EVALUATION AND MODELLING OF A POTENTIAL REPOSITORY SITE - OLKILUOTO CASE STUDY

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Abstract

The observations, interpretations and estimates resulting from site investigations were developed into conceptual bedrock model of the Olkiluoto area. Model development has been an interdisciplinary process and three major iterations have occurred. Geochemical sampling and a programme of electromagnetic and electrical soundings were carried out and interpreted to model occurrences of groundwater types.

The parametrisation and modifications needed between geological models and groundwater flow simulation model is discussed. The latest groundwater flow modelling effort comprises the transient flow analysis taking into account the effects of density variations, the repository, post-glacial land uplift and global sea level rise. The main flow modeling result quantities (the amount, direction, velocity and routes as well as concentration of water) are used for evaluation of the investigation sites and of the preconditions for safe final disposal of spent nuclear fuel.

Integration of hydrological and hydrogeochemical methods and studies has provided the primary method for investigating the evolution. Testing of flow models with hydrogeochemical information is considered to improve the hydrogeological understanding of a site and increases confidence in conceptual hydrogeological models. Bedrock model allows also comparisons to be made between its time-varying versions. The evolution of fracture frequency, fracture zone structures and hydraulic conductivity has been studied. A prediction-outcome comparison was made in selected boreholes and showed that the rock type was the easiest parameter to predict.

1 Introduction

Posiva (formerly TVO) is carrying out site characterisation for disposal of spent fuel in the Finnish bedrock. At Olkiluoto field investigations has been in progress since 1980s. The first preliminary study phase lasted from 1987 to 1992 (abbreviated as SITU). Detailed site characterisation programme took place during 1993 - 96 (PATU). Now the work is under PARVI site evaluation phase (1997 -). Modelling activities of varying type have taken place during the years course some of which are discussed in this paper. The particular studies discussed and their position in time has been depicted in Figure 1.

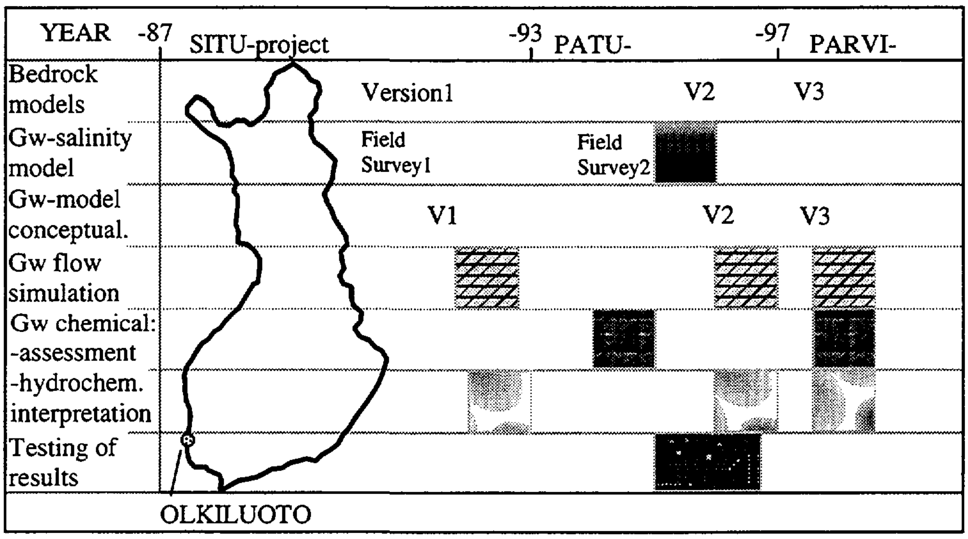

Figure 1. Occurrence of modelling and evaluation studies discussed.

2 Modelling

2.1 Development of the geological model

The observations, interpretations and estimates resulting from site investigations have been developed into conceptual bedrock models of Olkiluoto area, located at south-west coast of Finland. The site area covers the western and central parts of the island. Geological models cover both lithology and structures. Model development has been an interdisciplinary process and several iterations have taken place. The bedrock model is compiled to Posiva's computer aided geological ROCK-CAD™ modelling system (Saksa 1995).

The Olkiluoto site consists of Precambrian metasediments and plutonic rocks, 1850 - 1900 million years in age. Migmatitic mica gneisses with cordierite and garnet porphyroblasts are the most abundant supracrustal rocks. They contain 20 to 50% neosome, which is most often granitic in composition. The mica gneisses are intruded by felsic plutonic rocks including oriented tonalites and granodiorites and massive, coarse-grained granites and pegmatites. The granites and pegmatites are very heterogeneous containing numerous mica gneiss restites.

The bedrock of the site records a polyphase deformational history. Five successive plastic deformational phases have been defined. The main deformation stage, D2, is a complex chain of events characterized by intense stratiform deformation with continuous production of neosome. During this phase the original bedding of the argilleous or sandy sediments was more or less destroyed, and foliation and metamorphic banding trending east-west were formed. Tonalite bodies were intruded into sediment layers. During the later deformation phases migmatites were folded by three subsequent folding phases. The main folding phase (D3) consists of NE trending folds with granitic veins and plastic faults parallel to the axial plane. After the plastic deformation phases the bedrock of the area began to respond to stress in a more brittle fashion resulting in scarp minor faults trending north and northwest.

First bedrock model was developed to cover interpretations and estimates of preliminary site investigations (in Fig. 1, version 1). It was based on surface studies and six core drilled boreholes. Both regional and site scales were covered. Modelling benefited from experience and observations of VLJ-repository volume.

Second modelling round took place during mid 1990s. New scanner type borehole logging tools were utilised in data collection. The bedrock model (version 2) contained data from eight boreholes, two investigation trenches and their interpretations. Lithological description was updated and more in detail. The knowledge of the lithological trend dipping between SE and SW was strengthened. The bedrock structure was described by 29 fracture zones four of which were completely new ones. Certain former interpretations had to be changed or abandoned. This was due to new seismic reflections observed. Properties or geometry was changed to 12 structures of the previous version of the model. Fracture zones were interpreted to be fairly conformant to lithology. Zone discrimination was based on expert judgment and statistical principal component analysis. Both interpretations and new observations indicated that fracture zones were likely to be more local and gently dipping than what was considered earlier.

The latest model revision took place in 1997 covering now 10 boreholes of the site. Observations lead to modification of four existing structures. One new fracture zone was introduced (version 3). Particular alternative conceptualisation has been formed to a unit comprised of two subhorisontal major zones (R17 and R20) as a whole.

Faulting can be a prominent structural phenomena within the bedrock volume studied. It might manifest itself in the form of difficulty to connect fracture zones from the surface to the boreholes and between the boreholes during interpretation. It has been suggested (Paulamäki & Paananen 1996) that the small scale faults parallel to NE trending D3 fold axis, can also be seen in site scale. One explanation to the discontinuous fracture zones could be, that the gently dipping fracture zones parallel to the foliation are cut and faulted by reactivated D3 fault zones, illustrated in Fig. 2. One of the interpreted fault zones has been found in the investigation trench TK2 near borehole KR1 (Fig. 1).The trench demonstrated that the fault is a plastic one, but it has later been reactivated resulting in brecciated zone with calcite filled fractures. The subjothnian diabase dikes (age c. 1650 million years) found in the archipelago of southwestern Finland and the diabase of Olkiluoto are in this same direction indicating opening of fracture systems related to the intrusion of rapakivi magmas (Bergman 1986, Haapala & Rämö 1992).

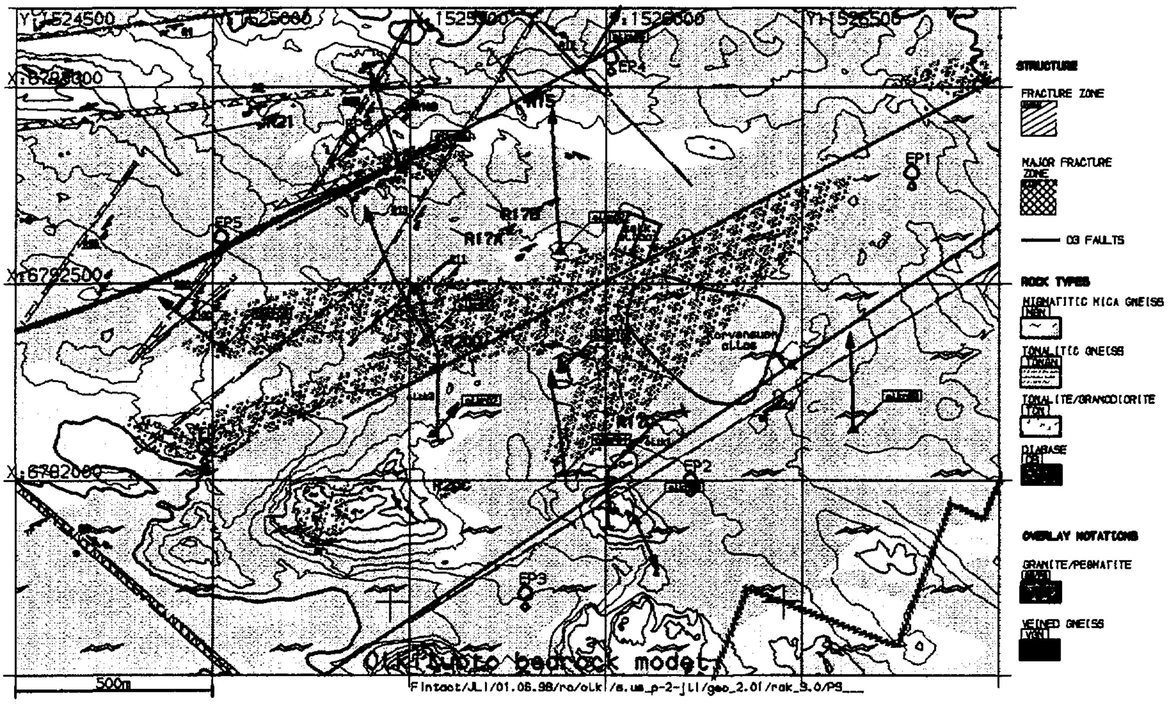

Figure 2. Excerpt of the surface map of the Olkiluoto site bedrock model.

2.2 Groundwater salinity distribution and modelling

Previous drilling and related studies revealed saline groundwater, Total Dissolved Solids (TDS) over 35 g/l, below a depth of few hundred meters at Olkiluoto. From geochemical sampling, the origin of salinity was deduced to be partly from relictic seawater and partly from bedrock fluids. The knowledge of location of saline groundwater will serve as basis of evaluation of chemical corrosion risk, and providing starting values for numerical hydraulic flow modelling.

A model of bedrock groundwater salinity distribution was compiled. Starting point for model generation has been geophysical electromagnetic soundings (more than 350 in amount), that provided information on resistivity variations down to a depth of over one kilometer. Approximately 230 of the curves were interpreted using 1D layer model inversion. Observations from drilling, groundwater sampling, geophysical electrical (VES) survey and borehole logging, have been connected to the model and interrelated.

Obtained results have been gathered to ROCK-CAD system as TDS distribution model. The framework of the model is a set of undulating layers of downwards increasing salinity, Figure 3. Upper surface of saline water starts in the depth range 300 - 1000 m depending on the location. Varying weaker saline layers and bodies cover the upper part of the bedrock. In places, where weak mineral conductors do not disturb observation, a layer of brackish water has been found. A plume of fresh water, possibly controlled by fracture zones, has partly replaced saline water. TDS distribution model shows within depth 0 - 500 m also large spatial variations which are complex in form.

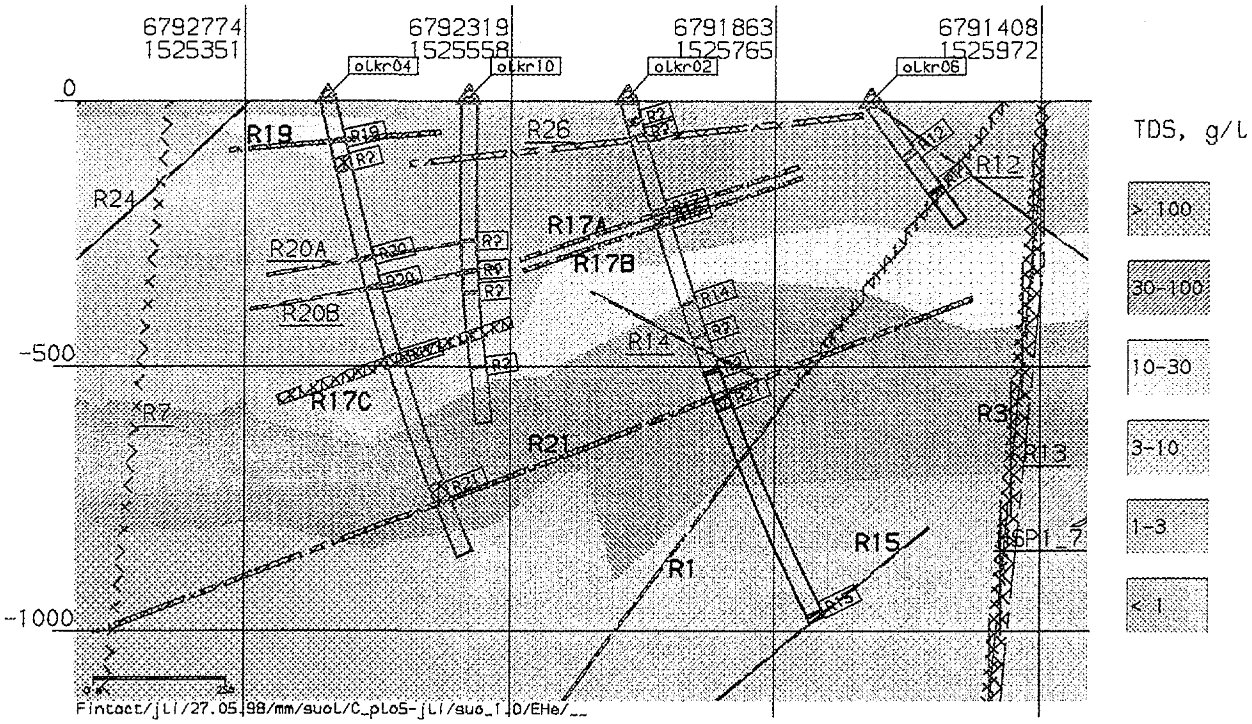

Figure 3. Cross section along holes KR2, KR4, KR6 and KR10 of the TDS model with the bedrock structures (version 2 model).

2.3 Groundwater flow modelling on the site scale

2.3.1 Conceptualisation

The objective of the modeling has been to provide results that characterize the groundwater flow conditions deep in the bedrock, and that can be used for evaluation of the investigation site and of the preconditions for safe disposal. The latest groundwater flow modeling effort of the site comprised the transient flow analysis taking into account density variations, the repository, post-glacial land uplift and global sea level rise. The analysis was performed by means of numerical simulation of coupled and transient groundwater flow and solute transport. The simulations were carried out until 10000 years after present.

The basis for the numeric groundwater flow simulation has always been the most up-dated structural model. The model part was, however, complicated in its piecewise composition. Interference tests supported certain simplified and continuous structures in site scale and shown in Figure 4, for example, labeled as R19HY and R20HY. These structures together with nearly parallel structures R21, R17HY and R24HY explained almost all hydraulically active sections in different boreholes. Hydraulic conductivity in the rock mass is very low and strongly decreasing with depth.

The salinity of water samples may indicate that fresh surface water is infiltrating or migrating from recharge areas along some intersecting structures to deeper parts of the bed-rock. This would happen especially within the central recharge area of the island. This evidence has supported the existence of some discrete hydraulic connections to be tested by numeric groundwater flow modelling.

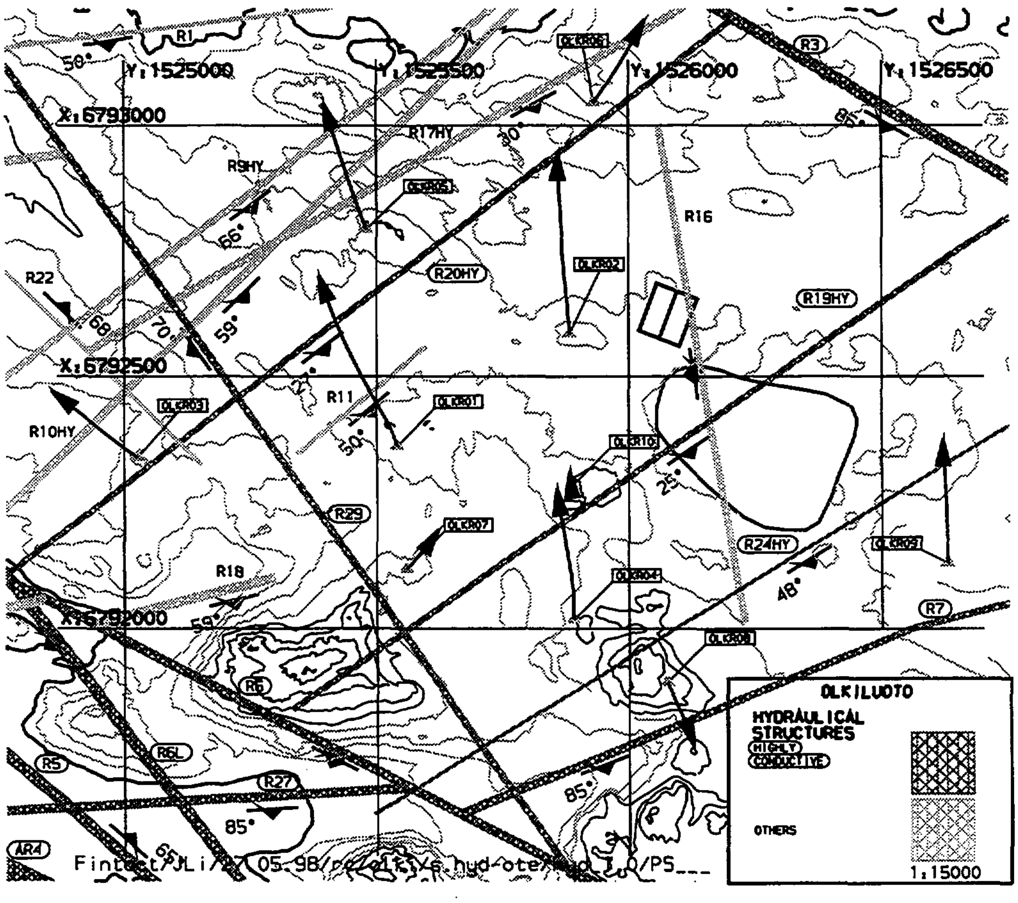

Figure 4. Excerpt of surface map of the Olkiluoto site hydraulic-structural model.

Classification of fracture zones on ground of transmissivity was based on measured values. Structures without measured values were classified on the basis of geological significance. Measured transmissivities and two depth dependent curves for classification used are presented in Fig. 5. These gave the initial values of transmissivity for numerical simulations. In versions V1 and V2 (Fig. 1) structures were classified up to four classes and depth dependency of transmissivity (logT) was linear and stronger especially for deeper parts of the bedrock. It was estimated that linear extrapolation of transmissivities gave too low values especially for depths deeper than 1000 m. Numerical simulations indicated that values deeper than 1000 m are of minor importance. Reclassification simplified the structural model. Several minor structures with relatively low transmissivity were part of a larger structures or local in extent.

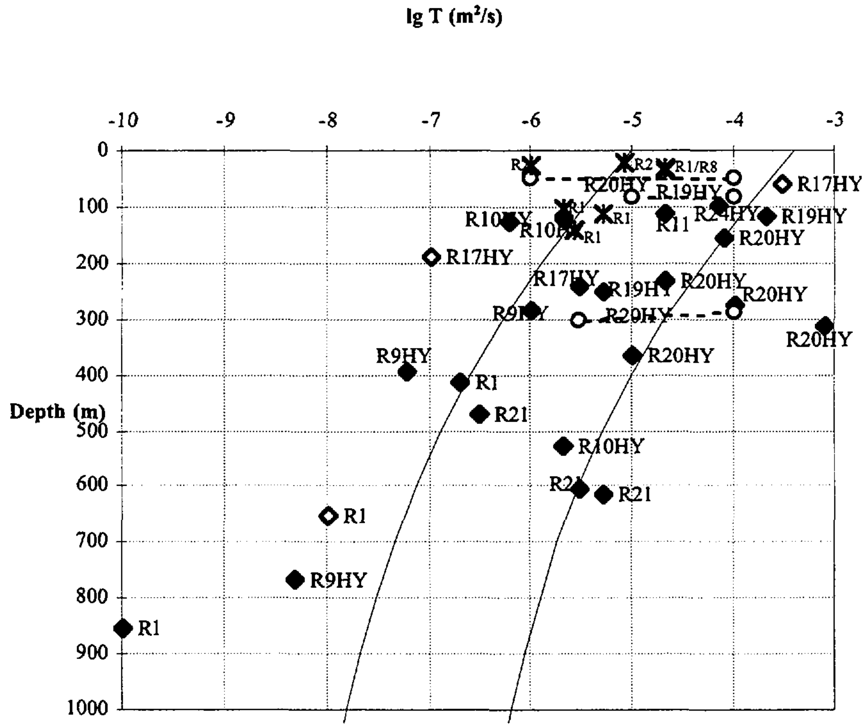

Figure 5. *Measured transmissivities and two depth dependent curves for classification of structures for numerical simulations. Uncertain values depicted with open markers, crosses are values from VLJ-site studies. Range is given for certain structures by open circles.*

In the hydrogeochemical field investigations at Olkiluoto salinity concentrations as high as 43 g/l (Cl) have been observed (Pitkänen et al. 1998). Variations in the density of water, caused primarily by the variations in the salinity of groundwater, have an effect on groundwater flow. The postglacial land uplift enlarges the area of the Olkiluoto island and raises the water table increasing flow of fresh water deeper into the bedrock and a mixing of water of different types. Because the remaining uplift is still expected to be several tens of meters (Eronen et al. 1995, Påsse 1997), the flow conditions at Olkiluoto are slowly evolving causing ongoing changes in the hydrology of the area. Because of the varying salt content of groundwater and the effects of the land uplift, the flow analysis called for coupled and transient modelling of flow and solute transport. The analysis was performed from the present until 10000 years after present (A.P.), when the next ice age is assumed to occur.

The fractured bedrock was modelled employing a concept of hydraulic units: the two-dimensional, planar shaped fracture zones and the remaining part of the bedrock (intact rock). Within each hydraulic unit the equivalent-continuum (EC) approach was applied, i.e. each fracture zone and intact rock were separately treated as a homogeneous and isotropic continuum with average characteristics. The repository was modelled as a two-dimensional object.

2.3.2 Flow and transport model for the Olkiluoto site - Results

The modelled volume was disretized into finite element mesh containing three-dimensional hexaedral elements representing the intact rock embedded with two-dimensional quadrilateral and triangular elements for the fracture zones. The location and size of the repository were based on the repository layouts (Saanio 1997). The present groundwater table (Saksa et al. 1993) together with a mathematical model describing the land in the Olkiluoto area (Påsse 1997) were employed as a boundary condition at the surface of the model, while the initial and boundary conditions in the rest of the modeled volume were based directly on the measured salinity concentrations along the cored boreholes (Pitkänen et al 1998). TDS distribution model supported the geometry of salinity chosen to numerical simulations.

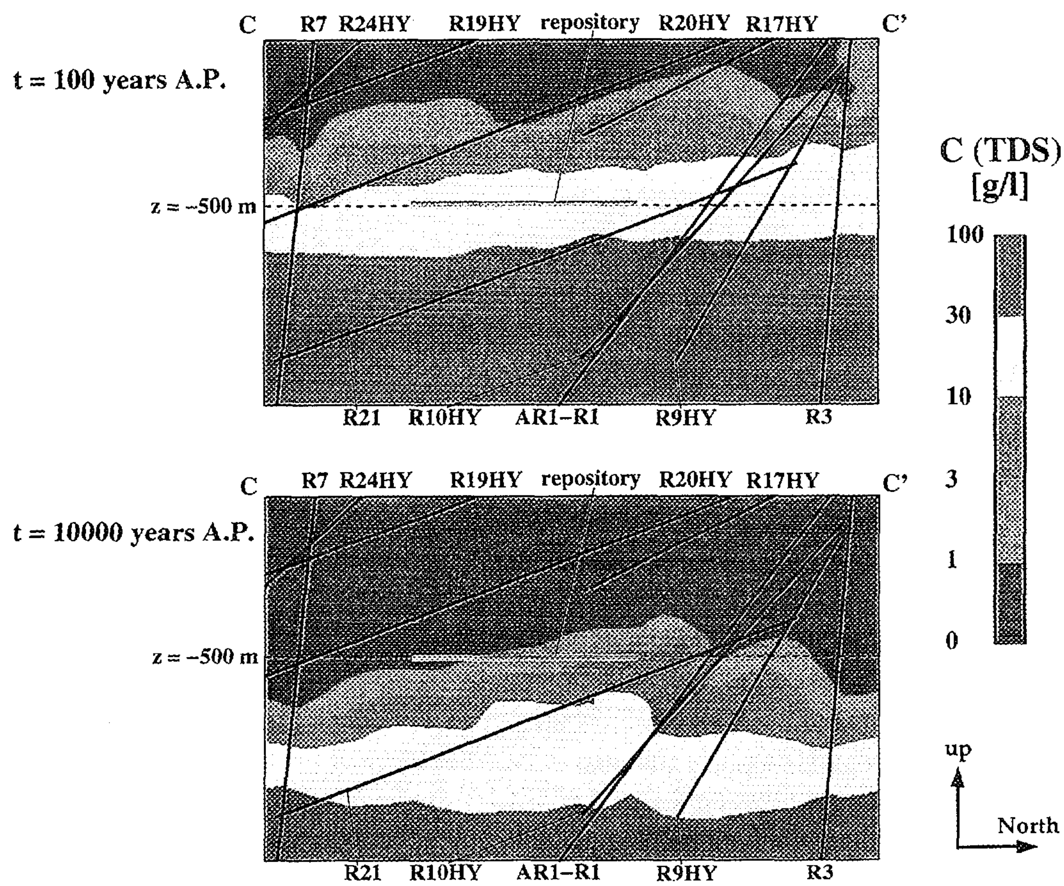

Figure 6. Computed TDS concentration at vertical south-north cross-section (same as in Fig. 3) of the modelled volume.

The result quantities were the amount, direction, velocity and routes as well as concentration of water, which were considered especially in vicinity of the repository. A major part of water flows into (out of) the repository from above (downwards) along the intersecting fracture zones R10HY and R16, and through the rock matrix. Situation is illustrated by Figure 7. The amount of water flowing through the repository increases with time as a result of land uplift and fresh water intrusion. The most important flow routes from the repository to the surface are along the fracture zone R21, which dips from the north-west below the repository, and along the zone R27, which is directed to west (Figures 3 and 7). The results computed with and without the repository showed that it has only a small effect on the flow conditions. The salinity of groundwater in the bedrock decreases with time, and at 10000 years after present there is practically only fresh water at the depth of repository (500 m) (Fig. 6).

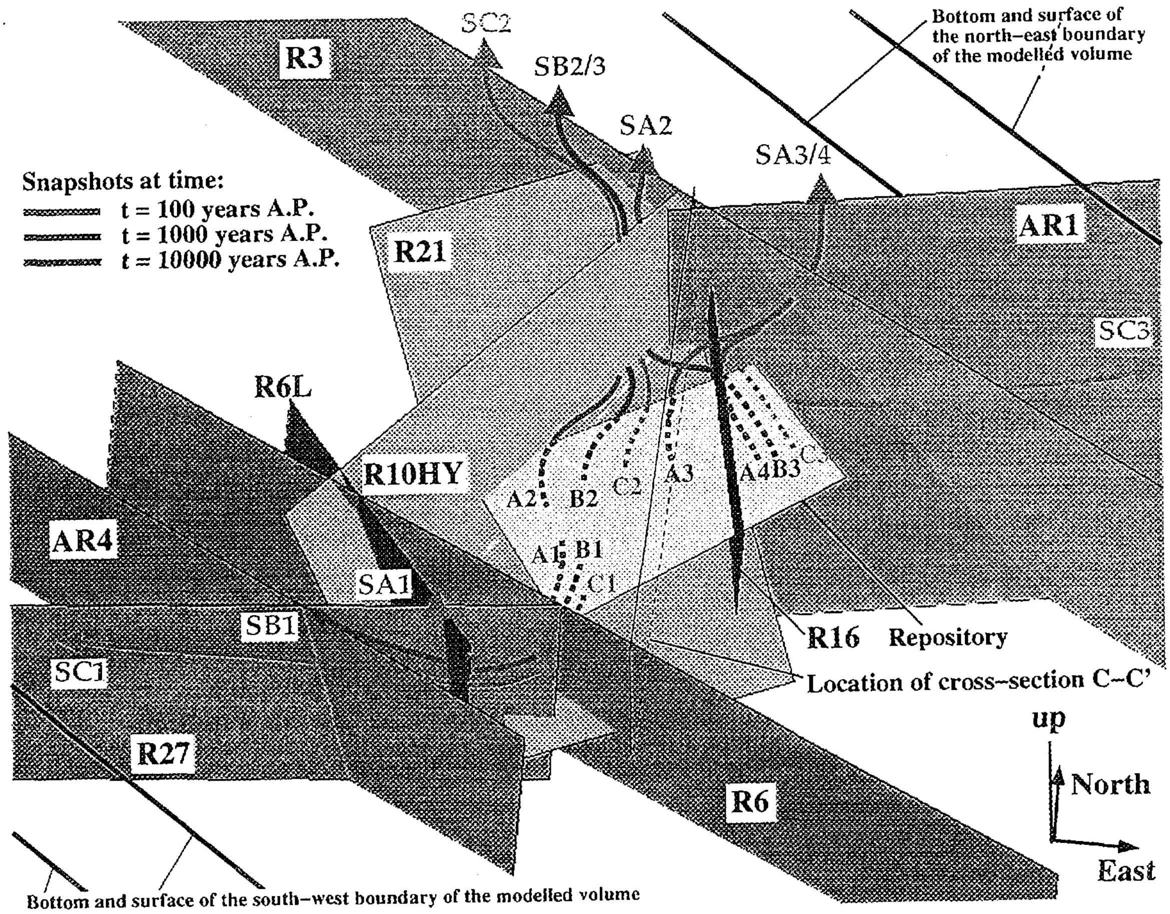

Figure 7. The dominant flow paths from the repository.

2.4 Hydrogeochemical assessment and implications to flow modelling

Integration of hydrogeological and hydrogeochemical methods and studies provides the primary tool for investigating the evolution in the past, and for predicting future conditions. In addition hydrogeochemical information has been used to screen relevant external processes and variables for definition of the initial and boundary conditions in hydrological simulations.

Hydrogeochemistry shows that the groundwater at the Olkiluoto site is a mixture of at least five end-member water types (Table 2-1) derived during paleohydrogeological and modern processes (Pitkänen et al. 1996). Fresh, diluted groundwater is confined to shallow depths. Brackish Na-Cl type water occurs at depths of 100 - 500 m, and salinities as high as 70 000 mg/l has been observed in deep-occurring saline Ca-Na-Cl type groundwater.

Brackish Na-Cl groundwater enriched with SO_4 has been identified at a depths of 100 - 300 m. The salinity of this water type clearly exceeds the present value of the Gulf of Bothnia (Cl ≈ 3 600 mg/l), while the Br/Cl and stable isotope ratios of water are similar to that of sea water. Below this SO_4-rich layer of brackish groundwater the level of heavy stable isotopes falls, reflecting the mixing with colder climate water. At greater depths, the stable isotopic composition of saline groundwater (Cl_{max} 43 000 mg/l) tend to shift above the global meteoric water line. The Br/Cl ratio of this water also rises significantly above the value for sea water.

At Olkiluoto fresh, meteoric groundwater has been infiltrating since the land rose above the sea level 2500 years ago. According to the hydrochemical and isotopic characteristics of the SO_4-rich brackish groundwater, it is most likely that the infiltration has come from the Litorina Sea. The depletion of heavy stable isotopes can be explained by mixing with colder pre-Litorina water, probably meltwater from the Weichselian ice sheet. The chemistry implies that the displacement of meltwater by denser Litorina water decreases in the brackish groundwater below the SO_4-rich layer and, in addition the proportion of the saline end-member gradually increases. The deep location below the cold end-member and elevated stable isotopes are indicative of a pre-glacial origin for the saline water. Hydrogeochemical characteristics are assumed to reflect hydrothermal conditions (Blyth et al. 1998) and an early pre-Quaternary origin for the saline end-member according to the known geological history of the Fennoscandian Shield (Pitkänen et al. 1996).

Table 2-1. Main water-types at Olkiluoto and predicted age of dominant end-member-types (Pitkänen et al. 1996).

Depth of occurrence	Water-type	Origin of dominant end-members	Age estimate of main end-members
<150 m	Fresh-slightly brackish HCO3 -	Meteoric water and modern Baltic water	0 - 2 500 BP
100-300 m	SO_4-rich brackish Na-Cl water	Litorina Sea water	2 500 - 7 500 BP
100-500 m	Brackish-saline Na-Cl water	Pre-Litorina water with fresh glacial meltwater	10 000 BP
>500 m	Saline Ca-Na-Cl water	Preglacial water influenced by hydrothermal brines	>> 10 000 BP

3 Evaluation of the model

3.1 Testing of previous results and assumptions

One of the topics of the characterisation programme 1993 - 96 was the testing of the site knowledge and previous results. The subjects considered were rock type, fracture density, occurrence of fracture zones and hydraulic conductivity of the intact rock. Each subject had an established claim in the background - like "regional rock types are prevailing within the site volume" - which was tested. Results from the earlier work phases were compared with the latest data available and the trend was studied.

For Olkiluoto the outcome of the testing was:
- the main rock types (gneisses, granite/pegmatites and tonalite) are dominating by all measures.
- distributions of the fracture densities are similar, no statistically significant differences existed. This applied both to the surface 0 - 300 m and to deeper > 300 m bedrock part.
- fracture zones have occupied earlier 12.8 % of the total borehole length. This has reduced to 9.4 %. The average intersection length has lowered from 10.4 m to 9.2 m. The number of interpreted fracture zones has accompanied the increase of borehole meters. New investigation methods have increased the knowledge level somewhat - model structures explained during 1992 64.1 % of borehole sections and during 1996 68.8 %.
- statistics of the hydraulic conductivity values were the same in the depth range 0 - 300 m for the both investigation phases. Data for deeper bedrock shows slight increase for conductivity values.

3.2 Prediction-outcome tests for the borehole data

Also a prediction-outcome comparison tests were made in boreholes KR2 extended part and in borehole KR10. Lithology prediction diverged (statistically) from the observations but only a few percents of the rock was of accessory type. Predictions for the fracturing overestimated the fracture density. This is partly due to the assumption that the rock within the fracture zones would be densely fractured throughout which not seemed to be the case. Hydraulic conductivity estimates gave lower and higher values than what was measured in the holes. More than 90 % of the observed hydraulic conductivities were within estimated 90 % confidence limits.

3.3 Other evaluation activities

Recent pumping tests (spring -98) have strengthened the existence of the most dominant fracture zone R20HY - e.g. strong pressure responses deep in the borehole KR9 at a distance of almost 500 m. On the basis of long-term pumping test and flowmeter measurements it was found too that the very high transmissivity value measured with double packer injection test at depth of 310 m (see Fig. 5) is a local phenomena i.e. the transmissivity (log) of structure R20HY in the borehole KR4 is about -4.5 instead of having value of -3 given in Figure 5.

References

Bergman, L., 1986. Structure and mechanism of intrusion of postorogenic granites in the archipelago of southwestern Finland. Acta Academiae Aboensis. Ser. B, Mathematica et Physica, Vol. 46, pp. 1 - 74.

Blyth, A., Frape, S., Blomqvist, R., Nissinen, P. & Mc Nutt, R. (1998). An isotopic and fluid inclusion study of fracture calcite from borehole OL-KR1 at the Olkiluoto site, Finland. Posiva Oy. Report Posiva 98-04.

Eronen, M., Gluckert, G., van de Plassche, O., van de der Plicht, J. & Rantala, P., 1995. Land Uplift in the Olkiluoto-Pyhäjärvi Area, Southwestern Finland, during the Last 8000 Years. Report YJT-95-17, Nuclear Waste Commission of Finnish Power Companies, Helsinki.

Haapala, I. & Rämö, O.T., 1992. Tectonic setting and origin of the Proterozoic rapakivi granites of southeastern Fennoscandia. Transactions of the Royal Society of Edinburgh: Earth Sciences, Vol. 83, pp. 165 - 171.

Paulamäki, S. & Paananen, M., 1996. Characterization of bedrock structures in Olkiluoto study site, Eurajoki, southwestern Finland. Posiva Oy, Work Report PATU-96-28, Helsinki, Finland.

Pitkänen, P. et al. 1998. Geochemical modelling of groundwater evolution and residence time at the Olkiluoto site (in preparation).

Pitkänen, P., Snellman, M. & Vuorinen, U. (1996). On the origin and chemical evolution of groundwater at the Olkiluoto site. Posiva Oy. Report Posiva -96-14.

Påsse, T., 1996. A Mathematical Model of the Shorelevel Displacement in Fennoscandia. Technical Report 96-24, Swedish Nuclear Fuel and Waste Management Co. (SKB), Stockholm.

Saanio, T., 1997. Adaptations of the Repository for Spent Nuclear Fuel in Olkiluoto. Memorandum T-2000-38/97, Saanio & Riekkola Oy, Helsinki. (In Finnish).

Saksa, P. 1995. ROCK-CAD - Computer Aided Geological Modelling System. Report YJT-95-18, Nuclear Waste Commision of Finnish Power Companies, Helsinki.

Saksa, P., Ahokas, H., Paananen, M., Paulamäki, S., Anttila, P., Front, K., Pitkänen, P., Hassinen, P. & Ylinen, A., 1993. Bedrock Model of the Olkiluoto Area, Summary Report. Report YJT93-15, Nuclear Waste Commision of Finnish Power Companies, Helsinki.