Session II

EXAMPLES OF KEY PROCESSES AFFECTING THE GEOSPHERE FOR CRYSTALLINE ROCK

LIKELIHOOD OF TECTONIC ACTIVITY AFFECTING THE GEOLOGICAL STABILITY OF A REPOSITORY IN JAPAN: DEVELOPMENT OF NUMO'S ITM METHODOLOGY

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Abstract

We define the structure of a methodology being developed by NUMO to assess the likelihood that volcanic or rock deformation processes could significantly affect sites that may emerge from the Japanese volunteer siting process. Simple criteria are used to exclude clearly unsuitable areas at the outset: the present methodology is developing probabilistic techniques to look at likelihood in non-excluded areas. These are based on scientific models for the occurrence of volcanism and a range of proxy indicators for potential future rock deformation.

Introduction

The potential for volcanic and rock deformation impacts on a repository must be considered at each stage of NUMO's programme for siting its geological repository for HLW (Tsuchi *et al.,* 2005). Nationwide evaluation factors for qualification (EFQs) of sites as Preliminary Investigation Areas (PIAs) were designed to remove clearly unsuitable sites from consideration, but cannot guarantee that, over tens of thousands of years, the risks of tectonic hazard for a chosen PIA will be acceptable. Large parts of Japan that are potentially suitable for siting are directly affected to varying extents by rock deformation, the peripheral impacts of volcanic activity or the possibility of new magma intrusion or volcanic activity. The EFQs were intended as a "blunt instrument" to prevent obviously poor candidates entering the siting process. Consequently, additional "sharper" and more refined techniques are required to evaluate sites that pass the EFQ test, so that NUMO can have a clear idea of the likelihood and potential impacts of tectonic events and processes at each PIA. The ITM project aims to provide NUMO with such a methodology, based upon state-of-the-art approaches used internationally, developed and extended for the specific purposes of NUMO and the specific conditions of Japan: hereafter, we refer to it as the **"**ITM Methodology**"**.

The methodology can be used at three important stages of NUMO's siting programme:

- SITING STAGE 1: during the literature survey (LS) stage when potential PIAs are being assessed. The ITM methodology will use currently available information to allow comparison of sites in terms of confidence that they are likely to prove acceptable with respect to tectonic impacts.
- SITING STAGE 2: during the planning of the PIA site investigations, to identify geoscientific information requirements that will be needed to refine the Stage 1 analysis.
- SITING STAGE 3: at the point where PIAs are being evaluated and compared in order to select a preferred site (or sites) for detailed investigation (as DIAs).

To date, the ITM project has been mainly concerned with Stage 1. Application of the methodology in Siting Stage 3 is several years into the future and it will be most efficient to carry out any necessary updates/refinements on a region-specific basis during the PIA investigations when NUMO has narrowed down to a group of sites.

This short paper is intended to outline only the methodological approach being developed and does not present details of the results that have been obtained so far, although some results will be illustrated in the workshop presentation.

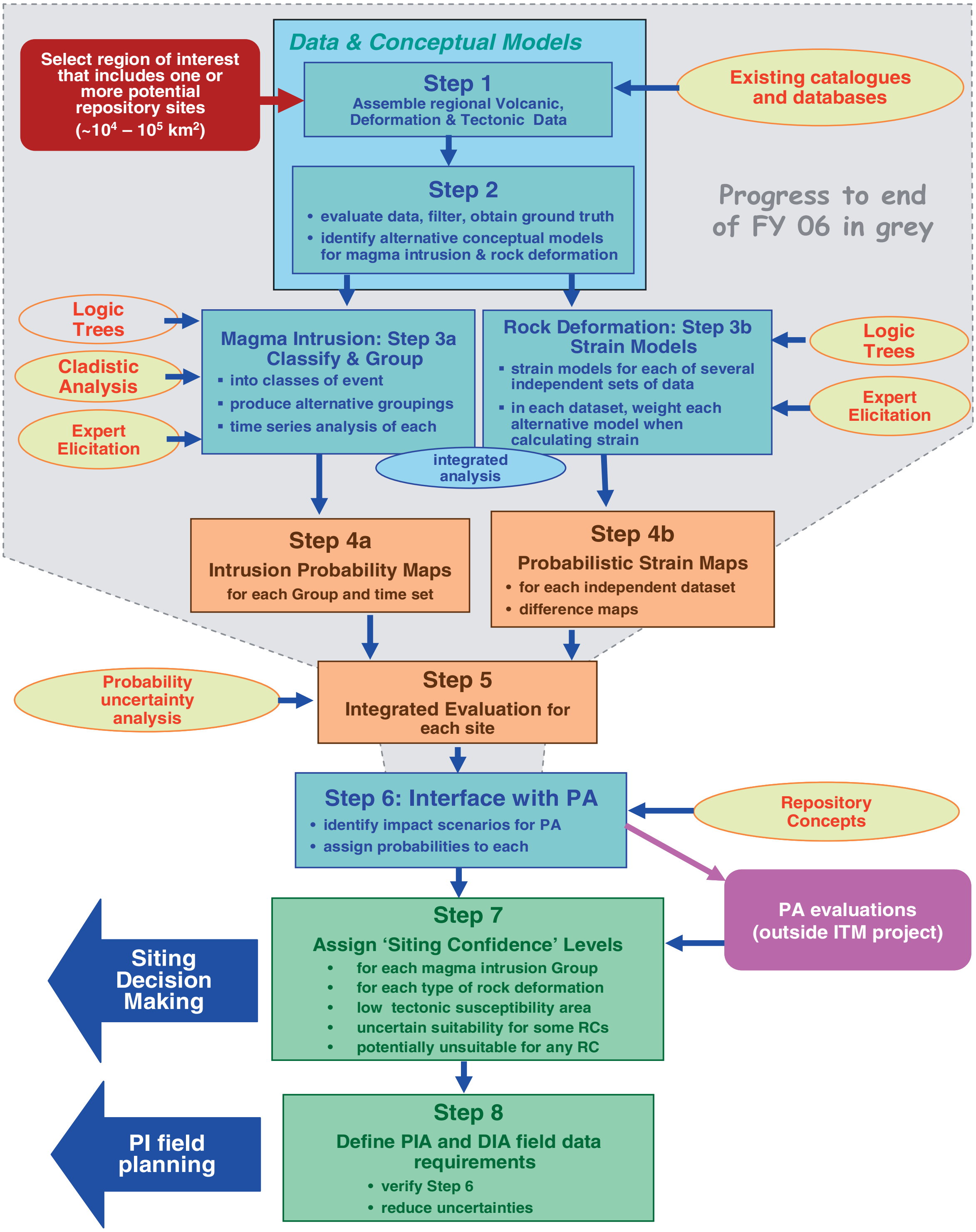
Outline of the ITM Methodology

The overall structure of the ITM methodology consists of:

- assembling nationally available data and alternative models of the nature, causes and locations of tectonic processes and events;
- using probabilistic techniques to evaluate the likelihood and scale of future tectonic processes and events, shown as a function of their type and geographical distribution;
- feeding information on these potential likelihoods and impacts to NUMO's performance assessment team so that feedback can be provided on repository performance under tectonic stress;
- providing clearly justified and traceable input to decision-making on consequent site suitability.

A probabilistic approach has been selected for the ITM methodology as it is seen as the only realistic means of addressing the uncertainties in predicting possible hazards when there is such variability in the spatial distribution, the timing, the intensity and the style of the volcanic and deformational events and processes being evaluated. Naturally, the probabilistic approach being developed is based upon and strongly supported by deterministic models of the underlying tectonic processes that lead to magma intrusion, volcanism and rock deformation.

ITM is developing its approaches for rock deformation and volcanic hazards as parallel tasks. The concept of each approach is similar but, in some parts of the methodology, they differ in detail. The broad structure is shown in more detail in the top-level "road-map" in the Figure. It comprises a series of eight Steps distinguishing between the "rock deformation" approach and the "volcanic" approach, where they involve significantly different activities. These are described below.


Select region of interest that includes one or more potential repository sites
(~10^4 – 10^5 km^2)
Data & Conceptual Models
Step 1
Assemble regional Volcanic, Deformation & Tectonic Data
Existing catalogues and databases
Step 2
• evaluate data, filter, obtain ground truth
• identify alternative conceptual models for magma intrusion & rock deformation
Progress to end of FY 06 in grey
Logic Trees
Cladistic Analysis
Expert Elicitation
Magma Intrusion: Step 3a
Classify & Group
▪ into classes of event
▪ produce alternative groupings
▪ time series analysis of each
Rock Deformation: Step 3b
Strain Models
▪ strain models for each of several independent sets of data
▪ in each dataset, weight each alternative model when calculating strain
Logic Trees
Expert Elicitation
integrated analysis
Step 4a
Intrusion Probability Maps
for each Group and time set
Step 4b
Probabilistic Strain Maps
• for each independent dataset
• difference maps
Probability uncertainty analysis
Step 5
Integrated Evaluation for each site
Step 6: Interface with PA
• identify impact scenarios for PA
• assign probabilities to each
Repository Concepts
PA evaluations (outside ITM project)
Step 7
Assign ‘Siting Confidence’ Levels
• for each magma intrusion Group
• for each type of rock deformation
• low tectonic susceptibility area
• uncertain suitability for some RCs
• potentially unsuitable for any RC
Siting Decision Making
Step 8
Define PIA and DIA field data requirements
• verify Step 6
• reduce uncertainties
PI field planning

STEP 1: Assembling the Data

Step 1.1: Define region of interest: The region of interest is defined. For the development work, we use two Case Study areas. Tohoku, in Honshu, was selected principally to develop an approach to assessing the likelihood of new polygenetic volcanic activity in areas not affected by magma intrusion in the last ~2 Ma. It also provides a test-bed for developing the rock deformation methodology and for looking at the combined effects of magma intrusion on rock deformation processes. The second Case Study area is the island of Kyushu, which displays qualitatively and quantitatively different drivers and manifestations of rock deformation, as well as allowing the volcanic methodology to be extended to assess monogenetic volcanism.

In Siting Stage 1 (the LS stage), we expect the region of interest identified around a site, or group of nearby sites, to be ~10^4 – 10^5 km^2. Regions need to be large enough to contain a statistically large enough number of features that are manifestations of the processes being evaluated (e.g. volcanic edifices) and a spread of data-points for modelling these processes (e.g. GPS stations).

Step 1.2: Data gathering: Data are obtained from the literature to constrain possible models of magma intrusion and rock deformation. The principal source data have been: topographic maps (onshore and offshore); gravity maps; volcanic edifices/features location, nature and age (Catalogue of Quaternary Volcanoes); national onshore and offshore active fault map; recorded distribution of seismic events (locations, magnitudes, depths); GPS strain records for all monitoring stations. Additional geological maps, heat flow data and interpretations of the geological, structural and tectonic histories of the region are needed to support the development of conceptual models of the processes of interest (in Step 3).

STEP 2: Sorting the Data and Identifying Alternative Conceptual Models

Step 2.1: Data Sifting and Ground-truth: The databases used were not gathered for the specific purposes of the ITM methodology so they are not necessarily organised in an appropriate fashion, with data in the form in which they will be used in Steps 3 and 4. This Step requires a close evaluation of what the data actually represent and whether datasets are internally consistent and of uniform quality. Experience from the Tohoku Case Study shows that it is essential to obtain ‘ground truth’ on observations included in some of the databases.

Step 2.2: Underlying Conceptual Geological Models: These need to be identified (or developed) to explain the distribution of features (volcanic edifices) and different styles of rock deformation. In simple terms, the models are as follows:

- Distribution of polygenetic volcanoes in the Tohoku region: during the Quaternary, and for the next tens of thousands of years (up to ~100 ka) this is controlled by variable magma generation potential in the mantle overlying the subducting oceanic plates. The origin of this variability is not fully understood but is manifest in “clusters” of volcanoes with intervening ‘gaps’ in the Tohoku region. The distribution of clusters and gaps is correlated to varying extents to gravity, basement topography and the seismic tomographic structure of the crust and mantle wedge beneath the Japanese archipelago.
- Distribution of monogenetic volcanoes: correlations are being explored and a specific database of monogenetic volcanism is being developed to support ITM methodology development as we move further into the Kyushu Case Study.
- **Regional and local strain budgets:** the upper crustal rocks of the Japanese archipelago are undergoing progressive deformation as a result of horizontal and vertical strain responses to

dynamic plate tectonic forces. The amount and style of deformation varies from region to region depending on the geological formations present and the location with respect to the major plate boundaries and other large-scale deformation zone features, such as major (>100 km long) strike-slip fault zones. Deformation includes compression, extension, subsidence and elevation. The resultant strain is manifest as faulting (episodic movement along Quaternary active faults), folding and rotation of major tectonic blocks. The overall strain 'budget' for an area is accessible using a range of indicators, each of which characterises different strain manifestations: GPS data on relative surface movements; slip rates along active fault zones; coseismic movements, accessible through the seismological database; uplift/subsidence rate.

STEP 3a: Classifying and Grouping Magma Intrusion Features

For the evaluation of possible future magma intrusion in areas that have not been affected by intrusion in the last ~2 Ma, it is first essential to classify the indicators of past intrusion (the mapped volcanic features in the Quaternary catalogue). No internationally accepted scheme of volcano classification exists, so the ITM methodology has had to develop one.

Step 3a.1: Cladistic analysis: A cladistic approach has been developed to facilitate this classification (Hone *et al.,* 2007 in press). It involves defining characteristic properties (such as size, morphology, age, chemical composition, intrusive or eruption style) to each mapped feature and then using an analysis package (PAUP) to assess all possible ways of grouping the features using these characteristics. The different groups are called clades: we use the term "Alternative Group". The cladistic method has been found to work well for polygenetic volcanoes and provides a deeper understanding of the strengths and limitations of the volcano database.

Step 3a.2. Database analysis: identification of alternative datasets that can be used in the probabilistic analysis: using the clade groups and field data to verify alternative groupings of volcanoes and volcanic features.

Step 3a.3: Time-series analysis: of each alternative dataset to assess whether they display different periodicity (dormancy and activity) and whether this periodicity is structured (i.e. related to eruption history, rather than being random), which is used in Step 4a.

Step 3a.4: Sensitivity analysis: to test the sensitivity of the groupings to the size of the region considered (by extending or reducing the area the number of edifices included is increased or reduced and the statistical groupings may change) and by adding "synthetic" volcanoes: a large change in group characteristics could indicate model instability.

STEP 3b: Developing Strain Models and Estimating Strain Rates for each

For rock deformation, the objective is to calculate strain rates across the region of interest using independent data sources that reflect widely different time averaging: GPS areal strain (years), active fault strains (tens of thousands of years) and seismic strains from the seismic moment of earthquakes (centuries). These can then be compared and, in Step 4b, presented as strain maps.

Each data source may indicate strains that are the result of one or more processes, for each of which there may be alternative tectonic models and interpretations (e.g. boundaries of regions that can be defined as discrete tectonic blocks, dips of major fault zones, amount, degree and depth of subduction coupling). The way that strain is calculated from the raw data will need to account for the relative contributions of these different processes, factoring in the inherent uncertainty introduced by having alternative conceptual models. The contribution from different processes is estimated by expert judgement on the importance of different processes/mechanisms (reflecting the alternative conceptualisations of what drives rock deformation in the region).

Step 3b.1: Defining tectonic blocks: to consider whether the region of interest (or an even larger area if appropriate) can be divided into stable rock blocks that behave internally in a relatively homogeneous way or respond in a similar way to external, large scale tectonic driving processes. This assessment forms the basis for the subsequent development of strain models and there may be alternative ways of defining such blocks, which affects the number of models developed.

Step 3b.2: Assembling alternative conceptual models in a Logic Tree: this brings together all alternative conceptual models identified and is constructed by asking questions of the form: 'How many alternative explanations (models) could describe strain in this block?'; "If Model A is correct, what are the alternative ways of describing its impact on deformation?" A tree is generated that incorporates as many alternative conceptualisations of deformation mechanisms and associated uncertainties as are deemed feasible. Following down any one branch to the end defines how strain will need to be calculated for that particular set of model assumptions. Expert judgement, elicited from a group of experts in Japanese tectonics at a workshop, is factored into the construction of the tree to ensure that it is sufficiently comprehensive of alternative models. The experts then contribute by agreeing weightings for each branch (degree of belief in the validity of each conceptualisation). Each strain indicator requires its own Logic Tree, in order to calculate strain rates. The three indicators used to date to estimate strain are:

- Active fault slip rate + process region (i.e. width of fault zone) = mm/km/yr strain. The period over which this indicator has "recorded" strain is ~10 000s years.
- Gradients in GPS velocity = mm/km/yr strain. The period over which this indicator has 'recorded' strain is ~10s years.
- Recorded earthquakes = seismic moment + Kostrov equation (seismic strain rate as a function of the sum of seismic moment tensors of all earthquakes occurring in a given volume of crust during a given time-interval) = strain. The period over which this indicator has 'recorded' strain is ~100s years.

Despite the fact that these indicators record strain over many orders of magnitude of time, the processes that they are recording are widely considered to have been stable in magnitude and direction for about 100 000 years. The uplift/subsidence indicator that will be included in future (to complete this part of the methodology) will also address timescales ~100 000s years.

Step 3b.3: Calculating strain rates**:** For the GPS Logic Tree there were 148 different strain models (branches) for the Tohoku region. The strain rates for each of these are calculated separately and as a weighted average. A histogram can be produced of the frequency of calculated strains of a given magnitude, using all the model results

STEP 4a: Magma Intrusion Probability Maps

Step 4a.1: Assessing Correlations: how far the spatial distribution of volcanoes can be correlated with topographical and geophysical indicators of crustal processes. This provides evidence that distribution is not simply random. The check can be made both for all volcanoes in the region of interest and for the groupings derived from Step 3a. The probabilities and related uncertainties can then be suitably weighted to reflect these correlations. In the Tohoku Case Study, the broad distribution of volcanoes is correlated to the isostatic gravity anomaly map of the region. The isostatic anomalies reflect magma generation potential, with the rate of magma accumulation at the intra-crustal

Conrad discontinuity and, possibly, the rate of magma flux at the surface (hence the likelihood of future volcanicity) being indicated by isostatic anomalies.

Step 4a.2: Calculating probabilities of magma intrusion: For the probabilistic mapping, three types of probability could be estimated:

- P1 – recurrence rate of volcano edifice forming in the region of interest during the period of interest (e.g. 2 x 10^{-4} per year)
- P2 – given that a volcano edifice forms, the probability that it will form in a specific area, such as a region extending to 15 km beyond the boundaries of the PIA (e.g. 1 x 10^{-4} / km^2);
- P3 – given that a volcanic event occurs in this specific area, the probability that it will impact the repository site itself.

A variety of well-developed statistical methods is available for estimating such probabilities, and the estimations can be done either for all magma intrusion modes or for the various groupings defined in Step 3a. For subsequent assessment of impact scenarios in Step 6 it is important to assess the probability of different types of event occurring, so looking at each cladisitic group is a primary strategy of the ITM methodology. To date, only P1 has been addressed and the data available from the Case Studies have been used to produce regional probability maps. Geostatistical and Bayesian methodologies provide a way to assess conceptual, spatial and parametric uncertainty. The methods used so far are a Kernel Method (generation of a non-homogeneous distribution map, using a Gaussian or Epanechnikov kernel method, with an applied smoothing function) and the Cox Process Method, which uses different sets of geoscientific data (to date, 3-D seismic velocity tomography of the crust and upper mantle on the assumption that the structures seen are related to magma generation potential: Jaquet *et al.,* 2006).

STEP 4b: Probabilistic Strain Maps

Step 4b.1: Constructing different strain maps: For each indicator, the calculated strain rates from Step 3b are converted to strain maps for each conceptual model branch of the Logic Tree. The maps show calculated strains within 5 km x 5 km areas: a reasonable resolution for the datasets used and a useful size with respect to expected repository footprint (~10 km^2). Strain rates are also combined on a single map, using the weightings assigned to each branch of the Logic Tree. The weighted map is thus a probabilistic representation of strain, representing the most likely strain averaged over the time period for which the particular indicator has been 'recording'.

Step 4b.2: Comparison and differencing: The weighted, probabilistic maps for each separate indicator are compared and differenced, to pick out areas where the datasets are inconsistent in their strain estimates. Combined with the variability shown in the strain rate histograms for any selected area, such inconsistencies will identify locations where there is significant uncertainty regarding deformation process, which may also be reflected in a wider range of strain rate potential. If a potential repository site lies within such a region, this would require special attention in Step 8, to ensure that adequate data were gathered during the PIA investigation programme to try to reduce the uncertainty.

STEP 5: Integrated Evaluation of Each Potential Repository Site

Depending on the location of the sites it may be necessary to carry out a combined magma intrusion and rock deformation evaluation. A combined, higher level logic tree can weight belief in relevance of the strain measures and factor volcanic strain into the weighting process. Individual site assessments will provide a description of the geological and tectonic setting, an evaluation of the likelihood of each type of magma intrusion considered possible, in both the region around the site and at the site itself, over a period of up to 100 000 years[1], an evaluation of the uncertainties in the likelihoods and an evaluation of the best estimate rock deformation potential (expressed as strain probability histograms) and mechanisms over the same period of time – and the related uncertainties.

STEP 6: Interfacing with the NUMO Performance Assessment work

The methodology up to this stage is designed to deliver a set of probability maps that have taken account of uncertainty in both conceptual models and data and which contain integrated interpretations of the sites being investigated. ITM also provides the PA team with information on the nature of the tectonic hazards:

1. Description of the nature of each magma intrusion event and rock deformation process that could feasibly affect the repository.
2. Likelihood of each magma intrusion event impacting both the repository directly and the surrounding rock mass.
3. Variation of this probability with time over the next 100 000 years.
4. Best estimate of magnitude and duration of rock deformation that could affect the repository.
5. Description of how the events and processes would initiate, develop and progressively impact the repository and the barriers.

Using this information, the PA team will be able to develop scenarios for tectonic impacts and assign probabilities to them.

STEP 7: Assigning "Siting Confidence" Levels

This Step will involve joint input from the ITM group and the PA team. The objective of this Step is to allow NUMO to make a judgement on the importance of future tectonic hazards at each site. This will first be done during the LS stage. This judgement will form an important aspect of the justification of NUMO's overall decision-making process on site suitability. This aspect of the ITM Methodology is not described in the current paper.

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[1] The methodology could be developed to provide estimates for 1 Ma, but would require the use of much larger (longer duration, ~10 Ma) datasets and would involve greater uncertainties (especially concerning the time stability of the underlying tectonic processes). Knowledge of future volcanic hazard is, in any case, of diminishing interest for safety assessment at times, even after only 10 000 years, as the hazard of the waste has decreased to levels equivalent to natural uranium ores by this stage.

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CLIMATE CHANGE AND ITS POTENTIAL IMPACT ON MECHANICAL, HYDRAULIC AND CHEMICAL CONDITIONS

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Abstract

The strategy for managing climate related conditions in SKB's safety assessments are based on the notion that it is not possible to predict climate in a 100 000-year time perspective. Instead, the approach in the SR-Can safety assessment was to identify and analyse both moderate climate evolutions as well as extremes within which the climate in Scandinavia may vary. To this end, knowledge on general climate variations in Scandinavia was used to identify characteristic climate domains which in turn were used to build a number of selected climate scenarios. The relevant climate domains for the Forsmark and Laxemar sites in the 100 000-year time perspective are; 1) a temperate climate domain, 2) a periglacial climate domain, and 3) a glacial climate domain. Also submerged/non-submerged conditions at the sites are of importance. In the SR-Can safety assessment several climate scenarios were investigated, including a reference evolution based on a repetition of reconstructed conditions for last glacial cycle (the Weichselian glaciation and the Holocene interglacial). For this reconstruction, extensive numerical simulations of ice sheets, isostatic changes, and permafrost were conducted. The resulting scenario showed site-specific timing and duration of the three climate domains and submerged periods for the full glacial cycle. This scenario is not a prediction of a future climate evolution. Instead it is one example of a future evolution that in a realistic and consistent way covers all relevant climate related changes that can be expected in a 100 000-year time perspective. Subsequently, this scenario formed the basis for the construction of additional climate scenarios that were used to analyse the effects of more extreme climate evolutions than during the last glacial cycle. Examples of complementary scenarios are a warmer and wetter climate scenario caused by an increased greenhouse effect, and colder scenarios with deeper permafrost or thicker ice sheets than in the reference case. As expected, the largest impact on the geosphere and a KBS-3 repository at the suggested Swedish sites occur during climate conditions supporting glacial conditions. The peak of impact on the geosphere, in terms of stress changes and increased groundwater flow, occurs when the ice sheet margin passes the sites. During periglacial periods, the geosphere and hydrosphere may also be heavily affected by frozen permafrost conditions, which change groundwater flow and composition. Periods of temperate climate conditions, including a suggested future anthropogenically induced warmer and wetter climate in Sweden, are mainly beneficial for geosphere stability and KBS-3 repository safety.

Introduction

The present paper is to a large extent based on information from the reports SKB (2006a), entitled "Climate and climate-related issues for the safety assessment SR-Can", and SKB (2006b) "Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation. Main report of the SR-Can project."

For a KBS-3 repository, several geosphere parameters are affected by climate and climate-related processes. Examples of such parameters of importance for repository safety are:

- the maximum hydrostatic pressure occurring at repository depth for glacial conditions;
- the maximum depth of permafrost;
- the possible penetration of oxygen to deep ground waters during glacial conditions;
- groundwater salinity at repository depth;
- glacially induced faulting.

Several of these parameters relate to the formation of ice sheets and/or permafrost over the repository. Considering the safety assessment period of one million years in the SR-Can assessment of SKB (SKB, 2006a), the effect of changes in climate and climate related processes on repository safety needs to be analysed in detail.

Strategy for managing climate related factors in SR-Can

The strategy for managing climate related conditions in SKB's safety assessments are based on the notion that it is not possible to predict climate in a 100 000-year time perspective. Instead, the approach in the SR-Can safety assessment was to identify and analyse both moderate climate evolutions as well as extremes within which the climate in Scandinavia may vary (SKB, 2006a, 2006b). To this end, knowledge on general climate variations in Scandinavia was used to identify characteristic *climate domains* which in turn were used to build a number of selected climate scenarios. A climate domain is defined as a climatically determined environment in which a set of characteristic processes of importance for repository safety appear (SKB, 2006b). Examples of such processes are the growth of an ice sheet or the development of permafrost. For the investigated sites in Sweden, the identified relevant climate domains are:

- a temperate climate domain;
- a permafrost climate domain;
- a glacial climate domain.

The temperate domain is defined as regions without permafrost or the presence of ice sheets. It is dominated by a temperate climate in a broad sense, with cold winters and either cold or warm summers. Precipitation may fall at any time of the year, i.e. there is no dry season. The precipitation falls either as rain or snow. The temperate domain has the warmest climate of the three climate domains. The temperate climate domain also includes the range of possible warmer future climates in Sweden as envisaged in e.g. IPCC (2007). Within the temperate domain, a site may also at times be submerged by the sea or by an ice-dammed lake.

The permafrost domain is defined as periglacial regions that contain permafrost. It is a cold region but without the presence of an ice sheet. The permafrost occurs either in sporadic, discontinuous, or continuous form. In general, the permafrost domain has a climate colder than the temperate domain and warmer than the glacial domain. Precipitation may fall either as snow or rain.

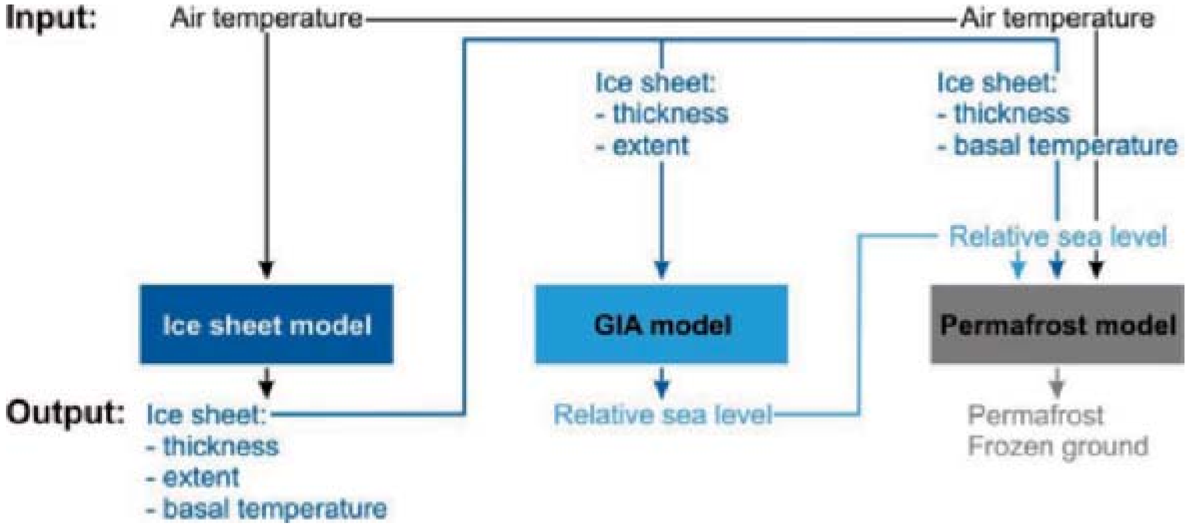
The glacial domain is defined as regions that are covered by ice sheets. Within the glacial domain, the ice sheet may in some cases be underlain by sub-glacial permafrost. In general, the glacial domain has the coldest climate of the three climate domains. Precipitation normally falls as snow in this domain.

It is currently not possible to make confident predictions of future long-term climate. It is, however, likely that the three climate domains will appear repeatedly during the one million year SR-Can assessment period. It is necessary to analyze a range of climate scenarios in order to cover possible future climate evolutions, especially if the suggested repository sites are located in previously glaciated terrain that might be ice covered again in a distant future. Also effects of an increased greenhouse effect need to be included in the range of analysed climate conditions.

Modelling approach

In order to construct and describe climate scenarios, numerical simulations were made using three types of models; 1) a thermodynamic ice sheet model, 2) a Global Isostatic Adjustment (GIA) model, and 3) a permafrost model (Figure 1). The ice sheet model was used to reconstruct ice sheet configurations and properties over Fennoscandia for the last glacial cycle. The climate forcing of this simulation was proxy data on paleoairtemperatures from the GRIP ice core on Greenland (Dansgaard *et al.,* 1993). Data from the ice sheet model was subsequently used as input to the GIA model for simulations of changes eustasy and isostasy, resulting in site-specific information on changes in relative sea-level. Finally, data from both the ice sheet model and the GIA model was used together with site-specific information on e.g. bedrock thermal properties in order to simulate 1D permafrost development at Forsmark and Laxemar sites. For all climate scenarios that were analyzed in SR-Can, various combinations of these modelling simulations were performed. Detailed information on all simulations, as well as descriptions of input data and assumptions made, is found in SKB (2006b).

Figure 1: **Numerical models, and the data flow between them, used for construction of the climate scenarios. In addition, ice sheet melt rates were extracted from the ice sheet model for the numerical simulations of groundwater flow and chemistry during glacial conditions.**



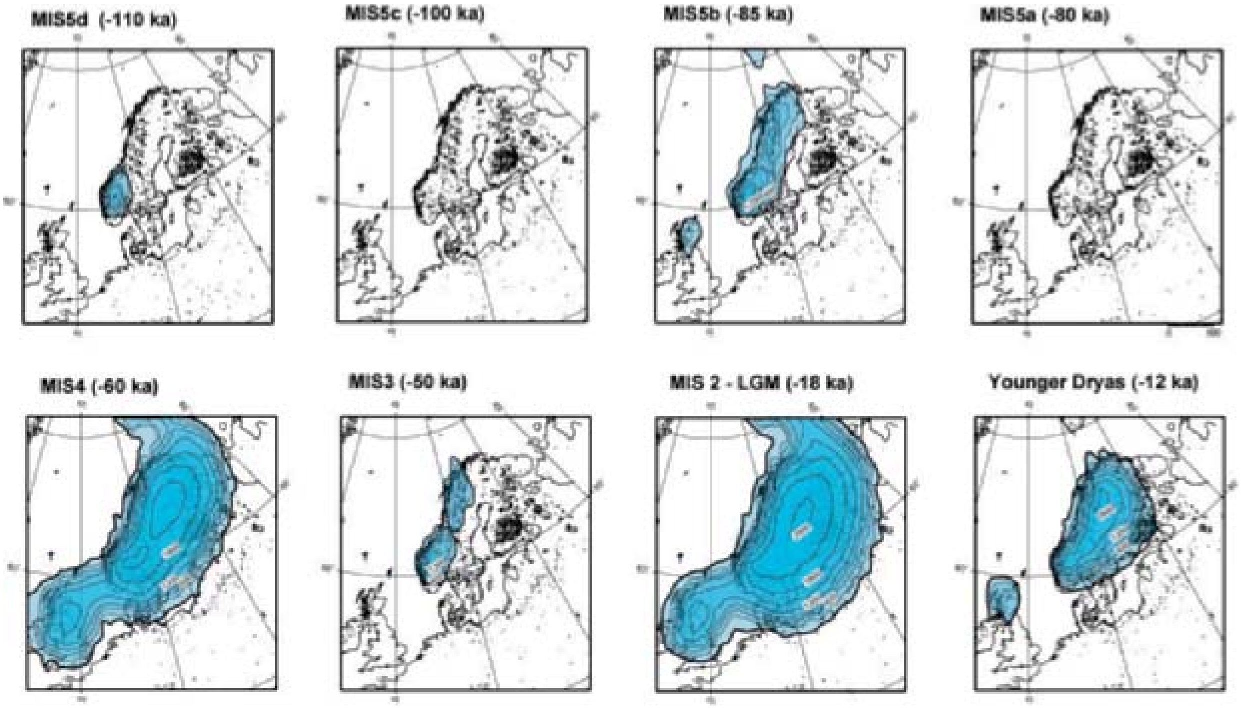
Reference evolution – repetition of last glacial cycle conditions

As mentioned above, it is very likely that the potential repository sites in the long-term will experience periods of all the identified climate domains and the associated transitions between them. A reference evolution should therefore include periods of temperate conditions, including shore-level displacement, as well as permafrost and glaciation of different extent, and also the possible transitions between these climate domains. A relatively well known evolution including all the mentioned components is the one covered by the Weichselian glacial and the Holocene interglacial, i.e. the evolution from the end of the Eemian (Marine Isotope Stage 5e) at about 120 000 years ago to present. In the SR-Can assessment, this last glacial cycle was chosen to constitute a reference evolution of climate-related conditions at the potential sites.

The reason for choosing the Weichselian as the reference evolution is twofold. Firstly, it is the glacial cycle we have most information about, and the evolution and variability of climate-related conditions can be investigated by reference to associated geological information. Secondly, the available geological information makes it possible to test or constrain the supporting analysis and modelling efforts aiming at process understanding and the studies of the, often complex, coupled processes related to climate changes.

Examples of reconstructed ice sheet configurations for the reference evolution from the ice sheet model are seen in Figure 2. During the glacial cycle, the ice sheet grows progressively larger in a number of distinct growth phases, with intervening phases of more restricted ice coverage. The Last Glacial Maximum is reached about 18 000 years before present. The reference evolution also included reconstructions of shore line migration and permafrost development for the last glacial cycle.

Figure 2. **Examples of reconstructed ice sheet configurations at major cold and warm periods during the last glacial cycle. Contour lines show ice surface elevation with a 300 m contour interval. All maps show present day shoreline position. Explanation of text: MIS5d (-110 ka) denote Marine Isotope Stage 5d at time 110 000 years before present**



Climate scenarios

Four ~100 000 year long climate scenarios were included in the SR-Can safety assessment:

1) A main scenario based on the reference evolution, i.e. the repetition of the last glacial cycle.
2) A greenhouse variant of 1) with a warmer climate due to an increased greenhouse effect.
3) A scenario with a drier climate than in 1, supporting extensive permafrost growth.
4) A scenario with a colder climate than in 1), resulting in larger and thicker ice sheets.

Main scenario – base variant with repetition of last glacial cycle

The main climate scenario of SR-Can was identical to the reference evolution, i.e. the reconstruction of conditions during the Weichselian glaciation. This climate scenario is neither an attempt to predict a probable future development, nor a "best estimate" of the Weichselian evolution, but a scientifically defensible starting point for the analysis of climate impact on repository safety. One important purpose of this climate scenario is to obtain up-to-date knowledge on climate and climate related processes on a glacial cycle time scale. The Base variant of the Main scenario also form basis for the construction of additional scenarios with potentially larger impact on geosphere and repository safety.

The evolution of climate-related conditions of importance for repository safety is illustrated by the succession of climate domains and development of climate related parameters for Forsmark and Laxemar in Figures 3 and 4. Through the periods free of ice sheets, temperate conditions are gradually replaced by permafrost conditions. The trend with gradually more dominating permafrost conditions is a natural result of the progressively colder climate during the glacial cycle. The maximum calculated permafrost depth is ~250 metres in Forsmark and ~160 metres at Laxemar.

Forsmark and Laxemar are exposed to two major ice advances and retreats, the first around 60 000 years into the scenario and the second after about 90 000 years (Figures 3 and 4). The maximum ice sheet thickness for Forsmark and Laxemar is 2 920 and 2 430 metres, respectively.

Figure 3. **Evolution of important climate-related variables at Forsmark in the base variant of the Main scenario**

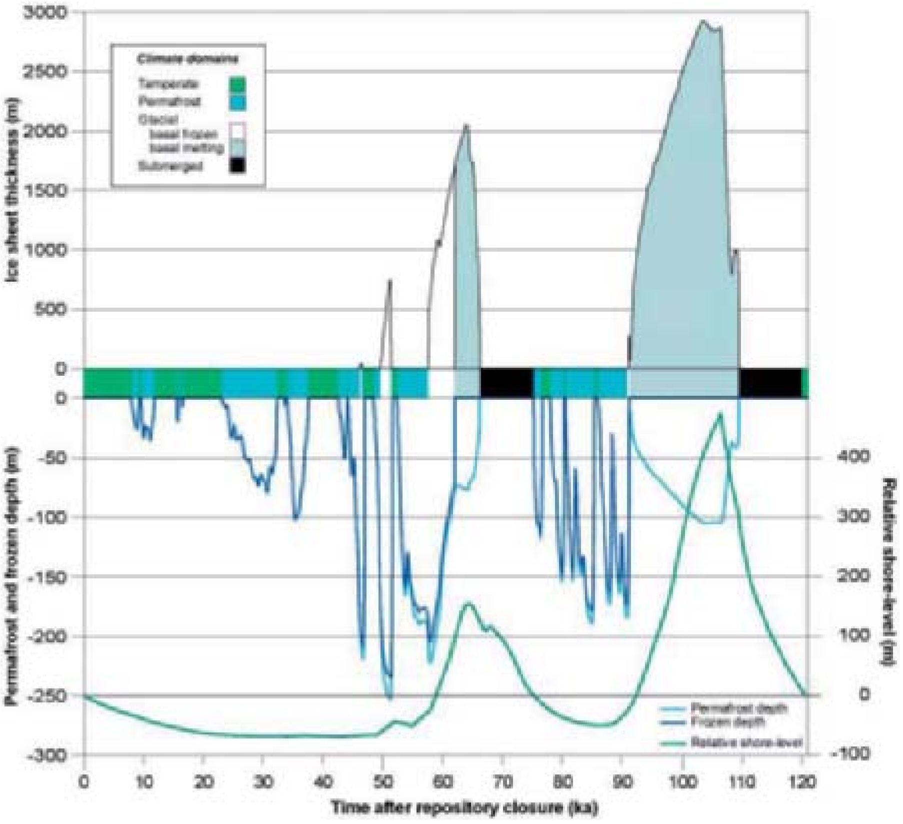
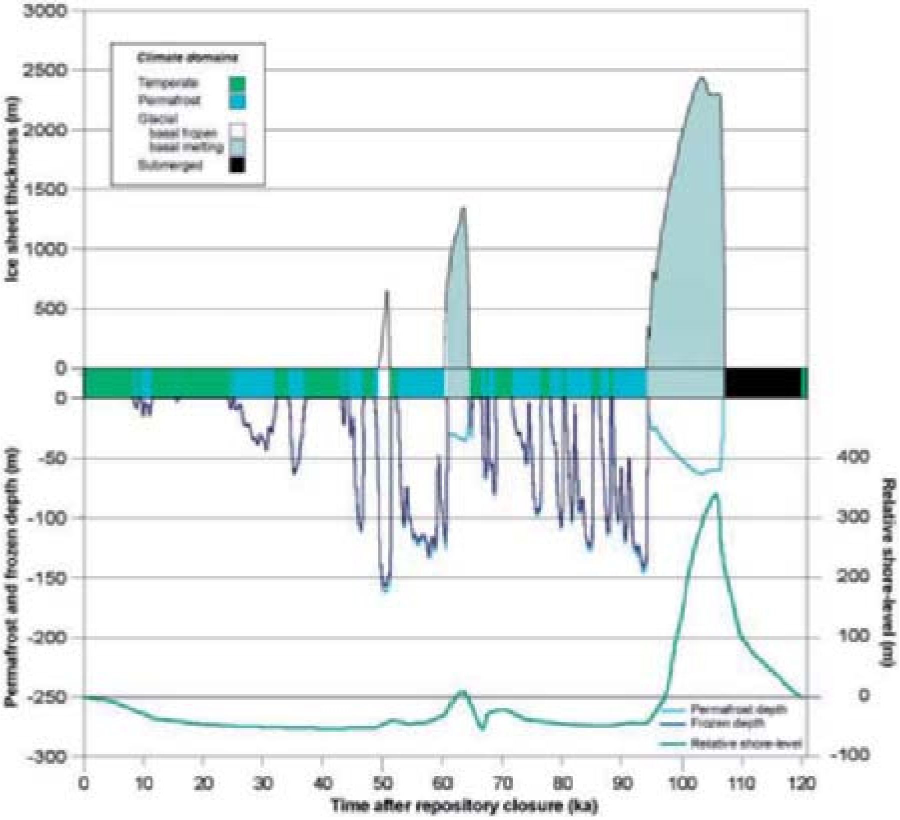


Figure 4. **Evolution of important climate-related variables at Laxemar in the base variant of the Main scenario**



Main scenario – greenhouse variant

An additional factor related to future climate evolution is introduced by the impact and duration of human influence on climate due to emissions of greenhouse gases. Several studies envisage a very long period of relatively warm climate conditions (e.g. IPCC, 2007). Therefore, as a variant of the evolution based on the repetition of the last glacial cycle, a greenhouse variant comprising a 50 000 year long period of temperate domain, followed by the first, relatively mild, 70 000 years of the base variant was analysed. The climate and climate-related conditions during the long period of temperate climate conditions are based on results from SWECLIM (Rummukainen 2003, Tjernström *et al.,* 2003), BIOCLIM (2003), and on the shore-line migration resulting from complete melting of the Greenland ice sheet, corresponding to a sea-level rise of 7 m (SKB, 2006b). For further details on the chosen approach regarding the greenhouse variant, see (SKB, 2006b).

For both sites, the climate is dominated by an initial ~100 000 year long warm period without ice-sheet coverage, a period that gets successively colder towards the end. During a large part of this warm period, mean annual air temperatures at the candidate sites may be warmer than, at present. During this initial long warm period, it is likely that climate within the temperate domain may vary significantly. The length of the initial period of temperate domain in the SR-Can greenhouse variant should not be taken as a prediction or statement on future greenhouse climate change. Under a future warming climate, this period could be shorter or longer than that described in this scenario. The greenhouse variant reduces the effects of most climate-related processes of importance for repository safety, such as the time of glacial domain conditions.

Figure 5. **Evolution of important climate-related variables at Forsmark in the greenhouse variant of the Main scenario**

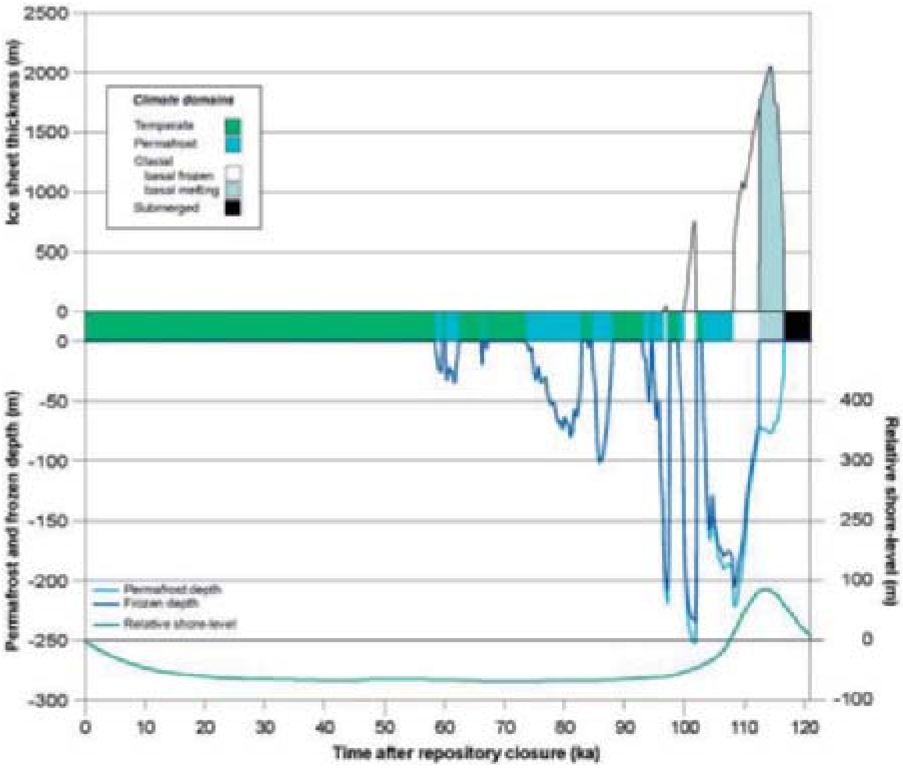
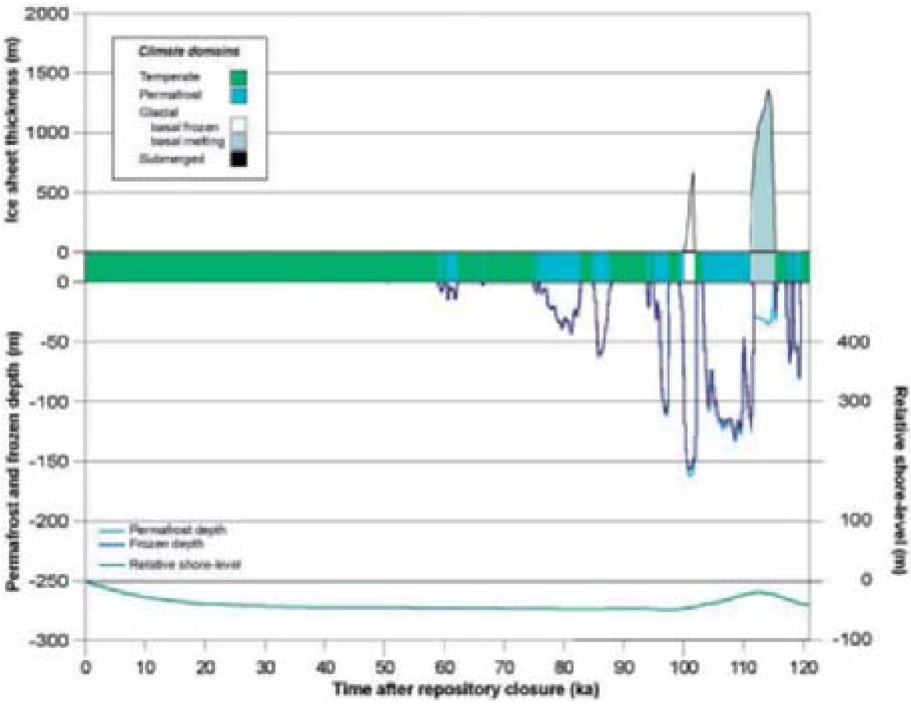


Figure 6. **Evolution of important climate-related variables at Laxemar in the greenhouse variant of the Main scenario**



Freezing of the geosphere – Climate scenario with more permafrost

This scenario concerns the criterion of minimum buffer temperature, namely that the temperature in the clay buffer of a KBS-3 repository should not fall below –5°C to avoid that water contained in the buffer would freeze (see also SKB, 2006a, and Hedin *et al.,* 2008). In order to analyse if the buffer may freeze under more severe, but still not unrealistic, climate situations than in the main scenario, permafrost simulations were made with assumptions much more favourable for permafrost growth. Air temperatures were assumed to fall according to the temperature curve of the reference glacial cycle, but in an extremely dry climate not supporting ice sheet growth over the sites. To favour permafrost growth further, the effects of protective snow cover and vegetation were excluded, and the sites were assumed to always remain above sea level. For further information on the setup of these simulations, see SKB (2006b). The resulting permafrost depths are seen in Figure 7, while the associated development of bedrock temperature at repository depth is seen in Figure 8.

This climate scenario contains significantly longer periods of permafrost conditions, and also deeper permafrost, than in the main scenario (Figures 4 and 5). The maximum permafrost depth in this scenario is 400 m at Forsmark and 270 m at Laxemar (Figure 7). The –5 °C isotherm reaches a depth of 200 m at Forsmark and 130 m at Laxemar. Without the heat contribution from the repository, the lowest temperature at repository depth is –0.71°C at Forsmark, and +6.1°C at Laxemar (Figure 8). Several sensitivity tests were also made in this scenario. One of the showed that in order to make the –5°C isotherm reach repository depth at Forsmark and Laxemar, the regional temperature curves of the last glacial cycle would have to be lowered *more* that 10°C and 17°C, respectively, which is considered unrealistic. The results of these analyses show that freezing of the clay buffer is ruled out, also under very pessimistic climate conditions. For details on the simulations made for this climate scenario, including further sensitivity tests, see SKB (2006b and 2006a).

Figure 7. **Calculated permafrost (0°C isotherm) depth, frozen depth and depth of the –5°C and –10°C isotherms at Forsmark and Laxemar for environmental conditions exceptionally favourable for permafrost development**

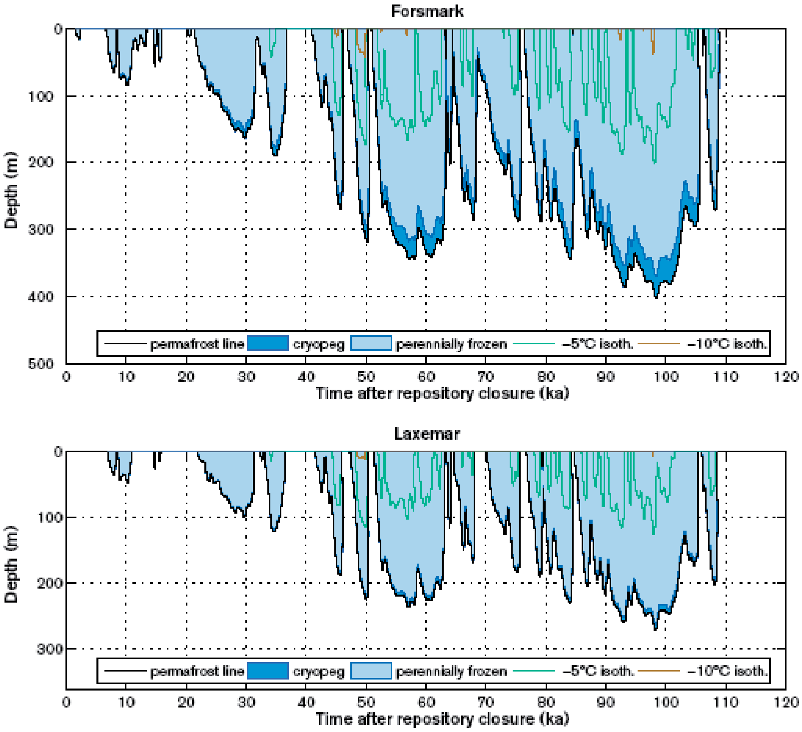
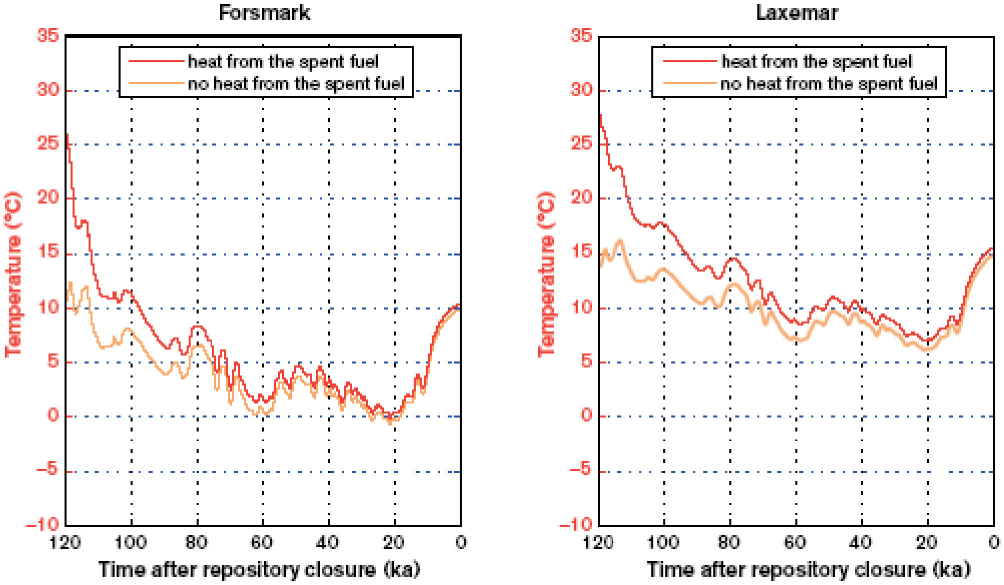


Figure 8. **Evolution of bedrock temperature at a repository depth of 400 m at Forsmark and 500 m at Laxemar, for environmental conditions exceptionally favourable for permafrost growth. The temperature development both with and without the heat contribution from a KBS-3 repository is presented.**

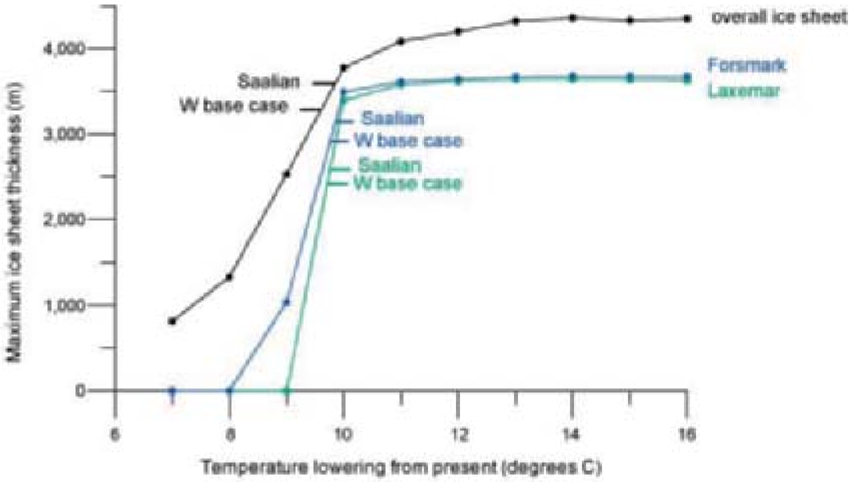


Hydrostatic pressure in the geosphere – Climate scenario with larger ice sheets

This scenario concerns the criterion of maximum hydrostatic pressure to avoid canister failure due to isostatic load (see also SKB, 2006a and Hedin *et al.,* 2008). The scenario was constructed to analyze if the load from ice sheets *larger* than the reconstructed Weichselian ice sheet of the main scenario could, together with the buffer swelling pressure and the load of overlying bedrock, induce an isostatic load that could cause a mechanical collapse of the canister.

Using the numerical ice sheet model, ice sheets were allowed to grow to their maximum steady-state configuration under a series of colder climate assumptions. In these sensitivity tests, temperatures were lowered between 4 and 16°C. Ice sheets only developed for temperature lowering cases of –7°C and colder. As expected, the maximum ice-sheet thickness increases with colder climates (Figure 9, black line). However, the degree of increase in thickness with temperature lowering declines as colder cases is considered. For a temperature lowering of more than approximately 13°C, colder climates do not generate thicker ice sheets. This result is in line with what is known from e.g. Antarctic ice-sheet variations. The maximum reconstructed ice sheet thickness for the largest ice sheet during the past 2 million years supported by geological observations (the Saalian ice sheet) is for the Forsmark and Laxemar sites 3 200 and 2 600 m respectively (Figure 9). This gives a contribution to the hydrostatic pressure at repository depth of 28 and 23 MPa respectively.

Figure 9. **Developed maximum ice-sheet thicknesses for various temperature lowering assumptions. The three curves represent extracted maximum ice thicknesses for the Forsmark region (blue), Laxemar region (green), and overall largest ice-sheet thickness (black). The short lines marked W Base Case show the maximum ice thickness obtained in the Weichselian reconstruction of the main scenario, whereas the short lines marked Saalian show the estimated maximum ice thickness for the largest Fennoscandian ice sheet configuration supported by geological observations.**



Climate effects on groundwater flow and chemistry

In the climate scenarios above, the geosphere is to various degrees affected by changes in e.g. isostatic load, stress, temperature etc. The degree at which the geosphere is affected is reflected in the length of the individual climate domain periods. For instance, long periods of permafrost domain typically generate deeper permafrost than shorter periods, which in turn have a more profound impact on the groundwater flow.

During periods of temperate domain, the groundwater flow pattern is similar to the present ice free situation, with a mixture of local areas of groundwater recharge, typically at topographically high positions, and discharge, typically in low positions. The groundwater flow is at this time driven by topographic gradients in the landscape.

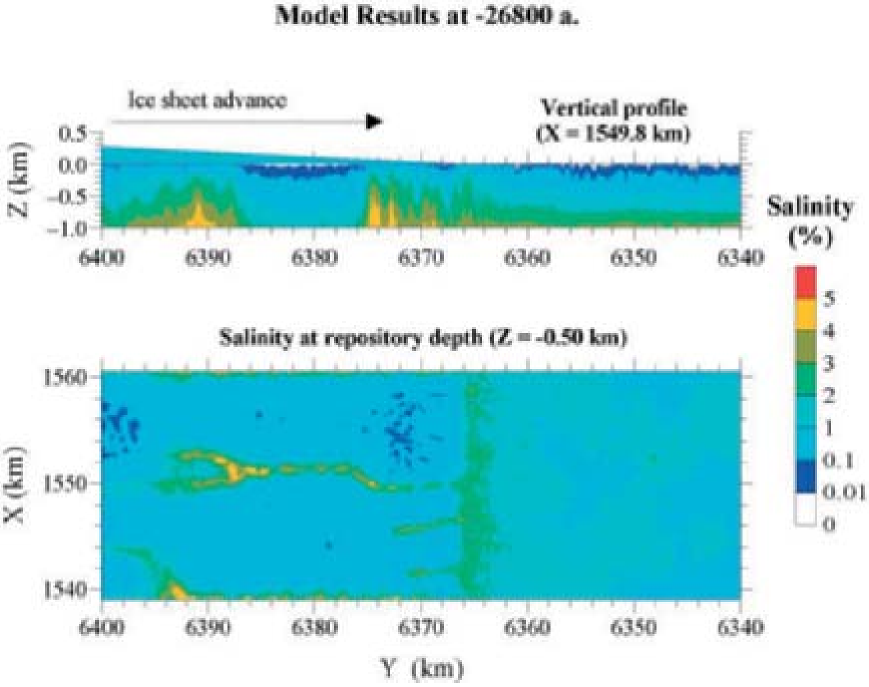
During the initial periods of permafrost domain, the permafrost distribution in the landscape is sporadic or discontinuous. This result in a modified pattern of groundwater flow, but still with major groundwater recharges and discharge areas. When climate gradually gets colder, permafrost grows progressively thicker and more widespread. The very flat topography at both sites is favourable for the formation of more or less continuous permafrost once climate is cold enough. When continuous permafrost occurs, the precipitation recharge of groundwater is strongly reduced or stopped, since permafrost influences subsurface hydrology by reducing the hydraulic conductivity of the frozen soil and bedrock. At this stage, the bedrock beneath large lakes may still be unfrozen, forming so called taliks, within otherwise frozen bedrock conditions. Local recharge or discharge of groundwater may still take place at these taliks.

In the scenarios that includes periods of ice sheet coverage (Figures 3-6), the ice sheet overrides ground with permafrost when it advances over the sites. Subglacial permafrost under the ice sheet margin acts as a hydrological barrier for groundwater flow. Therefore, these initial phases is characterised by periods without groundwater recharge.

After these initial phases, subglacial groundwater recharge takes place due to basal melting of the ice sheet and due to that permafrost has diminished. This results in that local areas of former groundwater discharge, experience a general reversal of groundwater flow direction under glacial conditions (Breemer *et al.,* 2002, Jaquet and Siegel, 2006). In other words, the result is a dominant subglacial groundwater flow directed downwards under the major part of the ice sheet, recharging the groundwater aquifer. However, in the area in front of the ice sheet groundwater discharge is dominating. During periods of ice margin passages, the increased hydraulic gradient would increase groundwater flow in bedrock compared to temperate domain conditions (Jaquet and Siegel, 2006), even if the hydraulic permeability of bedrock were to decrease under the load of an ice sheet.

Groundwaters will become progressively diluted during temperate periods, such as the initial period following repository closure. During periods of permafrost, the process of freezing-out of salts beneath the migrating permafrost front can move salts to repository depth from the upper parts of the geosphere. For instance, calcium concentrations are expected to increase at repository depth during permafrost periods. During the advance of an ice sheet, upconing of deep saline waters may occur (Jaquet and Siegel 2006), exemplified in Figure 10. During this phase salinities of up to 5% (≈52 g/L TDS) may be reached locally at repository depth. According to Jaquet and Siegel (2006), dilute waters are expected at repository depth under warm-based ice sheet coverage, with most of the waters having a calculated salinity ≤ 0.1 g/L. After deglaciation, the infiltration of waters of marine origin will increase the salinity of groundwaters at repository depth that had been diluted under a warm-based ice sheet. For more information on the geochemical evolution in the base variant of the main scenario, see section 9.4.7 in SKB (2006a).

Figure 10. **Contour plots showing salinities for a site affected by an advancing ice sheet such as in the base variant of the main scenario (Figures 3 and 4), calculated using the model described in Jaquet and Siegel (2006). The plots are centered on the Laxemar area: the upper diagram shows a North-South depth profile centred at the site (vertically exaggerated), and the lower diagram a slice at 500 m depth. The results indicate that, due to the upconing of deep saline waters, groundwaters at repository depth may reach salinities up to 5% (≈52 g/L) during phases of glacial advance. However, most of the groundwaters at repository depth a few kilometres behind the ice margin have salinities between 0.1 and 1%.**



In a significantly warmer climate, such as envisaged due to an increased greenhouse effect, the warmer temperatures at the ground surface would not affect repository safety functions at either of the sites. If precipitation increases, this would not affect groundwater formation significantly, since, on a regional scale, the major part of the groundwater aquifer is filled by present-day precipitation rates.

Climate effects on the mechanical conditions of the geosphere

The temporal evolution of an ice sheet, such as in both variants of the main scenario of SR-Can, causes time-varying stress and deformation in the Earth. Due to the long time spans, both elastic and viscous deformation occurs. Properties of the ice sheet controlling the deformation and stress change are areal extent, thickness and slope of the ice sheet margin (Lund, 2005).

As the ice sheet advances and the load from the ice increases, the elastic lithosphere will bend and the viscoelastic mantle will flow laterally. This will, on a large scale, result in a depression beneath the load and an upwarping bulge outside the ice sheet margin. The thicker the ice sheet and the longer an area that is covered by ice, the larger bending stresses are induced. At great depths in the crust, where elastic properties are very high, horizontal stresses induced by the bending will be much larger than the corresponding increase in vertical stress due to the load of the ice. This is of importance for the potential of glacially induced faulting. However, the upper part of the crust is considerably softer and hence, the horizontal stresses generated from the ice loading at repository depths are smaller than the increase in vertical stress.

The evolution of stresses in the crust during a glacial cycle has been studied by means of numerical finite element modelling by Lund (2006) using Lambeck's SCAN-2 model of the Weichselian glaciation. As the ice sheet retreats, the depressed elastic lithosphere will experience an isostatic rebound. This rebound is a much slower process than the removal of the ice load, and consequently, high horizontal stresses are left in the lithosphere for a long time after the vertical stress induced by the ice sheet is gone.

The pore pressures in the crust are increased during glaciation, as a result of the consolidation of the bedrock as well as the recharge of meltwater available at the base of the ice sheet. This means that the effective rock stress (i.e. the total stress reduced by the water pressure) is affected by a glacier advancing over a site, through the interaction of load and pore pressure. The evolution of effective stress will dictate the mechanical behaviour and properties of rock fractures, and hence, also their water-conducting ability, see Hökmark *et al.* (2006).

In a non-glacial stage, such as during temperate or permafrost climate conditions, both horizontal principal stresses are larger than the vertical stress at shallow depths. As an ice sheet advances over the site, the increase in vertical stress is much larger than the increase in horizontal stress. This means that the stress axes may rotate so that the vertical stress will be the intermediate or even largest principal stress within the upper part of the bedrock. In general, the increase in stress will act to reduce the transmissivity of fractures and fracture zones. However, these stress changes, together with the increase in pore pressure as compared with non-glacial hydrostatic conditions, may result in changed transmissivity anisotropy.

Outside the margin of the ice sheet, initial horizontal stresses may be reduced by the bending stresses (Lund, 2006). This will give rise to a decreased normal stress acting across steeply dipping fractures leading to an increase in transmissivity. Calculations by Hökmark *et al.* (2006) indicate, however, that the increase will be very modest. Deviatoric stresses may also give rise to shearing of critically oriented fractures, which in turn can yield larger fracture apertures. The same effect may also result from hydraulic shearing, in which the enhanced pore pressure acts to reduce the shear strength. As described by Hökmark *et al.* (2006), hydraulic jacking of fractures is also possible, but most likely not much deeper than a couple of tens of metres.

The general consequence of a large ice sheet covering an entire region is that faults in the crust are stabilised and seismic activity is suppressed. On deglaciation, however, the rapid decrease in vertical stress tends to destabilise the crust. The pore pressure in the crust is of great significance in the faulting process, since an increased pore pressure decreases the effective normal stresses on faults, and hence, reduces their shear strength. If the pore pressure is still enhanced at the end of glaciation, when the vertical load from the ice disappears, fault stability will be further reduced. There exists evidence that intense seismic activity, with end-glacial or post-glacial faulting, took place in northern Scandinavia at the end of the last glaciation. The fault displacements are considered to have occurred as reactivation of existing structures. As described in SKB (2006c), there are two different views concerning the mechanism of this faulting; release of tectonically generated stresses accumulated under the influence of the stabilising ice sheet or an asymmetrical unloading of the ice sheet.

Conclusions

In safety assessments for repositories for spent nuclear fuel, it is necessary to analyze a range of climate scenarios in order to cover the extremes within which the climate may vary in the coming 100 000 years. These include e.g. a warmer climate than at present as well as permafrost and glacial conditions.

The climate at the ground surface, as such, has a minor impact on the geosphere and a KBS-3 repository. Instead, the geosphere and repository might be heavily affected by *indirect* climate effects, such as growth of ice sheets and permafrost.

The advance and retreat of an ice sheet over the site brings about the largest climate-related changes the geosphere and repository will experience during a 100 000 year time frame, such as groundwater flow and composition (dilution), hydrostatic pressures, bedrock stresses, and fault stability, factors which all are of importance for KBS-3 repository safety.

When analyzing scenarios that include glacial and permafrost conditions, the SR-Can safety assessment shows that both suggested sites in Sweden have the potential of fulfilling the safety requirements for a KBS-3 repository.

The predicted warmer climate due to an increased greenhouse effect (e.g. IPCC 2007) would mainly have positive effects on geosphere stability and KBS-3 repository safety. This is achieved by delaying the onset of periods of glacial conditions.

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UPLIFT AND EROSION: POTENTIAL IMPACT ON THE GEOLOGICAL ENVIRONMENT

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Abstract:

The Japanese Islands located in the plate convergent boundary zone at the eastern edge of the Eurasian Continent have been impacted by severe natural environmental condition such as tectonic and volcanic activity. In this condition, fault movement, volcanic activity and uplift movement of the crust are important factors to impact the long-term performance of the repository site. Although the area where the fault and the volcano exist is excluded from the repository site, for the upheaval movement, it is necessary to reflect appropriately the estimated amount of uplift in the underground water scenario etc. The marine terraces which fringe the Japanese coast have been formed by the combination of sea-level fluctuation and crustal uplift. Therefore it is possible to estimate the amount of tectonic uplift in the future based on the height of former shoreline of the marine terraces. The performance evaluation taking into account the future uplift is done for the planning and construction of the low-level nuclear waste disposal facilities in the Shimokita Peninsula in the northern most part of Honshu Island.

Introduction

In the active tectonic region, the crustal uplift and the related erosion which may shallow the underground depth of the nuclear repository site should be considered as important factors for the safety ensuring and performance preservation of the site. The Japanese Islands consisting of several island arcs are located in the plate convergent zone at the eastern edge of the Eurasian Continent, and characterized as one of the most active tectonic region in the world by the intensive uplift and igneous activity. Moreover, abundant rainfall brought by the temperate monsoon causes the intensive erosion and sediment discharge of land surface including the mass movement in the uplifting area.

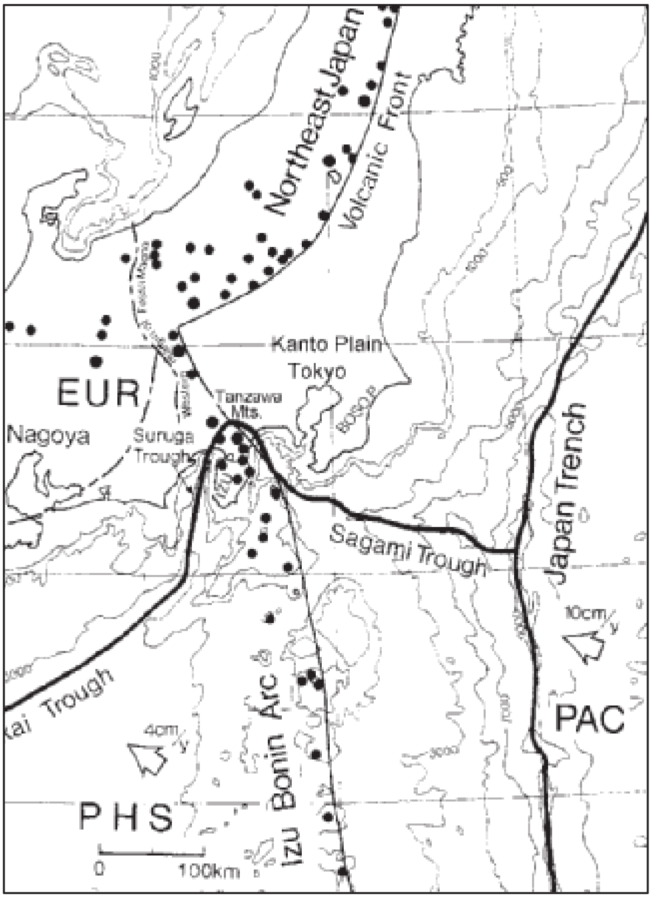
In this paper, the authors intend to present some feature of natural environment in Japan, and to point out some important geological phenomenon that should be considered for a long-term stability of the geological environment including the lithology and hydraulic conductivity of host rock for the repository site. And, we also introduce the estimate method of the amount of crustal change, which will be caused by the upheaval and erosion of land in the future.

Natural environment in the Japanese Islands, especially geological phenomenon affecting the performance of repository site

Plate tectonics

Around the Japanese Islands, two oceanic plates, Pacific Plate (PAC) and Philippine Sea Plate (PHS), are subducting beneath the continental Eurasian Plate (EUR). In addition, the subduction of west moving PAC under the northwest moving PHS results in the formation of buoyant island arc with thick volcanic crust, called Izu Bar or Izu-Ogasawara Arc, at the western edge of PHS. Izu Bar is difficult to subduct easily under the EUR along the convergent boundary between PHS and EUR, because it is composed of thick volcanic crust. Therefore, recurrence of several collisions of volcanic blocks on Izu Bar against EUR has occurred at the northern edge of Izu Bar. These collisions result in the large northward bending of onshore plate boundary, and have formed the Tanzawa Mountains where severe uplift and heavy erosion has prevailed in the Quaternary at the northern side of the boundary (Figure 1). The biggest Kanto Plain, in which Tokyo metropolitan district is located, has been formed by the landfill of a fore arc basin that normally occurs in the deep sea bottom. Thus, the plate convergence around Japan plays an important role to the crustal movement and the topographical formation of the Japanese Islands.

Figure 1. **Setting of Plate tectonics in and around central Japan (Yamazaki, 1992)**



Huge earthquake along the plate subduction zone and coastal uplift

Subduction of the oceanic slabs under the continental plate has periodically caused the M8 class huge earthquakes along the mega-thrust at the plate contact surface. Coseismic deformation, uplift and subsidence, were historically recognized along the coastal region on the upthrown side of the source mega thrust. However, aseismic slow crustal movement showing the opposite sense of the coseismic movement occurs in the dormant period during the interval of two huge earthquakes. Almost all the marine terraces, which well develops along the coastal region of Japan, has been formed by the intermittent uplift associated with the coseismic crustal movement and glacio-eustatic sea-level fluctuation caused by the global climate change.

Onshore active faults and related formation of mountains and basins in Japan

Although most of the compressional stress imposed by the plate convergent movement to the Japanese Island is released by the periodical huge earthquakes along the plate boundary, a part of them accumulates in the crust of onshore region. And stress concentration to the weak line in the crust causes the intermittent and periodical fault movement. These fault movements has played an important role for the formation of topographic relief such as mountains, basins, and coastal plains in the Japanese Islands. Active faults which have the potential to reactivate in the future are recognized from the displacement of topographical features and young superficial deposits. A detailed survey conducted by the academic society and government in these decades for the earthquake disaster prevention has revealed the distribution and activity of the active fault in Japan (Figure 2). As a result, it is confirmed that active faults in Japan have kept the movement in the Quaternary concordant with a present compressional stress field, and many of major active faults are reactivated one of the old geologic structure formed in the tensional field before the middle Miocene.

Figure 2. **Active faults in Japan. Active faults make the topographic relief and accord with the geomorphic boundary between lowland and hilly area, and between hilly area and mountains.**

Formation of volcanic front parallel to the island arc

About 100 km in depth along the subducting oceanic PAC and PHS slabs, mantle melts due to the effect of water exhausted from the slabs, and magma is formed. Because the magma rises by its buoyancy, the alignment of volcanoes referred as volcanic front appears on the ground surface of the island arc. This volcanic front runs parallel to the trench, and its location on the map is corresponded to the 100 km depth contour of the subducting slab. Thus volcanic front divides the Japanese Island into the non-volcanic outer-arc to the east or south and volcanic inner-arc to the west or north. As for Japanese Islands, it is known that more than 100 of volcanoes have intermittently repeated the large eruptions including the caldera formation with huge pyroclastic flows since the late Pleistocene.

Paleoclimate and sea-level changes

The Japanese Islands located in the temperate climate zone were not covered with the large glacial ice sheet in the past ice ages; however, they received much impact of the eustatic sea level fall caused by the growth of huge continental ice sheets. The sea level decreased up to -120 m at Wurm maximum, the continental shelf dried up, and some wide coastal plains extended into the present offshore region. The snowline and timberline declined their height 1 000 m or more in the mountainous district of central Japan, and the vegetation was uncovered from the high mountain slope. As a result, the collapse, denudation, and mass movement occurred frequently in the mountain, and an erosion process was accelerated on a steep slope. Moreover, in the coastal region, the river deeply incised the land due to the decline of base level of erosion associated with the sea-level change. These processes resulted in the steep inclination of river profile.

On the other hand, in the warm interglacial period, the recovery of vegetation and the increase of precipitation resulted in the river incision in the mountainous region, and the rise of sea-level and related retrogression of coast line resulted in the formation of alluvial plains in the coastal region. As a result, the river inclination became more gradual than the ice age. These major glacial and interglacial ages have repeatedly occurred in about 100 000 year cycles since the last one million years.

Important geological phenomenon that impacts long-term performance of repository site in Japan

Impact to the geological environment of the repository site

The long continued uplift associated with the tectonic movement has a possibility to cause the change of groundwater flow system due to the potential energy changes of the repository site. Moreover, the uplift activates the erosion process, shallows the isolation distance from the repository to surface of the earth, and increases the possibility that the repository will be exposed to ground surface by the end of evaluation period.

The fault activity directly damages facilities in the repository site by the fault displacement, and accelerates the leakage of the radioactive material to the outside of the repository system. The volcanic and igneous activity has a potential to cause the disruption of facilities and thermal change of radioactive materials by magma intrusion, and scattering of radionuclide into the atmosphere by volcanic eruption. Although the global climate change does not make any direct impact to the deep underground repository site, the sea-level fluctuation and vesitation changes associated with the climate change cause the accelerated erosion process which increase the possibility of repository exposure in the future.

Therefore, it is thought that the co-seismic upheaval and the subsidence movements in the coastal region, the igneous activities, and the active fault displacements and related crustal deformation in the inland region directly have a big impact on the geological environment of the repository site in the Japanese Islands. The climatic change also indirectly impacts the performance maintenance in the repository site.

Nuclear Safety Commission of the Japanese government has installed some requirements on the geological condition for the selection of candidate repository sites. For this requirement, candidate site where a remarkable uplift movement is known by published paper, where the active fault exists, and where volcano is close, is excluded from the repository site. Moreover, the region where useful subterranean resources exist is also excluded.

Estimate of future amount of crustal movement

Dangerousness of directly hit of the repository site by the active fault and the igneous activity can escape to avoid the place where they exist. However, the uplift movement is a phenomenon commonly recognized in anywhere in Japan, and it is necessary to evaluate the amount of future uplift in the evaluation period for the stability evaluation of repository site.

Because most of the crustal movement in the Japanese Islands is related to the intermittent and periodic geological phenomenon such as coseismic crustal deformation, the amount of displacement shows the cumulative feature. The relationship between the amount of displacement and the time show a normal linear change. Therefore, this relationship between time and displacement can be extrapolated to the future based on the recent geological record.

Because these crustal movements are ruled by the long sustained plate tectonics, though the uncertainty increases about the far future, it is not possible that the direction and the speed of the movement change greatly in a short term as long as the plate motion is changeless. Therefore, the amount of the crustal movement in the future can estimate for some period based on past geological information. It is thought that the forecast until several hundred thousand years ahead on the crustal movement is possible in the region where the past geological data are well preserved, though there is a regional variation on a predictable period by geological condition in the Japanese Islands.

Estimate of future uplift using the height of marine terrace

The marine terrace fringes well along the coast of the Japanese Islands. The marine terrace is the uplifted paleo-shoal including the wave-cut bench and the submerged depositional surface. The boundary on the inland side is called a former shoreline, and shows the peak position of the sea level of the past transgression. Therefore, the height of former shoreline formed with the same transgression was originally same, and a present distribution altitude indicates the amount of the crustal uplift afterwards.

The most distinguishable marine terrace in Japan is the one formed with a transgression peak of Riss-Wurm interglacial period (MIS5e) at 125 000 years ago. This marine terrace is variously named in Japan such as Middle terrace or M surface, Shimosueyoshi terrace or S surface, and MIS5e terrace etc. Difference between the present altitude of MIS5e former shoreline and original peak sea-level of MIS5e which is estimated to be about + 5 m, is cumulative uplift since the formation of MIS5e terrace. Moreover, mean (average) uplift rate is obtained to divide above difference value by 125 000 years. Accumulated uplift of the marine terrace is thought to have been formed with the repetition of intermittent coseismic movement judging from the historical earthquake record.

When such an altitude of former shoreline is recognized about a lot of marine terraces which were formed by different transgression age, temporal change of the average uplift rate is recognized about the research area. If the average uplift rate obtained from different age of terraces is the same, it indicates that a constant uplift including intermittent coseismic crustal deformation has continued for a long term in this region under the stable tectonic condition. Because it is not possible that the crustal movement will change its sense and rate rapidly in the future when the cause of the uplift is related to a wider tectonics of the plate motion etc., the amount of the crustal uplift in the future can be estimated based on the average uplift rate of marine terrace.

Age determination of marine terrace

The precise age determination of marine terrace is an important key to estimate the mean uplift rate of crustal movement in the coastal region. Although many radiometric dating methods applicable for the late Pleistocene terrace are proposed, it is difficult to determine the quantitative age of middle Pleistocene and MIS5e terraces because of the problem of accuracy and coverage except for the Uranium-series dating in the coral reef. However in Japan, it is possible to estimate the age of middle Pleistocene marine terrace, using the thickness of volcanic ash covering the terrace surface, the correlation of intercalated wide spreading key tephra, and combination with paleo-climatic fluctuation data such as proposed by Martinson *et al.* (1987).

A case for the estimation of future crustal movement

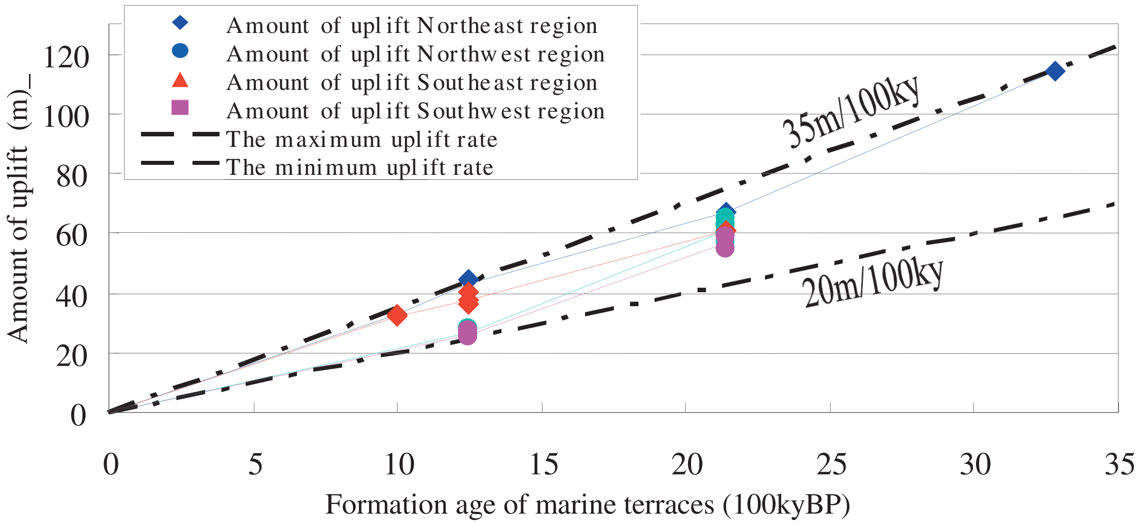
The disposal of the low-level nuclear waste is planned at the 100 m depth in the underground of the Shimokita peninsula, at the northern edge of Honshu Island of Japan. The appropriate quantitative estimation of amount of long-term crustal movement which will be accumulated in the future is an important requirement to secure the long term stability of the repository site. The marine terraces since the middle Pleistocene develop well in the Shimokita peninsula, and the altitude of their former shorelines can be understood clearly.

These terraces are covered with the volcanic ash intermittently supplied by the explosive eruption of Osorezan volcano and Towada and Hakkohda volcanoes located to the west of repository site. These volcanic ashes are useful for the chronology of marine terraces. Existence of Takadate, Tengu-Tai and Shichihyaku terraces correlated to MIS5e, MIS7 and MIS9 respectively are recognized based on the tephrochronology and detailed classification of the terraces (Figure 3; Sasaki *et al.,* 2007).

Figure 3. **A sample of detailed terrace classification map in the Shimokita Peninsula, northeast Japan (Sasaki *et al.,* 2007)**

As shown in Figure 4, constant average uplift rate of about 3 m per thousand years are obtained from the height of former shorelines and age of each terraces. Based on these uplift rates, it is estimated that these terraces will increase their altitude about 30 m after the 100 000 years, and about 60 m after the 200 000 years.

Figure 4. **Uplift rate in the Shimokita Peninsula, showing the constant uplift for the past 210Ka (Sasaki *et al.*, 2007)**



Naturally, an increase of the height of marine terrace by crustal uplift increases the erosion process on the terrace, and decreases the height of terrace surface. As for terrace erosion, it is commenced from a cliff of terrace edge by the formation of gully. Then the gully evolves to small valley through the stream by the dissection of terrace. Moreover, when the sea level decreases by the coming at the next ice age, the river and the stream must deepen and expand their size.

The dissection and the topographic evolution model for the terrace are made in consideration of these, and it is used for the underground water scenario to evaluate the long-term stability of the geological environment.

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PREDICTABILITY OF THE EVOLUTION OF HYDROGEOLOGICAL AND HYDROGEOCHEMICAL SYSTEMS: GEOLOGIC DISPOSAL OF NUCLEAR WASTE IN CRYSTALLINE ROCKS

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Abstract

Confidence in long-term geologic isolation of high-level nuclear waste and spent nuclear fuel requires confidence in predictions of the evolution of hydrogeological and hydrogeochemical systems. Prediction of the evolution of hydrogeological and hydrogeochemical systems is based on scientific understanding of those systems in the present – an understanding that can be tested with data from the past. Crystalline rock settings that have been geologically stable for millions of years and longer offer the potential of predictable, long-term waste isolation. Confidence in predictions of geologic isolation of radioactive waste can measured by evaluating the extent to which those predictions and their underlying analyses are consistent with multiple independent lines of evidence identified in the geologic system being analysed, as well as with evidence identified in analogs to that geologic system. The proposed nuclear waste repository at Yucca Mountain, Nevada, United States, differs in significant ways from potential repository sites being considered by other nations. Nonetheless, observations of hydrogeological and hydrogeochemical systems of Yucca Mountain and Yucca Mountain analogs present multiple independent lines of evidence that can be used in evaluating long-term predictions of the evolution of hydrogeological and hydrogeochemical systems at Yucca Mountain.

Predictability of hydrogeological and hydrogeochemical systems

Predictions of future hydrogeological and hydrogeochemical conditions rely on projected uniformitarianism. That is, the assumption that those processes that have generated and controlled past and current conditions will generate and control conditions in the future. Geologic disposal of high level nuclear waste can require periods of isolation of hundreds of thousands of years and longer, and must consider processes that operate on the atomic scale over distances of tens of kilometers. The stratigraphic and mineralogic record and observations of naturally occurring isotopes provide evidence of long-term stability in some crystalline rock settings. In general, predictions of evolution of hydrogeological and hydrogeochemical systems require three components: conceptual models; analytical and numerical models; and physical and chemical properties of the systems. All three of these components must be determined for pertinent time and space scales.

Time and space scales of many natural geologic systems are amenable to analysis with respect to the capabilities of long-term nuclear waste isolation. For example, geologic and geophysical data permit credible predictions of climate, infiltration, seismicity, and volcanism over long repository (geologic) time and space scales. In contrast, experience with engineered systems in geologic settings has established confidence in the ability to predict the performance of those engineered systems over relatively brief periods of time.

Conceptual models are a fundamental component of the prediction of the evolution of hydrogeological and hydrogeochemical systems. Conceptual models are typically based on expert judgment, and form the core set of arguments about the processes that are important to the evolution of the hydrogeological and hydrogeochemical systems with respect to waste isolation. An example of expert judgment is the decision regarding representation of system dynamics. Steady-state hydrogeologic systems neglect changes in water storage over time, and thus are less burdensome to compute. At Yucca Mountain, for example, the DOE has chosen to represent the dynamics of climate change with a series of steady-state hydrologic simulations, bounded by step discontinuities. Other examples of expert judgment include: the choice of boundary conditions; the choice of scale of feature to represent; and the choice to exclude representation of system attributes thought not significant to waste isolation.

Some hydrogeological and hydrogeochemical systems are amenable to representation by multiple conceptual models. However, the existence of multiple conceptual models does not ensure model fidelity. For example, Konikow *et al.* (1997) examined a model test implemented by six independent groups and found that all groups made fundamental errors in the implementation of a boundary condition. Regardless whether one or more conceptual models is invoked, it is critical that hydrogeological and hydrogeochemical system analysts explicitly describe the conceptual model(s). Conceptual models should be consistent with theory and must be tested, evaluated, and compared against field and laboratory empirical data. Inconsistency with empirical observations diminishes confidence in conceptual models.

Analytical and numerical models are used to make estimations of future repository performance. The analytical and numerical models are based on scenarios and conditions developed in the conceptual models, and are a mathematical representation of the physical and chemical systems to be simulated. The representation of the hydrogeological and hydrogeochemical systems in the numerical models can and should be evaluated by comparison with field and laboratory observations. For example, confidence is gained in numerical models that are able to reproduce closed-form analytical results and that are able to reproduce field observations of fluid potentials or discharges or chemical concentrations. Sasowsky (2006) emphasized that for model studies to have credibility, tests that demonstrate model capabilities for the particular model application must be published. Note also that these models cannot be considered "validated" against conditions outside of the range of the experimental or observational data. Post-modeling audits have shown that hydrogeological model predictions are often incorrect. For example, Bredehoeft (2005) found that natural processes and model predictions diverged (producing model "surprises") in seven to 10 (out of 29 reviewed) model studies. Often the failure of a numerical model to reproduce field or laboratory observations with reasonable fidelity is the result of a fundamental flaw in the underlying conceptual model. Failures of conceptual or numerical models to predict with fidelity long-term behaviour of hydrogeologic and hydrogeochemical systems demonstrate the significant value of independent geologic, hydrogeologic, and hydrogeochemical observations in evaluating conceptual and numerical model predictions.

Physical and chemical properties are derived from investigations performed as a part of site characterization and from the geologic record, and provide primary information on hydrogeological and hydrogeochemical parameter values. These values can differ significantly from those posed in conceptual models developed prior to site characterization. Furthermore, site characterization provides information on past variations in hydrological and hydrochemical systems. Studies of natural analogs provide useful information on controlling processes and on potential geologic stability and variability, particularly with regard to effects of introduced materials and the unnatural hydrologic and hydrochemical perturbations due to waste disposal. Natural analog studies also yield information on hydrogeological and hydrochemical characteristics of analogous systems under potential future climatic or geologic conditions.

Characterisation of hydrogeological and hydrogeochemical systems is subject to both aleatoric uncertainty due to natural variability and epistemic uncertainty due to incomplete knowledge. Variability and uncertainty lead to ranges and distributions of variables. Although there will always remain some uncertainty with regard to understanding of natural systems, data derived from site characterisation and natural analog investigations can reduce epistemic uncertainty and can better constrain the natural system aleatoric uncertainty. New empirical data should be evaluated as they are collected. For example, new data sample values can be compared to statistics of previously collected sample populations. When new data values are inconsistent with previous population statistics, further investigation and explanation are required.

Introduction of engineered materials, nuclear wastes, atmospheric gases, exotic water, and sustained energy sources in a geologic repository can significantly perturb the natural stability of hydrogeological and hydrogeochemical systems and diminish the reliability of the predictability of those systems. Those perturbations are not addressed in this paper.

Prediction of groundwater flow

A conceptual model of groundwater flow includes consideration of hydrogeological system dynamics, boundary conditions, and initial conditions when required. The conceptual model of groundwater flow is based on expert opinion of what phenomena operating in the hydrogeological system are relevant to answering the questions posed in the analysis. Groundwater flow is a dynamic process within a relatively static geologic domain. Groundwater system dynamics result in transient changes in storage of water in the unsaturated and saturated zones. In the unsaturated zone, groundwater flow is highly non-linear because it depends strongly on the liquid water saturation state. In some hydrogeological systems, hydraulic responses significantly lag external stresses. For example, in the Pierre Shale of South Dakota, United States, mechanical rebound to erosion occurring at varying rates over the last two million years continues to change permeability and fluid pressure (Neuzil, 1993). In the Bure argillite – a host lithology being studied by the French high-level nuclear waste programme – recently observed over pressurised zones have been attributed to osmotic processes operating over geologic time spans (Neuzil, 2007). Steady-state flow occurs when there is no change in groundwater storage over time; the system is in hydrogeological equilibrium. Prediction of the long-term behaviour of steady-state hydrogeological systems is attractive to investigators because it requires fewer empirical data and less computational effort. All aspects of conceptual models of hydrogeological systems should be evaluated in comparison to multiple lines of evidence in the context of the problem to be solved.

Analytical and numerical hydrogeological models can be used to predict groundwater fluid potential, flow rates, flow paths, groundwater travel time, and groundwater discharge locations and magnitudes. Those predictions can be improved by forward and inverse calibration using measured water levels and measured transient responses to applied stresses such as pumping tests. Technical credibility is evaluated by comparison of model predictions to observed data not incorporated in the modeling process.

The suite of physical parameters required to perform hydrogeologic modeling is determined by the conceptual model. For a transient numerical hydrogeologic model, those parameters include determination of the spatial distribution of hydrologically-distinct rock units in the model domain, and determination of the permeability, porosity, and storage characteristics of those rocks. Where significant to flow (and thus to radionuclide transport), the distribution and hydraulic character of faults, fractures, and zones of fracture concentration must be taken into consideration. Rock stratigraphy, permeability, porosity, and storage characteristics can be measured empirically. Another required parameter, groundwater recharge, can be constrained by observational data and is commonly estimated through model calibration.

The geologic record provides primary information on local variations in groundwater flow systems such as variations in the groundwater table position and in surface discharge, variations that commonly result from changes in climate and geomorphologic conditions. Evidence of past water table elevations and discharge locations is preserved in diatomite deposits, subterranean and surface silicate and carbonate mineral deposits, zones of dissolution and karstification, and zones of alteration and mineral formation, among other indicators. In addition to climate variations, natural geologic processes can lead to variations in groundwater flow systems: seismicity can affect fracture characteristics; erosion, soil formation, and sedimentation can affect topography, infiltration, rock hydraulic properties, and subsurface flow; compaction and diagenesis can alter hydraulic properties of argillaceous and other sedimentary rocks; and mineral dissolution and deposition can alter hydraulic properties of evaporite rocks, to name a few. Over geologic time, it is common for these processes to occur simultaneously or in sequence, imprinting multiple generations of altered permeability and porosity on primary rock characteristics. For example, fluid flow (and thus radionuclide transport) in crystalline rocks is commonly influenced by rock fractures and faults that create multiple interacting scales of rock heterogeneity. Representation of rock heterogeneity – including rock fractures – in computer models has improved dramatically in the decades since Warren and Root (1963) published their dual-porosity model. Nonetheless, simulating fluid flow and radionuclide transport in fractured rocks remains an active and challenging research area.

Hydrogeochemistry

Groundwater chemistry is controlled by boundary conditions, e.g. soil zone or recharge zone chemistry, by coupled chemical transport and gas-water-rock chemical reactions (i.e, reactive transport) that depend on the geologic media, and by groundwater mixing along flow paths. Predictable hydrogeochemical parameters include concentrations and speciation of dissolved constituents, ionic strength, colloid concentrations and compositions, pH, oxidation potential, temperature, and sorption parameters.

Geochemical reactions are controlled by both kinetic and equilibrium processes. Realistic predictive geochemical models must generally involve thermodynamic and kinetic constraints as well as consideration of geochemical transport (e.g. Browning *et al.,* 2003). Many low temperature reactions between water and crystalline rock mineral constituents such as feldspar and quartz are slow and may not achieve thermodynamic equilibrium even on time scales relevant to nuclear waste isolation requirements. Other reactions including surface complexation and precipitation or dissolution of secondary phases such as calcite and amorphous silica can approach equilibrium conditions rapidly relative to repository time scales. Heterogeneity in hydrogeochemistry is influenced by gas-water-rock reaction progress, fluid mixing, bedrock heterogeneity, and aqueous diffusion and dispersion. Hydrogeochemistry evolves along hydrologic flow paths tending toward equilibrium with longer water-rock contact times and higher rock/water ratios. The spatial and temporal evolution of groundwater chemistry can sometimes be inferred from chemical and isotopic or temperature heterogeneity. Secondary mineralogy that is a product of water-rock interactions provides an important record of past hydrogeochemical conditions and variations in those conditions.

Illustrations from the proposed Yucca Mountain repository

Yucca Mountain is located in the arid Mojave Desert, approximately 150 kilometers northwest of Las Vegas, Nevada. It is composed of rhyolitic volcanic rocks of Miocene age (approximately 12 million years old; Ma) which have been rotated and block-faulted in response to extensional tectonic stresses. The proposed nuclear waste repository horizon is in hydrologically unsaturated, fractured volcanic rocks, about 200-300 meters above the water table and about 200-300 meters below the ground surface. Precipitation as rain or snow infiltrates through a thick sequence of variably welded, non-welded, bedded, and fractured tuffs. In non-welded rocks, groundwater flows as in other porous media, while in strongly welded rocks flow occurs almost exclusively in fractures. Present-day net infiltration is estimated to average about 3.6 mm/yr over the infiltration model domain, based on calculated differences between precipitation and evapotranspiration plus runoff (BSC, 2001). Those estimates are consistent with measurements of moisture content, temperature, and chloride concentrations in the unsaturated zone (Houseworth, 2007). Localised, fast unsaturated zone flow is indicated by bomb-pulse Cl-36 and other radionuclides at depth (e.g. Fabryka-Martin *et al*., 2006). At the water table, groundwater flow changes from generally vertical to nearly horizontal and follows the unconfined potentiometric surface (water table) gradient toward the south. The water table is relatively flat east and south of Yucca Mountain. However, on the western boundary of Yucca Mountain the water table drops approximately 50 meters from west to east as it crosses the Solitario Canyon Fault. Also, an upward gradient of approximately 20 meters has been measured between water in deep confined Paleozoic carbonate rocks and overlying volcanic rocks (Bredehoeft *et al.,* 2005). Shallow flow paths in the saturated groundwater zone traverse gently dipping silicic tuffs and eventually encounter heterogeneous alluvial deposits before exiting the site boundary. Groundwater discharges in some areas of the Amargosa River Valley including Franklin Lake Playa approximately 60 kilometers south of Yucca Mountain.

The gas phase in the unsaturated zone at Yucca Mountain is air at saturation with liquid water and with elevated CO2 partial pressure (Thorstensen *et al.,* 1998). The ambient unsaturated zone gas-water-rock system is pervasively oxidizing. Precipitation of amorphous silica, calcite, and smectite occurs in fractures and in lithophysal cavities in the welded tuffs of the repository emplacement horizon (e.g. Whelan *et al.,* 2002). These precipitates may be a consequence of slight evaporation associated with warming gas flow. Some formerly vitric (glassy) volcanic tuffs are partially or wholly altered to zeolite minerals, possibly due to hydrothermal activity in the geologic past.

Groundwater chemistry in the unsaturated zone is dilute, oxidizing, intermediate to slightly alkaline in pH, and rich in aqueous silica. Ratios of major cations and anions in the unsaturated zone are heterogeneous (e.g. Yang *et al.,* 1996), in part due to differences in groundwater flow paths in fractures and in the rock matrix. Fracture water chemistry shows less effect of water-rock interactions and evaporation, suggesting that water in fractures has a shorter residence time than water in the rock matrix. Fracture water chemistry is dominated by sodium bicarbonate, relative to matrix water chemistry, which is dominated to a greater extent by calcium chloride and calcium sulfate. Infiltrating water collected in the Exploratory Studies Facility within tens of meters of the ground surface exhibits much of the same variation in hydrochemistry as observed throughout the unsaturated zone. These data indicate that near surface reactions play an important role in controlling water chemistry throughout the unsaturated zone at Yucca Mountain. Aqueous calcium concentrations tend to decrease with depth in the unsaturated zone of the mountain, probably because of calcite precipitation and exchange of calcium for sodium in secondary minerals, particularly zeolites. The chemistry of groundwater extracted from boreholes in the volcanic rocks of the saturated zone tends to resemble the chemistry of the water in fractures and perched lenses in the volcanic rocks of the unsaturated zone at Yucca Mountain.

Some Lines of Evidence from the Geologic Record that Can Be Used to Evaluate Predictions of Evolution of Hydrogeological and Hydrogeochemical Systems at Yucca Mountain

Water table rise and long-term hydrologic stability in the unsaturated zone

Secondary mineral deposits in tuffs provide evidence of the maximum rise in the water table. Extensive alteration of originally vitric tuffs to zeolites, primarily clinoptilolite, occurred by water-rock interactions at elevations up to 100 meters above the present water table at Yucca Mountain (e.g. Vaniman *et al.,* 2001). Extensive zeolitization has been attributed to chemical alteration near or below the paleo-groundwater table (e.g. Levy, 1991; Bish *et al*., 2006). Major zeolitisation may have occurred shortly after deposition of the 12-Ma Miocene tuffs, even as they were cooling (Levy, 1991), although vitric tuffs may slowly weather to form zeolites even at the lower ambient temperatures of the present (e.g. Carlos *et al.,* 1995).

Under ambient temperature conditions, reactions among secondary zeolites and groundwater have an influence on hydrochemistry. Infiltrating groundwater exchanges divalent cations, such as strontium and calcium for sodium and potassium in the zeolites (e.g. Vaniman *et al.,* 2001). Mass balance calculations for strontium accumulations in zeolites suggest that zeolitic units are transmissive to fluid flow – despite the observation of perched water zones above these units – and that zeolites have concentrated strontium from percolating ground waters over geologic time (Vaniman *et al.,* 2001). Saturated zone ground water appears to be at equilibrium with analcime (Murphy *et al.,* 1996), which occurs as a secondary mineral at depth in Yucca Mountain.

Uranium-series and uranium-lead dates on opals in the unsaturated zone at Yucca Mountain have shown a general pattern of constant growth rates over geologic time (Paces *et al.,* 2001; Neymark *et al.,* 2002; Paces *et al.,* 2004). Dates have been obtained on silica phases from microstratigraphic positions approximately 25 µm in size across millimeter- to centimeter-thick layers of secondary mineral coatings on fracture and cavity surfaces. Although the temporal resolution of these data is not sufficient to record hydrologic transients of a few thousand years or less, these data indicate average deposition rates of one to five millimeters per million years consistently among all samples measured. "These data imply that the deeper parts of the unsaturated zone at Yucca Mountain maintained long-term hydrologic stability throughout periods of significant climate variations over the past 10 million years" (Neymark *et al.,* 2002).

Hydrothermal activity in the unsaturated zone

Petrography and microchemistry of secondary minerals in unsaturated zone fractures provides a record of long-term stable unsaturated fluid flow and geochemical conditions. Secondary mineral precipitates are found on less than ten percent of fracture and cavity surfaces of tuffs of the proposed repository emplacement zone. Calcite and silica deposits on footwalls and floors of lithophysal cavities – and not on the tops of cavities – indicate that those rocks never became fully liquid saturated and that flow was always percolating downward in those rock cavities dominantly under gravitational forces (Whelan *et al.,* 2002). Secondary mineral paragenesis in the devitrified tuffs of the repository emplacement horizon is consistently seen to evolve as follows: 1) calcite with quartz and other silica phases with occasional fluorite or zeolites; 2) calcite with opal and chalcedony; and 3) calcite containing magnesium-rich zones with clear opal (Whelan *et al.,* 2002; Wilson and Cline, 2006). Uranium decay series dating of opals of the last stage of secondary mineral precipitation indicates that this stage began at least two to three million years ago (Wilson *et al.,* 2003). Two-phase fluid inclusions in calcite, which may have formed at elevated (hydrothermal) temperatures, were shown to have been trapped only in the earlier (older) stages of secondary mineral precipitation. No data indicate repeated periods of two-phase fluid inclusion formation (Wilson *et al.,* 2003).

Alteration of clay minerals can provide evidence of hydrothermal activity in the geologic past. Smectite precipitation in small quantities occurs throughout unsaturated zone and saturated zone rocks at Yucca Mountain. In the unsaturated zone smectites are found on some fracture surfaces and in lithophysal cavities, indicating the presence of water. A clay mineral transition from smectite to illite occurs over a fairly short depth interval in borehole USW-G2, drilled north of the proposed waste emplacement zone to depths far below the water table. This transition has been interpreted to reflect the upper limits of a hydrothermal system that altered the rocks about 10 million years ago (Bish and Aronson, 1993). Estimated temperatures based on clay mineralogy approached 235°C in this system. Hypotheses of more recent hydrothermal activity in the unsaturated zone are inconsistent with extensive independent investigations, which found no evidence of hydrothermal activity at Yucca Mountain in the past five million years (e.g. National Research Council, 1992; Wilson and Cline, 2006).

Saturated zone flow

Demonstration of groundwater flow model fidelity is often accomplished by comparing observed and calculated water potential or hydraulic head. Where the residual difference between observed and calculated potential is small, the model is believed to be a credible representation of the natural hydrogeologic system. In a presentation to the U.S. Nuclear Waste Technical Review Board Panel on the natural system, a Center for Nuclear Waste Regulatory Analyses (CNWRA) hydrogeologist presented a model of the saturated zone at Yucca Mountain with a very small root mean square (residual) error of 1.1 m for the entire model domain (Winterle, 2004).

Confidence in the CNWRA model was further enhanced by a test comparing it with paleohydrological conditions. South of Yucca Mountain, a paleospring discharge formed a deposit known as the Horsetooth Diatomite. In simulating that past climate, the CNWRA analysts increased the groundwater recharge in the numerical model until discharge occurred from the model cell at the paleospring location (Winterle, 2004). The resulting water table rise under Yucca Mountain ranged from 50 to 100 m, consistent with geologic observations of alteration of vitric volcanic tuff to zeolites.

Using a novel thermal-perturbation technique, recent investigations in the volcanic rocks near the southern end of the Yucca Mountain saturated zone flow field identified zones of fluid velocity as high as 10 km/yr (Freifeld e*t al.,* 2006). Zones such as this were previously unknown at the Yucca Mountain site, and are not incorporated into DOE numerical groundwater models of the saturated zone at Yucca Mountain. The frequency and pervasiveness of these high-velocity zones has not been subsequently investigated, nor has the potential impact on model predictions of fluid flow and radionuclide transport been evaluated.

Extent of Fracture-Matrix Water Interactions

Saturated zone groundwater extracted from deep boreholes in the vicinity of Yucca Mountain is chemically undersaturated in calcite (Kerrisk, 1987; Murphy, 1995). However, core samples from the same boreholes contain calcite as a fracture filling material (Bish and Vaniman, 1985). These relations, together with information on the water producing zones in the boreholes, indicate that the ground water flowing in high permeability fracture systems is chemically isolated on a geologic time scale from water in a matrix pore system (Murphy, 1995).

Waste Form Stability and Alteration on a Geologic Time Scale

The Nopal I uranium deposit at Peña Blanca near Chihuahua, Mexico, is a natural analog of the proposed repository at Yucca Mountain (e.g. Murphy and Pearcy, 1992; Pearcy *et al*., 1994; Fayak *et al.,* 2006). The geology (fractured silicic tuffs in an active extensional tectonic setting), semi-arid climate, and deep hydrologically unsaturated zone are closely analogous to the Yucca Mountain hydrogeological and hydrogeochemical environment. The primary uranium ore at Nopal I was uraninite, a close chemical and structural analog of spent nuclear fuel. Information from Nopal I relevant to the stability and predictability of the proposed repository at Yucca Mountain comes from studies of the geochemical alteration of primary uraninite and the formation of relatively stable secondary uranyl minerals in the oxidizing environment. Persistence of primary uraninite for millions of years at this site depends on its physical isolation from oxidizing conditions by silica cements. Stability of secondary uranyl minerals, principally uranophane, at Nopal I attests to their potential role in sequestering radionuclides at Yucca Mountain on a geologic time scale.

Conclusions

Crystalline rock systems can provide hydrogeologically- and hydrogeochemically-stable environments for geologic disposal of nuclear wastes over long time scales. Numerous lines of evidence are present in the geologic record that can support evaluation of predictions of evolution of hydrogeologic and hydrogeochemical systems at Yucca Mountain – predictions required to ascertain the ability to isolate spent nuclear fuel and high-level radioactive waste. Confidence in those predictions is increased when conceptual models, analytical and numerical models, and empirical observations are internally consistent and are consistent with all available geological, hydrogeological, and hydrogeochemical evidence.

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GEOLOGICAL AND ROCK MECHANICS ASPECTS OF THE LONG-TERM EVOLUTION OF A CRYSTALLINE ROCK SITE

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Abstract

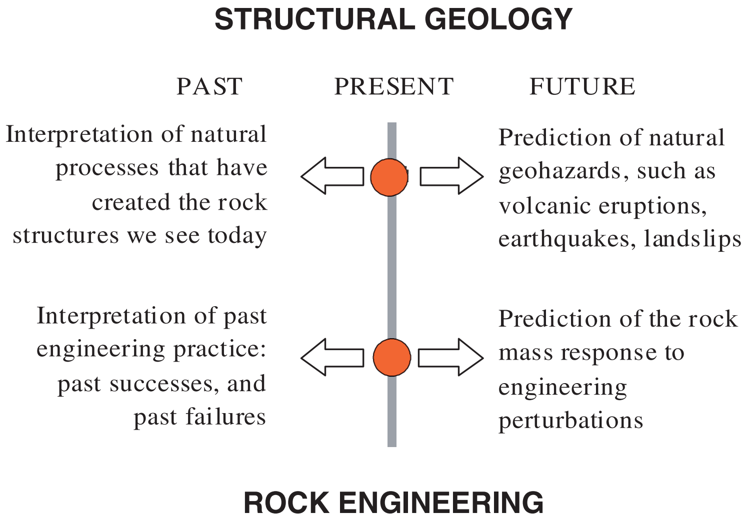
We consider the stability of a crystalline rock mass and hence the integrity of a radioactive waste repository contained therein by, firstly, identifying the geological evolution of such a site and, secondly, by assessing the likely rock mechanics consequences of the natural perturbations to the repository. In this way, the potency of an integrated geological-rock mechanics approach is demonstrated. The factors considered are the pre-repository geological evolution, the period of repository excavation, emplacement and closure, and the subsequent degradation and natural geological perturbations introduced by glacial loading. It is found that the additional rock stresses associated with glacial advance and retreat have a first order effect on the stress magnitudes and are likely to cause a radical change in the stress regime. There are many factors involved in the related geosphere stability and so the paper concludes with a systems diagram of the total evolutionary considerations before, during and after repository construction.

Introduction

In terms of the stability of the geosphere for the long-term hosting of a radioactive waste repository, it is necessary to consider the deformation mechanisms operating in the rock mass in the past, the present and the future. Analysis of past geological events is achieved through the techniques of structural geology enabling us to understand the current configuration of the rock mass elements; analysis of predicted future geological events enables us to evaluate the long-term integrity of the repository function, i.e. the continuing safe containment of radionuclides. Rock mechanics considerations apply both to the structural geology analyses and the rock engineering design analyses. In fact, there is a natural link between structural geology and engineering rock mechanics: in both fields, the same mechanical principles are used to understand the deformational behaviour of rock. The major difference is that of the physical and temporal boundary conditions under which the deformation occurs (Figure 1).

The structural geologist uses the rock mechanics principles to analyse the deformation which has already occurred to the rock mass in response to low strain rates linked to slowly changing boundary conditions which occur over an extended period of geological time. In contrast, the rock engineer uses these principles to predict the rock mass behaviour in response to the rapidly changing boundary conditions associated with excavation of the rock for the engineering project. However, it should be remembered that a conventional civil engineering structure built on or in a rock mass has a design life of 120 years, whereas the design life of a repository is measured in up to hundreds of thousand of years, so that subsequent geological changes have also to be taken into account in the engineering design of a repository.

Figure 1. **Structural geology and rock engineering objectives in the context of the past, present and future**



An understanding of the tectonic evolution that lead to the formation of the deformed and fractured rock mass being assessed by the rock engineer will prove invaluable in making an initial rapid assessment of its mechanical structure and intrinsic stability, as well as providing a sound basis for a detailed analysis of its likely response to the change in conditions linked to the construction of the engineering project. In fact, the key to successful engineering design is the ability to predict the future consequences of the engineering activities, and for this we need to understand the rock mass structure, the applied rock stresses, and the effects caused by the engineering activities.

The past geological evolution of crystalline rock masses

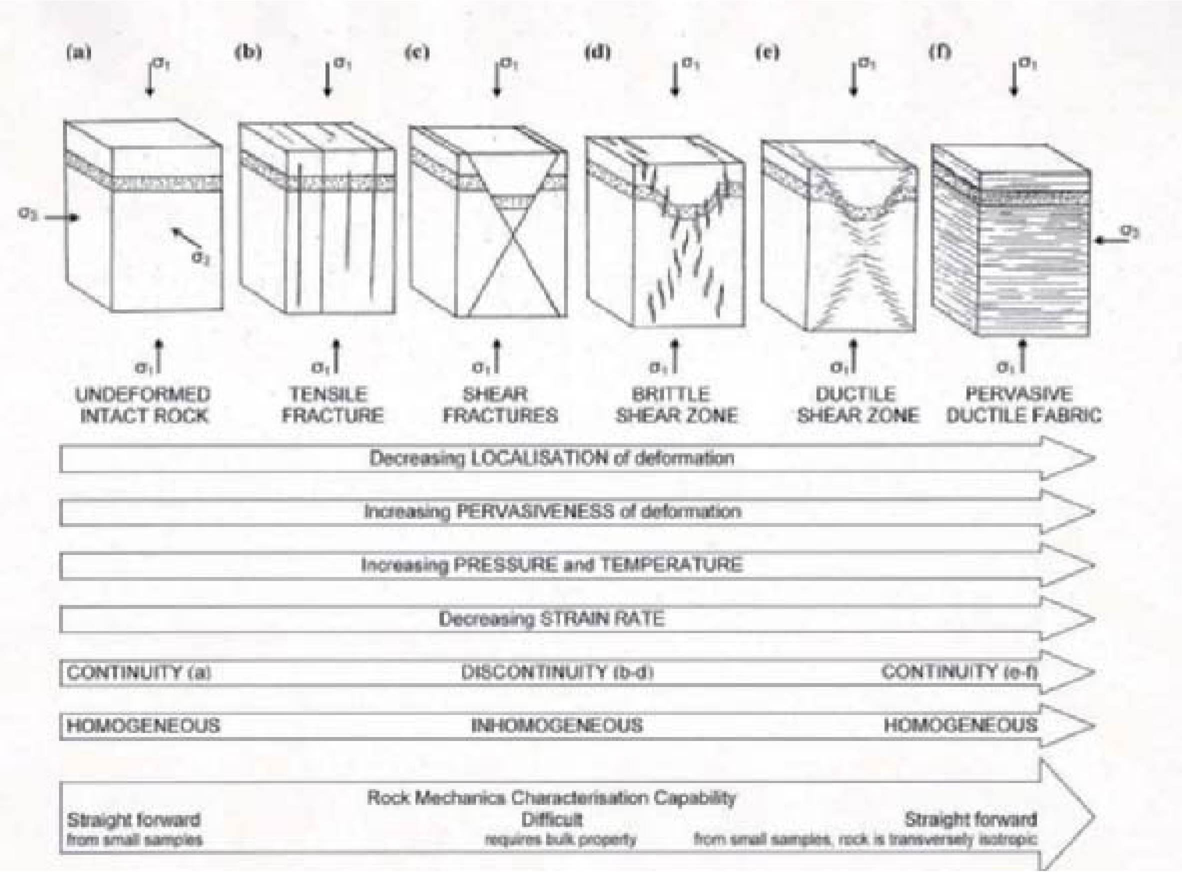
Crystalline is the term used to describe indurate rocks which have usually undergone multiple deformations over a long geological time period. They are generally metamorphosed and make up much of the Pre-Cambrian Shields which form the substrate of the major tectonic plates. They may currently lie beneath many kilometres of cover rock or they may be exposed at the surface. These exposures can cover many thousands of square kilometres, e.g. the Canadian and Scandinavian Shields.

As mentioned, the task confronting a structural geologist is that of determining the tectonic history (i.e. the sequence of stress regimes that have affected the rock) from the complex of ductile and brittle structures present in the rock. Most of the crystalline rocks making up the shields display a variety of ductile structures (for example folds and pervasive mineral fabrics) generated under conditions of relatively high pressure and temperature and slow strain rate (Figure 2), on which have been superimposed a succession of brittle structures (joints and faults), linked to relatively low pressure and temperature environments and high strain rates.

The ductile structure that impacts most on the mechanical properties of the rock is probably the pervasive planar fabric (Block f in Figure 2). This can range from a slatey cleavage through to a schistosity and ultimately a banded gneiss, depending on the intensity of the deformation and the protolith. These fabrics can have a first order effect on controlling stress orientation within the rock mass and, because they impart a mechanical anisotropy to the rock, are also likely to influence the orientation and propagation of fracturing linked to later stress regimes. This also applies to the rock around an excavation periphery – which will be illustrated later.

The crystalline rocks of the Pre-Cambrian shields have invariably been affected by several episodes of ductile deformation, each deforming earlier fabrics and superimposing their own fabric onto the rock. During the ductile deformation of a rock, any brittle feature is likely to be either annealed or completely obliterated. Consequently, the ductile structures observed in a crystalline rock mass represent the earliest detectable deformation features. It addition, and because any ductile deformation event will either obliterate or severely subdue any previous ductile fabric, it is the last major ductile event (specifically its associated pervasive ductile fabric) which will have the most important effect on the evolution of the fracture networks which are present in all Shields and which have a major impact on the mechanical properties of the rock.

Figure 2. **The variety of deformation features, both brittle and ductile, that characterise many crystalline rocks. Each is generated during a single deformation event and the result of many such episodes of these types of deformation leads to the superposition of the structures and the formation of a fractured and deformed rock mass.**

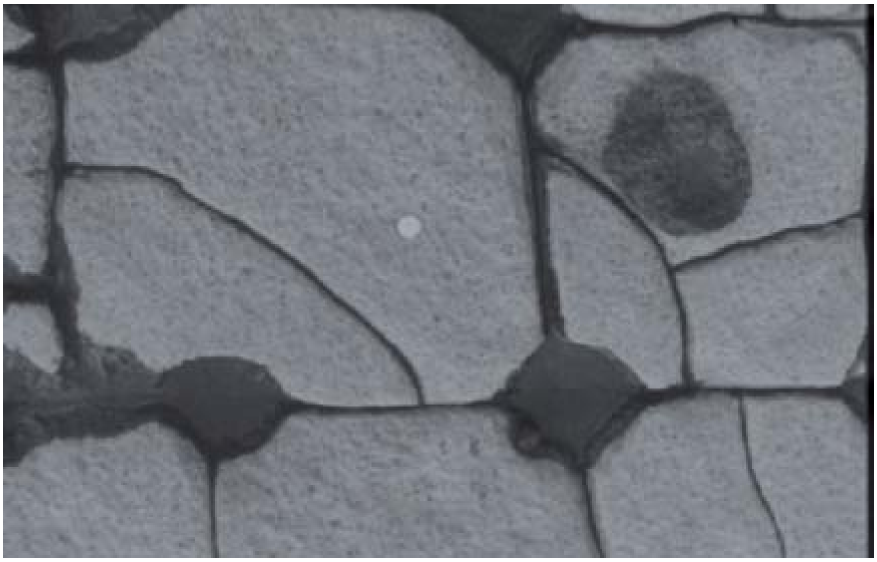


During the ductile deformation of a rock, any brittle feature is likely to be either annealed or completely obliterated. Consequently, the ductile structures observed in a crystalline rock mass represent the earliest detectable deformation features.

Fracture networks are built up by the superposition of several fracture sets (Blocks b and c in Figure 2) linked to a succession of geological stress regimes. However, individual fractures do not behave passively but are mechanical features that actively influence the orientation and magnitude of a subsequently applied stress field – in the same way that the planar ductile fabrics influence the orientations of later stress regimes. This interaction is demonstrated in Figure 3 which shows the effect of early fractures on later fractures. If the early fractures are open, there can be no shear stress parallel to their walls; consequently, any applied stress must become re-oriented (curved) as it approaches a fracture so that the principal stresses become parallel and normal to the fracture walls. By exactly the same argument, the principal stresses around an open engineered excavation are parallel and perpendicular to the excavation walls. Moreover, this phenomenon is independent of scale.

Because of the intimate relation between stress orientation and fracture orientation (for example, Type I fractures, i.e. extensional fractures, which form normal to the minimum principal stress), any fractures linked to the later deformation will follow this curved trajectory and will intersect the old open fracture at right angles. In addition, the mechanical discontinuity represented by the early fracture prohibits the propagation of the later fractures which consequently terminate against it. This curving and abutting of later fractures against earlier ones provides a technique for determining the relative age of fractures and permits one to place the various fracture sets making up the fracture network into a chronological order. This is the basis of fracture analysis.

Figure 3. **Curvature and abutment of subsequent fractures as they approach and meet earlier open fractures (Liassic limestone from the Bristol Channel Coast, United Kingdom)**



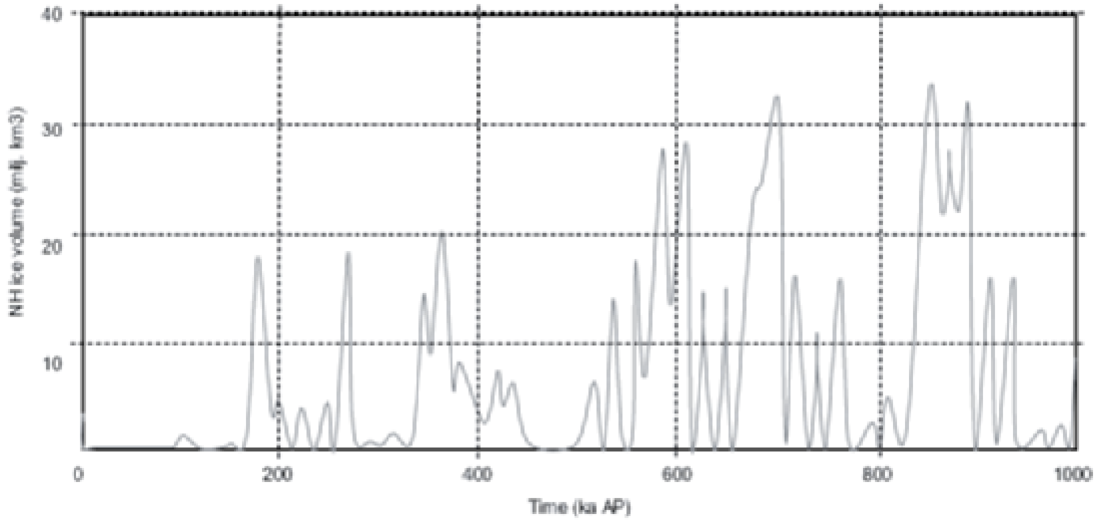
Hence, the structural geologist can, by considering the ductile fabric and fracture network imposed upon it, determine the sequence of stress regimes to have affected the rock over geological time and obtain a clear understanding of the geometry of the mechanical discontinuities and of their likely impact on rock mass properties. These data go to the rock engineer who uses them to support the rock engineering design analysis. In this way, the structural geologist determines what has happened to the rock and hence its current properties; whereas, the rock engineer predicts the future through the different types of design analysis, determining for example the appropriate depth, dimensions and orientations of the underground openings.

The future geological evolution of crystalline rock masses

However, the task of siting a nuclear waste repository requires further input from the structural geologist. This is because the stability of an underground excavation with a design life of hundreds of thousands of years requires an understanding of the natural events that can potentially affect the repository integrity in the future. For a repository in the Pre-Cambrian Fennoscandian shield, the predicted glaciation cycles are likely to produce the most severe mechanical perturbations. An idea of the magnitude of these glacially induced perturbations can be seen from the predictions illustrated in Figure 4 for the continental ice volume versus time for the next million years.

The ice sheet thickness associated with the volumes in Figure 4 will be in the order of kilometres and hence will significantly alter the *in situ* rock stress state. So, although it is unlikely that the tectonically-induced stress will alter (because it is caused by the mid-Atlantic ridge opening), there will be transient stress changes as each glaciation advances and retreats. Note that we are assuming here that northern latitudes are being considered and so we will not be considering deep tropical weathering which can affect both the stress state and the rock properties.

Figure 4; **The Northern Hemisphere (NH) continental ice volume (vertical axis in millions of km^3) for the emission-M scenario (0-1 million years AP) based on simulations from (BIOCLIM 2001), from Posiva 2006-05**



Long-Term Evolution of Crystalline Rock: The Rock Mechanics Impacts

The repository will be contained within a pre-loaded rock mass because of the pre-existing stress state. The two main types of rock mechanics effects are:

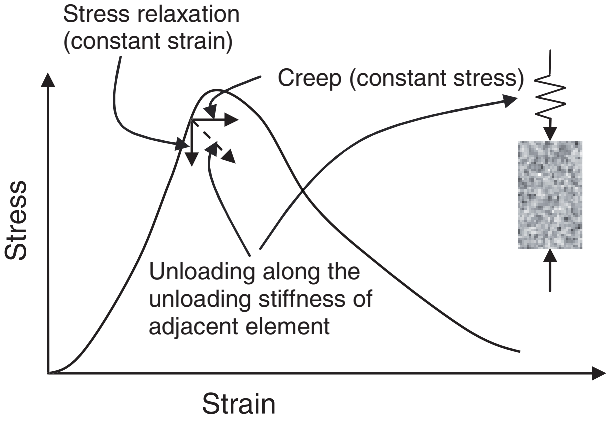
- the deterioration that will take place regardless of any geological change; and
- the consequences of any geological changes, mainly alterations to the stress state caused by glaciation as described in the previous section.

Long-term time deterioration

In the context of long-term time deterioration, there can be confusion concerning the meanings of the terms creep, stress relaxation, and fatigue. In Figure 5, a rock specimen is illustrated being loaded in compression through an adjacent rock element represented by the spring. Creep is defined as increasing strain while the stress is held constant. Stress relaxation is defined as decreasing stress while the strain is held constant. Fatigue refers to cycling of the stress or the strain.

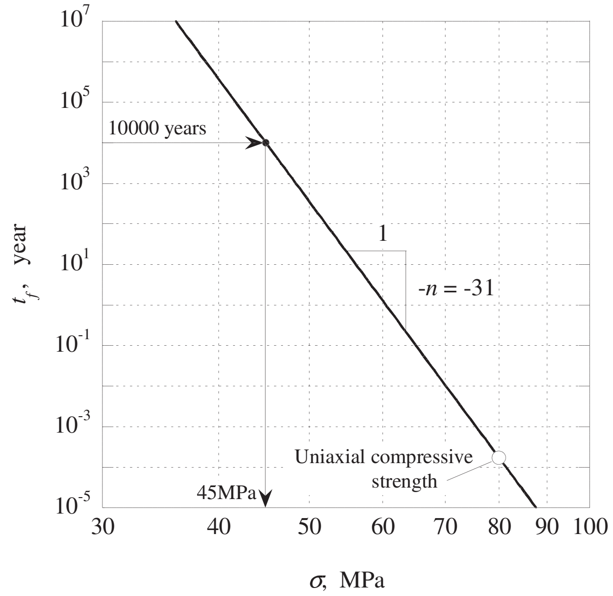
In practice, and especially for the rock around an underground excavation, a rock element will be loaded via the stiffness of an adjacent element and so the time-dependent behaviour will be somewhere between the ideal conditions of creep and stress relaxation, as illustrated in Figure 5.

Figure 5. **Definitions of creep, stress relaxation and time dependent unloading along the stiffness of the adjacent element**



The time-dependent displacements associated with creep and fatigue arise from sub-critical crack growth, which is most affected by stress intensity, chemical environment, temperature and microstructure. This is particularly significant for a nuclear waste repository because the conditions (i.e. the depth, stress state, chemical environment and temperature) are more severe than those observed in conventional underground tunnels at shallower levels. Thus, given the extremely long design life of a repository compared to the 120 years or so for more conventional underground excavations and given the isolation objective, it is important to understand the time-dependent effects. The long-term behaviour of the rock mass hosting a nuclear waste repository has been considered in the Evolution Report (Posiva, 2006-05) which discusses the evolution of a KBS-3V repository planned for the Olkiluoto site in Finland.

Figure 6. **Example plot of rock strength versus time (Jeong *et al.*, 2007)**



The diagram in Figure 6 shows the rock strength time-dependency for Kumamoto andesite and was established in a study of the influence of a water vapour environment on rock strength to establish whether water is the most effective agent in promoting stress corrosion of rock. From Figure 6, we can see that, for an unconfined compressive rock strength of 80 MPa measured under normal 8-hour day-to-day testing (10^{-4} years), the long-term 10 000 year strength is estimated to be 45 MPa – which is almost a 50% strength reduction. This type of strength deterioration is particularly significant for a radioactive waste repository where the design life is likely to be in excess of 100 000 years, in terms of spalling due to:

- the pre-existing rock stress;
- the enhanced rock stress induced by the thermal load; and
- the rock stress induced by the glacial load.

In addition to these temporal variations in the applied rock stress and hence the variation in the concentrated stress around the deposition holes and tunnels, there can be a wide variation in rock strengths, as illustrated by the data in Figure 7. Furthermore, numerical analysis can be conducted of the excavation damaged zone (EDZ) around a repository opening. For example, in the work by Golshani *et al*., 2007, the model is capable of reproducing the three characteristic stages of creep behaviour (i.e. primary, secondary, and tertiary creep) leading to failure of the modelled excavation in 600 years, see Figure 8.

Figure 7. **The distribution of rock strengths at the Olkiluoto site, Finland (from Posiva, 2007-03)**

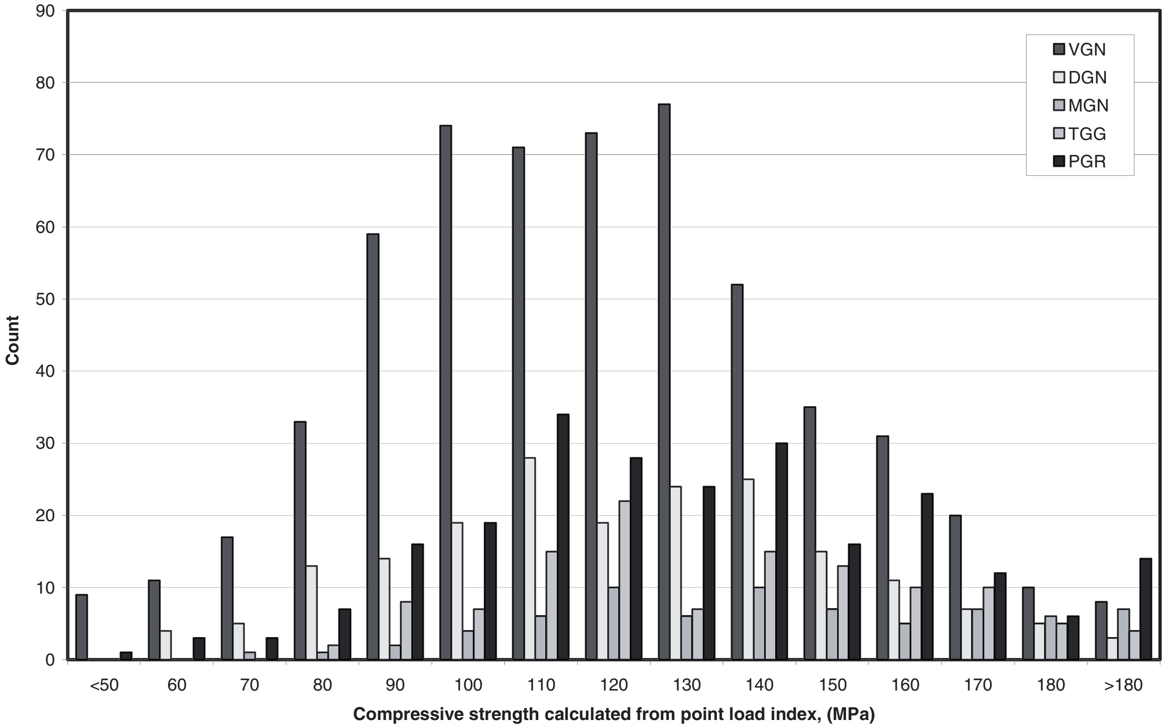
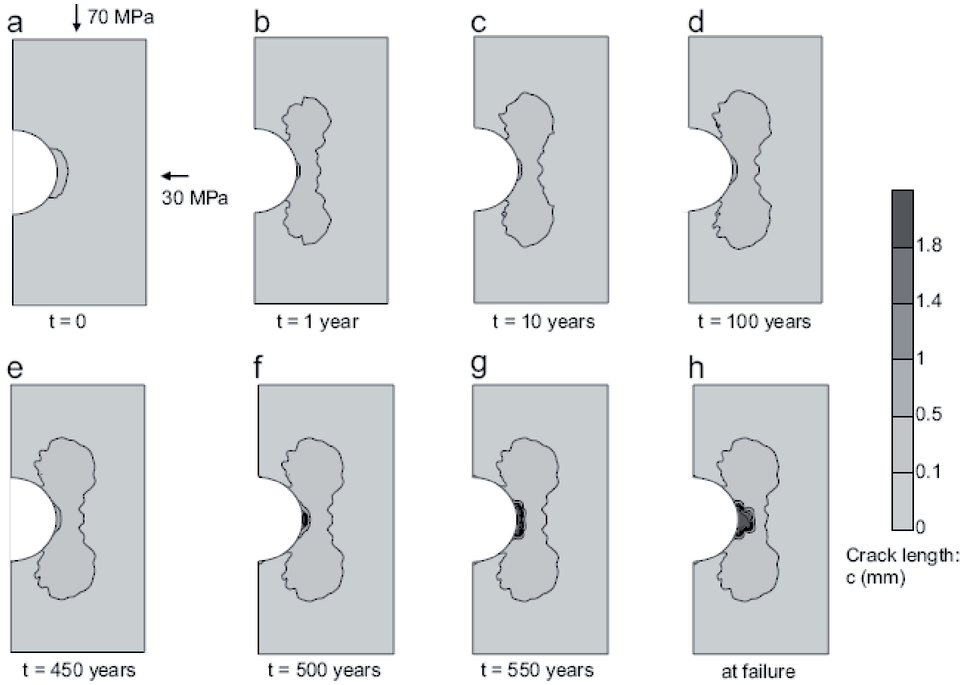
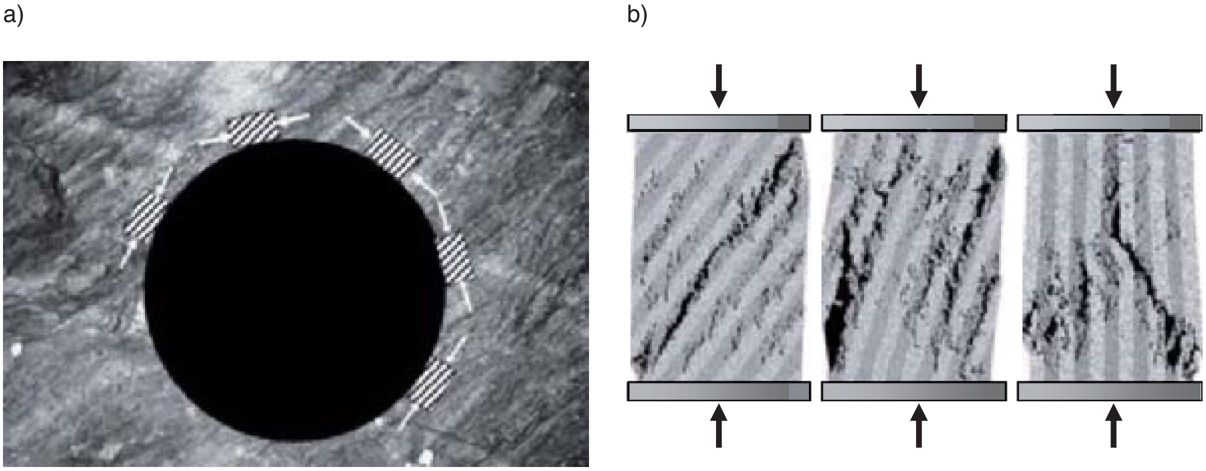


Figure 8. **Numerical Model of the Time-Dependent Degradation of the Excavation Damaged Zone (EDZ) around an Underground Excavation (From Golshani *et al.*, 2007)**



Other factors governing the failure around an underground excavation include the foliation. In the same way that in structural geology the presence of foliation will affect the development of new fractures as discussed earlier, the black and white line sketches superimposed on the photograph in Figure 9 (a) indicate how the exact position of rock spalling around an excavation in a foliated rock will be a function of both the location of the concentrated stress and the orientation of the foliation. The numerical modelling output in Figure 9(b) (Wang S. – personal communication) shows how the failure mode will depend on the relative orientations of the foliation and the applied stress.

Figure 9. **Influence of the foliation on potential failure of the rock at the periphery of an underground excavation**



Changes to the stress field

Consider a generic calculation of the stress state both before, during and after a glacial advance. For every 40 m of rock overburden, 1 MPa of vertical stress is generated. Assuming that this is the minimum of the three principal stresses, we expect the maximum horizontal stress to be in the order of 2.5 times the vertical stress (Harrison *et al.*, 2007, see Table 1). So, at a typical repository depth of 500 m, the vertical stress component will be 500/40 = 12.5 MPa and the maximum horizontal stress component will be 2.5 x 12.5 = 31.25 MPa. Similarly, the intermediate principal stress, also horizontal, is in the order of 1.5 x 12.5 = 18.75 MPa. Hence the three principal stresses (σ_1, σ_2, σ_3) at 500 m are (31.25, 18.75, 12.5 MPa) which is a thrust fault regime, the minimum stress component being vertical.

Table 1. **Ratios between the principal stresses observed in different countries (from Harrison *et al.,* 2006)**

Stress ratio/Country	σ_1/σ_2	σ_2/σ_3	σ_1/σ_3
Australia	1.5	1.5	2.3
Chile	1.6	1.6	2.6
Finland	1.7	1.7	3.0
United Kingdom	1.6	1.4	2.4

To estimate the likelihood of spalling, these stress components are used to calculate the concentrated stress around the periphery of the deposition holes and tunnels, noting that there will be distributions of both stresses and strengths (see the strength variation in Figure 7). Moreover, once the temperature is elevated throughout the repository from the canister heating, an extra stress component must be added to the concentrated stress because of the thermal loading. This is typically an extra hydrostatic 24 MPa throughout the maximally heated rock volume.

Within the framework of this Workshop theme, the long-term stability of the geosphere, we also have to consider the effect of the glacial loading on the stress state described above. For each ice thickness of 100 m, an extra 1 MPa should be added to the vertical stress. Thus, for a glacier with a thickness of 3 kms, an extra 30 MPa has to be added to the vertical stress. Due to the Poisson's ratio affect, this 30 MPa vertical stress induces a $30(\nu/(1-\nu)$ MPa stress in the horizontal directions, where ν is Poisson's ratio. For $\nu = 0.25$, an additional horizontal stress of 10 MPa is induced by the vertical ice loading. Adding 30 MPa to the previous vertical stress component and 10 MPa to the horizontal components, the values of the *in situ* stress state components become (41.25, 28.75, 42.50). These "before glaciations" and "after glaciations" stress states are summarised in Table 2.

Table 2. **Generic *in situ* stress states before and after glaciation in a crystalline rock mass**

State of glaciation	Principal stress (acting horizontally)	Principal stress (acting horizontally)	Principal stress (acting vertically)
Without	31.25	18.75	12.5
With 3 km thick glacier	41.25	28.75	42.5

The pre-glacial stress state assumed here is a thrust fault regime (i.e. the minimum principal stress is vertical) and the stress state during glaciation is a normal fault regime (i.e. the maximum principal stress is vertical). In the transition between these two stress regimes (both during loading and unloading), the conditions for wrench faulting (intermediate principal stress is vertical) will occur. The increase in the stress magnitudes and the accompanying changes in the stress regimes indicate that many previously stable fractures will be susceptible to reactivation as a result of glacial advance and retreat, depending on their orientation and shear strengths.

This generic stress state can also be locally altered by the presence of fractures because they represent a discontinuity in the mechanical continuum. The "with" and "without" a brittle deformation zone diagrams in Figure 10 showing the displacements caused by excavation of a tunnel in a horizontally stressed medium demonstrate the considerable effect of an adjacent fracture zone on the local stress and displacement field.

Figure 10. **"Without" and "With" a brittle deformation zone displacement and stress diagrams showing the effect of excavating a tunnel in a horizontally stressed medium**

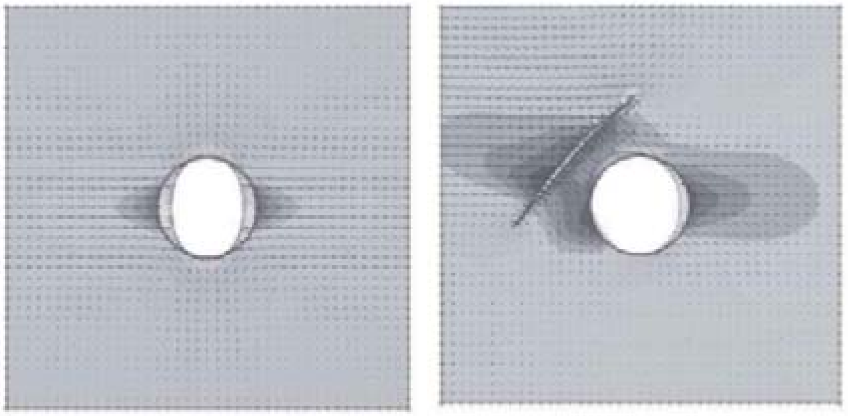


Figure 11. **Interactions between seven of the key rock mechanics factors**

ROCK STRESS	Rock fracturing	Normal and shear displacement	No direct effect	No direct effect	Minimal direct effect	No direct effect
Stiff rocks attracts stress	**INTACT ROCK**	Fracture type	Primary permeability	No effect	Mineral content	No direct effect
Perturbation of stress state	No direct effect	**FRACTURES**	Secondary permeability	Minimal direct effect	Fracture filling	No direct effect
Effective stress	No direct effect	Erosion	**WATER FLOW**	Heating or cooling	Dilution or concentration	No direct effect
Coefficient of linear expansion	Increased alteration rate	No direct effect	Convection	**TEMPERATURE**	Solubility	No direct effect
No direct effect	Solubility, alteration, replacement	No direct effect	No direct effect	No direct effect	**GROUNDWATER CHEMISTRY**	No direct effect
Significant changes	EDZ	EDZ	Alteration of hydraulic head	Heat source or sink	Ionic changes	**PERTURBATIONS**

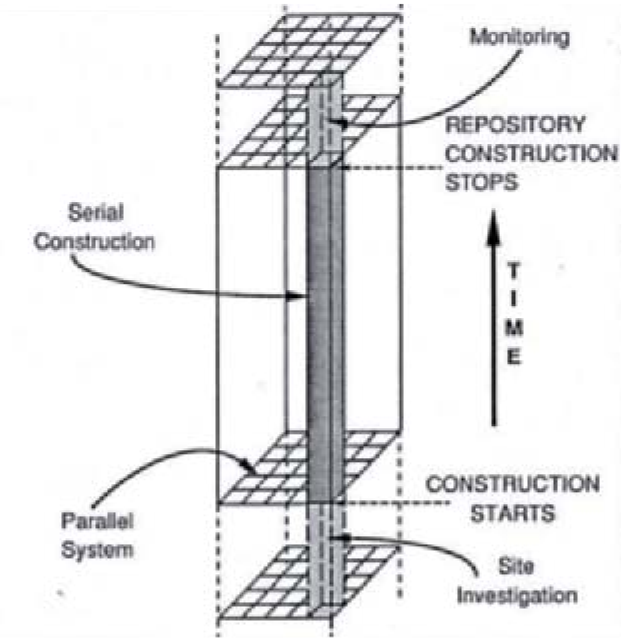
Interactions between the rock mechanics factors and their evolution

Given the many factors involved in the geological and rock mechanics aspects of the repository design problem, it is helpful to have a method of holistically considering all the interactions between the factors. This can be achieved using an interaction matrix, as shown in Figure 11 where the seven factors of rock stress, intact rock, fractures, water flow, temperature, ground water chemistry, and perturbations are listed and highlighted along the leading diagonal (from top left to bottom right). The binary interactions between each pair of factors are noted in the off-diagonal boxes using a clockwise convention.

To encompass the unusually long engineering time span (say 100 000 years) for the repository, the systems diagram in Figure 12 is a helpful concept. The matrix in Figure 12 is shown more schematically than in Figure 11 but is of the same type using any number of appropriate variables in the leading diagonal:

- Before site investigation begins, the natural system operates and is described via geological techniques
- Then site investigation begins and the engineer perturbs the natural system with boreholes and possibly pilot tunnels.
- Construction of the repository is indicated by the continuing perturbations introduced via the lower right-hand box in the matrix (as also in Figure 11).
- Considering emplacement of canisters as part of the construction, the temperature is then increased
- The repository is backfilled and closed and "repository construction" stops
- Then the system is no longer subjected to further perturbations by the engineer and is passively monitored
- Beyond this state, the geological conditions will change as described in this paper.

Figure 12. **Systems evolution of the site and repository over geological time**



Conclusions

In this paper, we have described the geological evolution before and after repository construction, emplacement and closure. The pre-repository geological processes dictate the rock mass conditions that will be encountered and we emphasised the different types of deformational features that will occur in a crystalline rock mass. Unusually for an engineering project, it is also necessary when designing a radioactive waste repository for the geological evolution after construction to be taken into account, particularly the rock degradation and likely changes in the stress state due to glacial loading. The generic stress states before and during a glacial advance were numerically illustrated, thus demonstrating the significant impact of the additional stresses. Finally, the total system in time and space was summarised through a systems diagram encompassing the key variables and their evolution.

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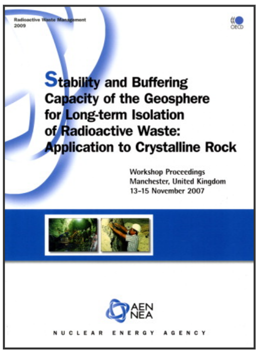

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