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Investigations of potential repository sites for spent nuclear fuel at Forsmark and Laxemar-Simpevarp, Sweden

Abstracts, 33rd International Geological Congress, Oslo

Compiled by

Kaj Ahlbom, Svensk Kärnbränslehantering AB

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August 2008

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Contents

Preface

The 33rd International Geological Conference (33rd IGC) in Oslo is a major event for the geoscientific community. During nearly ten days in August 2008, thousands of geoscientists will present and discuss results of research in all the fields of geoscience. In addition, there are several pre- or post-conference excursions that will show and discuss features or processes in the field that are subject to research.

The SKB site investigations to locate potential geological repositories for spent nuclear fuel at Forsmark and Laxemar-Simpevarp have recently been completed. They probably represent the single, most significant geoscientific undertaking that has been carried out in Sweden and have resulted in a vast amount of data and models that are open to the public, including the professional geoscientific community. In order to share the knowledge gained and to have it discussed in this community, SKB have encouraged researchers that have been involved in the site investigations and the modelling work to present their findings at the 33rd IGC. New findings from the Äspö hard rock laboratory will also be presented.

Together with our Finnish sister organisation Posiva, we are also in the process of preparing an excursion guide that summarises the geology and describes key field localities at the three sites that have been investigated for the disposal of highly radioactive nuclear waste in Finland and Sweden: Forsmark, Laxemar-Simpevarp and Olkiluoto.

The contributions related to SKB activities at the conference will be presented in different symposia and on different days. In order to see the full extent of the contributions, all abstracts have been compiled in this report. It is intended that the compilation should provide the reader with an overview of the geoscientific knowledge gained during the SKB site investigation programme and also what will be presented and discussed at the 33rd IGC. The excursion guide will be published as a separate report during 2009.

Olle Olsson

SKB Nuclear Fuel Repository Programme

Symposium NWG-02:

Geology and disposal of nuclear waste: Nordic approach – special aspects of the disposal in crystalline bedrock

Conveners
Lars-Olov Ericsson, Liisa Wikström

Structural characterization of brittle deformation zones in crystalline rocks: contribution to SKB site investigation study for the disposal of highly radioactive nuclear waste

Viola, G., Nordgulen, Ø., Saintot, A. and Venvik-Ganerød, G.
NGU, Geological Survey of Norway, Trondheim, Norway

The Swedish Nuclear Fuel and Waste Management Company (SKB) is undertaking site investigation at two different locations in south-eastern Sweden, Forsmark and Laxemar-Simpevarp, with the aim of identifying the most suitable area for the construction of a deep repository for the disposal of highly radioactive nuclear waste. As a part of this programme, the Geological Survey of Norway (NGU) has undertaken a study of predominantly brittle structures (i.e. brittle deformation zones, faults, fractures and associated fault rocks) with the aim to document their character and kinematics as an input to an evaluation of the brittle deformational history of the regions under investigation. The results are used in the development of the conceptual model for especially brittle deformation zones in the target rock volumes.

All cored boreholes drilled were logged using the Boremap methodology and oriented BIPS images were acquired for the whole length of the holes. Single-hole interpretation studies identified possible deformation zones within the cores based on fracture frequency, rock alteration, geophysical logs, radar reflectors, visual inspection etc. In order to better characterize these possible deformation zones in the boreholes, NGU initially carried out field structural mapping on selected outcrops and trenches. The results of the field study were then integrated with the constraints derived from the logging of chosen deformation zone intervals in a variety of drill cores. Oriented structural features were systematically documented, described and characterized for a number of structurally relevant zones. In addition to the mapping of planar structural features, particular attention was paid to shear striations along broken fault planes. These linear features were oriented and measured with the help of fracture orientation data from Boremap and a drill core holder, which allowed the core to be correctly positioned in 3D space. Statistically significant fracture and striation orientations and fault-slip data allowed the determination of the kinematics of many of the deformation zones investigated as well as the identification of multiple reactivation events. The data were also used to compute paleostress tensors and therefore to frame individual deformation events into a consistent sub-regional brittle deformation scheme. When present, fault rocks were studied in order to better constrain the deformation mechanisms that controlled the brittle structural evolution at the two sites. Petrographic studies and SEM work on thin sections prepared from samples of representative fault rocks provided a valuable tool to unravel the details of the local brittle history. Information gathered during the study provided in summary a robust basis for the fine-tuning of the single-hole interpretation work and for the 3D modelling of the target rock volumes. Examples will be presented of the characterization of deformation zones and of the paleostress inversion study.

Geoscientific understanding of the Forsmark site

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Multidisciplinary investigations to characterize a potential repository for spent nuclear fuel have been completed in two areas in Sweden: Forsmark and Oskarshamn. The results from ongoing integrated modelling and repository engineering evaluation provide input to forthcoming safety and environmental impact analyses to be included in the application to construct a repository at one of the sites.

Forsmark is located 150 km north of Stockholm. The candidate area is approximately 10 km^2 in size. It is located within a tectonic lens, composed mainly of c. 1870 Ma years old metagranite, that trends NW-SE. The lens is surrounded by highly deformed and heterogeneous bedrock, which is strongly anisotropic. The multidisciplinary investigations have included a wide range of surface and borehole surveys to evaluate geological, ecological, hydrogeological, hydrogeochemical, transport, rock mechanical and thermal conditions and properties. Rigorous measures have been taken to ensure data quality.

The integrated analysis of the results have been continuously presented in site descriptive reports that describe the current state of knowledge, as well as the natural processes that affect the long-term development of the area. The models have been updated successively as the database has developed with time. During the recurrent modelling procedure, data needs were identified and the site investigation programme was adjusted accordingly.

Key characteristics of the bedrock are:

- The bedrock inside the candidate area is geologically homogeneous and dominated by metagranite with high quartz content from surface down to at least 1,000 m depth. It has high thermal conductivity and high compressive strength.
- The candidate area is divided into two structural elements by a gently dipping fracture zone. The potential repository is located in the footwall to this zone and is transected solely by steeply dipping zones. Gently dipping zones are common in the hanging wall.
- The fracture frequency outside fracture zones in the repository bedrock is low below c. 200 m depth and even lower below 400 m depth. Only a few of these fractures carry water.
- Down to a depth of c 200 m, there is a high frequency of sub-horizontal fractures with apertures. These are hydraulically interconnected over long distances and, together with the gently dipping zones, are the main water conductors.
- Rock stresses are relatively high in the upper part of the bedrock but the gradient towards depth in the repository rock is low.
- Both the salinity and age of the groundwater increase with depth but the water composition at depth in the repository bedrock is different from that in the gently dipping zones to the south-east. It is inferred that water in the repository bedrock has been isolated from the surface for a long time (^{36}Cl and ^{4}He analyses indicate > 1.5 Ma), whereas the water in the gently dipping zones contains signatures from the Littorina Sea that covered the area 9,500 to 5,000 years ago.

Geoscientific understanding of the Laxemar-Simpevarp site

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[b]Conterra AB, Partille, Sweden

Multidisciplinary investigations to characterize a potential deep geologic repository for spent nuclear fuel have been completed at two areas in Sweden; Forsmark and Laxemar-Simpevarp. The results from ongoing integrated modelling and repository engineering evaluation provide input to forthcoming safety and environmental impact analyses to be included in the application to construct a repository at one of the sites.

Laxemar-Simpevarp is located in the municipality of Oskarshamn some 230 km south of Stockholm and c. 20 km north of the town of Oskarshamn. The site is dominated by well preserved intrusive rocks belonging to the c. 1800 Ma generation of the Transscandinavian Igneous Belt (TIB). The bedrock in the Laxemar candidate area is dominated by rock types of quartz monzodioritic to granodioritic compositions, two porphyritic varieties called Ävrö granite and Ävrö quartz monzodiorite and an equigranular quartz monzodiorite. The multidisciplinary investigations have included a wide range of surface and borehole surveys to evaluate geological, hydrogeological, hydrogeochemical, transport, rock mechanical, thermal and ecological conditions and properties. Rigorous measures have been taken to ensure data of high quality.

The integrated analysis of the results have been continuously presented in site descriptive modelling reports that describe the current state of knowledge, as well as the natural processes that affect long-term development of the area. The models have been updated successively as the database has developed with time. During the recurrent modelling procedure, data needs were reassessed and the site investigation programme was adjusted accordingly.

Key characteristics of the bedrock are:

- The bedrock inside the focussed area is geologically homogeneous and dominated by quartz monzodiorite and Ävrö quartz monzodiorite with low quartz content, associated with reduced thermal conductivity and uniaxial compressive strength (UCS)
- The focused area is bounded by subvertical deformation zones. Interpretation of deformation zones inside the focused area is facilitated by minute soil cover, high resolution DEM, laser scanning and detailed ground surface magnetometry. No major gently dipping deformation zone is found.
- The fracture frequency outside the identified fracture zones in the focused area is low and below c. 400 m depth there is a significant decrease in water conductive fractures.
- Rock stresses are compatible with the situation at Äspö HRL with the greatest horizontal stress in northwest-southeast direction (coinciding withy the most transmissive vertical fracture set) with a magnitude of 25 – 30 MPa at 500 metres depth.
- Both the salinity and age of the groundwater increase with depth. In the upper part, down to c. 750 m, Na-HCO_3 waters dominates followed by Na-Ca-Cl, Ca-Na-Cl and an interface to deep saline water at a depth of c. 1,200 m.

The engineering focus for repository design in hard rocks

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The geoscientific data collected by SKB during the Site Investigations form the bases for a Site Descriptive Model (SDM) for the Final Repository. Running in parallel with the development of the SDM is the repository design. For design purposes the repository is partitioned into three functional areas: Repository Access consisting of shafts and ramps for transportation and ventilation; Central Area at approximately the repository depth which consists of caverns and auxiliary rooms required for depositional activities; and Depositional Area consisting of depositional tunnels and boreholes. While each functional area will have specific design requirements the overall major tasks that must be addressed in the preliminary design are: selection of the repository depth considering the characteristics of the rock mass with respect to both long term safety and constructability; and selection of a repository layout for the specified number of deposition holes that meets the safety and functional criteria. This includes: the adaption of the repository to site conditions and constraints, such as avoiding deformation zones by a specified respect distance; and dimensioning the repository to satisfy the thermal criteria and the specified degree of utilization. Within the Depositional Area the layout design must balance the alignment of deposition tunnels with the state of stress and dominant joint sets to minimize the loss of deposition holes. The final optimised design can only be completed once the site meets regulatory approval.

The repository underground design must be safe, economically feasible and meet the requirements for long term safety based on a realistic estimate of the expected ground conditions and their potential behavior as a result of various loading scenarios. The design process has several steps with each step updated as additional information from the Site Investigations becomes available. The inherent complexity and variability in the geological setting will prohibit a complete picture of the ground conditions before the facility is excavated. Thus statistical methods will be used to evaluate the robustness of the design.

One of the methodologies used in underground design and construction to address uncertainty and variability in the geological setting and ground structure interaction is the Observational Method (OM). The OM is a risk-based approach to underground design and construction that employs adaptive management, including monitoring and measurement techniques. The objective of this approach is to substantially reduce costs while protecting capital investment, human health, and the environment. SKB plans to carry out the design process for the Final Repository project in agreement with the European standard for construction, Eurocode, and in particular the standard for geotechnical design and OM, EN 1997-1:2004.

Äspö hard rock laboratory – most essential results in a 20 year perspective

Peter Hultgren
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The Äspö Hard Rock Laboratory (HRL) provides an important scientific and technical basis for the programme of implementation and operation of a future deep repository in Sweden. The need for such an underground laboratory was identified at an early stage in the Swedish programme. Initially, the Stripa mine could be used, but at the beginning of the 1980:s it was realised that an underground laboratory at a virgin site would be needed, because Stripa was an abandoned iron mine and disturbance on water flow in fractures had occurred in decades. Äspö HRL was constructed 1990 –1995 to provide an opportunity for research, development and demonstration in a realistic and undisturbed rock environment down to the depth planned for a future deep repository for spent nuclear fuel.

Äspö HRL is located on the Äspö Island in the municipality of Oskarshamn some 230 km south of Stockholm and c. 20 km north of the town of Oskarshamn. The site is dominated by well preserved intrusive rocks belonging to the c. 1.8 Ga generation of the Transscandinavian Igneous Belt (TIB). The bedrock in the Äspö area is dominated by generally porphyritic rocks of quartz monzodioritic to granodioritic, composition. Subordinate rock types comprise granite, generally porphyritic, fine-grained granite and various mafic rocks,

The Äspö HRL is a laboratory for the development and testing of methods for detailed characterisation of the rock volume from excavated tunnels. Further, Äspö is a full scale laboratory for testing construction and handling techniques and for the demonstration of important parts of a repository system. Finally, it provides a multitude of data for development of our knowledge of important processes in deep crystalline bedrock and for testing of models for groundwater composition, groundwater flow and radionuclide migration. It is, in essence, a “dress rehearsal” for the deep repository.

Outcome of some key experiments were:

- A comparison between the prediction from pre-investigation data and the outcome from tunnel documentation has made it possible to judge the reliability of the site investigation methods based on surface and borehole data.
- Comparison of excavation induced damage of drilling and blast compared to full face drilling has been made. Advance studies of Excavation Disturbed Zone (EDZ), looking at cross sections from tunnel walls by sawing cuts was fruitful to understand the distribution of the damaged zone around the tunnels.
- Rock stress measurements, both from boreholes drilled from the surface and boreholes in the tunnel, have determined the rock stresses at Äspö HRL. Rock mass properties have been obtained from different locations in the tunnel.
- Special designed experiments in different scales have improved our understanding of how radionuclides are transported in a fractured network.

Methodology for iterative and integrative geomodelling in a multidisciplinary workspace

Raymond Munier
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The safe disposal of radioactive wastes imposes a formidable challenge and requires expertise from a broad range of scientific disciplines. The application for the construction of a repository requires a site description within which the geological model, i.e. the interpreted geometries and properties of relevant components of the geosphere, constitutes a cornerstone. As two sites are currently being investigated in Sweden, the methodology for geoscientific modelling needs to be predominantly site-neutral to ensure means of adequate comparison of the sites.

A vital component of the modelling process is to establish a consensus among the geoscientific disciplines within the modelling project regarding terminology. The process of data gathering by different methods (e.g. airborne or ground geophysics), the method-specific interpretations (e.g. lineament model) and the modelling (e.g. co-interpretation of topographic and geophysical data) needs to be formalised such that each activity is self-contained regarding quality assurance, analysis and reporting. In essence, this means breaking the analysis process into small, independent activities, the outcomes of which are collected and modelled in batches.

The geological modelling is initiated by the construction of models of various dimensions. Each borehole is first interpreted independently (single hole interpretation, SHI), using the outcome of integrated interpretation of various independent methods, producing 1-D geological maps. Similarly, interpretation of geophysical data yields various 2-D lineament maps whereas the geological outcrop mapping and sampling yields 2-D outcrops maps.

The integrative modelling is the process in which lineament- and outcrop maps are ennobled to form deformation zone- and lithological maps respectively. The resulting integrated product is a 2D bedrock geological model. This process endorses multiple lines of evidence for the interpretation and aids to assess uncertainty issues and level of confidence. The 3-D modelling process consists of collecting all 1-D and 2-D models into a 3-D container for cross-hole and surface-hole modelling, yielding the ultimate outcome; a 3-D geological model which forms the geometrical framework for all geoscientific disciplines in the project.

A formalised feedback process from neighbouring disciplines is essential to ensure inter-disciplinary consistency in the resulting site description. For this purpose, we have found it fruitful to make use of domains, (e.g. lithological domains, hydraulic domains, etc) to endorse integration. The process of domaining is the purpose driven subdivision of the model volume into internally homogeneous sub volumes with respect to a specific collage of properties.

Major and trace elements in surface and ground waters in two near-coastal granitoidic settings in eastern Sweden

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This study focuses on the hydrochemistry of surface water and groundwater at two different areas in eastern Sweden, Forsmark, which has a carbonate-rich till and Oskarshamn with a carbonate-poor till. In these areas the Swedish Nuclear Fuel and Waste Management Company (SKB) is currently conducting extensive scientific investigations and environmental monitoring. The goal with these investigations is to find out which of these two areas is most suitable for the construction of a bedrock repository for spent nuclear fuel. The hydrochemical data collected within these investigations has been used in this study, in order to increase the understanding of how natural waters in near-coastal granitoidic settings are affected by various processes.

The result showed that in streams there were strong temporal (4 years) patterns of major solutes with some inversely correlated with flow (e.g. Na, Mg, K, Cl- and Br-), others showing summer maxima (e.g. Fe and DOC) and still others summer minima (Mn, NH4+, NO3- and SO42-). A lake (Bolundsfjärden) in Forsmark that was studied in more detail had both similar and dissimilar hydrochemical features to that of its inflowing stream (Kungsträsket). Another stream (Bredviken) in Forsmark had a strongly different hydrochemical signature to that of all other surface waters in both areas. This is interpreted as being the result of oxidation of biogenic metal sulphides in fine-grained sediments and associated increased weathering rates of the surrounding carbonate-rich till. Rare earth elements (REEs), which consist of analogues for several actinides (e.g. Am3+ and Cm3+) were strongly enriched in overburden groundwater as compared to surface water and bedrock groundwater, and their fractionation patterns were diverse indicating complex and spatially variable controls. Speciation modelling predicted strong REE association with dissolved organic matter, which to some extent contrasts previous studies emphasizing carbonate complexation. The uranium data for waters in Forsmark and Oskarshamn were compared with that of other surface and ground waters throughout Boreal Europe. Despite strongly elevated U concentrations at certain depths (100–650 m) in the Forsmark bedrock groundwater, these concentrations were not considered anomalous as similar values are not unusual elsewhere in this region.

To conclude, the patterns identified in this study have increased the understanding of the chemical dynamics of natural waters in near-coastal granitoidic settings in the boreal zone. In addition, since either Forsmark or Oskarshamn will be suggested as a site for the construction of a bedrock disposal for spent nuclear waste, the processes and patterns identified in this study provide valuable information also in that sort of context.

Strategy for determination of thermal properties in crystalline rocks

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The Swedish Nuclear Fuel and Waste Management Company (SKB) is developing site descriptive models at the Forsmark and Laxemar areas, with the objective of siting a repository for spent nuclear fuel. The spatial variation of thermal conductivity in the rock mass is described in the thermal site descriptive model.

The local temperature field around a canister is of primary concern for the design of a repository. The current design criterion is specified as the maximum temperature allowed in the bentonite buffer outside the canisters. To fulfil the temperature requirement, a low rock thermal conductivity leads to larger distance between canisters than in the case of a high thermal conductivity. Therefore, the spatial variability of the thermal properties of the rock mass is important for the canister spacing.

The strategy for the thermal site descriptive modelling is to produce spatial statistical models of both lithologies and thermal properties and perform stochastic simulations to generate a spatial distribution of thermal properties that is representative of the modelled rock domain. The total variability within a rock domain thus depends on the lithology and the thermal properties of each rock type. Although the thermal conductivity of a single rock type may be close to normally distributed, the statistical distribution of thermal conductivity for the domain as a whole is far from normally distributed. Depending on their fraction of the total volume, the low-conducting rock types may determine the lower tail of the thermal conductivity distribution and influence the canister spacing.

The methodology involves a series of steps, eg. choice of simulation scale, definition of Thermal Rock Classes (TRCs) within the rock domain, stochastic simulation of TRCs (lithology in the domain), stochastic simulation of thermal conductivity within each TRC, and finally merging of the realisations of TRCs (lithology) with the thermal conductivity realisations. The result is a set of 3D realisations describing the spatial variability of thermal conductivity within the rock domain. These realisations can thereafter be upscaled to a desired scale. The described methodology can also be used for other types of rock properties.

The distribution of thermal conductivities comes primarily from TPS-measurements on rock samples in laboratory. In order to describe the spatial structure of thermal conductivity a very large number of samples are needed. A correlation between thermal conductivity and density has been found. The relationship can be explained by the mineral distribution for different rock types and the density and thermal conductivity for the minerals. For acid rock the thermal conductivity decreases when density increases, for basic rock the relationship is opposite. The relationship makes it possible to use density logging to estimate the spatial correlation structure within each rock type, instead of huge amount of thermal conductivity determinations.

Laboratory investigations of porosity, diffusivity and sorption characteristics of crystalline rock

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Investigation of transport properties such as porosity, diffusion and sorption, on rock samples, provide information about the retardation properties of a rock mass.; i.e. the decrease in flow rate of a solute relative to that of the groundwater flow. During the site investigations at Forsmark and Oskarshamn, laboratory measurements of these transport properties have been conducted by Swedish Nuclear Fuel and Waste Company (SKB). Rock properties as grain-size, texture, mineralogy, microfractures and alteration are considered to influence the porosity, the diffusivity and the sorption capacity. Therefore, rock samples from various fresh and altered rock types, as well as different fracture materials, have been included in the laboratory program.

Porosity The focus during the laboratory work has been on the connected porosity, defined as the porosity available for water saturation. The connected porosity is the result of micro fractures and grain boundary porosity together with intragranular porosity in the rock.

In this specific program, water saturation technique according to standard method SS-EN 1936 has been used. Briefly summarized, the rock core samples are dried in 70° until constant weight is reached, followed by water saturation under vacuum conditions. Complementary porosity investigations using the ^{14}C-PMMA technique have been performed with the purpose to measure microfracturing, the two-dimensional distribution of porosity and porosity gradients in altered rock materials. The method entails drying slices of drill cores and impregnating with a ^{14}C-tagged methylmethacrylate monomer, whereby both the connected porosity and its spatial distribution in the rock matrix are determined.

Diffusion Matrix diffusivity measurements have been performed by measuring how quickly an added substance diffuses through a piece of rock, so-called through-diffusion measurements. The measurement is normally performed on a 3 centimetre thick rock slice of a drill core placed in a measurement cell. One side of the core piece is in contact with a synthetic groundwater and the other is in contact with a synthetic groundwater tagged with the radionuclide to be studied (in this case tritiated water, H^3HO). Samples are then taken on the un-tagged side, and the effective diffusion coefficient, D_e, for the rock matrix can be calculated based on the concentration increase.

Batch sorption In batch sorption measurements, crushed rock samples are contacted with groundwater and the distribution of a dissolved species between the aqueous and the solid phase is measured. In this specific case, three size fractions of crushed rock material are used, together with various types of site-specific groundwater such as saline, fresh and brine water in combination with several different tracers in form of radionuclides, e.g. $^{137}Cs^{+}$, $^{85}Sr^{2+}$ and $^{226}Ra^{2+}$.

Bridging the gap between site characterisation and performance assessment models for radionuclide transport modeling in the Äspö task force on modeling of groundwater flow and transport of solutes

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During the last few decades, significant efforts have been devoted to understand groundwater flow and solute transport processes in deep rock formations. These efforts have been made in order to assess the suitability of such rock formations to host geological repositories for spent nuclear fuel.

The Äspö HRL (Hard Rock Laboratory) is an underground research laboratory where the Swedish Nuclear Fuel and Waste Management Company (SKB) compile and refine knowledge of all the processes that occur in a final repository, among which groundwater flow and transport of solutes are of paramount importance. The overall objective of the Task Force on Modelling of Groundwater Flow and Transport of Solutes is to increase the understanding of retention of radio-nuclides transported in crystalline rock and to increase the credibility in the computer models. The group provides a platform for interaction in the area of conceptual and numerical modeling of groundwater flow and solute transport in fractured rock. In particular, the Task Force proposes, reviews, evaluates and contributes to such work in the HRL project. Presently, five organizations in addition to SKB are participating in the Task Force.

The modeling tasks challenge experienced modelers and provide training for new modelers. The tasks can also be used in the confidence building process and provide strength to arguments and knowledge on pertinent topics for the participating organizations. The tasks drive the development for codes and provide benchmark examples. One more important element is the building and testing of conceptual models.

So far, six modeling tasks have been completed, one task is on-going and one task is in the planning phase. Recently Task 6, which involves Performance Assessment modeling using Site Characterization data (PASC) was completed. Task 6 concerns the usefulness of in situ tracer experiments for performance/safety assessments. Normally, in situ tracer experiments are dominated by rather fast processes. Task 6 tries to bridge the gap between performance /safety assessment and site characterization models by applying both approaches for the same tracer experiments.

Task 6 turned out to be a useful exercise from several aspects. The task provided development of numerical models able to capture the various retention processes of relevance for both time scales. Furthermore, the developed models provided a deepened insight and quantification of when different processes contribute to observable transport characteristics of migrating radionuclides. One of the main outcomes was the understanding and quantification of how and to what extent short-term tracer tests may be used to parameterize models used for long-term assessment. These findings are now used directly in on-going performance/safety assessment studies and in the development of safety cases for potential repositories.

Importance of geosphere in hard rock nuclear waste repositories

Johan Andersson
JA, Streamflow AB, Stockholm, Sweden

Hard rock is a suggested host medium for nuclear waste repositories in many countries. For example, the nuclear industry in both Finland and Sweden plan to construct such repositories according to the KBS-3 concept, where the spent fuel is encapsulated in copper canisters with a cast iron insert, surrounded by bentonite clay buffer and deposited at about 500 m depth in the crystalline basement rock.

In order to ensure that the repository is safe, safety assessments are carried out. These aim at describing the future evolution of the repository in its geological environment, to quantify the potential for releases of radionuclides from the deposited waste and to establish the confidence in this assessment.

The geological environment is an important part of the initial state. Field data are obtained from various investigation activities, such as surface mapping, geophysics, borehole drilling, borehole testing or underground mapping. The field data are interpreted and evaluated into an overall inter-disciplinary Site Descriptive Model (SDM), being a synthesis of geology, rock mechanics, thermal properties, hydrogeology, hydrogeochemistry, bedrock transport properties and surface system properties.

Repository evolution is modelled considering the processes judged to affect the repository and the geological environment. Different time periods are considered e.g. the excavation and operational phase, closure and initial temperate period, a first glacial cycle expected to last about 120 000 years and subsequent glacial cycles. Alternative climate evolutions are also considered.

Radionuclide release could only occur in case the canister integrity is breached, e.g. in case of adverse chemical or mechanical conditions. Furthermore, also if the canister is breached the release from the spent fuel and the migration through the bentonite barrier into the rock is small and limited. The host rock contribution to safety is thus primarily to ensure adequate conditions for the canister and the buffer and only secondarily to ensure good retention for the released radionuclides.

Only some site conditions are really important for safety. These include, the geometry of deformation zones and fractures affecting the mechanical stability of canisters, the rock stress and the intact rock strength affecting the stability of deposition holes, the rock thermal conductivity that together with the repository design affects the repository temperature and the groundwater flow at the deposition hole affecting both the stability of the buffer and the copper canister as well as the release of radionuclides for the case of an intact buffer. Both the current distribution of groundwater composition as well as the processes effecting this, need to be determined in order to assess the chemical evolution of the barriers. A prerequisite for confidence is also to develop sufficient understanding of the processes and mechanisms governing the general evolution of the site.

Symposium HYH-07:

Groundwater flow and water–rock interaction in compact fractured rocks: Storage of nuclear waste, field evidence and mathematical models

Conveners
Tomas Paces, Gert Knutsson, Peter Wikberg

Site-descriptive modeling of geological repository sites in Sweden

Jan-Olof Selroos
Svensk Kärnbränslehantering AB, Stockholm, Sweden

The Swedish Nuclear Fuel and Waste Management Company (SKB) is undertaking site characterization at two different locations in Sweden, the Forsmark and Laxemar-Simpevarp areas, with the objective of siting a geological repository for spent nuclear fuel. An integrated component in the characterization work is the development of site-descriptive models that constitute descriptions of the sites and their regional settings, covering the current state of the geosphere and the biosphere as well as those ongoing natural processes that affect their long-term evolution.

The site-descriptive models include the following disciplines: bedrock geology, rock mechanics, thermal properties, bedrock hydrogeology, bedrock hydrogeochemistry, bedrock transport properties, and descriptions of the surface system. For each discipline, the models are based on extensive sets of site-characterization data. A number of data freezes constitute well-defined points in time for which given versions of the models are developed. For each successive model version, the different models within each discipline are integrated more fully such that the final model versions provide consistent inter-disciplinary descriptions of the sites. The site-descriptive models have multiple objectives: first, the models are intended to explain the features and processes of the sites in order to provide confidence that SKB understands the relevant characteristics of each site. Second, the models are used as input for repository engineering activities, safety assessment studies of the long term safety of possible repositories, and for environmental impact assessment studies.

In the current presentation, it is exemplified how the models of the different disciplines are integrated and depend on each other. Specifically, the hydrogeological flow model of the Forsmark site is taken as an example, and it is shown how hydrogeological data, and data and models from other disciplines, respectively, are used in the derivation of the hydrogeological groundwater flow model.

In the subsequent SKB-related presentations within the current session, more detailed descriptions of the bedrock geology, bedrock hydrogeology, near-surface hydrogeology (soil and near-surface rock) and bedrock hydrogeochemistry models are given. Examples on site characterization methods deployed in the field are also given within both the hydrogeological and bedrock transport properties disciplines. Moreover, a presentation on how a site-descriptive groundwater flow model relates to the larger regional groundwater flow context is provided.

Deformation zones and fracture domains at Forsmark, Sweden: A basis for hydrogeological and hydrogeochemical modelling

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Selection of a site for the disposal of highly radioactive nuclear waste requires a robust understanding of the bedrock geology prior to modelling work in other disciplines, repository design, and the assessment of safety and environmental impact. At Forsmark, in eastern Sweden, geological modelling has addressed three aspects that serve the needs of different users; rock domains (RD), deformation zones (DZ) and fracture domains (FD). Attention is focussed here on the modelling of deformation zones and different fracture domains in the intermediate rock mass, knowledge of which is a prerequisite for particularly the hydrogeological, hydrogeochemical and design work.

At Forsmark, steeply dipping, ductile high-strain belts with WNW to NW strike surround tectonic lenses, where the Palaeoproterozoic bedrock is folded and generally affected by lower ductile strain. The potential repository is situated inside one such lens. Rock contacts and ductile structures vary from steeply dipping in the north-west, inside the potential repository volume, to more gently dipping further to the south-east. The ductile deformation has contributed to the development of a strong bedrock anisotropy that has steered the development of younger brittle deformation at the site.

Steeply dipping deformation zones with WNW to NW and occasionally NNW strike are restricted to the margins of and to the high-strain belts outside the tectonic lens. Several of these zones show both ductile and polyphase brittle strain. By contrast, the potential repository volume at 400−500 m depth inside the lens is transected by steeply dipping fracture zones that strike ENE to NNE and show a trace length at the ground surface that is c. 3.5 km or less. The damaged and core parts of these predominantly strike-slip zones are up to a few tens of metres thick and contain a high frequency of sealed fractures. Some gently, south- and SE-dipping fracture zones occur in the rock volume above 400 m depth. However, such zones are more conspicuous to the south-east of the potential repository volume, where gently dipping ductile structures prevail.

At Forsmark, six fracture domains have been recognised. The two domains that include the potential repository volume at 400−500 m depth show a low frequency of fractures with apertures. By contrast, a near-surface fracture domain, which extends downwards from the surface to a maximum depth of c. 200 m above the potential repository, shows a high frequency of open fractures. It is suggested that unloading of younger sedimentary material, including Quaternary glacial deposits and ice, resulted in the extensional failure of especially sub-horizontal and gently dipping, ancient fractures and the development of joints. Furthermore, in the uppermost few tens of metres, newly formed fractures with wide apertures in the form of sub-horizontal sheet joints developed. These features are coupled to the release of high rock stresses in the bedrock during the unloading.

Hydrogeological character of the bedrock in the Forsmark area, Sweden, based on single-hole hydraulic tests

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During site investigations, the bedrock at Forsmark, Sweden, has been thoroughly hydrogeologically characterised with both single-hole and cross-hole hydraulic tests. Constant-head injection tests and difference flow logging have been used to characterise the fracture properties close to the boreholes, and cross-hole pumping tests have been used for larger-scale studies. The overall experience from these investigations is that the anisotropy of the structural model governs the groundwater flow at all depths. In addition, there is a considerable depth trend, where the uppermost part of the bedrock is found to be significantly more conductive than the deeper parts. The following conceptual structural-hydraulic model regarding the observed deformation zone transmissivities has been proposed:

- The geological division of the deterministically modelled deformation zones into major sets and subsets is useful from a hydrogeological point of view. Most of these structural entities are steeply-dipping and strike WNW-NW, NNW and NNE-NE-ENE; one is gently-dipping (G).
- All deformation zones, regardless of orientation (strike and dip), display a substantial decrease in transmissivity with depth. The data suggest a contrast of c. 20 000 times for the uppermost one kilometre of bedrock, i.e. more than four orders of magnitude. Hydraulic data below this depth are lacking.
- The horizontal heterogeneity in transmissivity is also substantial (a few orders of magnitude) but more irregular in its appearance and governed by the depth trend.
- The observation that the mean transmissivity of the gently-dipping deformation zones is c. one to two orders of magnitude greater than the mean transmissivities of all categories of steeply-dipping deformation zones may be due to the anisotropy in the stress field, where the maximum stress is horizontal and has an azimuth of c. 140°. The hypothesis is supported by the deformation zones that strike WNW and NW. These two categories of steeply-dipping deformation zones have, relatively speaking, higher mean transmissivities than steeply-dipping deformation zones in other directions.

Concerning the bedrock in between the deterministically modelled deformation zones, the following conceptual model has been suggested:

- The geological division of the bedrock in between the deterministically deformation zones into six fracture domains is useful from a hydrogeological point of view.
- The conductive fracture frequency shows very strong variations with depth, and it is proposed that a discrete fracture network model be split into three layers: above the elevation –200 m, between the elevations –200 and –400 m, and below the elevation –400 m.
- The hydraulic character of fracture domains is also structurally anisotropic, being dominated by the G set, and only with a small contribution from the NNE and possibly NE subsets. However, the depth trend in fracture transmissivity is not as conclusive as for the deformation zones.

Experiences from large-scale, hydraulic cross-hole tests in the Forsmark area, Sweden

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Multidisciplinary investigations to characterise a potential area for a repository for spent nuclear fuel have been completed in two areas in Sweden: Forsmark and Oskarshamn. At Forsmark, located at the coast and 120 km north of Stockholm, the investigations have been focused to an area within a tectonic lens. The lens is composed mainly of c. 1870 Ma years old metagranite, trends NW-SE and is surrounded by highly deformed and heterogeneous bedrock, which is strongly anisotropic. The multidisciplinary investigations have included a wide range of surface and borehole surveys to evaluate geological, ecological, hydrogeological, hydrogeochemical, transport, rock mechanical and thermal conditions and properties. In particular, large scale hydraulic cross-hole tests have been used to improve the understanding of the connectivity of the fracture networks at the site and to verify the hydraulic models.

During the summer of year 2006, a three-week long cross-hole test was performed in the Forsmark area. The 130 m deep pumping well was situated in the central part of the site, intersecting a complex network of highly transmissive gently dipping and sub-horizontal fractures, interpreted partly to belong to an ancient gently dipping deformation zone that extends to great depth, and partly to be related to more recent release of stress due to unloading. About 100 observation sections at various elevations between the surface and about 1,000 m depth were monitored during the test. In the following summer, 2007, the test was repeated but with a prolonged pumping period to about three months. The number of observation sections now extended to c. 170.

The results from both tests showed rapid pressure responses in all directions within the uppermost bedrock. For example, responses were observed c. 500 m from the pumping well within the first hour of pumping, and within 10 hours of pumping clear responses were observed as far as c. 1 km away. The results support the existence of a high yielding sub-horizontal fracture network with large lateral extension in the uppermost bedrock.

Clear responses were also recorded, within hours, within the highly transmissive gently dipping deformation zone about 1,600 m from the interpreted intersection with the pumping borehole at c. 500 m depth. At depth, below the gently dipping fracture zone, few responses were recorded in spite of many observation sections.

The two tests resulted in almost identical final drawdown in many observation points, disregarding a pumping time of three weeks 2006, or three months 2007. The results indicate a hydraulic border of constant head, likely to be the Baltic Sea. However, further pumping tests in the area also showed that pressure responses also could travel long distances in the bedrock below the sea bottom.

Key features of the near-surface hydrogeology in the Forsmark area, Sweden

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Hydrological and hydrogeological field investigations are conducted in the Forsmark area by the Swedish Nuclear Fuel and Waste Management Co. (SKB) for siting of a repository for spent nuclear fuel. The surface and near-surface parts of the investigations include monitoring of surface water levels and discharge, groundwater levels, and hydraulic characterisation of Quaternary deposits (QD). The main objectives of these investigations are to provide a detailed description of the surface and near-surface hydro(geo)logy as a basis for key aspects of the site investigation as safety and environmental impact assessment. Hydrogeological investigations of the bedrock and hydrochemical characterisation of surface water and groundwater are performed in parallel activities.

The study area is characterized by a small-scale topography and is almost entirely located below 20 m.a.s.l. Till is the dominating QD, covering 75% of the area, while granite is the dominating rock type. The annual precipitation and runoff are 560 and 150 mm, respectively.

Groundwater levels in QD are very shallow; on average less than 0.7 m below ground during 50% of the time. Shallow groundwater levels imply a strong interaction between evapotranspiration, soil moisture and groundwater. Diurnal fluctuations of the groundwater levels, driven by evapotranspiration cycles, are evident in many groundwater wells. Furthermore, groundwater level measurements in the vicinity of the lakes show that the lakes may act as recharge sources to till aquifers in the riparian zone during summer.

There is a close correlation between the topography and the groundwater levels in the QD. For groundwater levels in the upper bedrock there is no such strong coupling to the topography. This is most evident in the central part of the study area, where the groundwater level gradients in the bedrock are very small, indicating a high transmissivity. Here, the groundwater levels in the till in general are considerably higher than in the bedrock. The result is that local, small-scale recharge and discharge areas, involving groundwater flow systems restricted to QD, will overlay the more large-scale flow systems associated with groundwater flow in the bedrock. Also in the middle of Lake Bolundsfjärden, located in the central part of the study area, the lake level and the groundwater level in till are considerably higher than the levels in the bedrock down to 200 m depth, indicating a downward flow gradient from the lake and QD to the bedrock.

The flow systems around and below the lakes seem quite complex. The lake water/groundwater level relationship, under natural as well as disturbed conditions, indicates that the lake sediments and the underlying till have low vertical hydraulic conductivities. The groundwaters below the lakes have relict marine chemical signatures, whereas groundwaters in the riparian zones are fresh.

The hydrogeochemical modelling approach used within the Swedish site investigation programme

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Site studies for SKB's programme of deep geological disposal of nuclear fuel waste currently involves the investigation of two locations, Forsmark and Laxemar-Simpevarp, situated on the eastern coast of Sweden, to determine their geological, hydrogeochemical and hydrogeological characteristics. Present hydrogeochemical modelling employs hydrogeochemical methods such as conceptual postglacial modelling, explorative analysis, mathematical modelling (e.g. mass balance and mixing modelling) and construction of site descriptive models using a broad spectrum of hydrochemical data.

To various degrees, the sampled groundwater compositions reflect processes relating to ancient through to modern water/rock interactions and mixing. The major conclusion is that changes from glacial isostasy and, hence, hydrogeology seems to have a major influence on the groundwater chemistry. These complex data require a multidisciplinary approach to their interpretation.

The results of the detailed hydrogeochemical modelling methodology are used to produce a hydrogeochemical site descriptive model (SDM) used, for example, in hydrogeological, transport and safety assessment modelling. The hydrogeochemical SDM should represent a site-scale hydrogeochemical interpretation that is fully integrated with the corresponding final site descriptive versions of the geological and hydrogeological models.

This final hydrogeochemical model version should clearly show the following:

- the major lithological and structural units comprising the site;
- knowledge of the major groundwater flow directions from hydrogeological modelling;
- the relationship of chemistry (i.e. mixing of end members; chemical reactions etc.) to these major hydraulically conducting pathways;
- a clear indication of the groundwater types representative of the main hydraulic rock mass units characterised by fractures (fracture zones) of lower transmissivities;
- an indication of the chemistry of the rock matrix pore space fluid/groundwater.

The use of independent modelling approaches such as explorative analysis and mathematical modelling provides the possibility to compare the outcome of the different models and to use discrepancies between models to guide further modelling efforts. The use of independent and new modelling approaches, such as evaluation and modelling of the pore water chemistry and detailed hydrogeochemical and coupled modelling, has considerably facilitated the understanding of the complex groundwater system at these Swedish sites.

Super-regional groundwater modelling in hard rock terrain – evaluation of conceptual simplifications and model uncertainties

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One of many geoscientific questions in connection with the siting of a final repository for spent nuclear fuel has to do with understanding the large-scale flow patterns of the naturally circulating groundwater. A project was conducted in order to:

1) evaluate conceptual simplifications and model uncertainties in super-regional groundwater modelling,

2) carry out an in-depth of regional flow conditions in south-eastern Sweden. Achieving these goals has required an approach based on the use of available geoscientific data combined with an analysis of different conceptual assumptions.

The area studied consists of five regional catchment areas. The groundwater model represents a very large area, about 80×130 km2. The bedrock in the model area is dominated by rock types belonging to the "Transscandinavian igneous belt". Due to the large potential groundwater recharge in relation to the limited permeability of the rocks in the region the calculation cases were run with topography-determined top boundary conditions.

Flow paths from theoretical repository areas were studied with respect to: Flow pattern for groundwater passing repository depth, Outflow time (breakthrough time), Flow lengths, Specific flows at repository depth, Evolution of salinity in connection with density driven flow during the land uplift phase.

The following system properties were studied: Local topographic undulation, Quaternary deposits, Anisotropy in the conductivity field, Depth-decreasing conductivity, Varying conductivity depending on different lithological units, Regional vertical deformation zones, Regional horizontal deformation zones, Dolerite dykes, Local heterogeneity, Density-dependent flow and time-dependent aspects of the studied system.

The following general conclusions were drawn from the study: The factor of greatest importance for the regional flow pattern is the topography. Different lithological units, regional deformation zones, local heterogeneity, Quaternary deposits are of less importance

than the undulation of the topography. For areas described and analyzed with the most realistic assumptions, the groundwater flow pattern can be described as a primarily local flow process. The median flow path length in the study is on the order of 2 km, and the

fraction of super-regional flow paths (longer than 10 km) is very small. If hydraulic conductivity decreases with depth, flow cells of a smaller size are obtained than if this was not the case. Anisotropy in the conductivity field with greater horizontal than vertical

hydraulic conductivity results in relatively larger flow cells and long flow paths are extended. Anisotropy in the conductivity field with greater vertical than horizontal hydraulic conductivity results in relatively smaller flow cells. Hydraulic conductivity that decreases with depth and horizontal anisotropy has a greater influence on the flow pattern than lithological units, deformation zones, dolerite dykes and Quaternary deposits.

Detection of the near-surface redox front in crystalline bedrock, Sweden

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Oxidizing conditions in surface- and near-surface groundwaters usually change to reducing conditions in groundwater at greater depth, as oxygen is consumed through organic and inorganic reactions along the flow paths. Fracture minerals participate in these reactions and the fracture mineralogy/geochemistry can be used to trace the redox transition zone. An important task in the safety assessment of a potential repository for the disposal of nuclear waste in crystalline bedrock, at an approximate depth of 500 m in Sweden, is to demonstrate that reducing conditions can be maintained for a long period of time. This is because oxygen may harm the copper canisters that host the nuclear waste and oxidising conditions may increase the mobility of some radionuclides, if the canister starts to leak.

The present study of the near-surface redox front has been carried out with the help of mineralogical (redox sensitive minerals), geochemical (redox sensitive elements) and U-series isotope investigations of mineral coatings along open fractures. The fractures have been sampled along drill cores from closely spaced, 100 m deep boreholes. These were drilled during the site investigation work in the Laxemar-Simpevarp area, south-eastern Sweden, that has recently been completed by the Swedish Nuclear Fuel and Waste Management Co. (SKB).

The distribution of the redox sensitive minerals pyrite and goethite in open fractures shows that the redox front, manifested as the switch from mainly goethite to mainly pyrite, generally occurs at about 15-20 m depth. Scattered goethite occurrences below the redox front generally correlate with sections of high transmissivity or fracture frequency. Calcite distribution shows leaching of calcite down to 20-30 m and positive Ce-anomalies suggest oxidation of Ce close to the surface (down to 20 m). Slightly negative Ce-anomalies are found at depths of 20-70 m, whereas Ce-anomalies are generally absent below 70 m. The U-series isotopes show disequilibrium in most of the samples, indicating mobility of U during the last 1 Ma. In the upper 20 m, U is mainly leached (due to oxidation) or has experienced complex leaching and/or deposition. At depths of 30-55 m, both deposition of U and complex leaching and/or deposition are indicated. Below 55 m, recent deposition of U is mainly indicated. All of the methods used suggest oxidation in the upper 20 m, a redox transition zone at 20 to 55−70 m and reducing conditions at greater depths. Based on the U-series isotopes, this corresponds to conditions prevailing during the Holocene.

Confirmatory large-scale tracer tests at the Forsmark site

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Site investigation work at Forsmark has recently terminated with the completion of two large-scale tracer tests. The main purpose of the tests was to confirm the final hydrogeological and transport models developed from earlier investigations at the site. A second purpose was to determine *in-situ* transport parameters for comparison with laboratory data and finally, to compare parameters derived from multiple-hole tracer test with parameters from single-hole tracer tests. The latter type of test has been used in several boreholes at the site. Similar tracer tests are planned at the Laxemar-Simpevarp site during spring and summer 2008.

The first tracer test was focused on retention parameters and therefore included both non-sorbing and sorbing tracers. The test was performed at a depth of about 420 m within the major gently dipping fracture zone A2. Two cored boreholes, KFM02A and KFM02B, about 50 m apart, were used as source and sink for the test. The test sequence included tracer dilution tests to determine flow responses from the pumping, a pre-test using a single non-sorbing dye tracer (Rhodamine WT), and finally the main test. Only a limited number of sorbing cation tracers (Cs, Rb and Li) could be used due to high background concentrations in the native saline groundwater. The non-sorbing dye tracer Uranine was used as reference. Large efforts were made to keep a constant chemical environment during the test e.g. by using a synthetic groundwater and keeping an inert atmosphere for the tracer solution. All injected tracers were recovered in the withdrawal well and significant retardation of the sorbing species could be observed. Numerical inverse modelling of the test was performed and showed retardation parameters similar to the ones derived from single-hole tracer tests performed at the same location in KFM02A.

The second tracer test focused on the connectivity of the fracture system at Forsmark. Non-sorbing tracers were injected at six locations at distances ranging between 70 to 500 metres from the sink borehole. The sink borehole HFM14 is located in the central part of the site and the borehole is inferred to intersect the superficial part of zone A2. The tracer injections included five rare-earth metal complexes (Tb, Gd, Dy, Ho and Eu-DTPA) and perrehnate (ReO_4), all previously verified as being non-sorbing. The results of the test verified the hydrogeological model, indicating good connectivity along fracture zone A2, and all injected tracers were recovered in the withdrawal well. The test also verified less good connectivity with some of the other hydraulic features at the site.

The hydraulic anisotropy of the fractured crystalline rocks at the Äspö hard rock laboratory

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The hydraulic conductivity of fractured crystalline rocks is normally found to span over several orders of magnitude within short distances. The frequency and orientation of the fractures indicate that they also show hydraulic anisotropy. This may further be enhanced by the anisotropy of the rock stress field. Several attempts to assess the hydraulic anisotropy of fractured rocks have been made using discrete fracture network models (DFN), but so far very few attempts to quantify the anisotropy directly from field data are published. The reason is naturally that few comprehensive data bases exist that makes this possible. This paper is an attempt to identify and assess the hydraulic anisotropy of the fractured crystalline rocks of the Äspö Hard Rock Laboratory (ÄHRL).

The ÄHRL, Sweden, built and operated by the Swedish Nuclear Fuel and Waste Management Co (SKB), provides a comprehensive database on geological, geohydrological and geochemical properties of a granitic rock volume of approximately one km3 Today the laboratory comprises an access tunnel down to 450 m depth, experiment sites underground and laboratory and office facilities. Before and during the construction period the rock was characterised and data were used to build up, validate and update geological, geohydrological and hydrogeochemistry models of the site. The ÄHRL database offers a unique opportunity to analyse these questions on the basis of geoscientific evidence. In generic analyses of repository design, there is a great advantage if simple analytical formulae can be used for design calculations rather than numerical models. This makes it possible to test a large number design alternatives by simple means, which later can be analysed for site specific conditions by more sophisticated methods.

The empirical basis for the performed analysis is the hydraulic tests in investigation boreholes from the surface and probe-holes made during the construction period. The database used comprises more than 700 tested sections. Hydraulic tests were performed during the pre-investigation period, mainly from steep boreholes, and from nearly horizontal probe-holes drilled in front of the tunnel during its advance. Since the tunnel forms a spiral, tests thus were made for boreholes in all directions.

In the paper a basic assumption is that the fractured rock locally can be approximated as a stochastic continuum. This continuum has properties that vary in space and also shows anisotropy. Data show an outspoken anisotropy that complies well with the directions of the dominating fracture sets. The major principal rock stress also may influence the conditions since it is sub-parallel to the dominating fracture set. As for rock-stress principal directions for the transmissive boreholes also can be identified. With the third main direction assumed to be vertical a tensor of directional hydraulic conductivities was estimated.

Three-dimensional discrete fracture network simulations of flow and tracer migration based on Laxemar site data (Sweden)

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We study particle transport in a 3D DFN scenario based on Laxemar site characterisation data in Sweden, which is a candidate repository site for high level radioactive waste in the Swedish nuclear waste management program. The site characterisation data has revealed several interesting geometric and hydraulic fracture properties, such as power-law distributed fracture sizes and transmissivities.

A fundamental aspect towards understanding tracer migration in subsurface sparsely fractured rock formations is the relationship between the Eulerian flow field at a sub-fracture scale with the Lagrangian flow field at a characteristic (model domain) scale.

In this work we present results from a new technique for upscaling particle transitions obtained from Eulerian flow statistics to predictions of tracer discharge at a characteristic transport scale, based on previously developed methods used for 2D DFN's. This includes a mapping algorithm for transforming Eulerian into Lagrangian flow statistics without a priori knowledge of network connectivity, and by retaining the correlation between the water residence time τ and the hydrodynamic control of retention β we present accurate tracer discharge predictions. These results are illustrated using the unlimited diffusion model, and for some hypothetical tracers with properties designed to capture the behaviour of many common radionuclides. Finally we emphasise the importance of capturing the early arrival and peak of tracer breakthrough curves, i.e. to capture the bulk of the tracer mass arrival, in order to make accurate and conservative predictions.

Symposium HPP-01:

General contributions to Precambrian geology

Conveners
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Structural framework, tectonic cycles and conceptual model for the tectonic evolution of the Fennoscandian Shield in south-eastern Sweden between 1.91 and 1.75 Ga

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The Swedish Nuclear Fuel and Waste Management Company (SKB) has recently completed investigations in the Forsmark and Laxemar-Simpevarp areas in the Fennoscandian Shield, south-eastern Sweden, aimed at locating and characterizing a site for the disposal of highly radioactive nuclear waste. The safety analysis of a selected site requires an understanding of the past geological evolution, from the time of crystallization of the bedrock up to historical time with its low seismic activity. With this aim in mind, a synthesis of the geological evolution inside the Fennoscandian Shield in south-eastern Sweden has recently been completed. This contribution aims to present the results of the synthesis for the time interval 1.91 to 1.75 Ga.

The bedrock geology in south-eastern Sweden is divided into six major tectonic domains. The boundaries between these domains consist, at least partly, of belts that are affected by high ductile strain. Furthermore, two of these belts are sufficiently wide to merit definition as separate tectonic entities. These domains trend WNW more or less parallel to the Archaean continental nucleus to the north-east. The different domains have been distinguished primarily on the basis of differences in the character and timing of ductile deformation in combination with the timing of igneous activity. It is proposed that different phases of igneous activity and ductile deformation in this part of the shield belong to three different tectonic cycles. Each of these cycles extended over c. 50 Ma in time from 1.91 to 1.86 Ga, from 1.87 to 1.82 Ga and from 1.83 to at least 1.79 Ga. Furthermore, the focus of tectonic activity migrated in space from one tectonic domain (or groups of domains) to another between the different cycles. The geodynamic regime involved an accretionary orogenic setting, with oblique subduction of oceanic crust north-eastwards beneath an active continental margin, conceptually very reminiscent of that envisaged by studies during the 1970´s and 1980´s.

A conceptual model for each tectonic cycle involves migration of the subduction hinge away from and, at a later stage, towards the overriding continental plate. This gave rise to alternating extensional and compressional tectonics, respectively. It corresponds to the model referred to as tectonic switching in the younger accretionary orogens of eastern Australia (Lachlan orogen) and New Zealand. In south-eastern Sweden, continental back-arc basins developed during the extensional phase. Compressional deformation was transpressive in character with dextral strike-slip, ductile deformation along the boundary high-strain belts. This was combined with shortening in a north-east direction across these belts and strongly constrictional strain with folding and stretching, with variable plunge to the south-east, between them. Crustal behaviour in the form of a “moving concertina” summarises the diachronous ductile deformation and igneous activity in the different domains.

Geological evolution, characterization and 3D modelling of the Palaeoproterozoic crystalline bedrock at the Laxemar-Simpevarp site, Sweden

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The Swedish Nuclear Fuel and Waste Management Company (SKB) is undertaking site investigations at Forsmark and Laxemar-Simpevarp in south-eastern Sweden, with the aim of identifying a suitable crystalline bedrock for the disposal of highly radioactive nuclear waste. In this context, a comprehensive understanding of the bedrock geology, including geological evolution, character and modelling in 3D space, is of vital importance for both sites. This paper presents the results from the Laxemar-Simpevarp site.

The bedrock at Laxemar-Simpevarp is composed of c. 1.8 Ga intrusive rocks that belong to the 1.86-1.65 Ga Transscandinavian Igneous Belt (TIB). $^{40}Ar/^{39}Ar$ amphibole age data indicate that the bedrock had cooled below 500°C at 1.76 Ga, while there remains more uncertainty concerning the cooling history after 1.76 Ga, in particular concerning the time at which the bedrock passed through the brittle-ductile transition in the crust. However, $^{40}Ar/^{39}Ar$ biotite ages indicate that the bedrock had entered the realm of brittle deformation at c. 1.5 Ga, and possibly prior to c.1.65 Ga. Local reheating at c. 1.45 Ga in conjunction with the emplacement of two younger granite intrusions, north and south of the investigated area, have been documented by resetting of the $^{40}Ar/^{39}Ar$ biotite system. Far-field effects of the Sveconorwegian and Caledonian orogenies are also present.

The TIB rocks in the area show variable composition (granite to quartz monzodiorite to diorite-gabbro), grain size and texture. They have been affected by magma-mingling and magma-mixing processes, and a close genetic relationship between the rocks is inferred. The latter has been confirmed by U-Pb zircon dating. Although there is a non-uniformly developed faint to weak ductile fabric in the rocks, discrete, low-temperature, brittle-ductile to ductile shear zones form the most prominent ductile structures in the area. The latter formed in response to an approximately NNW-SSE shortening during the waning stages of the Svecokarelian orogeny. As with other Precambrian shield areas, complex networks of brittle deformation zones (faults) transect the bedrock in the Laxemar-Simpevarp area.

Rock domains, which comprise predominantly different rock types, are defined both at the surface (2D) and at depth along cored boreholes (1D). Deformation zones are identified at the surface by the interpretation of detailed geophysical and topographical data, and at depth by the interpretation of geological and geophysical data from cored boreholes. By an integration of the detailed surface and subsurface data, it has been possible to construct deterministic 3D geological models for rock domains and deformation zones. The resulting rock domain and deformation zone models constitute the geometric basis for subsequent geoscientific modelling based on thermal, rock mechanical, hydrogeological, and solute transport properties.

AMS data and their relationship to ductile deformation in Palaeoproterozoic crystalline bedrock at two sites in the Fennoscandian Shield, Sweden

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The Swedish Nuclear Fuel and Waste Management Company (SKB) has recently completed investigations in the Forsmark and Laxemar-Simpevarp areas in the Fennoscandian Shield of central and south-eastern Sweden, respectively. These investigations have aimed to locate and to characterize a possible repository site for the disposal of highly radioactive nuclear waste. In the context of these investigations, anisotropy of magnetic susceptibility (AMS) measurements have been carried out on samples from both areas. The aim of the AMS study was to provide independent, complementary data to standard structural geological data from both the field and from drill cores, as a support to the 3D structural modelling work.

The bedrock in the Forsmark area has been affected by penetrative ductile deformation under amphibolite facies conditions. The AMS study (529 specimens at 134 locations) was focussed on a tectonic lens with NW-SE strike, which mainly consists of metagranite, and a banded complex of metagranitoids and metavolcanic rocks, immediately to the south-west of the lens. This is in contrast with the Laxemar-Simpevarp area (499 specimens at 111 locations), where the bedrock is dominated by well-preserved, 1.80 Ga granite to quartz monzodiorite, which only displays a weak foliation. However, ductile to brittle-ductile deformation zones at different scales are conspicuous.

At Forsmark, the AMS data provided complementary information bearing on the contrasting style and degree of ductile strain within and immediately outside the tectonic lens. Inside the tectonic lens, the rocks are folded, and the inferred fold axis (132º/43º) is parallel to the magnetic lineation. Constrictional deformation with extension parallel to the fold axis is apparent. Stronger and more oblate ductile strain characterizes the subarea with banded and heterogeneous rocks to the south-west of the lens. These results are in excellent agreement with the structural geological field data.

In the Laxemar-Simpevarp area, the degree of anisotropy is generally low. The magnetic foliation shows a variable orientation and the magnetic lineation plunges gently to the north-west. These data are in good agreement with the structural geological data. The AMS fabric is inferred to have developed at a late stage during the magmatic evolution, due to the effects of the regional stress field that prevailed during and after emplacement of the rocks. The AMS data from samples collected across a regional ductile deformation zone with NE-SW strike indicate a sinistral strike-slip component of movement, which is in agreement with independent kinematic data from field and microstructural studies. Furthermore, the AMS data from well outside the shear zone indicate rotation of the magnetic foliation in rocks that do not show any optical sign of ductile strain. This implies the existence of a c. 250 m wide transition zone outside the deformation zone, which is c. 300 m thick inside the investigated section.

Magnetic lineaments and their relationship to ductile structures and steeply dipping fracture zones at Forsmark, Fennoscandian Shield, Sweden

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The Swedish Nuclear Fuel and Waste Management Company (SKB) has recently completed investigations in two areas in the Fennoscandian Shield in Sweden, to locate and characterize a possible repository site for the disposal of radioactive nuclear waste. One of these areas is located at Forsmark, c. 120 km north of Stockholm.

Since lineaments can provide important information on the surface extension of possible deformation zones in crystalline bedrock, interpretations of lineaments from topographic and geophysical data have been carried out to support the 3D geological modelling work in each area. The Forsmark area is characterized by low surface relief and the morphology of the ground surface does not conform with the morphological contact between the crystalline bedrock and the Quaternary cover. For this reason, magnetic lineaments have proven to be the most reliable source to discriminate possible deformation zones in the bedrock. Commonly, the magnetic susceptibility of rocks is low in fractured, altered or porous bedrock, due to the destruction of ferromagnetic minerals.

During the different phases of the site investigation work, the degree of resolution of available magnetic data has radically improved. Initial, airborne magnetic data with a line spacing of 200 m was followed by a helicopter-borne survey with a line spacing of 50 m. Finally, a detailed ground magnetic survey grid provided a spatial resolution of 10*5 m. The marked increase in structure details are related to both the lower altitude of the surveys and a higher station density.

Magnetic lineaments have been distinguished according to length and character. Two main types are present: 1. Magnetic minima connections that are concordant with the ductile, planar tectonic fabric, the boundaries to rock units and the banded magnetic anomaly pattern in the area. 2. Magnetic minima that are markedly discordant to the same geological and geophysical features.

Excavation work at the ground surface and drilling activity has been carried out to investigate the geological character of the lineaments. Concordant minima connections are related primarily to lithological contrasts that are aligned parallel to the ductile, planar tectonic fabric in the bedrock. Both locally and more regionally, the minima connections define fold structures in the area. However, fracture zones are known to occur along the ductile planar fabric in areas where there is a strong banded magnetic anomaly pattern. The lineaments defined by discordant magnetic minima primarily represent steeply dipping fracture zones with predominantly sealed fractures, along which magnetite in the bedrock has been affected by hydrothermal alteration including hematization. At least the strike-slip component of displacement along these fracture zones is minor. Granite dykes and pegmatite have magnetic signatures that are similar to those observed along fracture zones, which introduces an important element of uncertainty in the interpretation.

Character, kinematics and conceptual model for deformation zones at Forsmark in the Fennoscandian Shield, Sweden

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A study of the character and kinematics of deformation zones has formed a part of the site investigation work recently completed by the Swedish Nuclear Fuel and Waste Management Company (SKB) in two areas in the Fennoscandian Shield in eastern Sweden. A synthesis of the results from the Forsmark area, situated c. 120 km north of Stockholm, is presented here.

At Forsmark, high-strain belts that formed under high-T conditions anastomose around a tectonic lens, which corresponds to the candidate volume for a possible nuclear waste repository. These structures with contrasting ductile strain lie within a steeply dipping segment of 1.89−1.85 Ga crust that strikes WNW-ESE. A dextral strike-slip component of movement is present in the high-strain belts that are also folded. Spatially more discrete deformation zones, with a low-T ductile and brittle deformational history, dip steeply to the SSW and SW, along the high-strain belts. They can be followed for distances >10 km. The brittle fault core in these zones is defined by sealed fracture networks, intense hydrothermal alteration, and cohesive fault rocks including cataclasite and cemented breccia.

The deformation zones inside the tectonic lens strike predominantly ENE-WSW to NNE-SSW and are either sub-vertical or dip gently to the SSE or SE. These zones are generally less than 3 km in length at the ground surface, show brittle deformation and are in part truncated by the surrounding regional zones. The character of brittle deformation in thin core segments is similar to that observed in the regional zones. However, fault rock is absent in several of them. Minor disturbance of geophysical anomalies, in combination with the limited occurrence or absence of observed shear striae in some zones, further attest to the subordinate character of the zones inside the lens.

Epidote occurs along fractures with different orientation in all sets of zones, both inside and outside the tectonic lens. The presence of fracture fillings that belong to younger mineral assemblages indicate that more than one phase of reactivation has occurred. The variable character of kinematic data along each set of deformation zones also indicates that they have been affected by different stress regimes during a long geological history. Inside the tectonic lens, there is a dominance of strike-slip motion along the steeply dipping zones and reverse or strike-slip motion along the gently dipping zones.

A conceptual structural model has been developed that takes account of the regional geological relationships in the Fennoscandian Shield and geochronological data at Forsmark that address the timing of growth of adularia. This model invokes activation of the different sets of deformation zones in the low-T ductile and brittle regimes during the later part of the Svecofennian orogeny, continued activation or reactivation during the Gothian tectonothermal event, and at least major reactivation during the Sveconorwegian/Grenvillian orogeny.

Sub-horizontal reflections at 2–5 km depth at three different sites along the Baltic Sea and the Gulf of Bothnia: Fracture zones or mafic sheets?

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High resolution reflection seismic surveying has proven to be a useful tool for locating fracture zones in crystalline rock. Siting of potential high-level nuclear waste repositories is a particularly important application of this method and seismic surveys have been carried out at the Oskarshamn site in southeastern Sweden, the Forsmark site in central Sweden, and the Olkiluoto site in southwestern Finland. All three sites are close to the coast and the site investigations at the three locations have focused on relatively undeformed granitic rock. Borehole control shows that many of the sub-horizontal reflections in the upper 1 km of rock can be correlated to fractures zones at all three sites, particularly at the Forsmark and Olkiluoto sites. At the Forsmark site, mafic amphibolites associated with some of the fracture zones may increase the reflectivity. Steeply dipping reflections (70-80 degrees) have also been imaged at the Oskarshamn site and can be correlated to a regional lineament. Also common for all three sites is the presence of deeper sub-horizontal to gently dipping reflections originating from depths of 2-5 km and extending over nearly the entire investigation areas. These reflectors have not been drilled. Mafic sills in granitic rock at other locations are known to generate strong seismic reflections over large areas and are a potential candidate for the source of the deeper reflectivity at the three investigation sites. However, deep fracture zones or shear zones cannot be ruled out. If the reflections originate from fractures zones then these are likely to contain fluids that could influence the large scale water circulation patterns near a radioactive waste repository. Further reflection seismic and/or drilling is necessary to clarify the nature of the reflections and their geological significance.

Integrated U/Pb and $^{40}Ar/^{39}Ar$ geochronology, and a conceptual model for tectonic developments in the Svecofennian orogen, central Sweden, from 1.91 to 1.84 Ga (poster)

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The Swedish Nuclear Fuel and Waste Management Company (SKB) has recently completed investigations in two areas in the Fennoscandian Shield, Forsmark and Oskarshamn, to locate and characterize a possible repository site for the disposal of highly radioactive nuclear waste. The modelling and safety analysis require an understanding of the geological history at each site. This contribution addresses the early tectonic history at Forsmark, which lies c. 120 km north of Stockholm.

U/Pb zircon dating, in combination with detailed field studies, has revealed the existence of two calc-alkaline igneous suites at Forsmark. The older and most voluminous plutonic suite intruded at 1.89−1.87 Ga and is affected by penetrative ductile deformation under amphibolite-facies metamorphic conditions. The younger, predominantly hypabyssal suite intruded at 1.86-1.85 Ga, during the waning stages of this deformation. These relationships constrain the main phase of penetrative ductile strain to 1.87-1.86 Ga. Cross-cutting granite dykes place an absolute minimum age for this event to 1.85 Ga.

U/Pb titanite data support the time constraints on the penetrative ductile deformation. However, both these data and $^{40}Ar/^{39}Ar$ hornblende data suggest that the Forsmark area has been affected by one or more tectonothermal events after the intrusion of the 1.85 Ga granite dykes. The $^{40}Ar/^{39}Ar$ hornblende data indicate the presence of two age generations at 1.83-1.82 Ga and 1.81-1.80 Ga. The older generation is spatially restricted to less deformed tectonic lenses, whereas the younger generation occurs within these lenses and along enveloping ductile high-strain belts. It is suggested that the age generations may represent two separate events, with cooling beneath c. 500°C at 1.83-1.82 Ga and subsequent resetting of the argon isotope system in response to deformation under retrogressive, metamorphic conditions at 1.81-1.80 Ga. Alternatively, slow cooling initiated at 1.83 Ga and continued until 1.80 Ga, causing some variation among ages within the tectonic lenses. Near the high-strain zones, temperatures remained elevated and cooling occurred simultaneously at 1.81-1.80 Ga. $^{40}Ar/^{39}Ar$ biotite data suggest that cooling beneath 300°C took place at 1.73-1.67 Ga. The estimated uplift rate was at this time c. 22 m/m.y. It is inferred that the bedrock at Forsmark started to behave in a more brittle manner between c. 1.80 and 1.70 Ga.

A compilation of available geochronological data for the time interval 1.91-1.84 Ga in central Sweden indicates at least two major tectonic cycles. Each cycle is characterised by igneous activity associated with extension, a short interval of compression, and migration of the tectonic activity. A conceptual tectonic model involves continuous subduction beneath an active continental margin, combined with alternating subduction hinge retreat and advance. This model includes migration of what has been described as tectonic switching in some younger orogenic belts.

Symposium MPC-04:

Constraining timing and rates of surface processes by low temperature thermochronology

Conveners
Bart W.H. Hendriks, Tim F. Redfield

Systematic shift in apatite (U-Th)/He and fission track ages in Palaeoproterozoic domains, south-eastern Sweden

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The Swedish Nuclear Fuel and Waste Management Company (SKB) has recently completed investigations at Forsmark and Oskarshamn, south-eastern Sweden, aimed at locating and characterizing a site for the disposal of highly radioactive nuclear waste. The safety analysis of a selected site requires an understanding of the past geological evolution. In this context, the knowledge of the younger tectonothermal history is of vital importance. The bedrock in both areas consists of crystalline rocks that are predominantly Palaeoproterozoic in age. Apatite from several levels along c. 1000 m deep boreholes and a number of surface samples have been dated using apatite (U-Th)/He thermochronology. A few borehole samples at both sites were also dated with the apatite fission-track (AFT) technique.

The age/depth slopes for the apatite (U-Th)/He and AFT data at Oskarshamn are in excellent agreement. At Forsmark, these two slopes are similar. However, at both sites, the corrected apatite (U-Th)/He ages are older than the AFT ages, i.e. are incompatible with the generally accepted closure temperatures for the two systems of c. 70°C and 110°C, respectively. The age discrepancy is clearly systematic, and may be related to: 1) enhanced He retention in U-rich apatite, which may increase the closure temperature of the (U-Th)/He system, and/or 2) enhanced annealing of fission tracks in U-rich apatite that may lower the closure temperature of the AFT system, and/or 3) an invalid F_T-correction factor in the (U-Th)/He system due to heterogeneous distribution of U. The latter could have a profound effect in slowly cooled terrains. Considerable intra-sample (U-Th)/He age variations were obtained on apatite grains from Forsmark, most probably due to zonation of U or grain morphology. Etched apatite internal grain surfaces show that many grains are strongly zoned in U concentration. This phenomenon appears to be less pronounced for apatite in samples from Oskarshamn. Furthermore, apatite grains at Forsmark are often small, anhedral, elongate or broken, whereas most of the apatite grains at Oskarshamn are unbroken and have an euhedral shape. These factors are also inferred to potentially affect (U-Th)/He ages.

The thermal models based on the AFT ages indicate that both Oskarshamn and Forsmark experienced temperatures higher than 100°C prior to 200 Ma, consistent with a several km thick sedimentary cover at this time. This is in agreement with earlier studies in these areas, and probably reflects Palaeozoic sedimentation, firstly in a passive continental margin and, thereafter, in a Caledonian foreland basin setting. Subsequent uplift may be linked to far-field effects of transtensional tectonics along the Sorgenfrei-Tornquist Zone in southernmost Sweden and doming effects from extensive volcanism in areas to the west at c. 300 Ma, and to the south during the Mesozoic. Uplift waned at c. 100 Ma and, thereafter, denudation and exhumation have occurred at a much slower rate.

Low temperature geological evolution recorded by $^{40}Ar/^{39}Ar$, $^{87}Sr/^{86}Sr$ and stable isotopes in fracture minerals at Forsmark, Fennoscandian Shield, central Sweden

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The present study shows how detailed microscopy complemented by $^{40}Ar/^{39}Ar$, $^{87}Sr/^{86}Sr$ and stable isotope data from fracture minerals increase the understanding of the low-T geological evolution in an area. At Forsmark, central Sweden, deep boreholes have been drilled through the crystalline bedrock as part of the site investigations conducted by the Swedish Nuclear Fuel and Waste Management Company (SKB). A sequence of several events of fluid circulation and mineral formation has been distinguished, based on e.g. cross-cutting relations between different parageneses and stable isotope data. $^{40}Ar/^{39}Ar$ dating has been carried out to obtain absolute time constraints. Four main events of fracture mineral precipitation have been distinguished:

Generation 1 consists of epidote, quartz and chlorite, and brittle-ductile to brittle cataclasite sealed with these minerals (T >300°C). They are conspicuous in sub-horizontal and gently dipping fractures or in steep, WNW-ESE to NW-SE fractures. However, they are also present along fractures in other steeply dipping sets. This generation formed between 1.8 and 1.1 Ga, and is possibly related to the late Svecokarelian and/or Gothian tectonothermal events.

Generation 2 consists of a sequence of hydrothermal fracture minerals (T~150-280°C) dominated by adularia, albite, prehnite, laumontite, calcite, chlorite and hematite. Generation 2 minerals are particularly common along steep, ENE-WSW to NNE-SSW and NNW-SSE fractures. $^{40}Ar/^{39}Ar$ ages from adularia indicate that this mineral either formed or the isotope system was reset in connection with early Sveconorwegian tectonothermal activity at 1.1 to 1.0 Ga. Formation of new fractures and breccias are inferred during this period and dissolution of fracture minerals occurred before the formation of generation 3 minerals.

Generation 3 consists of minerals precipitated under low-T conditions during the Palaeozoic. The most abundant minerals are calcite, quartz, pyrite, corrensite and asphaltite. Stable isotopes in calcite and the presence of asphaltite indicate that the formation fluid was influenced by organic material, which may have emanated from an overlying sedimentary cover. The orientation of fractures with generation 3 minerals suggests reactivation of fractures filled with older minerals.

Generation 4 is dominated by chlorite/clay minerals and thin precipitates of calcite in predominantly hydraulically conductive fractures and fracture zones. These minerals are prominent along sub-horizontal and gently dipping fractures, but also in different sets of steeply dipping fractures. It is inferred that the hydraulically conductive fractures are ancient structures and that mineral precipitation has most likely occurred during a long period of time (after the Palaeozoic?). However, some of the near-surface, sub-horizontal fractures, which include sheet joints formed in connection with stress release, may be Quaternary in age.

Symposium MPN-03:

Mineral replacement and mass transfer in hydrothermal systems: From the nanoscale to the megascale

Conveners
Andrew Putnis, Ane K. Engvik

Hydrothermal alteration in Palaeoproterozoic metagranite, Forsmark, Sweden and its implications for the characterization of a site for the disposal of nuclear waste

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Hydrothermal alteration may influence the physical and chemical properties of a rock mass significantly. For this reason, the potential effects on properties such as rock strength and thermal conductivity need to be addressed in connection with the location of a geological repository for spent nuclear fuel. A detailed characterization of the various types of alteration in crystalline bedrock down to 1000 m depth has formed a part of the site investigation work, conducted by the Swedish Nuclear Fuel and Waste Management Company (SKB) at Forsmark, central Sweden. Granite dated at 1.87 Ga, with a variably developed ductile LS fabric that formed under amphibolite facies conditions, dominates inside the target volume.

Oxidation is by far the most abundant type of alteration and is spatially associated with the earliest stages of hydrothermal fluid movement along fracture zones. Macroscopically, it is distinguished by a conspicuous reddening of plagioclase, due to hematite dissemination. Other features associated with this alteration include saussuritisation of plagioclase and chloritisation of biotite. The large-scale geochemical redistribution, including the degree of oxidation, is limited and only minor changes in the physical properties have been recorded.

The north-eastern part of the target volume is affected by albitisation. On a mesoscopic scale, this alteration is recognised by a whitening of the feldspar in the granitic rock and occurs as contact rims adjacent to amphibolite. Mineralogically, it is characterised by a deficiency of K-feldspar relative to plagioclase and a minor quartz enrichment. Since the alteration shows no simple relationship to fracture zones, and is absent in some of the younger rocks, it is inferred to be a syn-magmatic or syn-metamorphic feature, possibly triggered by the heat supply provided by the younger intrusions. Changes in physical properties, including rock strength and thermal conductivity, are related to the increased quartz content.

Vuggy rock, formed by the selective dissolution of quartz, corresponds to the alteration referred to as episyenitisation. The quartz dissolution, combined with strong oxidation, has affected all rock types indiscriminately, but the texture of the host rock has been maintained. Individual occurrences are typically a few metres in borehole length, although one occurrence is approximately 50 m. Most occurrences occur inside or immediately adjacent to fracture zones and the longer interval has been modelled as a steeply inclined alteration pipe between two fracture zones. Considerable uncertainty remains concerning the origin and timing of this alteration. However, it is inferred that it took place in the brittle regime, i.e. after 1.8−1.7 Ga, under the influence of hot hydrothermal fluids at temperatures corresponding to greenschist facies conditions. It gave rise to significant changes in the physical properties of the host rock, including decreased density, porosity and resistivity.

Symposium EIE-07:

High-resolution geophysical imaging of geological structures and processes in environmental studies

Conveners
Alan Green, Christopher Juhlin, Lars Nielsen

Detailed ground magnetic and resistivity measurements for a potential deep geologic repository for spent nuclear fuel in Oskarshamn

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Site investigations for a potential deep geologic repository for spent nuclear fuel are in progress in the municipalities Östhammar and Oskarshamn. A comprehensive site investigation program was initiated to characterise the properties of the bedrock, overburden, and ecosystems. The investigations at the sites were completed in 2007 and a licence application to construct the repository at one of the sites is expected to be submitted at the end of 2009.

The candidate area Laxemar is situated by the coast in south east of Sweden, close to the Oskarshamn nuclear power plant, the interim storage facility for spent nuclear fuel (the Clab facility) and the Äspö Hard Rock Laboratory (HRL). Site investigations, which started in spring 2002, involved detailed air photography and geophysical surveys over the regional area in order to reduce the 50 km^2 large candidate area to a size where the deep drilling programme could be concentrated. Accordingly, in spring 2003 the Laxemar and the Simpevarp subareas were selected and some investigations were performed in parallel on both subareas until Laxemar was prioritized. At the Laxemar subarea the investigations started in the beginning of 2004. In total, the investigation involved some 20 deep cored boreholes (with a length of c.1,000 m) and another 30; 100–600 m long core drilled boreholes. A typical investigation programme in these boreholes included hydraulic tests and water sampling during drilling, video imaging (BIPS), geophysical logging, borehole radar, core logging, difference flow meter logging, hydraulic injection tests and analyses of rock samples. The geophysical logging data were mainly used to support the core logging.

Ground geophysical measurements have been performed in the Laxemar area. A total of approximately 7.5 km^2 were covered with measurements of the total magnetic field. The survey was performed with a point separation of 5 metres and a line spacing of 10 metres. A mosaic map of the survey results has been produced. A number of low-magnetic semi-linear features appear in the results. More than 1,800 lineaments have been possible to identify in the presented data. Three areas, 400 by 400 metres each, were covered with resistivity measurements with the ABEM Lund imaging system. The measurements were carried out along east-west oriented profiles separated by 10 metres. The electrode separation was 5 metres and a total of 81 electrodes per line were used. Measurements were performed with a gradient array protocol resulting in a depth of investigation of up to 60 metres. The soil cover thickness has been estimated from the resistivity measurements. A map of soil cover thickness and bedrock relief are presented for one area. The three survey areas were located around north-south trending lineaments. One of the interpreted deformation zones was interpreted to dip to the west while the others were interpreted to be subvertical.

Symposium GHZ-04:

Earthquake hazard assessment and geotechnics

Conveners
Amir Kaynia, Michele Maugeri

Respect distances: rationale and means of computation

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Though Sweden is currently regarded seismically dormant, huge earthquakes ($M \geq 8$) have been shown to have occurred some 9000 years ago as the weichselian glacier retreated. Similar earthquakes are anticipated during the advance and/or retreat of future continental ice sheets. The safe disposal of radioactive wastes requires that the canisters are placed sufficiently far from deformation zones as to not jeopardise the canister integrity. The mechanical impact on the canisters, as an effect of earthquakes, is by far the dominating factor of those studied. As the wastes are hazardous for thousands of years, the large earthquakes anticipated in the future have potential to harm the repository, thereby threatening the biosphere. Though earthquake-generating structures can be safely avoided during the construction of the repository, the threat to the canisters lies mainly in the reactivation of fractures in the rock mass between deformation zones. The amount of slip that such a target fracture can host is a function of the fractures geometry and properties (e.g. size, orientation, surface friction) in relation to the distance to the hypocenter and the size (stress drop, slip velocity) of the earthquake. We propose a method to numerically simulate earthquakes of various magnitudes and the slip they induce on target fractures of varying geometry and distances to the earthquake source. Using rock properties from site investigations, analogue shearing experiments and modelling of shearing across canisters, our 3D simulations (using the distinct element code 3DEC) suggest that canisters can be safely emplaced at a distance of 100 m or larger from the boundary of a deformation zone, if the canister is not intersected by fractures with radii up to 75 m. Should fractures with radii up to 150 m be accepted in a deposition hole, the respect distance must be increased to 200 m.