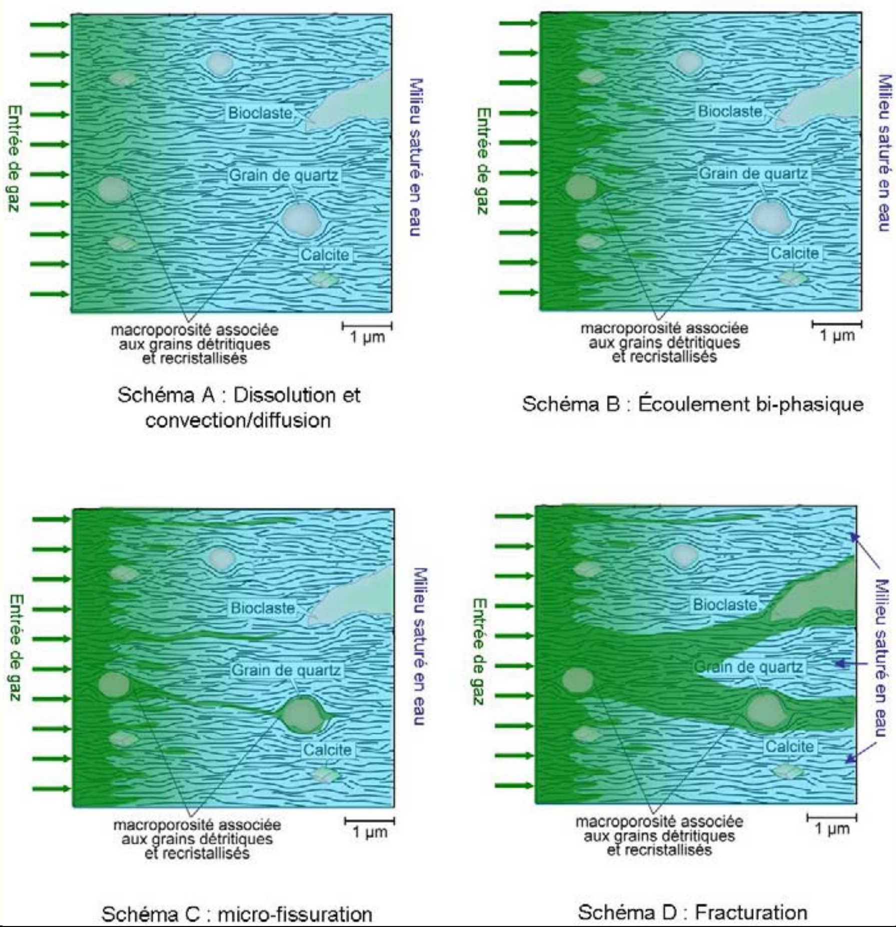
The mechanism of microfissuring can be initiated in the swelling clay as soon as gas pressure exceeds swelling pressure. The swelling pressure of the swelling clay at mechanical equilibrium with the argilite in the repository is

[10] Since the precise assessment of gas production in C waste disposal boreholes has not been performed within the framework of generic granite studies, the analysis is based on studies conducted for the case of the clay medium.

around 7 MPa.

- The fourth mechanism initiates if gas production flux is still too high to be evacuated by the previous three mechanisms. In this case gas pressure continues to build up beyond the mechanical stress field and reaches the clay **breakdown** threshold with regards to this stress field. A fracture is created as opposed to microfissures (diagram D, below). This fracture is oriented perpendicularly to the minor stress direction. For argilite and as suggested by bore-hole tests results, effective gas pressures over of 12 MPa are required to trigger this mechanism.

As in the case of microfissures, (i) fracture extent and aperture are function of partially the gas pressure and partially associated gas flux, (ii) there is no significant water displacement, as water only moves locally and while the fracture is opening up: only gas can flow there without causing water to flow, and (iii) self-healing after return to total saturation brings permeability back to its original level.



5.4.4.3 Sustainability of clay buffer swelling pressure

In the very long term, chemical exchanges between the granite water and bentonite result in ion exchanges especially between the Ca^{2+} ion likely to be contained in granite water and the Na^{+} ion in smectite. Modelling was carried out in Sweden (SKB, 1999a) to assess kinetics of exchanges of smectite and granite water ions, for three different sites (designated as “Aberg”, “Beberg” and “Ceberg”). Without being able to directly transpose the range of values considered to the French context, it appears on first approach indicative of the phenomena to be taken into account in the French context. In the case of one site (“Aberg”) where granite water is high in salinity and rich in Ca^{2+}, corresponding to hydraulic properties causing relatively prompt replacement water in the bentonite (in 3,000 years), modelling carried out indicates that the exchange between Na^{+} and Ca^{2+} ions takes place in around 100,000 years. Under other site conditions reviewed, exchange duration can be much longer. Calcite, accessory mineral of bentonite, also acts on exchanges between calcium and sodium ions, especially as a pH regulator in the case of moderately acidic granite groundwater.

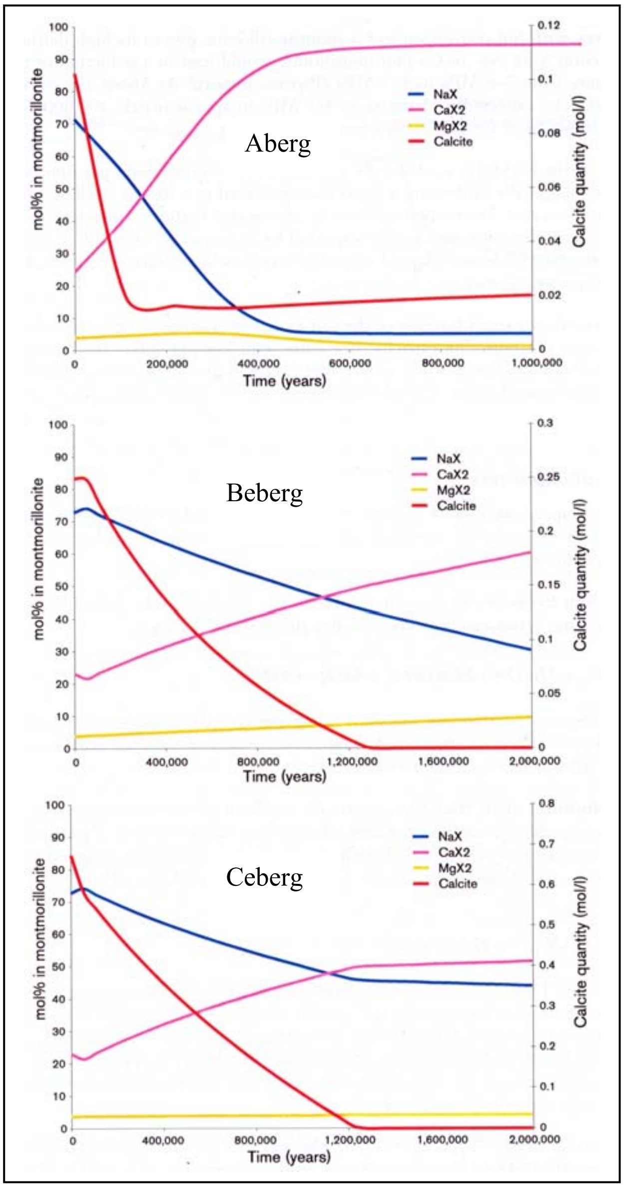


Figure 5.4.10 Modelling of kinetics of ion exchanges between granite groundwater and bentonite for three sites (SKB data, 1999a)

The consequence of exchanges between Na^+ and Ca^{2+} ions is relative loss of bentonite swelling pressure. It has been assessed that in the unfavourable case of the "Aberg" site, swelling pressure can also decrease from 7-8MPa to 4-5MPa in 100,000 years which should not incur any loss of mechanical and hydraulic functions for both the buffer and the plug in the disposal borehole.

5.4.4.4 Conclusions on disposal borehole chemical evolution

Phenomena related to interactions between the steel components in disposal boreholes (sleeves and over-packs) and buffer bentonite have been identified and the orders of magnitude of their effects assessed. These phenomena do not significantly modify bentonite properties which contribute to maintaining environmental conditions beneficial to waste confinement in the long term.

5.4.5 Glass dissolution, radionuclide release, transfer and retention in disposal boreholes

On the scale of several thousand years, loss of over-pack leak-tightness results in alteration of the stainless steel primary container followed by water arrival on the C waste glass matrix. This water arrival on the glass causes its dissolution and radionuclides release. Release kinetics thus depends on glass dissolution.

5.4.5.1 Glass dissolution and radionuclides release

The dissolution kinetics of vitrified packages is controlled by the thermal and chemical conditions of the water in contact with the glass. It also depends on chemical composition of the glass. On the other hand, αβγ self-irradiation processes which have been going on since the production of the vitrified packages do not influence glass dissolution kinetics, mainly due to the considerable self-repairing capacity of glass matrices (Andra, 2005i).

In C waste disposal boreholes, when water comes into contact with the glass (several thousand years), thermal conditions have returned to low enough temperatures, below 50°C, in order not to significantly accelerate dissolution kinetics.

Dissolution kinetics of the glass matrix are also influenced by materials located in direct contact with the glass and, therefore, by the presence of corrosion products from the primary container, over-pack and sleeve. This occurs only on the outer part (surface) of the glass. These materials act on the chemistry of water in contact with waste through their silica retention properties. Interstitial water chemistry in the glass core is relatively insensitive to the immediate environment of the packages (the product of steel degradation) due to its distance (Andra, 2005i).

Inset 5.11 ***Structure of (boro)silicate glass***

Introduction

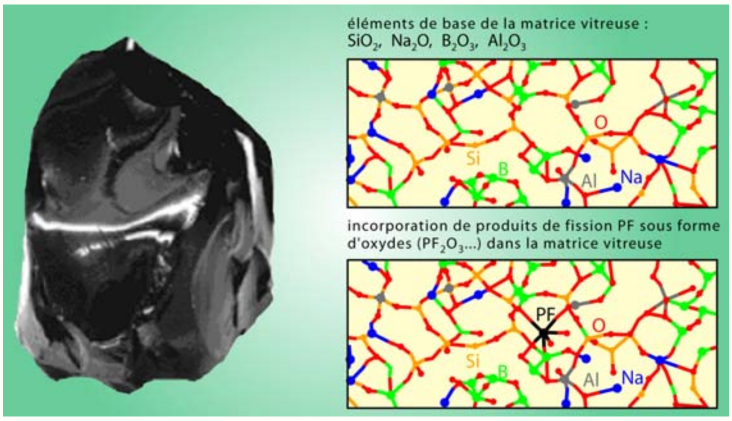
The structure of silicated vitreous materials has been the subject of studies for almost a century (Zachariensen, 1932 ; Zachariensen, 1933), particularly by the glass and nuclear industries, in order to better understand and optimise the chemical durability properties. From a physico-chemical viewpoint, a glass is a fixed super-cooled liquid with, thus, an amorphous structure (Scholze, 1991 ; Zarzycki, 1982). Furthermore, development of high-performance analysis tools (neutron diffraction (Wright, 1994), reflective infrared spectroscopy (Geotti-Bianchini & De Riu, 1995 ; Geotti-Bianchini *et al.*, 1991), molecular dynamic modelling (Aertsens & Van Iseghem, 1996 ; Ganster, 2004 ; Ledieu, 2004),…) has led over the years to refine observations up to the point of proposing a general structural model. This model is essential to the understanding of the dissolution processes.

Structure

The three-dimensional framework of silicated glasses consists of SiO_4 tetrahedra (Scholze, 1991 ; Zachariensen, 1932 ; Zarzycki, 1982). It is modified by the introduction of alkaline or alkaline-earth elements. A silicated glass thus has three different types of cations: network-forming cations (Si, B, P,…), network-modifying cations (Li, Na, K, Mg, Ca, Ba,...) and intermediate cations which may be network-formers or modifiers, depending on glass composition (Al, Pb, Zn, Ti, Fe,...).

Generally speaking, vitreous network-forming cations are cations that can adopt a tetrahedric environment and are interconnected by bridging oxygen. Modifying cations cause the breaking of the network's tetrahedric chain with the appearance of non-bridging oxygen, connecting a network-forming atom and a network-modifying one. It is not always possible to assign one or other of these types to all cations and certain can adopt mixed configurations whilst others can change type according to glass composition. These are then said to be "intermediate".

In nuclear glasses, the radioactive nuclides and chemical toxins are incorporated into glass structure as forming or modifying elements, depending on their electronic structure (see Figure below, (Andra, 2005i)).



Photograph of a piece of R7T7 glass and diagram of glass structure

Glass matrix dissolution is divided into three successive stages: (1) selective dissolution of the most soluble elements (boron and alkalis). This stage is short, lasting a few days; (2) dissolution of the glass at a linear rate of V_0. This phase may last from a few years to several tens of years; (3) a rapid decline in the rate until it reaches a very low residual rate (V_r). The sequence between stages 2 and 3 is shown as V_0 V_r. The transition phase between these two stages lasts a very short time and can be disregarded in the timescale representation of glass matrix dissolution.

Dissolution kinetics of the different types of glass (cf. § 3.1.2) and their evolutions have been assessed on the basis of a large number of experiments, some spanning several years, and models developed from them. Total dissolution times estimated to date for PIVER, UMo R7 and AVM glasses (package types C0.1, C0.2 and C0.3 respectively) are around a few thousand years (Andra 2005i). For R7T7 glass (type C1 and C2 packages) and vitrified UOX/MOX and Pu waste (type C3 and C4 packages), glass dissolution based on the V_0 V_r model leads to total dissolution of the glass in at least 300,000 years. Recent studies seem to indicate the possibility of a reduction of V_r with time and temperature (Andra, 2005d). Behaviour of radionuclides in glass alteration products depends on the nature of the radionuclide.

Inset 5.12 gives a list of "mobile", "intermediate" or "highly retained" radionuclides.

Inset 5.12 ***Radionuclide behaviour in glass alteration products***

Research into glass dissolution processes has shown the retention processes of the elements released by the glass in its degradation products (Andra, 2005i; Fillet, 1987).

The different elements released by the glass can therefore be classified on the basis of their retention in the alteration layer and other alteration products. (Andra, 2005i).

Elements that are not retained in the alteration layer are **mobile elements**. They comprise the alkalis (sodium, lithium), molybdenum and technetium. They are released congruently with the degradation of the vitreous matrix. (Andra, 2005). Among the chemical toxics, boron corresponds to this category of elements.

- In the case of molybdenum and technetium, their retention is possible and depends on the redox conditions in the alteration layer. In an oxidizing or slightly reducing medium, these two elements are only retained in the alteration layer in the case of an extremely advanced reaction (~ 10 %). However, under extremely reducing conditions (Eh < -400 mV), the change in the oxidation level of these elements leads to the formation of less soluble species that remain partially fixed in the alteration layer.

- Sodium and lithium are not generally retained by the alteration layer, except as charge compensators. (Munier *et al.*, 2004). This is also the case for boron.

So-called **intermediate** elements are partially retained in the alteration layer during glass degradation. These elements are caesium, alkaline-earth metals (calcium, strontium, barium), silicon and aluminium (Andra, 2005i).

- Caesium behaves more like an alkaline-earth metal and when degradation is advanced, it is notably retained in the alteration layer (~ 30 % - 60 %) or in the phyllo-silicates (Valle, 2001).
- Alkaline-earth metals retention in the alteration layer varies between 40 % and 60%. They probably serve as charge compensators for aluminium or zirconium.
- Silicon and aluminium retention in the alteration layer varies depending on the alteration conditions and, in static conditions with high surface/volume ratios, silicon retention can reach almost 95%. Aluminium is better retained than silicon, perhaps on account of its lower solubility at basic pH.

Highly retained elements are insoluble at the basic pH environment imposed by glass degradation. They include all the transition elements (iron, nickel, zinc, zirconium, etc.), lanthanides and actinides (Andra, 2005e ; Fillet, 1987).

- As a general rule, La, Ce, Nd, Th, Am and Cm are present in +III form (Andra, 2005e) and this charge favours a strong attraction with the negatively charged alteration layer. Actinides are retained to a greater or lesser extent depending on the elements. Almost 99.9 % of americium and curium is retained.
- Uranium and neptunium behave in a similar way to each other and are more mobile than the other actinides, especially in an oxidizing environment where they are in the forms U^{VI} and Np^{V}. In a reducing envoronment, neptunium IV is less mobile. It can be significantly retained (~ 35 %) depending on glass type (Andra, 2005i). In the presence of phosphates, neptunium retention in the alteration layer can reach 90% (Andra, 2005i ; Andra, 2005j).

Plutonium behaviour is intermediate between the lanthanides and uranium one. In some cases it is very highly retained (> 99 %) in the alteration layer by more stable phases than simple hydroxides or carbonates. (Andra, 2005i).

5.4.5.2 Radionuclides transfer and retention in disposal boreholes and handling drifts

In disposal boreholes, radionuclides are transferred by diffusion in bentonite from the waste glass matrix towards handling drifts, via disposal borehole plugs and towards small-sized granite fractures in the walls. Two phenomena lead to radionuclides retention by clay buffer in disposal boreholes: sorption by smectite sheets and chemical precipitation. A distinction can thus be made between different types of radionuclide (inset 5.8):

- So-called “mobile” elements”, like chlorine, iodine, carbon and boron with high solubility and low retention;
- Other elements, with (very) low solubility and/or high retention on clay surfaces (caesium, technetium, selenium actinides, etc).

In the handling drift backfill, radionuclides transfer and retention by the bentonite fraction of the backfill (15 to 30%) occur according to the same processes as retention in disposal borehole engineered barrier. Certain radionuclides are also retained by crushed granite, which is another backfill component (SKB, 1999a).

5.4.5.3 Conclusions

Radionuclides transfer phenomena in C waste disposal boreholes are essentially determined by hydraulic and retention properties of the clay buffer placed around packages. Maintaining these properties over the long term, makes the most of the very low dissolution kinetics of package glass, therefore ensuring a low flow of radionuclides towards handling drift backfill or small-sized granite fractures in the wall.

5.5 Spent fuel repository zone

The copper container concept, proposed for the fuel repository studies, is characterised from the long-term evolution viewpoint by lasting leak-tightness of the container over several hundred thousands to millions of years. The container physico-chemical environment should provide conditions conducive to thermodynamic stability of the copper which forms the container envelope throughout this whole period. The main function of the bentonite buffer placed between the packages and granite rock is to maintain these conditions. Its evolution determines that of the disposal borehole as a whole, to a great extent.

5.5.1 General comments: similarities to and differences from the evolution of type C waste repository

Many aspects of phenomenological evolution of a spent fuel repository module are comparable to the evolution of a C waste repository module:

- As for type C waste, the small-sized disposal boreholes have a clay buffer and a swelling clay cell plug;
- Handling drifts are filled with low permeability backfill consisting of crushed granite and a fraction of swelling clay, as is the case for type C waste.

Hydro-mechanical evolution of the backfill and disposal borehole buffer is therefore identical to that of type C waste during the initial phases of structure resaturation and bentonite swelling. In particular, the kinetics of disposal borehole resaturation and bentonite swelling results, as for type C waste, from the coupled actions of buffer hydration by water from the granite and partial desaturation by heat from the spent fuel. The absence of sleeve between the buffer and the container means that bentonite swelling exerts pressure directly on the copper envelope of the container. As a result of copper ductility and envelope design, bentonite swelling pressure does not damage the container.

5.5.2 Thermal changes and consequences on the granite medium

A spent fuel repository module is dimensioned to guarantee a maximum temperature below 90°C on the surface of the copper container. For granite with "average" thermal properties (inset 5.5), this corresponds to a pitch (inter-axial distance) between disposal boreholes of 12.5 metres for a pitch between handling drifts of 25 metres (the pitch between drifts being determined, as in the case of type C waste, to limit any mechanical interaction between drifts). This dimensioning results in the absence of significant thermal interaction between disposal boreholes.

After spent fuel containers emplacement, the temperature rises rapidly in the disposal borehole and reaches its maximum on the container surface (between 80 and 90 °C) after several tens of years. The temperature at the rock walls of the disposal boreholes reaches its maximum (60 to 70 °C) after around 300 years. Between two disposal boreholes or two handling drifts, the temperature is at its maximum in the rock after around 600 years.

Then, the temperature decreases relatively gradually until reaching less than 45 °C after some ten thousand years. Figure 5.5.1 shows this thermal evolution in a CU2 spent fuel repository module, assuming 100 year (approximately) storage before disposal (Andra, 2005k).

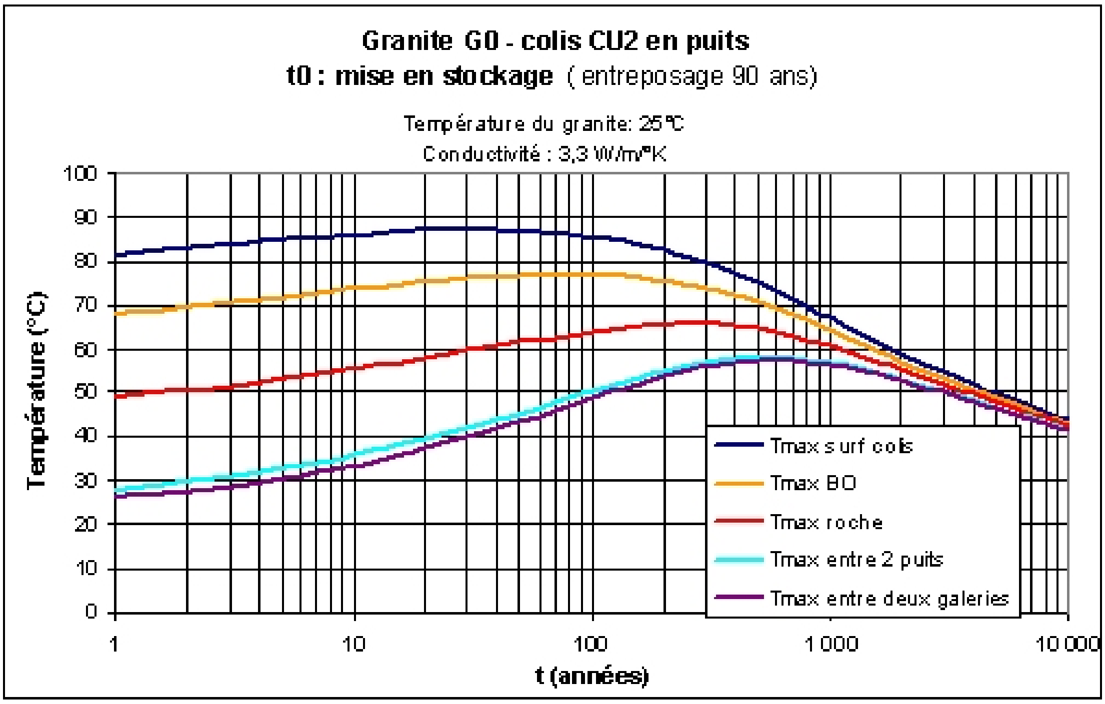
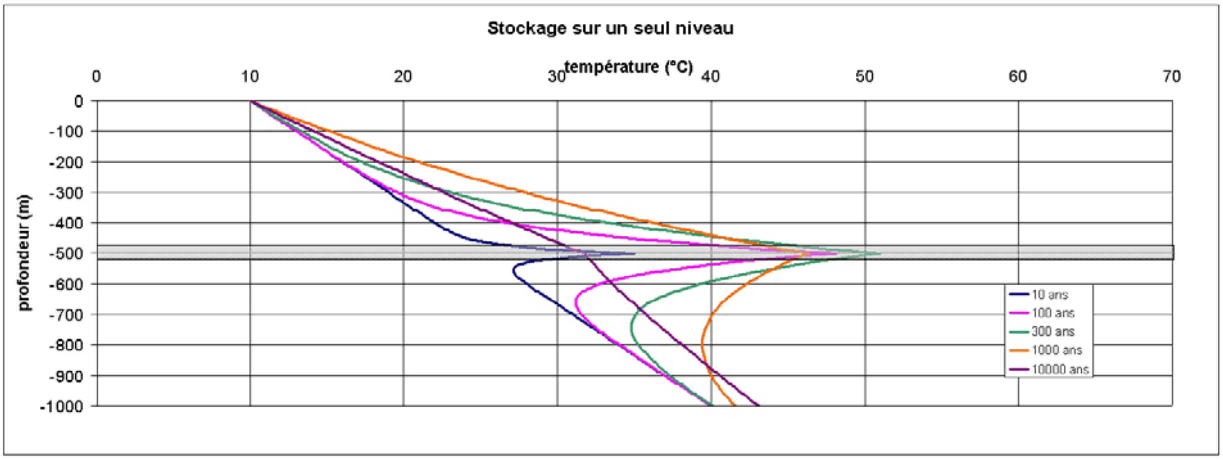


Figure 5.5.1 Evolution of the temperature of a CU2 spent fuel disposal borehole

On either side of the repository level, heating of the granite occurs, over a timescale of several thousand years. The maximum temperature (around 50 °C) is reached on the horizontal plane of the repository after a few hundred years. Then, the heat diffuses, by conduction, in the granite massif, while the temperature tends to become homogenous. This phenomenon is at its greater extent after approximately a thousand years. Beyond this, the temperature decreases steadily. Temperature distribution in the granite returns to a gradient close to the natural geothermic gradient after some ten or tens of thousands of years.

In the case of a two-level repository (levels 100 metres apart from each other), the evolution is similar with two temperature maxima on the two repository horizontal planes (and between the two planes) around 10 °C higher (60 °C) than the maximum in the single level case (Andra, 2005k). This does not affect repository dimensioning.



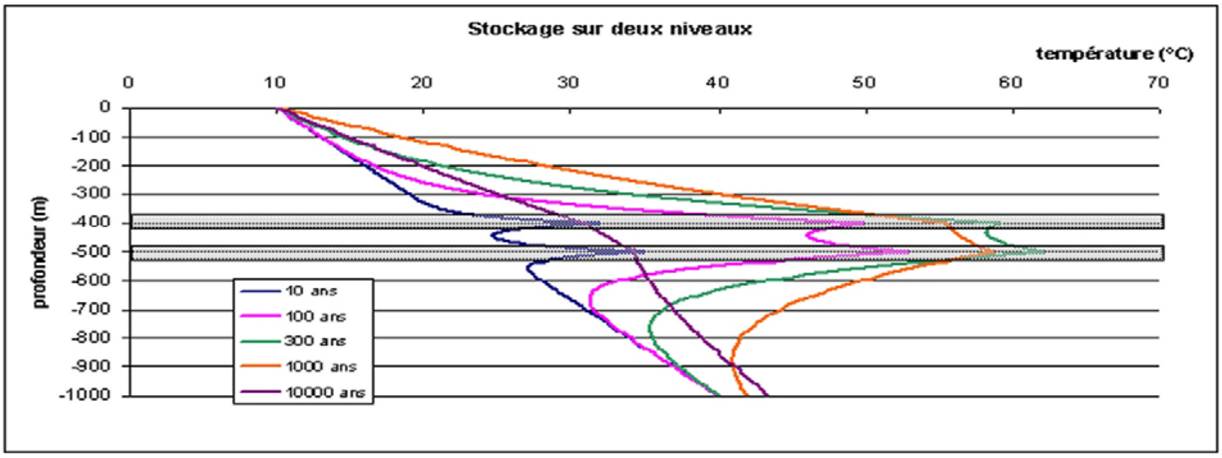


Figure 5.5.2 *Temperature evolution in the granite massif around a spent fuel repository: a) at the top, a single level repository. b) at the bottom: a two-level repository*

- **Mechanical and hydro-mechanical consequences on granite**

i) *On the spent fuel repository scale*, increased temperature can lead to differential mechanical stresses in the granite massif. In a fractured medium like a granite massif, mechanical deformation of the granite resulting from these stresses is absorbed by movements along the fault planes.

Modelling these movements involves knowing the 3D distribution of fractures on different scales. Overall assessments of the amplitude of movements taking into account the "major faults" have been carried out in Sweden (SKB, 1999a). Assuming that only the major faults absorb thermo-mechanical deformation, these movements along fracture planes would be at most around a centimetre.

Repository architecture is also involved in stress distribution. In Sweden, it was studied in particular whether or not a two-level spent fuel repository increased mechanical stress in the rock. Modelling carried out as part of this study shows that differential mechanical stress is essentially expressed on the repository plane (cf. figure 5.5.3, case of a 500 m deep repository).

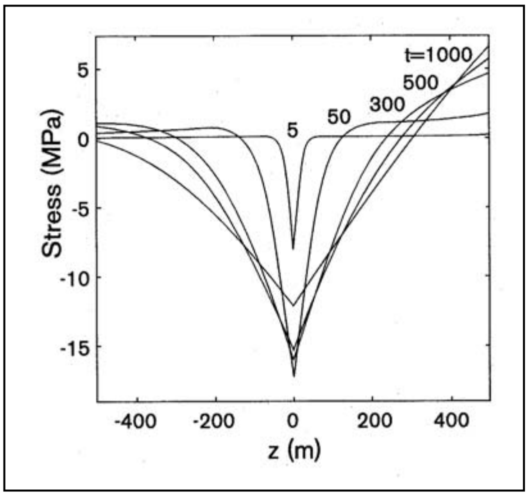


Figure 5.5.3 *Thermal stress related to a spent fuel repository (SKB data, 1999a). Level 0 corresponds to repository depth (500 m)*

Thus, in the case of a two-level repository, there is an increase in compressive stress on a larger section of geological formation. However, increased differential horizontal stress likely to cause movements in the formation located in between the repository levels is not very great and does not change the overall assessment mentioned above.

ii) *Between two disposal boreholes or two handling drifts,* heating of the rock results in the appearance of horizontal compressive stress, by dilatation. This stress tends to close up rock fractures between the two boreholes and the two drifts. There may be local opening by fracture shearing. During cooling, the deformation curve is the reverse one in the case of elastic behaviour by the granite, which may not be the case for some fractures. There may thus be a slight, irreversible change in granite hydraulic properties. In the area of slight deformation under consideration, changes are, however, slight and do not cause noticeable changes in water flows in the vicinity of disposal boreholes.

Deformation of handling drifts ("ovalisation") related to these thermal phenomena has been studied (Côme, 1988) and can occur in certain specific contexts. As handling drifts are not exactly on the horizontal plane of the disposal boreholes, this phenomenon cannot be significant for the disposal option proposed. .

- **Thermo-hydraulic consequences**

The temperature increase in the granite massif, particularly above spent fuel repository zones, is likely to affect hydraulic flows in granite faults. Overall, there is a modification in water viscosity, which is negligible; however, the issue concerning the possibility of creating thermo-convective flow phenomena in the faults where the main water flow occurs is to be considered.

For thermo-convection to be triggered, Archimedes forces (buoyancy) related to water density varaitions through thermal dilatation must be significantly greater than heat dissipation forces in the fractures. Preliminary modelling (Andra, 2005g) shows that, in the case of a vertical water conducting fault 40 metres away from a thermal waste repository module, this force ratio is not very high (0.05) and thus thermo-convection effects are slight.

Moreover, the possibility of placing thermo-convective cells is restricted by fracture network geometry, particularly fractures continuity and their connection mode. Flow continuity in a fault network assumes fault dimensions and thicknesses which are, according to the repository construction design, difficult to envisage in the repository footprint.

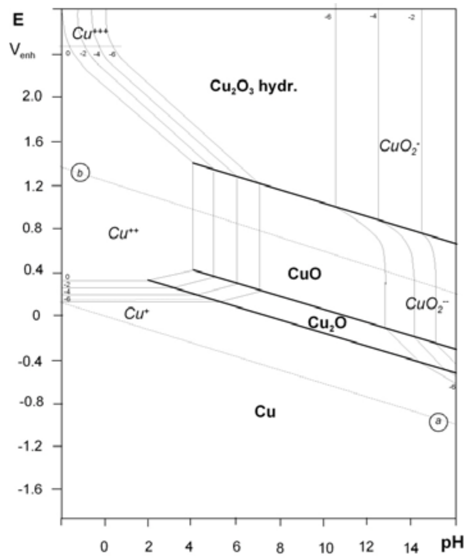
5.5.3 Copper container

Over the long term, copper container leak-tightness relies on environmental conditions which favour copper thermodynamic stability.

5.5.3.1 Thermodynamic stability of copper in repository conditions (Andra 2005l)

Copper is a relatively noble metal. It is thermodynamically stable (absence of corrosion) in the presence of pure de-aerated water. It does not corrode in a de-aerated medium, in the absence of complexing substances (figure 5.5.4).

Sulphates (including sulphuric acid) and carbonates do not form complexes with monovalent copper, in a de-aerated medium. On the other hand, monovalent copper complexes exist with Cl^- chlorides, HS^- sulphates, NH_3 ammoniac radicals, CN^- cyanides, $S_2O_3^{--}$ thiosulphates and SO_3^{--} sulphites (figure 5.5.5).



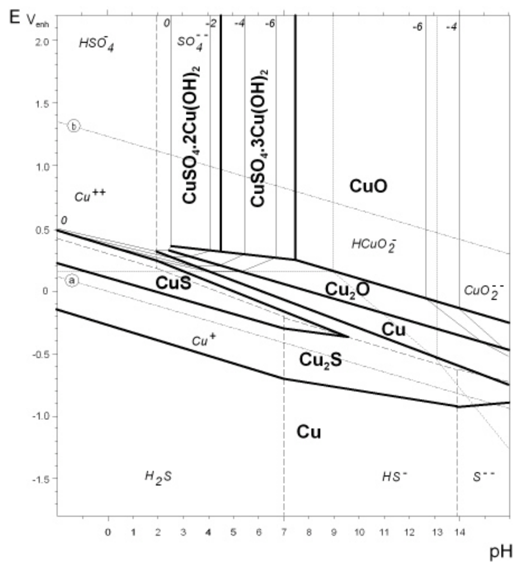


Figure 5.5.4: Diagram of E-pH balances for the Cu-H2O system at 25°C (taken from Delhez et al., 1962)

Figure 5.5.5: Diagram of E-pH balances for the Cu-S-H2O system at 25°C for total dissolved sulphur content of 10-1 mol.L-1, taking into account sulphides and sulphates (taken from Miranda, 1974)

The possibility of pitting corrosion seems unlikely, particularly if it is considered that copper potentials measured in a de-aerated medium are greatly below the potential which determines growth or stopping of pitting: -80 to -130 mV_{ENH}, after a month in compacted bentonite (Saario, 2004) to be compared with a criterion of + 270 mV_{ENH} for propagation.

Based on this data, the status of the different copper corrosion rates for different situations has been established: before closure, in an oxidising medium with progressive saturation, then in a saturated, non-oxidising medium, with progressive cooling (figure 5.5.6). In an oxidising medium, assessments of rates range from less than 0.001 mm/year to nearly 0.3 mm/year. In a reducing medium, estimates are below 0.05 µm/year (Andra, 2005i). This assessment highlights the fact that expected corrosion rates cannot cast any doubt on the leak-tightness of the 50 mm thick containers, on the million year scale.

5.5.3.2 Evolution of repository conditions and consequences for container leak-tightness

In the long term, physico-chemical environmental conditions in disposal boreholes may be changed by evolution of granite massif geodynamic context. Analysis of the French geodynamic context shows that foreseeable developments are not quick enough to significantly change the physico-chemical environment of modules and disposal boreholes over a scale of several hundred thousand years, for most of French granite massifs on the million year scale (see chapter 4.5).

Maintaining an environment conducive for lasting swelling of engineered barriers and thermodynamic stability of the copper ensures ongoing leak-tightness of the copper container over the long term, a factor on which the concept proposed for spent fuel disposal is based.

5.6 Radionuclides transfer and retention in a granite medium

Hydraulic properties of fractures in a granite massif (transmissivity and connectivity) determine, with environmental factors (topography), radionuclides transfer conditions in the massif: flow, water flow rate, transport system (advection/diffusion). The rock matrix, slightly permeable, plays only a very secondary role in radionuclide transport.

Radionuclide transfer in fractures is accompanied by their retention by granite: by the crushed or altered rock on the fracture planes or by minerals clogging the fractures.

Understanding and modelling radionuclides transfer and retention in a fracture network is thus an important theme for the granite medium on which large-scale studies have been carried out internationally (Winberg et al, 2002, Mazurek et al, 2001, Möri et al., 2003).

5.6.1 Phenomenology of radionuclide transport in a fracture network

Pathways of water and dissolved radionuclides in a fracture network depend on hydraulic properties of each fracture and of the network as a whole.

- **Fracture model**

The internal structure of a fracture is complex. It results from rock shearing which initiates fracturing. By their specific nature, the different fracture components contribute to the transport regime in the fracture (figure 5.6.1):

- In the open zones of a fracture, transport occurs by advection/dispersion; the more or less regular geometry of open zones acts on fracture transmissivity;
- Fractures develop small ramifications, with an aperture, but with no outlet to the rest of the network; in these “dead-end” zones, transport occurs through diffusion;
- Clay (“gouges”) are often present in fracture planes; transfer occurs there through diffusion; clay thickness and continuity affect the extent of diffusion in transport;
- Recrystallisation minerals, which result from granite hydrothermal alterations, frequently cover fracture planes; they complexify fracture planes geometry and water advection pathway in the open parts of the fractures,
- The wall rock is deformed and affected by hydrothermal alteration which leads to increased diffusion capacity compared to sound (unaltered) rock. As a result, transfer occurs by diffusion in the altered or deformed rock. Kinematic (connected) porosity of the deformed and/or altered rock as well as the depth of deformation and/or alteration are factors affecting the extent of transport by diffusion in fracture walls.

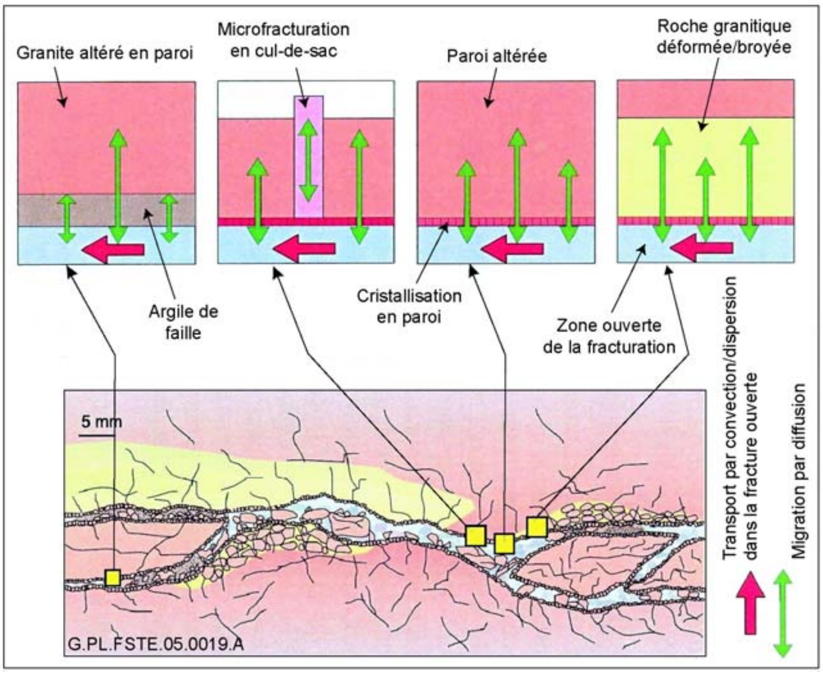


Figure 5.6.1 *Conceptual model of a fracture and associated transport phenomenology*

Fracture hydraulic transmissivity is determined by hydraulic borehole tests (cf. chapter 4.3.2). These measurements include the geometrical aspects affecting advective transport phenomena. The geometry of open fracture zones is determined by geological survey: their continuity can be assessed by resin injections (A. Möri et al, 2003) (figure 5.6.2).

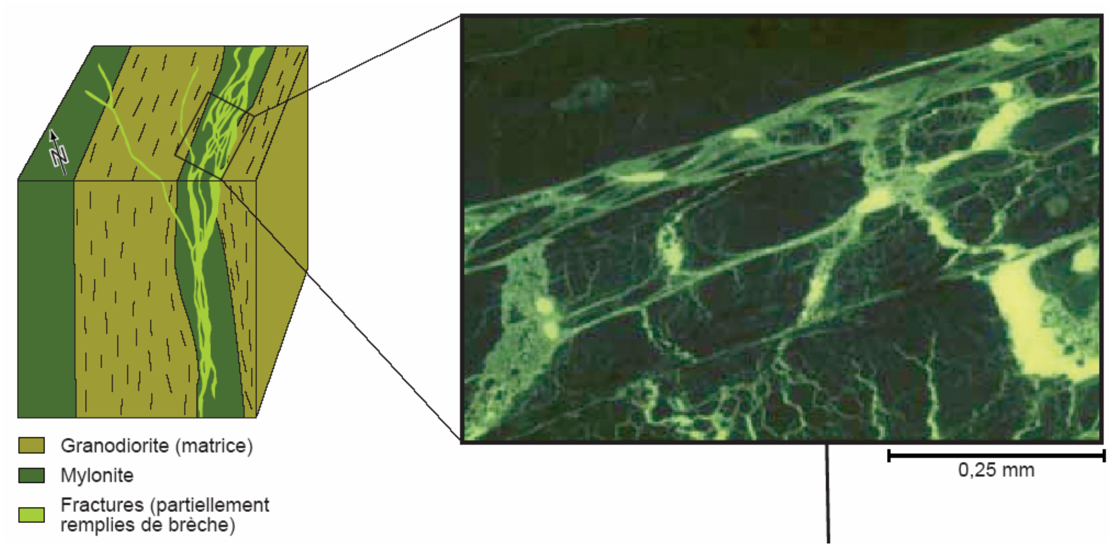


Figure 5.6.2 *Examination of open fracture zones by an injection of radioactively marked resin (carbon 14) then autoradiography (NAGRA data)*

Properties of deformed and altered rock are determined from samples. Analyses, carried out in particular on French granite, show the effect of hydrothermal alteration phenomena on granite diffusion coefficients at fracture planes.

Diffusion coefficients applying to tritiated water vary over several orders of magnitude between samples of “sound” rock with no hydrothermal alteration and samples of altered rock: 10^{-15} m²/s to 10^{-13} m²/s for “sound” granite; values greater than 10^{-12} m²/s for hydrothermally altered granite. The porosity accessible to tritiated water evolves at the same time from 0.1% for “sound” granite to 15% for highly altered samples (Virlogeux, 2005). The depth of alteration of sound rock at fracture edges also depends on the intensity of hydrothermal phenomena: they may be limited to the immediate fracture edges, or they may invade the rock more generally

- **Transport parameters of a granite massif fracture network**

The water flow rate in a granite massif facture network depends on site topographical and morphological configuration, elements determining underground hydraulic gradients (see chapter 2.2.3).

Fracture network hydraulic properties have a direct effect on water flows transferred and flow kinetics. These properties depend on fracture geometrical organisation and hydraulic connections of fractures in between themselves. Fracture distribution variability according to size, geometry and aperture into the massif introduces considerable variation in general fracture network hydraulic properties (De Dreuzy et al., 2004). These factors are specific to the massif studied. The characterisation methodology is based on the complementarity of geological analyses and hydro-geological measurements (in boreholes) as implemented in the Äspö laboratory “True Block Scale” program (inset 6.1).

On the granite massif scale, the largest fractures are the most transmissive. However, the extent of advective and diffusive phenomena depends on the structure of major fractures and their continuity. They are often composite of small-sized fractures whose organisation determines their hydraulic properties. The extent of advection and diffusion phenomena depends on this organisation, specific to the medium studied.

5.6.2 Radionuclides retention phenomena in a fracture network

Transport of radionuclides in fracture networks is accompanied by the retention through sorption of the majority of them by minerals in the crushed or altered rock on fracture edges or by minerals clogging the fractures.

Sorption intensity particularly depends on the type of radionuclide in question and granite mineralogy. Radionuclide distribution coefficients Kd (inset 5.5) are determined from samples of sound granite rock for several types of granite (cf. mainly SKB, 1999c and table 5.4). The measurements result in a distinction, in a way comparable to measurements taken in a clay medium, between non-sorbed elements (iodine, chlorine, etc.), slightly or moderately sorbed elements (carbon, selenium, caesium, etc.) and highly sorbed elements (actinides). In general, distribution coefficients Kd determined are of the same order of magnitude as for the different types of granite, given similar proportions between minerals.

Table 5.4 Radionuclide distribution coefficient in “sound” granite (taken from SKB, 1999c

Element	Saline water Kd (m3/kg)	Uncertainty	Non-saline water Kd (m3/kg)	Uncertainty
C	0,001	(0,0005-0,002)	0,001	(0,0005-0,002)
Cl	0	-	0	-
Se	0,001	(0,0005-0,005)	0,001	(0,0005-0,005)
Tc	1	(0,3-3)	1	(0,3-3)
Sn	0,001	(0-0,01)	0,001	(0-0,01)
I	0	-	0	-
Cs	0,05	(0,01-0,1)	0,5	(0,1-1)
Th	5	(1-10)	5	(1-10)
U	5	(1-10)	5	(1-10)

Element	Saline water Kd (m3/kg)	Uncertainty	Non-saline water Kd (m3/kg)	Uncertainty
Np	5	(1-10)	5	(1-10)
Am	3	(1-5)	3	(1-5)
Pu	5	(1-10)	5	(1-10)
Cm	3	(1-5)	3	(1-5)

The variability of water salinity leads to consideration of possible differences in radionuclide distribution coefficient values. The table shows that only caesium shows different values according to water salinity. It should also be noted that often value uncertainty range is of one order of magnitude.

Sorption efficiency of radionuclides sorbed by the rock at fracture edges depends essentially on rock diffusion properties and its porosity. The porous volume available for diffusion mainly depends on deformation and intensity of its hydrothermal alteration (see above). This results in factors delaying radionuclides migration through the rock which depend on intensity of deformation and alteration phenomena.

Rock deformations are often accompanied by the formation of a clay band ("gouge") along faults, where intensity of deformation is the greatest (cf. § 4.2.1.2). Sorption capacity of the "rock" at fracture edges is likely to be considerably increased by the existence of "clay gouges". Characterisation work thus aims to determine thickness and continuity of clay gouges along faults.

The filling minerals of fractures, especially small-sized ones, are also possible radionuclide sorption sites. The clay or carbonated nature of the minerals has an effect on radionuclide sorption capacity.

The different components of a fracture, deformed rock and clay gouge at fracture edges, as well as the filling minerals, are thus factors delaying radionuclide migration.

These different factors can be taken into account in fracture network (DFN) transport and retention models. The results of modelling exercises related to the "True Block Scale" program experiments highlight the necessity of taking into account the role of each fracture component in order to perform non-pessimistic assessments of fracture retention capacities (Dershowitz et al, 2003).

Inset 5.13 ***The "True Block Scale" experiment of the Äspö laboratory in Sweden (Winberg et al., 2002***

The "True Block Scale" experiment carried out from 1996 to 2002, tested and modelled radionuclides transfer and retention in a fracture network. This experiment followed on from tests carried out on a single fracture.

The fractured granite rock volume ("block") investigated was around 250 m x 200 m x 150 m. It is located at a depth of between 350 m and 500 m (figure 5.6.3).

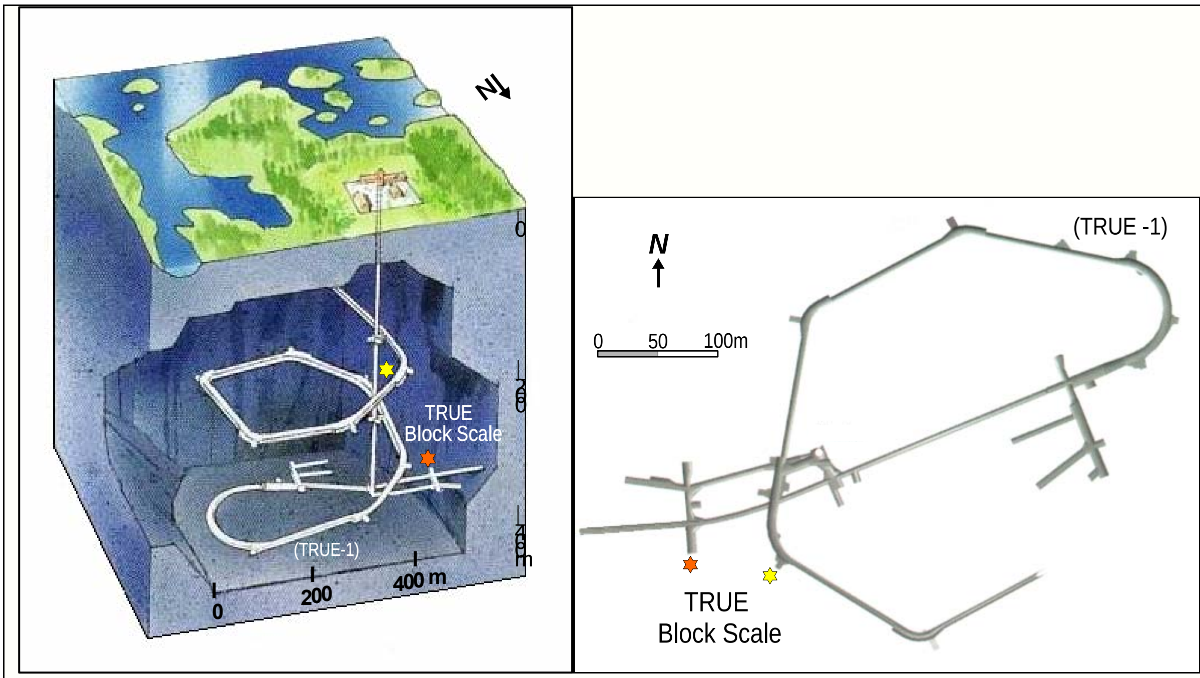


Figure 5.6.3 Situation of True-1 and True Block Scale laboratory experiments

The first stage of the experiment consisted of fracture network geological and hydrogeological characterisation. It resulted, by iteration through the drilling of boreholes and hydrogeological testing, in a hydro-structural model of the volume of granite investigated.

Six boreholes were enough to obtain a hydro-structural model deemed satisfactory for use in tracer tests (figure 5.6.3). Some twenty conducting structures, generally sub-vertical, were identified. A smaller volume (100 m x 75 m x 50 m) containing some ten fractures was used for carrying out the tracer tests. Transmissivity measured is distributed between $1.5.10^{-9}$ m²/s and 1.10^{-7} m²/s. Secondary fracturing, slightly conducting or conducting, but which could not be correlated from one borehole to another, was also characterised.

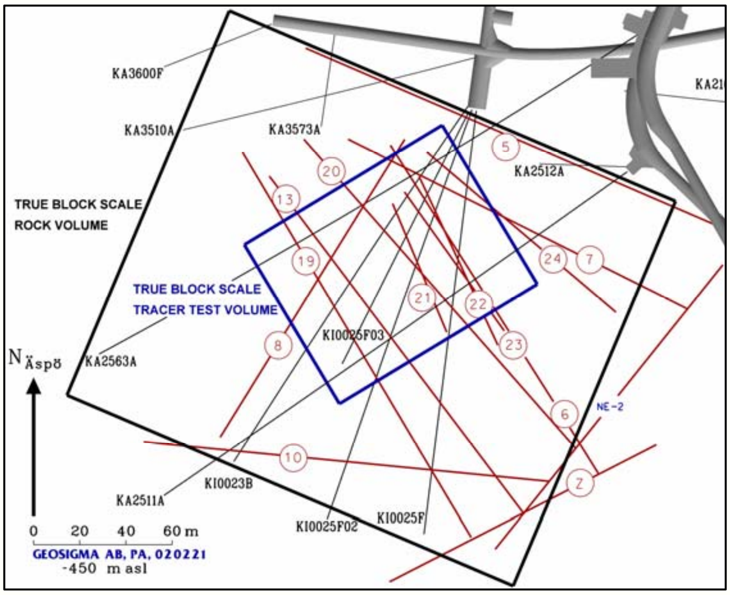


Figure 5.6.4 True Block Scale experiment: hydro-structural model (the volume undergoing tracer tests is shown in blue)

A series of analyses on samples specified the value and distribution of connected porosity at fracture planes:

- Kinematic porosity (connected) is obtained by measuring water absorption: "sound" Äspö diorite: 0.4% (+/- 0,2), altered diorite and cataclasite: 0.45 to 1.5%, mylonite: 0.3 to 0.6%, breccia elements of around a centimetre: 0.3 to 2.0% and millimetric filling fragments: 1.5 to 3.0%;
- Impregnation of samples with a carbon 14 marked resin, followed by sawing and autoradiography, shows that porosity decreases rapidly over a distance of 0.5 cm to 1.0 cm from the fracture surface on wall samples;
- Comparison of total density and density of solids after crushing provides an assessment of total porosity: around 0.7% for samples of non-altered diorite shows a connected porosity of around 0.4%.

The second stage of the experiment consisted of tracer tests. In total, 14 series were carried out representing 32 injections and 16 different hydraulic pathways.

The strong dilutions expected, added to the basic choice of using concentrations of the same order of magnitude as those naturally present in the water, resulted in the selection of a set of tracers suited to the specific context of the experiment, particularly radioactive tracers whose proportions can be simultaneously measured by on-line gamma spectrometry ($^{24}Na^{+}$ and $^{22}Na^{+}$, $^{42}K^{+}$, $^{47}Ca^{2+}$, $^{54}Mn^{2+}$, $^{57}Co^{2+}$, $^{65}Zn^{2+}$, $^{85}Sr^{2+}$, $^{83}Rb^{+}$ and $^{86}Rb^{+}$, $^{131}Ba^{2+}$ and $^{133}Ba^{2+}$, $^{134}Cs^{+}$ and $^{137}Cs^{+}$). Behaviour of these elements is representative of that of elements likely to be released by the repository.

Three particular pathways were studied in detail: a pathway contained in a single fracture (direct distance 16 m) and two pathways taking a succession of interconnected fractures (distances developed 33 m and 97 m). The restitution curves obtained showed different delays, depending on the considered chemical species, confirming the measurements on rock samples. A delay coefficient of 250 was found on the pathway in a single fracture for caesium compared to a non-delayed element (for example bromine) (figure 5.6.5).

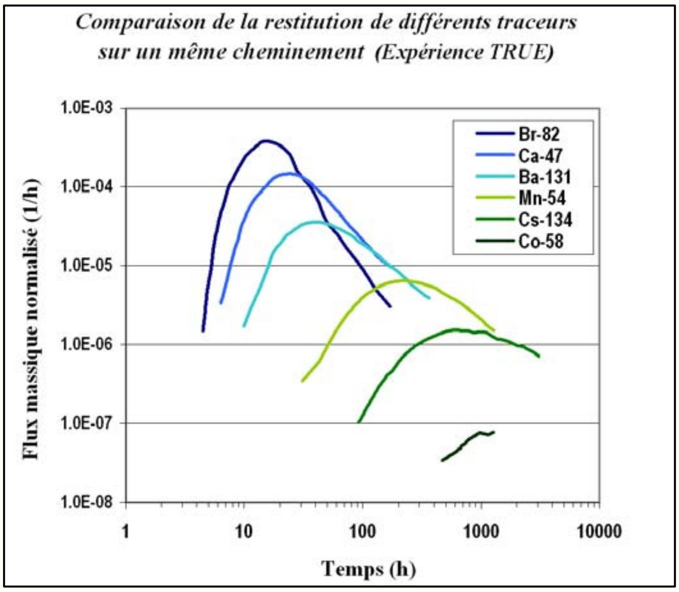


Figure 5.6.5 *True Block Scale experiment: tracer restitution curves*

5.6.3 Conclusions and information for granite site characterisation and modelling

Experiments and studies conducted over several decades on radionuclides transport and retention in granite fracturing has provided radionuclide transport and retention models for a fracture network, which have gained international consensus.

For most radionuclides, retention phenomena accompany transport phenomena. Diffusion in the altered and deformed rock at fracture edges is a factor beneficial to the retention of sorbing radionuclides along water pathways. Fracture filling and clogging minerals are other elements which can contribute to delaying radionuclide transfer.

Site characterisation thus consists of determination of fracture network hydraulic characteristics and that of properties of radionuclide sorption by the various components of granite massif fractures.

6 Conclusions

Within the context of studies without a specific site, Andra reviewed issues concerning understanding the processes acting on a repository in granite medium, drew up a report on the knowledge acquired and uncertainties arising and made conclusions for possible application to a particular site.

6.1 A study approach for identifying and addressing issues concerning repository phenomenology in a granite medium

In order to identify and address issues related to repository phenomenological evolution, analyses are supported by generic disposal concepts based on overall granite medium properties: mainly mechanical resistance and very low rock permeability. They also considered the presence of water conducting fractures likely to affect repository performance. Architectures proposed incorporate variability in granite properties within the French geological context, based on analysis of data available for granites in the Massif Central and the Massif Armoricain.

Options proposed are simple and avoid arrangements leading to poorly controlled phenomenological interactions. As a general rule, repository zone architecture aims to limit water circulations in the repository. Repository compartmentalisation limits chemical and thermal interactions between the different waste repository zones. Materials used for repository construction, often reduced in number, are compatible with each other. They are adapted to each category of waste according to its chemical nature and thermicity, which simplifies demonstration of long-term control of its environment.

As a general rule, the study approach was largely based on international cooperation. It thus benefited from constant availability of the research from three laboratories in granite medium, in Sweden, Switzerland and Canada. Numerous complementary experiments conducted there constituted the main support for the review of issues concerning the repository in granite medium: characterisation and modelling of the granite medium and its fracturing, repository structure performance and understanding and modelling of radionuclide transfer and retention in granite fractures.

Experiments results were analysed by incorporating the knowledge available on French granites so as not to transpose results obtained abroad to the French context without examining the scientific and technical relevance of such an approach.

In conclusion, through the approach adopted, issues concerning repository phenomenology in granite medium were addressed and responses for the main themes were obtained. This approach does not, however, claim to draw the same conclusions as an approach supported by granite site surveying works on the surface and then in an underground laboratory. Only such works would provide sufficient knowledge of granite properties to ensure the exhaustive nature and accuracy of analyses to be carried out to demonstrate repository safety.

6.2 Granite site surveying and modelling capacity

Understanding and modelling repository phenomenological evolution involves understanding and modelling the granite massif where it is to be constructed.

Analyses carried out show that knowledge available on granite geology is extensive and covers multiple site configurations. They allow to reconstitute geological history of a granite massif, its origins, its formation and the various tectonics affecting it since its crystallisation. This is mainly illustrated by reconstitution of the geological history of Hercynian granites in the Massif Central and the Massif Armoricain.

Knowledge of massif geological history is the basis for understanding its structure. It serves as support for extrapolating data collected from the surface and underground at some points in the granite, to sufficiently large volumes in the massif.

The various objects making up granite (rocks of various lithologies, hydrothermal alterations, fractures, veins, etc.) constitute elements structuring the site geological model. The aim of surveying works is to identify and characterise these objects. A vast quantity of experience feedback is available in this field: mining industry experience or repository site studies. It covers both the general approach of site surveying and the techniques implemented. The surveying strategy is largely shared at international level. It is based on an approach in stages gradually removing the uncertainties of site modelling, mainly concerning fracturing organisation on the different scales to be considered: on the scale of the granite massif, repository and repository module. It includes a final stage of "ongoing" surveying during repository operation to ensure a suitable structures siting in the granite with respect to fracturing.

Methods and techniques available are sufficiently complementary and redundant to fulfil the objectives of the successive surveying stages: geological surveys, geophysical methods and borehole measurements. Most of the techniques come under best tried and tested methods. Tests using seismic and electromagnetic methods carried out with cooperation from POSIVA in Finland illustrate the most recent progress in detecting and characterising fractures. It results in the possibility of extrapolating borehole data to increasingly larger volumes of rock, thus optimising borehole systems to be implemented.

Hydrogeological and hydro-geochemical measurements in boreholes are also sufficiently effective to assess fracture network hydraulic properties (hydraulic transmissivity and connectivity), including in the case of very slightly transmissive fractures which need to be characterised in the repository module environment.

Characterisation of granite rock and fracture mechanical properties come under best tried and tested methods. Determination of the underground geo-mechanical stress field can be based on complementary techniques (overcoring, hydraulic fracturing, etc) whose application field is well identified.

6.3 Significant acquired knowledge on the phenomenological behaviour of repository components

Control of the phenomenological behaviour of packages, buffer, backfills and seals in the disposal cells and drifts is an essential element in the demonstration of repository robustness in granite medium. For this purpose, numerous studies have been initiated by the countries aiming at siting and operating a repository in a granite massif. Significant full-scale experiments have thus been conducted *in situ* in the three laboratories of Äspö (Sweden), Grimsel (Switzerland) and Lac du Bonnet (Canada).

The "TSX" seal experiment conducted in the Canadian laboratory has demonstrated feasibility of seals composed of swelling clay of very low permeability. It identified phenomena brought into play in the hydraulic charging and bentonite swelling phase, a key stage in clay seal phenomenological evolution.

Behaviour of buffer and backfills, totally or partially composed of swelling clay, is the subject of large-scale study programmes abroad. Continuing on from the first generation of experiments in the 80s and 90s, the main current supports are the "FEBEX" experiments conducted in the Grimsel laboratory in 1997 by ENRESA and testing of a concept of spent fuel disposal in granite medium, "Prototype repository" in the Äspö laboratory which started in the year 2000, simulating the behaviour of a KBS-3 spent fuel repository with copper container, "TBT" in the Äspö laboratory since 2002, studying the reaction of buffer to thermal perturbations and "Backfill and plug", which also tests in Äspö, hydraulic performance of backfills containing clay.

These *in situ* experiments, completed by studies on mock-ups and specific analyses of clay materials, have helped to identify and model hydro-mechanical and thermo-hydro-mechanical phenomena coming into play in bentonite evolution in repository situations. In addition, numerous studies conducted on the different types of swelling clay guarantee the possibility of adapting formulations to site specificities and disposal concepts (C waste and spent fuel).

6.4 Methods for modelling radionuclides transfer and retention in granite fractures

Demonstration of performance of granite radionuclides confinement is based on control of radionuclides transport and retention phenomena by granite fractures. This significant theme has been the subject of research programmes for several decades. The “TRUE” programme, initiated by SKB, constituted a platform for international cooperation on this issue. It has established the link between, on one hand, fracture network characteristics and, on the other hand, radionuclides transfer (advection/dispersion) and retention (diffusion/sorption) phenomena.

Modelling reproduces the phenomena observed. Methods developed over the past few decades explicitly take into account fractures in increasingly larger volumes. Methods applied are sometimes complex and mainly based on statistical approaches. However, they help to establish an increasingly more direct link between fracturing characterisation of a specific granite massif and its effect in terms of performance assessment, mainly the variability in fracture hydraulic and retention properties of a granite massif. In the framework of safety analyses, they are a significant support for assessing uncertainties intrinsic to fracture network characterisation, and thus an element for controlling radionuclides transfer and retention phenomena in granite.

6.5 Taken as a whole, methods and tools for understanding and modelling repository phenomenological evolution in granite medium

The significant acquisition of knowledge concerning behaviour of both granite medium and repository engineered components provides methods and tools for reversible disposal system modelling during the operating-observation period and as well the post-closure phase.

Within a generic study context, the main uncertainties are related to granite massif fracturing organisation and distribution of its hydraulic properties. These uncertainties would be gradually reduced while characterising a specific site, mainly concerning fracturing of granite intersected by underground structures. However, uncertainties intrinsic to the knowledge of fracture distribution in a granite massif may remain and would be considered in safety analyses (Andra 2005h) and in repository architectural design.

Bibliographic references

Adler M. (2001). Interaction of claystone and hyperalkaline solutions at 30°C : A combined experimental and modelling study; Thèse de l'Université de Bern, Suisse, 119p

Aertsens M. & Van Iseghem P. (1996) Modelling Glass Dissolution with a Monte Carlo Technique. Mat. Res. Soc. Symp. Proc., 412, pp. 271-278

Ahokas H., Mäntynen M., Öhberg A. (2002). Downhole hydrogeological measurements POSIVA R&D Report 2002-12

Andersson J (2003). Site descriptive modelling-strategy for integrated evolution. SKB report R-03-05

Andra (2005a). Dossier 2005 argile Volume Évolution phénoménologique du stockage géologique. Rapport Andra n° C.RP.ADS.04.0025

Andra (2005b). Référentiel de connaissances et modèle d'inventaire des colis de déchets à haute activité et à vie longue. Rapport Andra n° C.RP.AHVL.04.0006

Andra (2005c) Projet HAVL granite Analyse fonctionnelle externe Rapport Andra G.RP.ADPG. 03.078

Andra (2005d). Projet HAVL granite Analyse fonctionnelle interne en période d'exploitation Rapport Andra G.RP.ADPG 03.079

Andra (2005e). Projet HAVL granite Analyse fonctionnelle interne en période post-fermeture Rapport Andra G.RP.ADPG 03.080

Andra (2005f). Dossier 2005 granite - Volume Architecture et gestion du stockage géologique. Rapport Andra n° G.RP.ADPG.05.0002

Andra (2005g). Analyse phénoménologique de situations de stockage en milieu granitique. Rapport Andra G.RP.ADPG.03.0086

Andra (2005h). Dossier 2005 granite. Volume Analyse de sûreté du stockage géologique-. Rapport Andra n° G.RP.ADSQ.05.0011

Andra (2005i). Référentiel de comportement des colis de déchets à haute activité et à vie longue. Rapport Andra n°C.RP.ASCM.04.0017

Andra (2005j). Référentiel de comportement des radionucléides et des toxiques chimiques d'un stockage dans le Callovo-oxfordien jusqu'à l'homme - Site de Meuse/Haute-Marne. Rapport Andra n° C.RP.ASTR.04.0032

Andra (2005k). Dimensionnement thermique d'un stockage générique en milieu granitique- Sensibilité à la variabilité des granites français Note technique Andra n° G.NT.ASTE.05.0373

Andra (2005l). Référentiel des matériaux d'un stockage de déchets à haute activité et à vie longue. 4 Volumes. Rapport Andra n° C.RP.ACSM. 04.0015

Autio J. (1997). Characterisation of the excavation disturbance caused by boring of the experimental full scale deposition holes in the research tunnel at Olkiluoto. SKB Technical report TR-97-24

Bonin B. (1990). Les granites des complexes annulaires. Collection Manuels et Méthodes n°4 ; BRGM édit. Orléans, 183p

Andra- BRGM-Antea (1999). Identification des massifs granitiques d'intérêt géologique à proposer en vue de la recherche d'un nouveau site de laboratoire souterrain. Rapport Andra n° D.RP.0ANT.99.018

Bourbon X. (2005). L'évolution chimique des ouvrages d'un stockage à base de béton : alvéoles de stockage de déchets B, appuis de scellements et de bouchons d'alvéoles, infrstructures des galeries- Site de Meuse/ Haute -Marne. Rapport Andra n° C.NT.ASCM.03.021

Brulhet J. (2005). Stabilité géologique des massifs granitiques français - Géodynamique interne et externe. Rapport Andra G.NT.ASMG.04.0061

Buschaert S. (2004) Apport de l'hydrogéochimie à l'étude des massifs granitiques. Rapport Andra n° G.RP.ASTR.02.031.

Cathelineau M., Fourcade S. (2005). Traçage des percolations de fluides et calage thermo-chronologique de l'évolution des socles cristallins : apport de l'étude des remplissages de fractures de l'ouest de la chaîne varisque. GdR Forpro action 98-III (extension) rapport final (draft)

Chandler N.A. et al. (2002). The five year report on the tunnel sealing experiment : an international project of AECL. Rapport JNC, ANDRA and WIPP, n° AECL-12127

Chappel B. W., White A.J.R. (1974). Two contrasting granite types. Pacific Geol. 8, 173-4

Chermak J.A. (1992a). Low temperature experimental investigation of the effect of high pH KOH solutions on the Opalinus Shale, Switzerland. Clays Clay Miner, 41, pp. 365-372

Chermak J.A. (1992b). Low temperature experimental investigation of the effect of high pH NaOH solutions on the Opalinus Shale, Switzerland. Clays Clay Miner, 40, pp. 650-658

Clarke D.B. (1992). Granitoïd Rocks ; Collect. Topics in the Earth Sciences n°7. Chapman and Hall edit. London ; 283 p

Côme B (1988). Evacuation géologique des déchets radioactifs. Dans « La thermomécanique des roches » Manuel et méthodes, P. Berest et Ph. Weber éditeurs

Commission Européenne (1982). Investigation par forages profonds du granite d'Aurait. Etude des possibilités de stockage des déchets radioactifs dans les terrains cristallins. Rapport EUR 8178 FR

Commission Européenne (1997). Evaluation of elements responsible for the effective engaged dose rates associated with the final storage of radioactive waste : Everest project. Vol. 4: Granite formation, site in France two apporaches and common conlusions on granite. EC report EUR 17449/4 EN

Commission Européenne (2000). Spent fuel disposal performance assessment (SPA project). EC report EUR 19132 EN

Cornet F.H. et Burlet D (1992). Stress field determination in France by hydraulic tests in boreholes. Journal of Geophysical Research, 97 (B8) ; 11829-11849

Derhowitz W., Winberg A., Hermanson J., Byegârd J., Tullborg E-L., Andersson P., Mazurek M., (2003). Äspö task force on modelling of groundwater flow and transort of solutes - Task 6c- A semi-synthetic model of block scale conductive structures at the Äspö HRL. SKB report IPR-03-13

De Dreuzy J.R., Darcel C., Davy P. et Bour O. (2004). Influence of spatial correlation of fracture centers on the permeability of two-dimensional fracture networks following a power law length distribution. Water Resources Research, v. 109

De Windt L., Pellegrini D. & van der Lee J. (2004). Coupled modeling of cement/claystone interactions and radionuclide migration. J. Contam. Hydrol., 68, pp. 165-182

Enescu N., Cosma C., Balu L. (2004). Reflection seismics using boreholes at Olkiluoto in 2003 - from investigation design to result validation. POSIVA Working Report 2004-62

ENRESA (2002). Expérience "FEBEX" Mid-term report. Rapport EC

Fillet S. (1987). Mécanisme de corrosion et comportement des actinides dans le verre nucléaire "R7T7". Thèse de l'Université du Languedoc, Montpellier, France, 338p.

Ganster P. (2004). Modélisation de verres intervenant dans le conditionnement des déchets radioactifs par dynamiques moléculaires classique et ab initio; Thèse de l'Université de Montpellier, 177 p

Garcia,M, Caussade (2002). Intégrating spacially variying capillary pressure functions in the simulation of GAM gas tracer tests. Rapport Andra D.RP.0FSS.02.001

Gaucher E., Blanc P., Matray J.M. & Michau N. (2004) Modeling diffusion of an alkaline plume in a clay. Appl. Geochem, Vol. 19, pp. 1505-1515

Genter A., Castaing C., Gros Y., Chilès J.P. (2000). Différences et invariants dans l'organisation de la fracturation des granites. Coopération scientifique Andra-BRGM. Rapport BRGM / RP-50115-FR

Geotti-Bianchini F., De Riu L., Gagliardi G., Guglielmi M. & Pantano C.G. (1991). New interpretation of the IR reflectance spectra of SiO2-rich films soda-lime glass. Glastech. Ber. - Glass Sci. Technol., 64, 8, pp. 205-217

Giffaut E. (2005). La solubilité et la rétention de radionucléides et de toxiques chimiques au sein des alvéoles de stockage de déchets B- Site de Meuse/Haute-Marne. Rapport Andra n° C.NT.ASTR.03.106

Giffaut E et Coelho D. (2005). La solunilité, la rétention et le transport de radionucléides et de toxiques chimiques au sein d'alvéoles de stockage de colis de déchets C et de combustibles usés- Site de Meuse/ Haute-Marne. Rapport Andra n° C.NT.ASTR.03.108

Golder (2005). Modeling of fractured granite rock: Hydrogeological modelling and transport modelling- Granite pluton: M1. Rapport Andra G.RP.0GOL.04.0003

Gray, M-N. (1993). OCDE/AEN International Stripa Project 1980-1992- Overview - Vol. 3: Engineered Barriers. OCDE/AEN Publication

Gunnarsson D. (2004). Enginneering studies relating to the project for an underground repository for high-level, long-lived radioactive waste- Study on drift backfilling technology Rapport Andra n° G.RP.1SKB 04-0002

Hlavacek M. C.P., Doods J.A. & Sardin M. (1995). Interpreting titration data of aqueous lattices by coupling surface ionisation and ion exchange equilibria. Colloïds and Surfaces. A: Physicochemical and Engineering Aspects, 95, pp. 101-111

Heikkinen E., Ahokas T., Saksa P. (2004). Interpretation of Olkiluoto electormagnetic Gefinax 400S soundings and pole-pole electrical soundings. POSIVA Working Report 2004-16

Hökmark H., Ledesma A., Lassabatère T., Fälth B., Börgesson L., Robinet J-C., Sellati N., Sémété P. (2005). Modelling heat and moisture transport in the Andra/SKB Temperature Buffer Test. Clays in natural and engineered barriers for radioactive waste; International meeting, March 14-18, Tours, France

Johannesson L-E., Börgesson L., Goudarzi R., Sandén T. (2005). Prototype repository; a full scale experiment at Äspö HRL. Clays in natural and engineered barriers for radioactive waste; International meeting, March 14-18, Tours, France

Jacquot E. & Michau N. (2005). La perturbation alcaline liée à un stockage : les argilites du Callovo-Oxfordien en champ proche et les composants à base d'argile gonflante - Site de Meuse/Haute-Marne. Rapport Andra n° C.NT.ASTR.03.069

Joubert J.M. (1998). Synthèse des reconnaissances hydrogéologiques - Site de la Vienne. Rapport Andra n° D.RP. OANT. 97.059

Laaksoharju M., Skärman C. (1995). Groudwater sampling and chemical characterisation of the HRR tunnel at Äspö, Sweden. SKB Progress Report 25-05-29

Laaksoharju M., Gurban I., Skärman C. (1998). Summary of hydrochemical conditions at Aberg, Berberg and Ceberg, SKB Technical report TR-98-03

Ledieu A. (2004). Altération par l'eau des verres borosilicatés : expériences, modélisation et simulations Monte-Carlo ; thèse de l'École Polytechnique, 190 p

Leutsch Y., Roux J., (2005). Méthodes de reconnaissance d'un granite affleurant. Rapport Andra n° G.RP.ADPG.02.016

Marre J. (1982). Méthodes d'analyse structurale des granitoïdes. Collection Manuels et Méthodes n° 3. Éditions BRGM, Orléans, 128p

Martin C.D., Read R.S. (1996). AECL's Mine-by Experiment - A test tunnel in brittle rock. In Proc. 2nd North American Rock Mechanics Symposium, Montreal (Ed. M.Aubertin, F.Hassani and H.Mitri) A.A Balkema, Rotterdam

Martin D., Su K. (2005). Thermo-hydro mechanical behaviour of a granitic rock and of its fracture network in the vicinity of a radwaste disposal- Scientific key questions and stakes in conceptual design Rapport Andra n° G.RP.ASMG. 95-0018

Mäder, U & Frieg, B. (2004). Nagra AN-04-216, 17 Nov. 2004 - Grimsel Test Site (Phase V) - Extended Minutes of the 12th HPF Project Meeting, Meiringen (Nagra), May 26-28, 2004

Möri A. et al.(2003). Grimsel test site The Nagra-JNC in situ study of safety relevant radionuclide retardation in fractured crystalline rock - IV The in situ study of matrix porosity in the vicinity of a water conducting fracture. Nagra Technical Report 00-08

Mosser-Ruck R. & Cathelineau M. (2004). Expérimental transformation of Na, Ca-smectite under basic conditions at 150°C. App. Clay Sci., 26, pp. 259-273

Munier R., Stenberg L, Stanfors R., Milnes, A.G., Hermanson J., Triumf C-A. (2003). Geological site descriptive model- a strategy for the model development during site investigation SKB report R-03-07

Munier I., Crovisier J.-L., Grambow B., Fritz B. & Clément A. (2004). Modelling the alteration gel composition of simplified borosilicate glasses by precipitation of an ideal solid solution in equilibrium with leachant. J. Nuclear Mat., 324, 2/3, pp. 97-115

Nagra (1999a). Diffusion and sorption on hardened cement pastes - experiments and modelling results. Rapport Technique Nagra n° 99-05

Olsson O., Emsley S., Bauer C., Falls S., Stenberg L. (1996). ZEDEX - A study of the zone of excavation disturbance for blasted and bored tunnels. SKB ICR report ICR 96-03.

Ouillon G. (1995). Application de l'analyse multi fractale et de la transformée en ondelettes anisotropes à la caractérisation géométrique multi échelle des réseaux de failles et de fractures. Documents du BRGM n°246, Éditions BRGM Orléans, 313p

Pearce J.A., Harris N.B.W. et Tindle A.G. (1984). Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. J. Petrol. 25, 956 - 83

Pitcher W.S. (1993). The nature and origin of granite. Blackie Academic and Professional, an imprint of Chapman and Hall edit. London, 321 p

POSIVA (2003a). ONKALO underground Characterisation and Research Programme (UCRP). POSIVA report 2003-03

POSIVA (2003b). Assessment of disturbances caused by construction and operation of ONKALO. POSIVA report 2003-06

Puigdomenech et al. (2001). O2 depletion in granitic media- The REX project. SKB report TR-01-05

Pusch R. (2003). The buffer and backfill handbook Part 3: Models fro calculation of processes and behaviour. SKB Technical report TR-03-07

Rhén I., Follin S., Hermanson J. (2003). Hydrologic site descriptive model- a strategy for its development during site investigations

Riss J., Gentier S., Archambault G., Flamand R. (1997). Sheared rock joints : Dependence of damage zones on morphological anisotropy. Int. J. Rock Mech. & Min. Sci., 36th U.S. Rock Mechanics Symposium, New York, 1997, 34 (3-4), paper n°258

Saario T. (2004). Effect of the degree of compaction of bentonite on the general corrosion rate of copper, Eurocorr 2004, Proceedings of the 2nd Internationnal Workshop « Prediction of Long Term Corrosion Behaviour in Nuclear Waste Systems », Publication Andra, Science and Technology Series, ISBN 2-9510108-6-9

Sandén T., De Combarieu M., Goudarzi R., Akesson M., Hökmark H. (2005). Temperature Buffer Test - Design, intrumentation and measurements. Clays in natural and engineered barriers for radioactive waste ; International meeting, March 14-18, Tours, France

Savage D., Noy D. & Mihara M. (2002). Modelling the interaction of bentonite with hyperalkaline fluids. Appl. Geochem, 17, pp. 207-223

Scholze H. (1991). Glass : Nature, Structure, and properties. Ed. Springer-Verlag. 454 p

SKB (1999a) SR 97. Deep repository for spent nuclear fuel, SR 97- Post closure safety. Main report- Vol.I, Vol.II and summary SKB Technical report TR-99-06

SKB (1999b) SR 97. Processes in the repository evolution. Background report to SR97 SKB Technical report TR- 99-07

SKB (1999c) SR 97. Data and data uncertainties Compilation of data and data uncertainties for radionuclide transport calculations SKB Technical report TR-99-06

SKB (2002). HRL hydro monitoring program- Report for 2001- SKB Report IPR-02-56

SKB (2004a). Interim process report for the safety assessment SR-Can SKB report R-04-33

SKB (2004b). Site Investigation Oskarshamn. Annual Report 2003

SKB (2004c). Site Investigation Forsmark. Annual Report 2003

Smith J., Qin Z., Shoesmith D.W., King F. & Werme L. (2004) Corrosion of copper nuclear waste containers in aqueous sulphide solutions. Mat. Res. Soc. Symp. 824 pp. CCI 12.1-12.6

Smith P.A., Alexander, W.R., Heer, W., Meier, P.M., Baeyens, B., Bradbury, M.H., Mazurek, M. & McKinley, I.G. (2001) : The Nagra-JNC in situ study of safety relevant radionuclide migration experiment - overview of investigations 1990-1996. Nagra Technical Report NTB 00-09, Nagra, Wettingen, Switzerland

Stephansson O, Hudson J., Jing L.(2003) Proc. International conference on coupled T-H-M-C processes in Geo-systems: Fundamentals, Modelling, Experiments and Applications, GeoPorc2003, Stockholm

Streckeisen A. (1976) .To each plutonic rock its proper name. Earth Sci. Rev.12, 1-33

Talandier J. (2005). La production et le transfert de gaz dans un stockage et dans la couche du Callovo-Oxfordien - Lien avec le transitoire hydraulique - Site de Meuse/Haute-Marne. Rapport Andra n° C.NT.ASCM.03.0042

Taubald H., Bauer A., Schäfer T., Geckeis H., Satir M. & Kim J.L. (2000). Experimental investigation of the effect of high-pH solutions on Opalinus Shale and theHammerschmiede smectite. Clay Minerals, 35, pp. 515-524

Valle N. (2001). Traçage isotopique (29Si et 18O) des mécanismes de l'altération du verre de confinement des déchets nucléaires : SON 68. Thèse de l'Université de Lorraine, Nancy, France. 260 p

Vidstrand P. (2003). Äspö Hard Rock Laboratory Update of the hydrogeological model 2002. SKB International Progress Report IPR-03-35

Vieillard P., Ramirez S., Bouchet A., Cassagnabère A., Meunier A. & Jacquot E. (2004). Alteration of the Callovo-Oxfordian Clay from Meuse/Haute-Marne underground laboratory (France) by alkaline solutions : II. Modelling of mineral reactions. Applied Geochemistry, 19, pp. 1699-1709

Villar M.V., Lloret A. (2005). Dismantling of the 1st section of the Febex in situ test: THM laboratory tests on the bentonite block retrieved. Clays in natural and engineered barriers for radioactive waste ; International meeting, March 14-18, Tours, France

Virlogeux D. (2002a). Typologie des massifs granitiques français - Questions liées à la stabilité (géomécanique et sismicité). Note technique Andra G.NT.ADPG.02.046

Virlogeux D. (2002b). Typologie des massifs granitiques français - Questions liées à la géomorphologie et à l’hydrogéologie. Note technique Andra G.NT.ADPG.02.048

Virlogeux D. (2005). Typologie des massifs granitiques français - Questions liées à la diffusion et à la rétention- Note technique Andra G.NT.ADPG.02.0047

Winberg A. et al. (2003). Final report of the TRUE Block project ; 4. Synthesis of flow, transport and retention in the block scale. SKB Technical Report TR-02-16

Wojtkowiak F. (1986). Les granites, propriétés thermiques, mécaniques et hydrauliques. Rapport BRGM 86 SGN 740 STO

Wright A.C. (1994). Neutron scattering from vitreous silica. V. The structure of vitreous silica: What have we learned from 60 years of diffraction studies? J. Non-Crist. Solids, 179, pp. 84-115

Zachariensen W.H. (1932). The atomic arrangement in glass. J. Am. Chem. Soc., 54, pp. 3841-3851

Zachariensen W.H. (1933). Die Struktur der Gläser. Glastech. Ber. - Glass Sci. Technol., 11, 4, pp. 120-123

Zarzycki J. (1982). Les verres et l'état vitreux. Ed. Masson, 391p

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