TECHNICAL
REPORT

**95-33**

# Geohydrological simulation of a deep coastal repository

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December 1995

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# GEOHYDROLOGICAL SIMULATION OF
# A DEEP COASTAL REPOSITORY

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## Abstract

This conceptual-numerical study treats the dewatering and resaturation phases associated with the construction, use and closure of a coastal nuclear waste repository located at depth in sparsely fractured Baltic Shield rocks. The main objective is to simulate the extent and duration of saline intrusion for a reasonable set of geohydrological assumptions. Long-term changes in the chemical environment associated with saline intrusion may affect the properties of the buffer zone material (bentonite). The first part of the study deals with history matching of a simple model geometry and the second part treats the dewatering and resaturation phases of the simulated repository. The history matching supports the standpoint that the occurrence of saline ground water reflects an ongoing but incomplete Holocene flushing of the Baltic Shield. The drawdown after fifty years of dewatering is highly dependent on the permeability of the excavated damaged zone. If the permeability close the repository is unaltered the entire region between the top side of the model and the repository is more or less partially saturated at the end of the simulation period. The simulations of a fifty year long recovery period suggest that the distribution between fresh and saline ground waters may be quite close to the conditions prior to the dewatering phase already after fifty years of closure despite an incomplete pressure recovery, which is an interesting result considering the objective of the study.

Keywords: Fractured rock, Saline Intrusion, Unsaturated flow, Excavated damaged zone, Repository construction

## Sammanfattning

Föreliggande rapport berör frågan om saltvatteninträngning till ett kustnära djupförvar vid den svenska ostkusten. Långtgående förändringar i grundvattnets kemiska sammansättning kan vara av betydelse för buffertmaterialets funktion. I studiens första del kalibreras en enkel modellgeometri mot kända koncentrationsprofiler i två djupa kärnborrhål. I den andra delen simuleras grundvattnets rörelser under en femtio år lång länshållningsperiod följt av en lika lång återhämtningsperiod. Kalibreringen indikerar att saltvattenfrontens läge är tidsberoende, ett resultat som stämmer med tidigare studier. Avsänkningen efter femtio års länshållning beror i stor utsträckning av permeabiliteten i den störda zonen. Om den störda zonen inte tas med i beräkningarna erhålles en mycket stor avsänkning närmast det simulerade förvaret. Saltvattenuppträngningen är också påtaglig med höga koncentrationer på förvarsnivån 500 m. Om man antar att bergets egenskaper är oförändrade under den efterföljande återhämntningen ger beäkningarna att saltvattenfronten drar sig tillbaka till ett nästan ursprungligt utseende efter femtio års återhämtning, vilket är ett intressant resultat med tanke på studiens syfte.

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# 1. Introduction

## 1.1 *Objective*

This conceptual-numerical study treats the dewatering and resaturation phases associated with the construction, use and closure of a coastal nuclear waste repository located at depth in sparsely fractured Baltic Shield rocks. The main objective of the study is to simulate the extent and duration of saline intrusion for a reasonable set of geohydrological assumptions, see Figure 1. Long-term changes in the chemical environment associated with saline intrusion may affect the properties of the buffer zone material (bentonite).

The study consists of two parts. Part 1 deals with history matching of a simple numerical model and Part 2 treats the dewatering and resaturation phases. The purpose of Part 1 is to provide initial geohydrological conditions for the simulations in Part 2. The numerical simulations use the US Geological Survey computer code SUTRA (Voss, 1984).

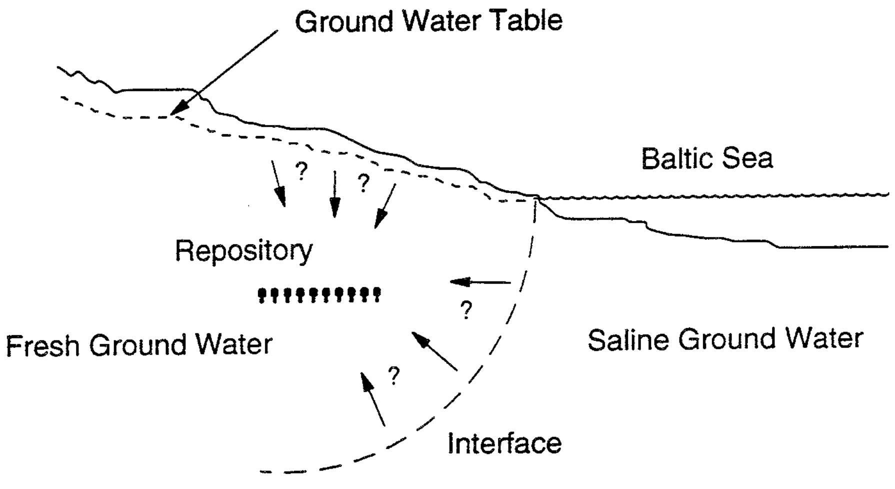


**Figure 1** Schematic cross section of the studied repository scenario.

## 1.2 *Limitations*

The reason for using SUTRA in this study is its documented capability to simulate two-dimensional variable-density flow and mass transfer in saturated and unsaturated porous media under isothermal conditions. For example, Voss and Andersson (1993) used SUTRA in a related study that focused on the historical occurrence of saline ground water and regional flow patterns in the Baltic Shield during the Holocene coastal regression.

The main difficulty with using SUTRA in this study, as in the study of Voss and Andersson (1993), is above all conceptual. The study addresses flow and transport problems through sparsely fractured crystalline rocks by using a continuum approach. A continuum model provides connection between any two points in a model, and flow is allowed along any pathway. Actual discrete fracture networks restrict flow to distinct pathways, and connections may not always exist between any two points.

The numerical simulations of the dewatering and resaturation phases are approximate for several reasons. First, SUTRA cannot simulate the fully coupled variable-density problem of simultaneous heat transfer, multiphase flow and mass transport. Hence, neither the geothermal gradient nor any production of heat and gas at the repository are considered in this study while simulating the variable-density saline-intrusion problem. Second, the relationships generally considered to govern unsaturated flow are essentially unknown for sparsely fractured rock. The required relationships are the capillary head versus the saturation and the relative permeability versus the saturation. Third, the net changes of the rock permeability associated with various underground activities such as blasting, excavation, grouting, etc. are also uncertain. Fourth, SUTRA simulations are two-dimensional, which implies an infinite extent of the conditions perpendicular to the modeled cross section.

### *1.3 Numerical Modeling*

The numerical modeling is characterized by using a simple model geometry, see Figure 2, and identical boundary conditions for the history matching and the simulation of the dewatering and resaturation phases. By history matching we mean here (1) an evolution of the hydraulic head profile of the modeled cross section between 10,000 years BP and today that is reasonable coherent with the documented land upheaval during the Holocene coastal regression (SNA, 1994), and (2) a likewise acceptable agreement between the simulated salinity distribution versus depth and the concentration profiles observed in KLX01 and KLX02, two deep core boreholes located close to the seashore and the Äspö Hard Rock Laboratory (Laaksoharju *et al.*, 1995). As shown in Figure 3, the two boreholes are located about 500 m and 1,500 m from the seashore, respectively. KLX01 is about 1,100 m deep and KLX02 is about 1,700 m deep, see Figure 4. The fresh ground water lens is somewhat thicker in KLX02 than in KLX01.

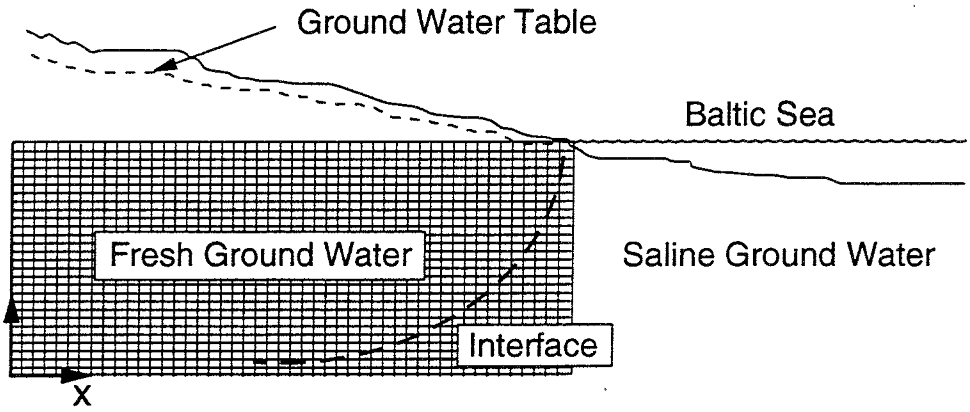


**Figure 2** Finite-element discretization for history matching. The mesh has 861 nodes and 800 elements. Each element is 2 km long and 100 m deep.

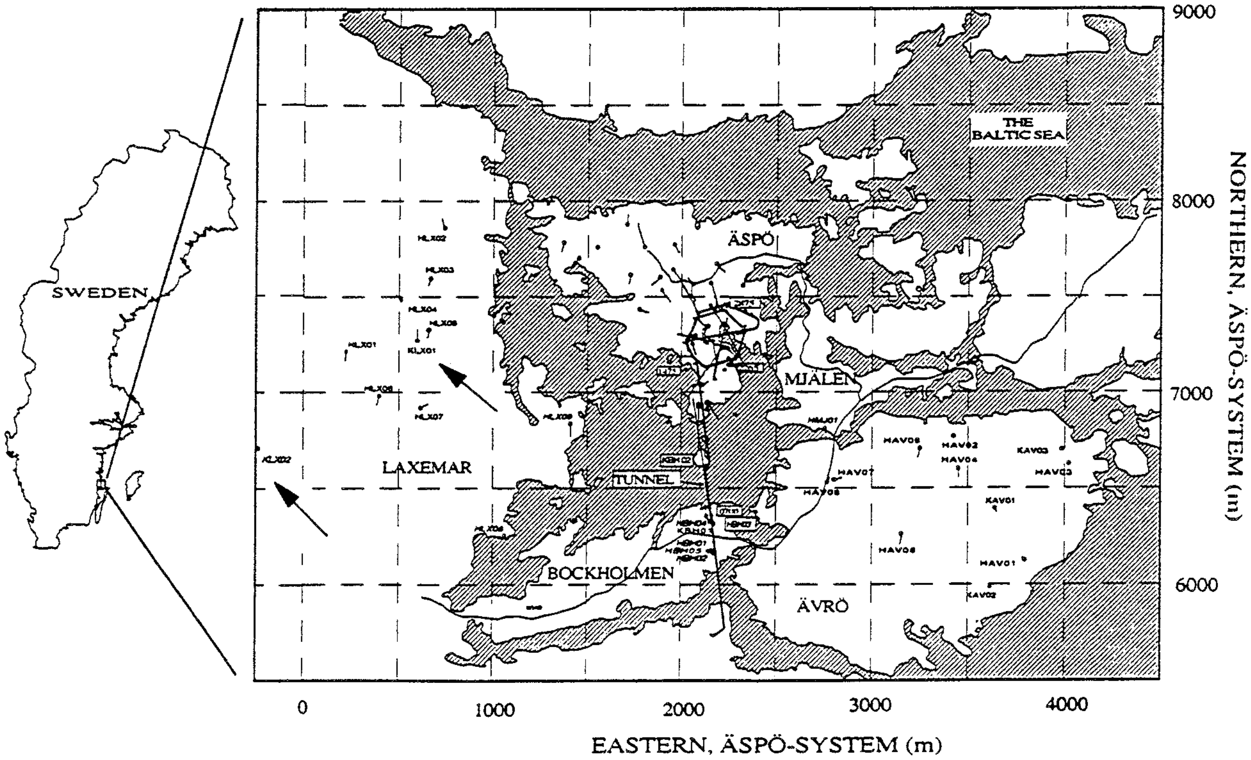


**Figure 3** Area view of the Äspö HRL site. The core boreholes KLX01 and KLX02 are located 500 m to the north and 500 m to the west of "LAXEMAR", respectively. KLX01 is about 1,100 m deep and KLX02 is about 1,700 m deep. (Reproduced from Stanfors *et al.*, 1994).

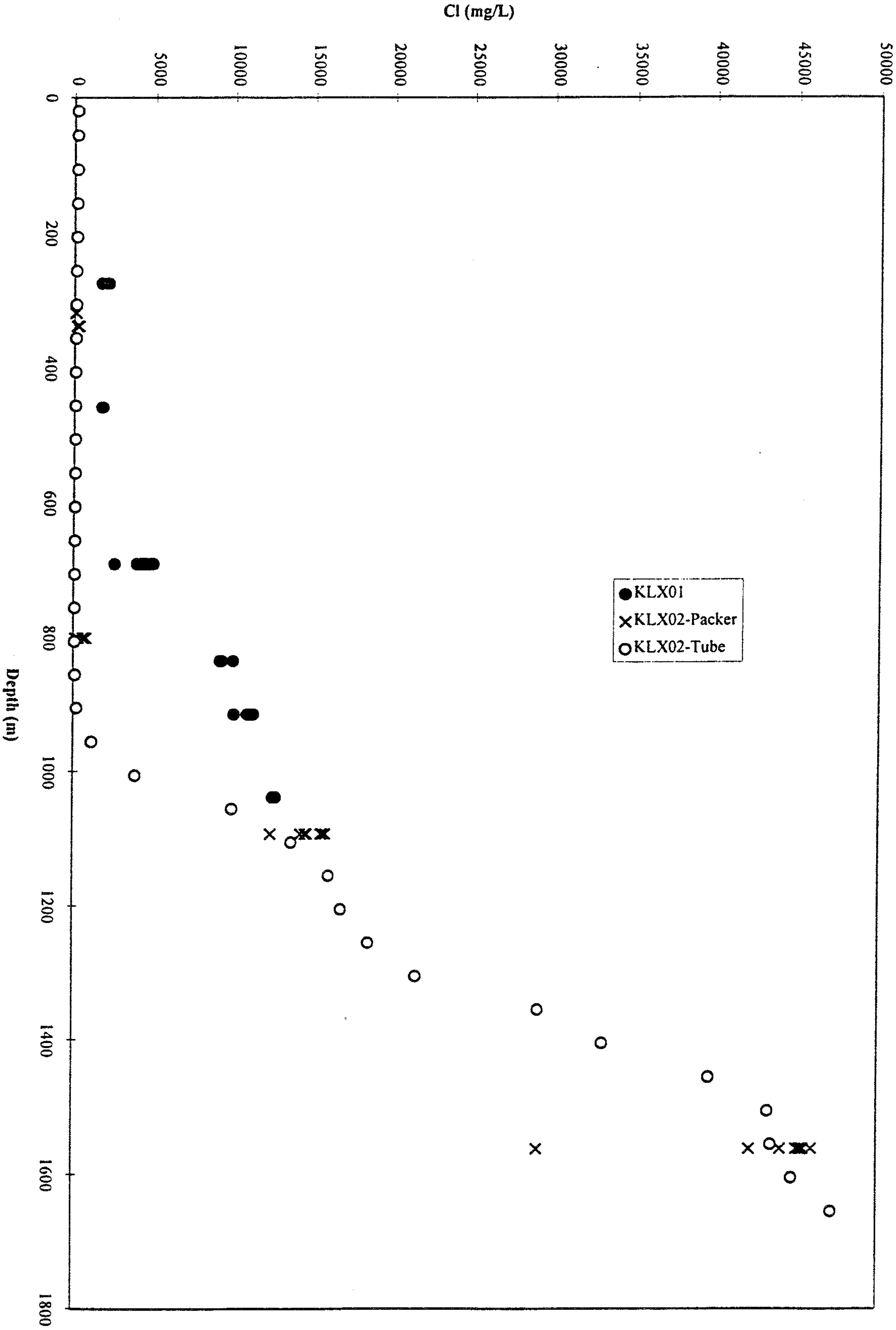


**Figure 4** Concentration profiles (chloride) from KLX01 and KLX02. After Laaksoharju *et al.* (1995).

# 2. Part 1 – History matching

## *2.1 Boundary Conditions*

The purpose of the history matching in this study is to provide reasonable initial geohydrological conditions for the simulation of the dewatering and resaturation phases in Part 2. The simple conceptual-numerical model is shown in Figure 5. Figure 6 shows the Holocene marine limit in Sweden about 10,000 years BP together with the locations of the modeled cross section and the regional run off divide.

The modeled cross section is assumed to be impervious at the landward and the bottom sides. This is equivalent to forcing flow to be vertical along the inland boundary, a probably acceptable boundary condition considering the location of the regional runoff divide, see Figure 6. The chosen location of the bottom boundary at 2,000 m below sea level is found to be beyond major significance for the study (cf. Voss and Andersson, 1993).

The boundary conditions at the top and seaward sides are important for this study. A flux boundary condition must be specified at the top side in order to allow for a drawdown of the water table while the repository is depressurized. This study assumes a fixed infiltration rate at the top side. It should be noted that a fixed infiltration rate does not allow for an increased infiltration within the radius of influence of the cone of depression. However, considering the objective of this study, the adopted boundary condition is conservative, i.e., the drawdown and the resulting saline intrusion will not be underestimated.

The fixed infiltration rate is adjusted to match the Holocene evolution of the hydraulic head profile of the modeled cross section between 10,000 years BP and today (SNA, 1994). Present-day heads of lakes close to the runoff divide are in the range 200–300 m above sea level (SNA, 1994).

If no fluid flow is allowed across the seaward side, the modeled cross section must be stretched out eastwards so that the boundary is located far enough from the region of interest (cf. Voss and Andersson, 1993). This study approximates the desired properties of a distant boundary by using a fixed concentration profile at the seaward side of the modeled cross section, see Figure 5. Thus, the pressure profile at the seaward side is hydrostatic and flow across the boundary is permitted. The reason for this approximation is to allow for an increased discretization of the simulate repository in Part 2.

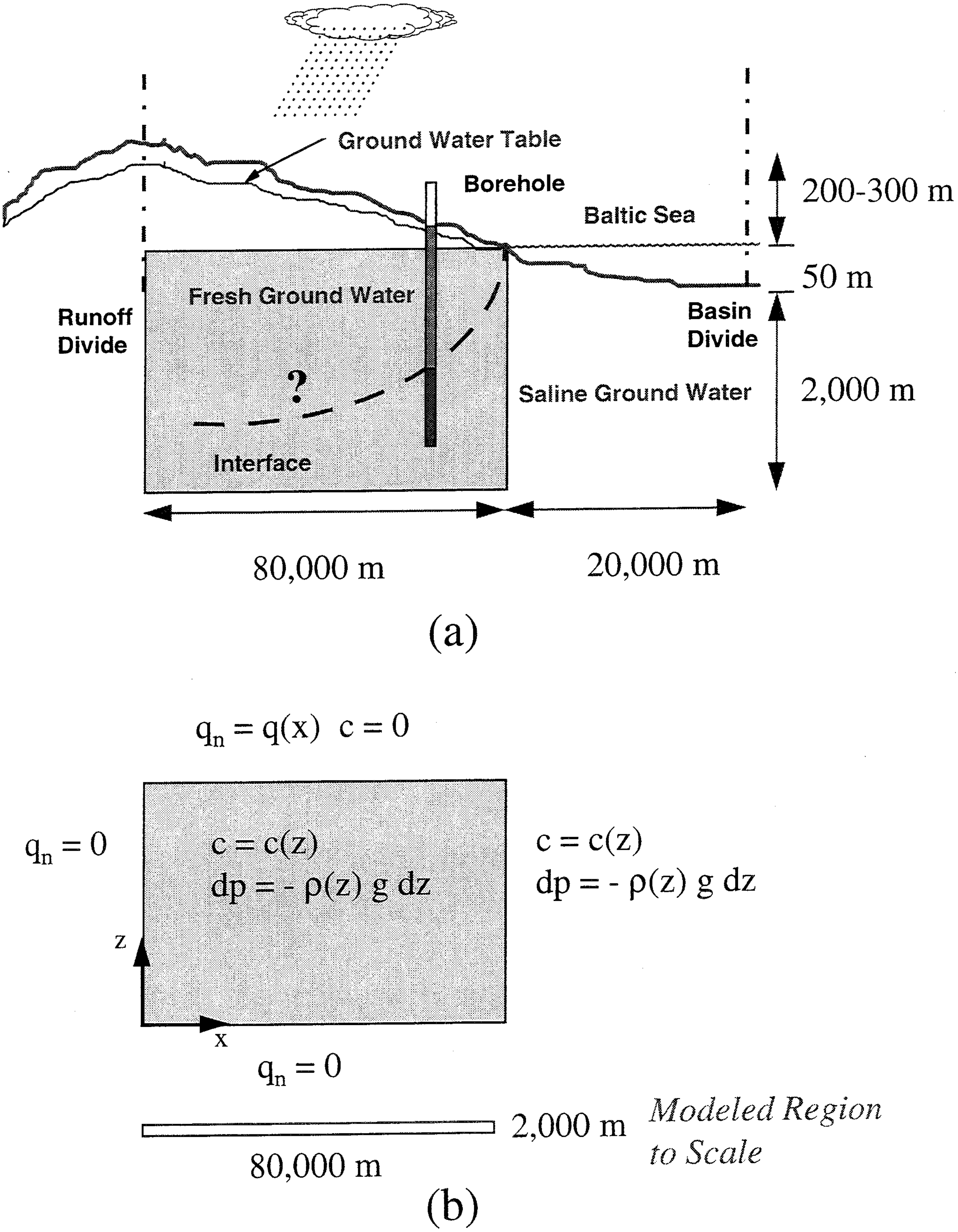


**Figure 5** (a) The conceptual model and (b) the boundary and initial conditions used for history matching.

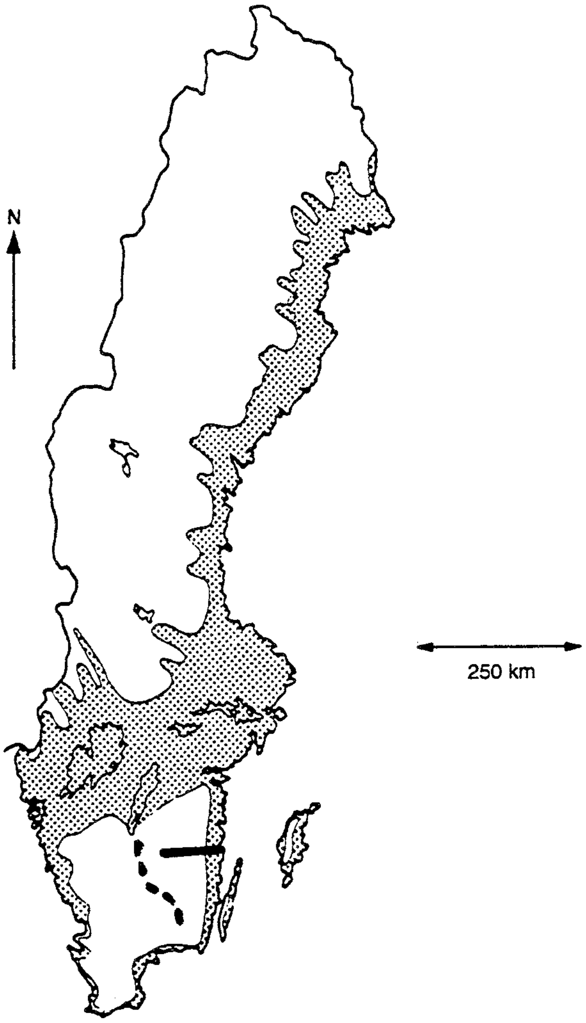


**Figure 6** Holocene marine limit in Sweden, about 10,000 years BP. Shaded region was inundated by sea water. The solid line shows the location of the modeled cross section. The dashed line shows an interpretation of the location of the major runoff divide for the region of interest. Modified after Lindewald (1985)

### 2.2 *Initial Conditions*

Fourteen thousand years ago Sweden was covered with ice. The Baltic Shield was isostatically depressed by the weight of the ice cap to over 200 m below sea level, and large areas were subject to marine excursion (SNA, 1994). As indicated in Figure 6, more than half of the cross section falls outside the region that was inundated by sea water after the latest glaciation.

For the purpose of this study it is assumed that between 14,000–10,000 years BP, the ground waters in the region of interest was saline. The reasons for this assumption are:

- Saline ground waters are always encountered at greater depth at all locations in the Baltic shield (Voss and Andersson, 1993).
- Most likely these saline waters are mixtures of meteoric water and residual metamorphic fluids, or the salinity is derived from rock-water interaction (Smellie and Wikberg, 1991).
- According to Bein and Arad (1992), growth of deep permafrost layers during previous glacial periods may give rise to further salinity increases.

Present-day depth-distribution of salt content in fluids residing the Baltic Shield rocks is not well known on the regional scale. For the purpose of this study, the information gathered at KLX01 and KLX02 is used. The two concentration profiles shown in Figure 4 imply that the present fluid density distribution is not uniform but increases at depth. For example, the salinity expressed as Total Dissolved Solids of the borehole fluid in KLX02 above 900 m depth is less than or equal to the present value of the Baltic Sea, which is about 0.7 % by weight (0.007 kg/kg or 7,000 ppm). At 1,700 m depth, the TDS value has increased to almost 7 % by weight, or ten times the present TDS value of the Baltic Sea (Follin, 1994).

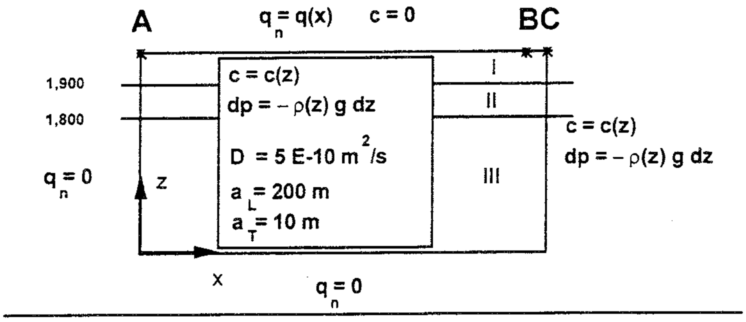
This study assumes that the initial TDS concentration 10,000 years BP varied linearly with depth between 0.7 % and 7 %. The linear concentration gradient is applied to the entire cross section as an initial condition for the history matching. For a linear relationship between fluid concentration and density (Voss, 1984), the linear concentration gradient leads to a linear fluid density gradient 10,000 years BP throughout the modeled cross section; ranging from 999,90 kg/m$^3$ at the top of the model to 1,049.40 kg/m$^3$ at the bottom. The ambient ground-water temperature in all simulations is +7 °C.

For the purpose of comparison only, the classical Ghyben-Herzberg equation yields that the effective density of the saline ground water in the Laxemar area is about 1,014 kg/m$^3$. This figure is based on the present elevations of the water table at KLX01 and KLX02 and a fresh water density of 999,90 kg/m$^3$.

### *2.3 Flow Parameters*

The flow and transport parameters of interest are the porosity (-), the permeability ($m^2$), and the dispersivity (m) . The representation of the fractured heterogeneous shield rock as a porous medium tacitly implies that values used are in some sense mean or effective values of the heterogeneous fabric. Voss and Andersson (1993) provide a good presentation of continuum approximations and their discussion applies to the present study.

For the purpose of this study different flow parameter combinations tested in the history matching. In short, the parameter values shown in Figure 7 were chosen. The considered case consists of a heterogeneous effective porosity, a heterogeneous and anisotropic permeability, and a homogeneous and anisotropic dispersivity. The initial and boundary conditions used are also shown in Figure 7. The solution, which defines the initial geohydrological state for Part 2, is shown in Figure 8.



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I $\phi = 0.1\text{-}0.075$ %

$k_h = 1.45\text{ E-15 m}^2$ $k_v = 1.45\text{ E-14 m}^2$

II $\phi = 0.075\text{-}0.025$ %

$k_h = 7.25\text{ E-16 m}^2$ $k_v = 7.25\text{ E-15 m}^2$

III $\phi = 0.025$ %

$k_h = 1.45\text{ E-16 m}^2$ $k_v = 1.45\text{ E-15 m}^2$

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| | h(A), m | h(B), m | h(C), m |
|---|---|---|---|
| Time (BP) | x = 0 | x = 78,000 | x = 80,000 |
| 10,000 | 0 | 0 | 0 |
| 9,000 | 61 | 2.5 | 0 |
| 5,000 | 175 | 7 | 0 |
| 0 | 276 | 10 | 0 |

**Figure 7** Final set of parameter values, initial and boundary conditions used to simulate the history matching.

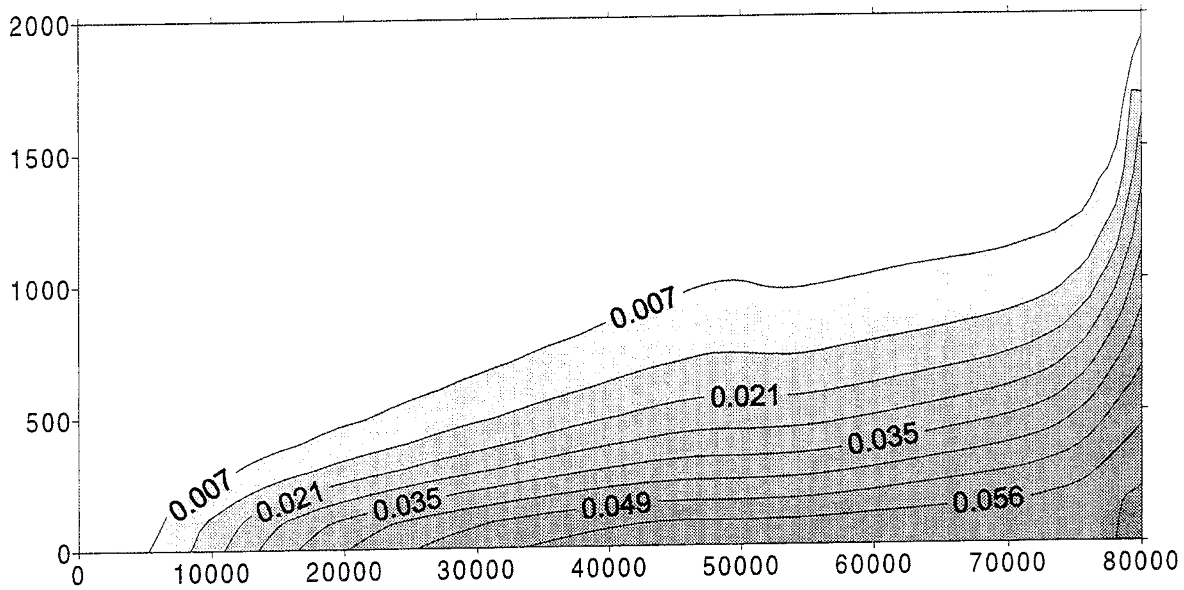

**Figure 8** Result of history matching for the parameter values and conditions specified in Figure 7. The salinity contours are in kg dissolved solids/kg solution. The magnitudes of the velocity vectors are relative only.

It is assumed that the values of the effective porosity and permeability values both decrease at depth, see Figure 7. There is evidence from the Äspö HRL project to support this assumption. Follin (1994) concluded, based on a long-term interference test , that the diffusivity of the shield rock between KLX01 and KLX02 increases about one order of magnitude between the ground surface and 1,000 m depth. For a multilayerd model, where each layer was 200 m thick, Follin (1994) found that the transmissivity decreased one order of magnitude, whereas the storativity decreased about two orders of magnitude.

The assumption of a permeability anisotropy is also consistent with recent findings from the Äspö HRL (La Pointe *et al.*, 1995). Moreover, the values of the principal components of the dispersivity tensor were taken from Follin (1992), who analyzed the spatial variability of 3 m double-packer test results from Äspö HRL and computed the resulting macrodispersivity by means of numerical simulation of uniform average flow through heterogeneous porous media.

## 3. Part 2 – Dewatering and Resaturation

### 3.1 Studied Cases

Three different cases A–C are studied. In cases A and B the distance from the repository center to the seashore is 1 km, whereas in case C the distance is 5 km to the seashore. The purpose of case B is to study the effect of a tentative excavated damaged zone close to the simulated repository. The permeability of the model elements adjacent to the simulated repository is lowered 2 orders of magnitude. Figure 9 shows the discretization of the repository.

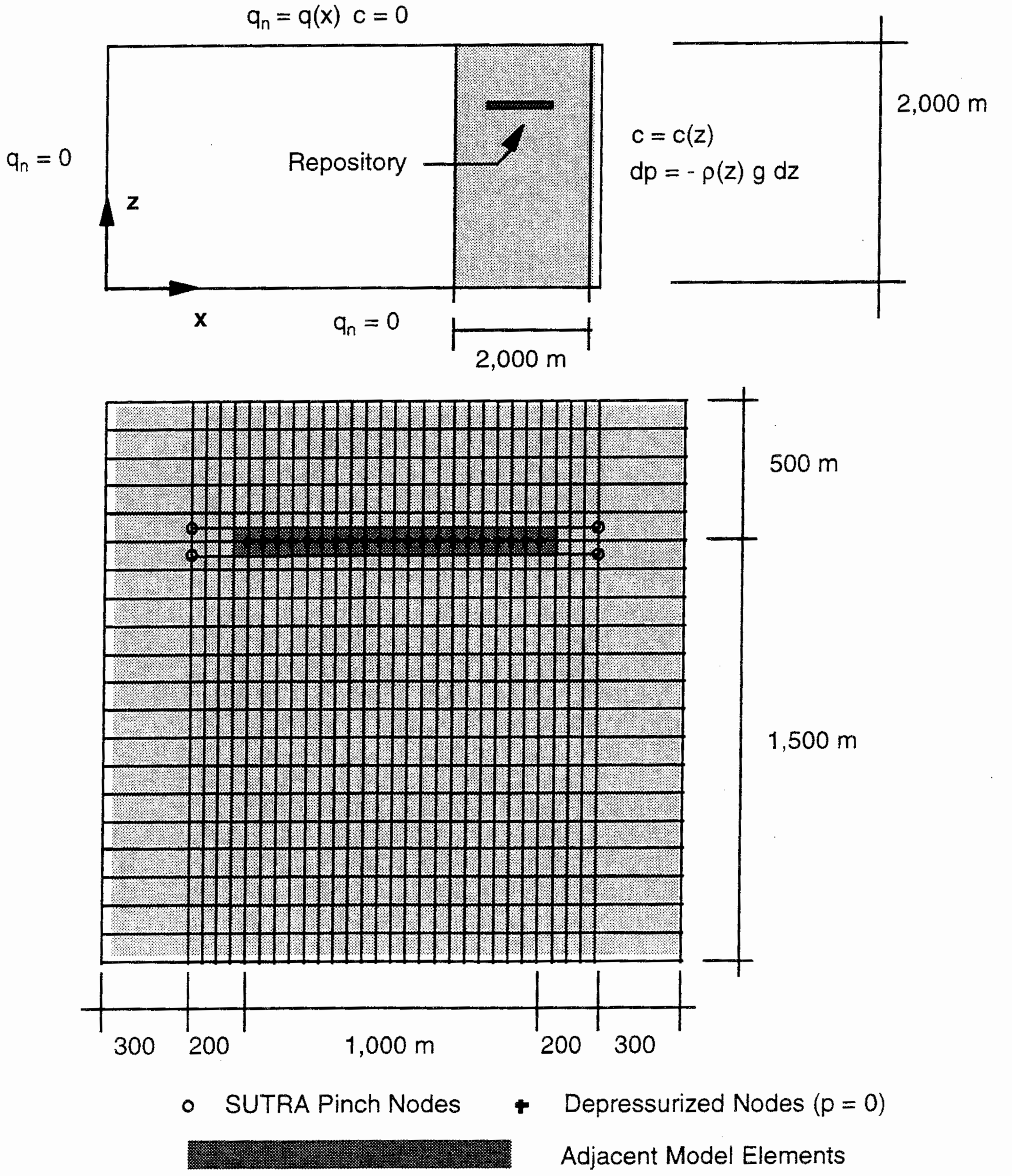

**Figure 9** Close-up of the finite-element discretization used for simulation of saline intrusion. Mesh consists of 1,528 nodes and 1,436 elements.

The simulation of the dewatering and resaturation phases requires a model for flow in the unsaturated zone. For the purpose of this study, van Genuchten's model (van Genuchten, 1980) is adopted. It should be noted that this empirical model is derived from experiments conducted in porous media (agricultural soils) ranging approximately from coarse sand to silt. Unfortunately, there is no generally accepted model for unsaturated flow in sparsely fractured rock. The relationships between capillary pressure versus saturation and the relative permeability versus saturation used in this study are shown in Figure 10. The graphs are approximately representative for a fine sand or silt (Voss, 1984).

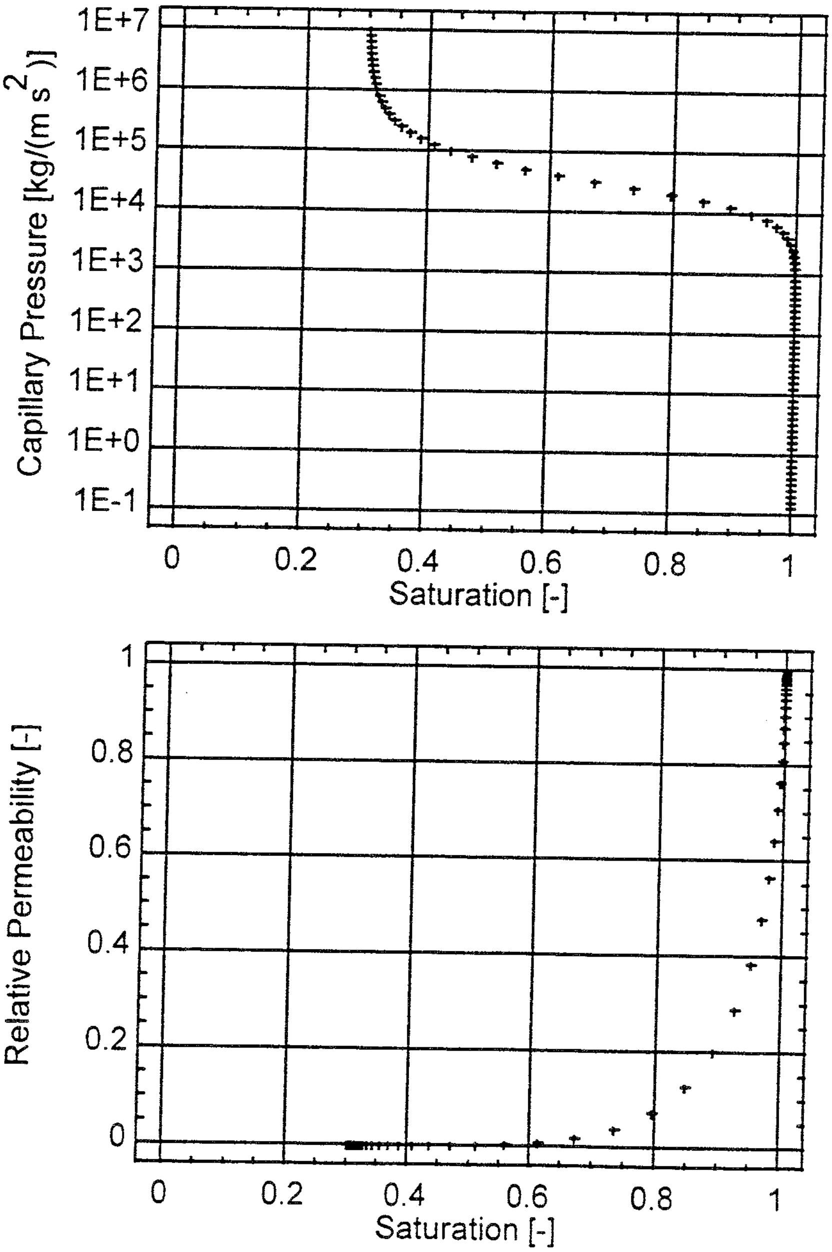

**Figure 10** The relationships used in this study to simulate unsaturated flow. The graphs are approximately representative for a fine sand or silt (Voss, 1984).

### *3.2 Dewatering*

Figures 11–15 show the simulation results for the three cases A–C after fifty years of dewatering, which is the expected period of time during which a deep repository will be depressurized. The underlying finite-element mesh behind these 2 km wide close-ups is shown in Figure 9. Figure 11 shows the result of the history matching between 0–2 km from the seashore and Figure 14 shows the corresponding result between 4–6 km from the seashore. The expected location of the repository is indicated with a rectangle.

Figures 12 and 13 show the results for cases A and B, respectively, and Figure 15 the result for case C after fifty years of dewatering. Again, the location of the depressurized repository is indicated with a rectangle. The solid line represent zero (atmospheric) pressure ($p=0$). Ideally, this isobar should coincide with the dashed contour line that represents unit saturation ($S=1.0$). In order to achieve reasonable computation times it was necessary to relax the iterative convergence criterion in SUTRA. In result, the accepted solutions are not perfect. The accepted simulation of a fifty year long period of dewatering required about 12 hours on a Pentium with a maximum time step of 24 hours.

The dewatering after fifty years of pumping is considerable for cases A and C. To some extent this be due to the fixed infiltration rate prescribed on the top side of the model. As shown in Figures 12 and 15 the region between the top side and the simulated repository is more or less partially saturated at the end of the simulation period. Indeed, most of this drawdown is developed already during the first two years after the repository is depressurized. The lack of significant differences between cases A and C suggests that the question of saline intrusion may be a phenomenon that is dominated by vertical upconing rather than lateral infiltration. In both cases the occurrence of saline ground water above the repository is notable, and the simulated TDS values at the level of the repository have increased about five times.

The permeability of the region close to the simulated repository affects the results drastically. In Figures 13, the effective permeability of the most adjacent model elements is lowered between 2 orders of magnitude. Pressure data from the tunnel at Äspö Hard Rock Laboratory yield that the hydraulic head at 450 m depth is about to 400 m as close as one meter behind the tunnel wall. This suggests a very low permeability of the skin zone. For instance, if one assumes serial flow close to the depressurized nodes in Figure 9 and a one meter thick skin zone, then a lowering of the effective permeability of the adjacent model elements in Figure 9 with $n$ orders of magnitude yields that the permeability of the skin zone is approximately $(n+2)$ orders of magnitude smaller than the undisturbed rock.

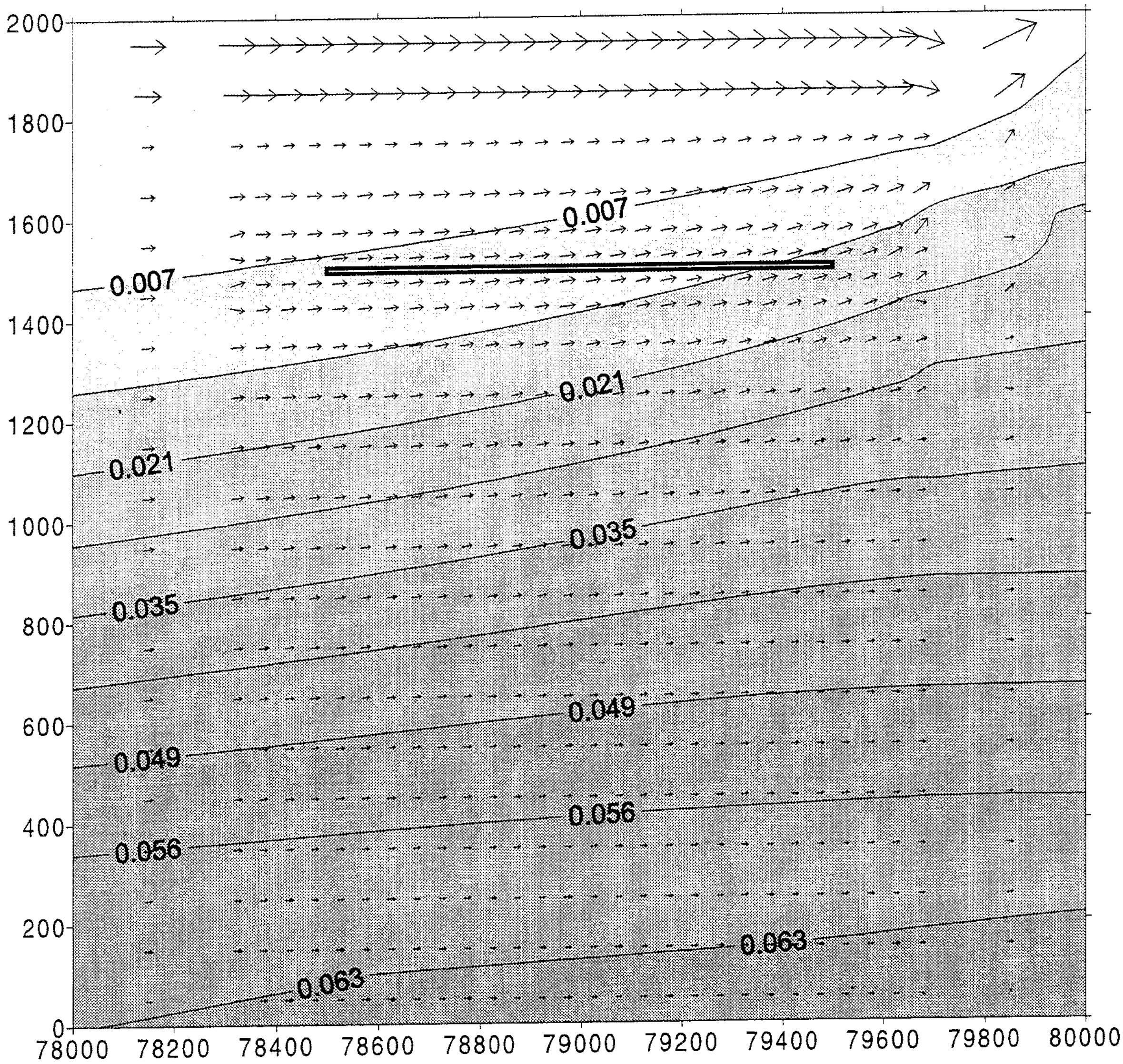

**Figure 11** Repository-scale situation prior to the start of the dewatering phase of cases A and B. The expected location of the repository is indicated with a rectangle.

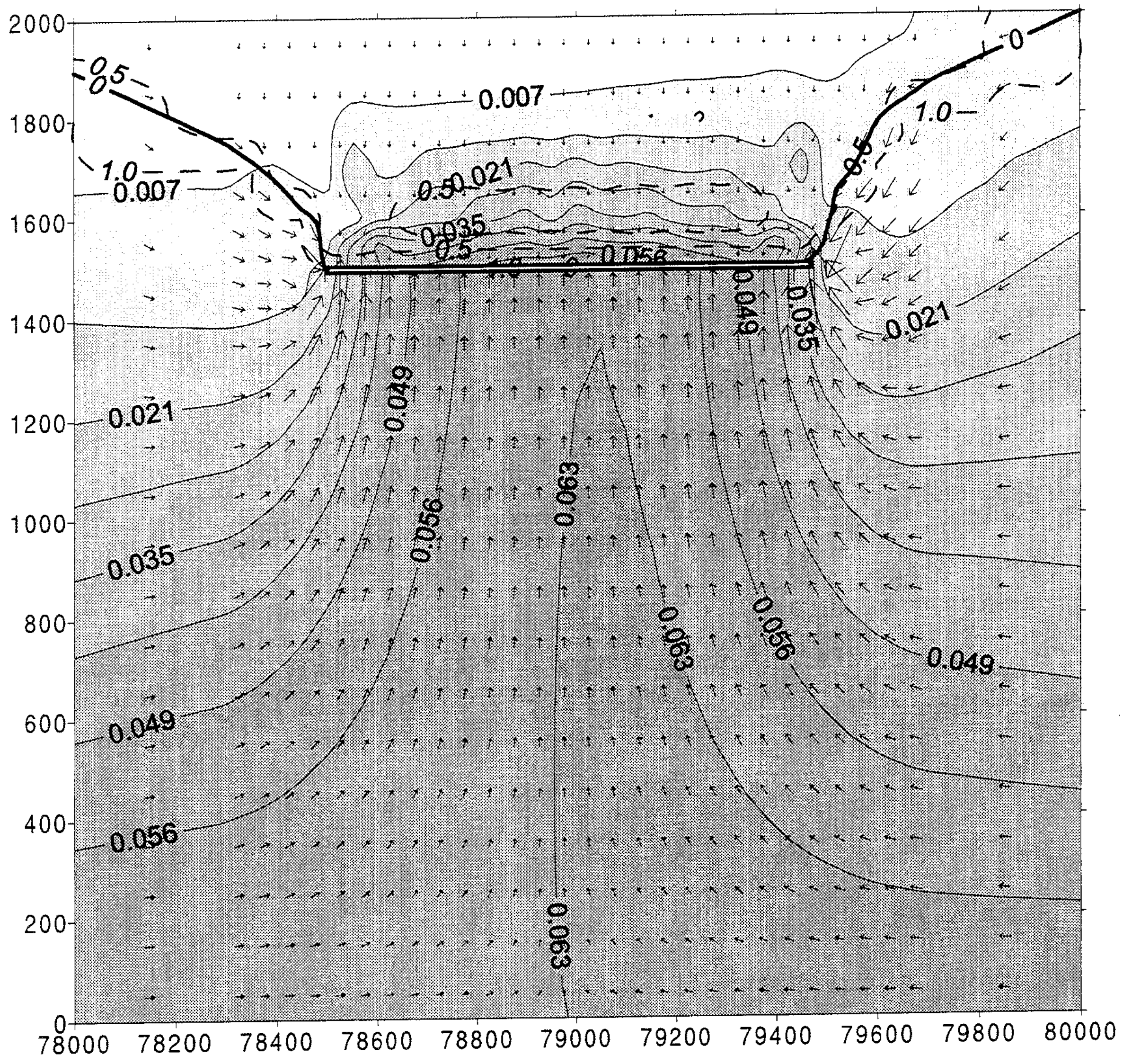

**Figure 12** Repository-scale situation after 50 years of dewatering of case A. The location of the depressurized repository is indicated with a rectangle.

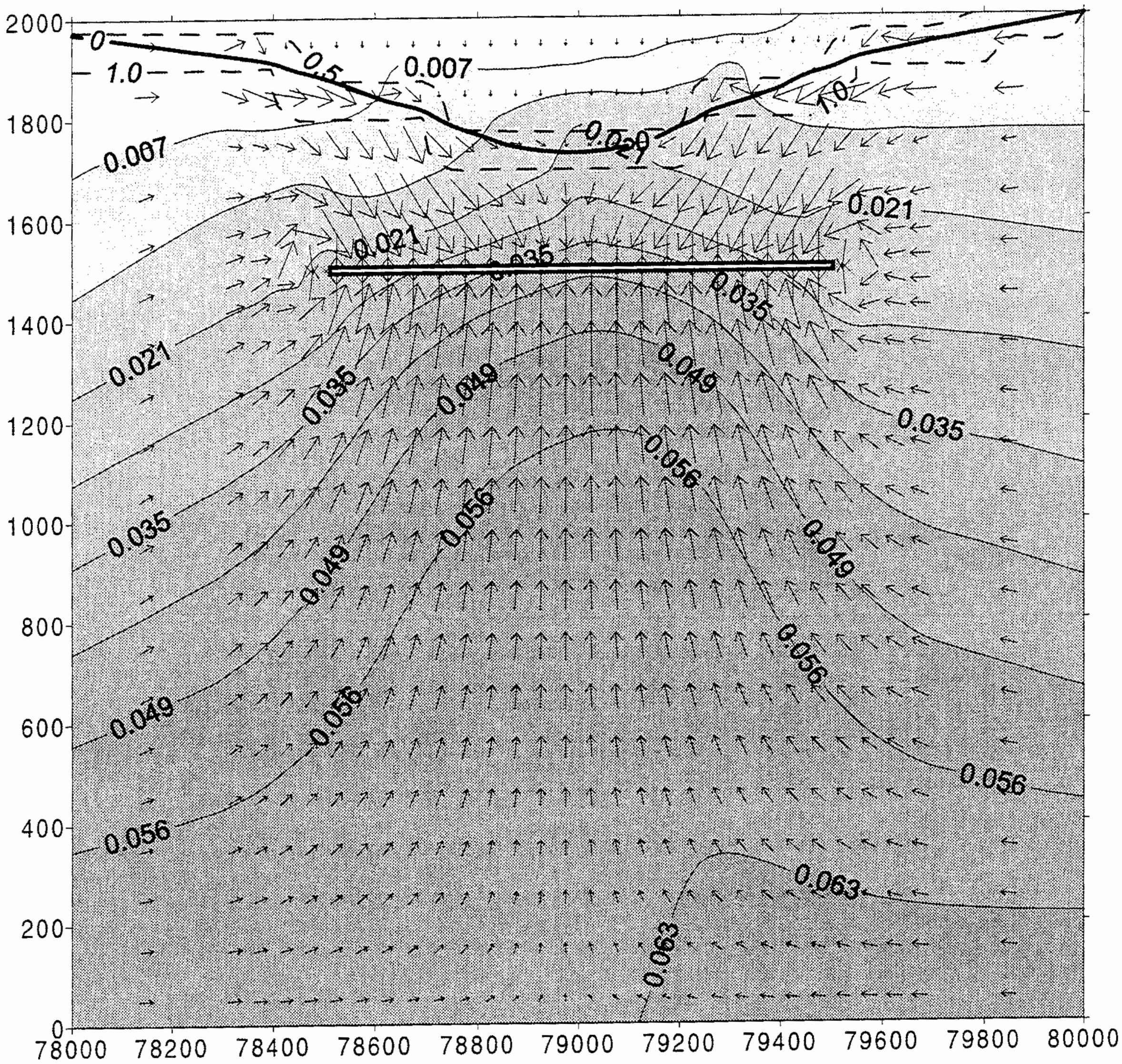

**Figure 13** Repository-scale situation after 50 years of dewatering of case B. The permeability of the model elements adjacent to the repository is lowered 2 orders of magnitude. The location of the depressurized repository is indicated with a rectangle.

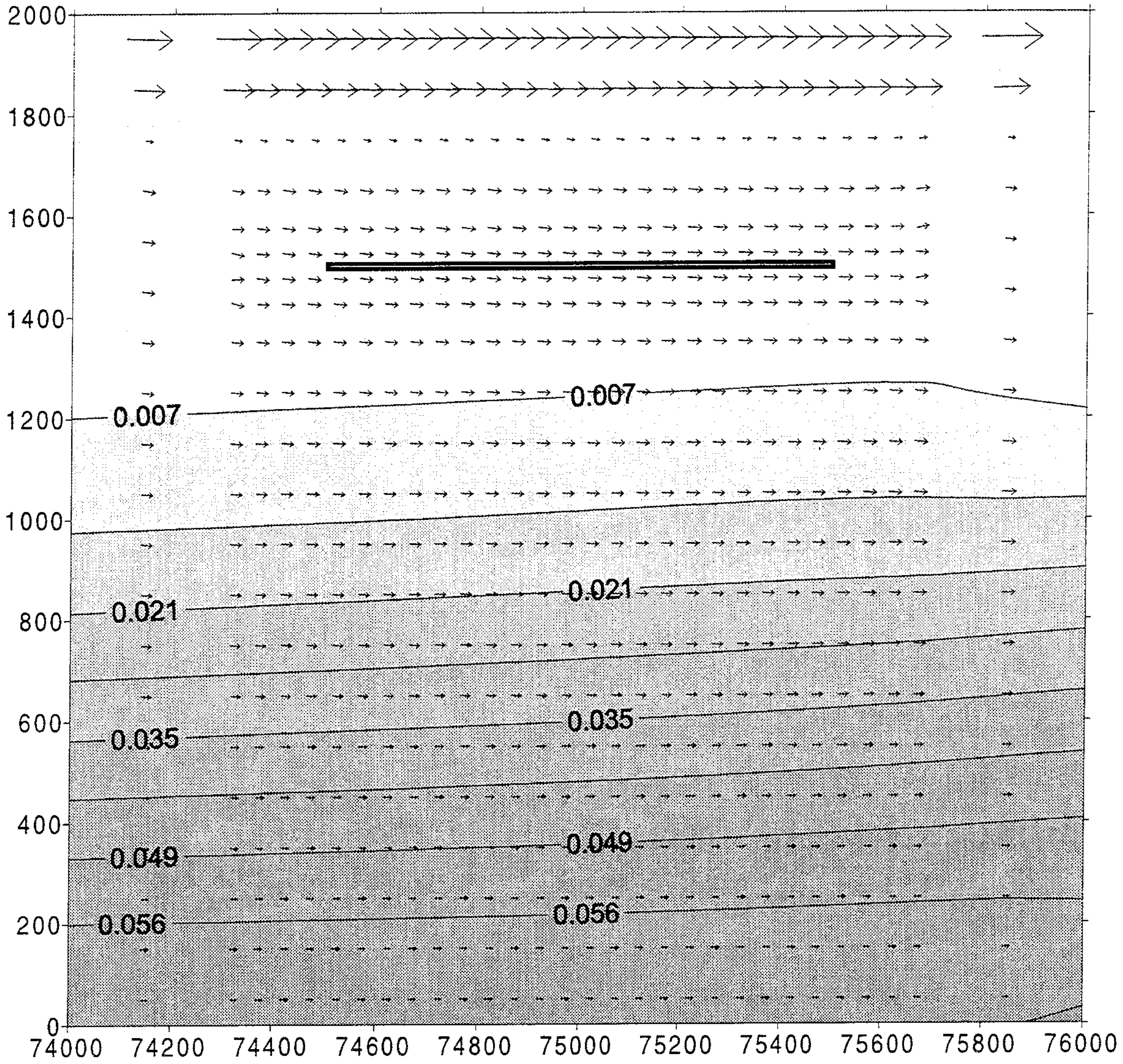

**Figure 14** Repository-scale situation prior to the start of the dewatering phase of case C. The expected location of the repository is indicated with a rectangle.

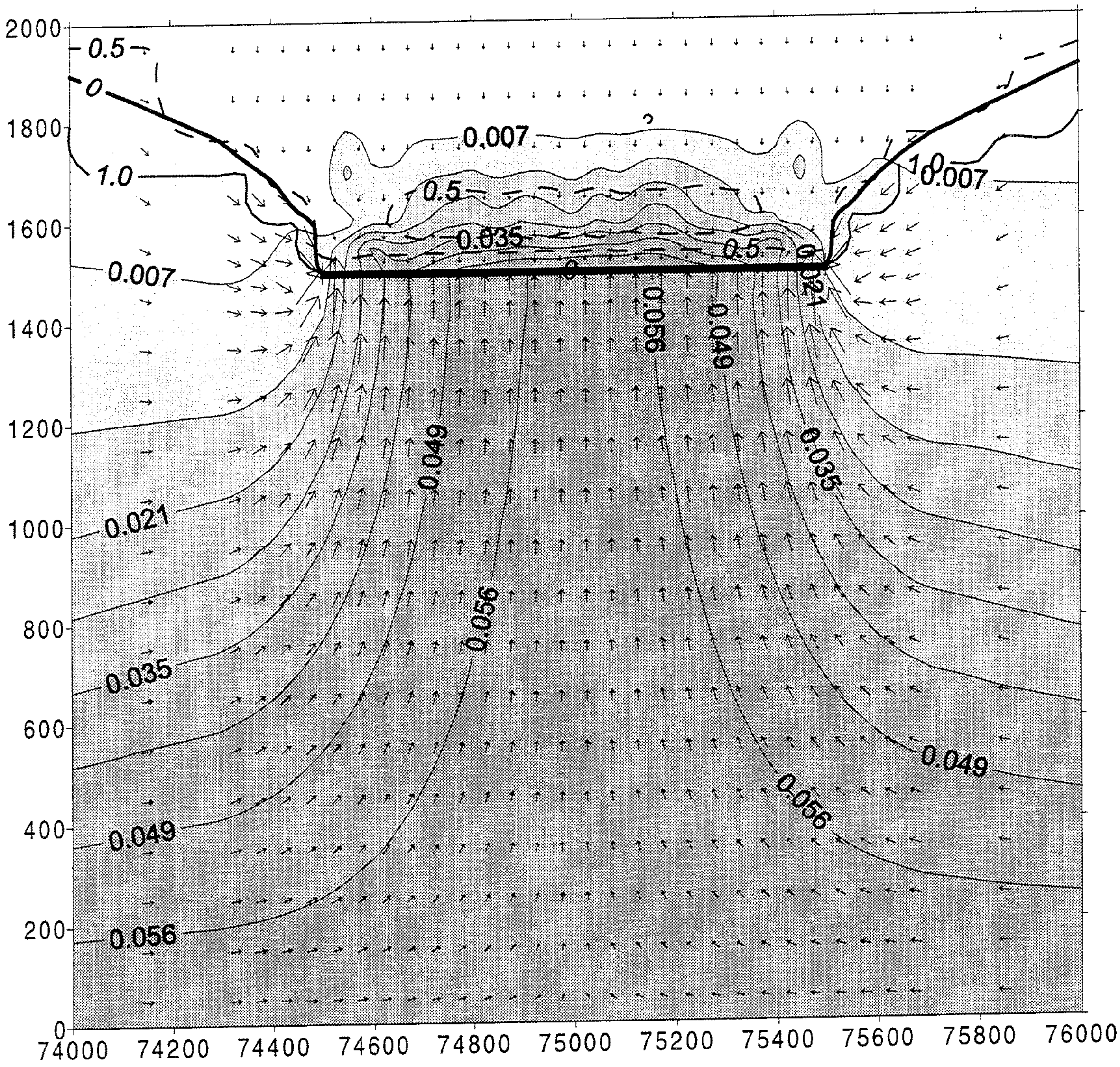

**Figure 15** Repository-scale situation after 50 years of dewatering of case C. The location of the depressurized repository is indicated with a rectangle.

### *3.3 Resaturation*

Figures 16 and 17 show the simulation results for cases A and C after fifty years of recovery. The location of the closed repository is indicated with a rectangle. Again, the solid line represent zero (atmospheric) pressure and for a perfect numerical solution this isobar should fall on top of the dashed contour line that represent unit saturation.

Figures 16 and 17 suggest an extensive residual drawdown. As pointed out before, this incomplete recovery is to some extent due to the small infiltration rate prescribed at the top side of the model. Notwithstanding, the distribution between fresh and saline ground waters is quite close to the conditions prior to the dewatering phase already after fifty years of closure (cf. Figures 11 and 14) despite the incomplete pressure recovery. This result suggests that the infiltration rate at the top side of the model does not have a major impact on the recovery of the concentration profile, which is an interesting result considering the objective of the study. Moreover, an incomplete pressure recovery implies a downward flow gradient at the depth of the simulated repository for the first couple of decades after the closure.

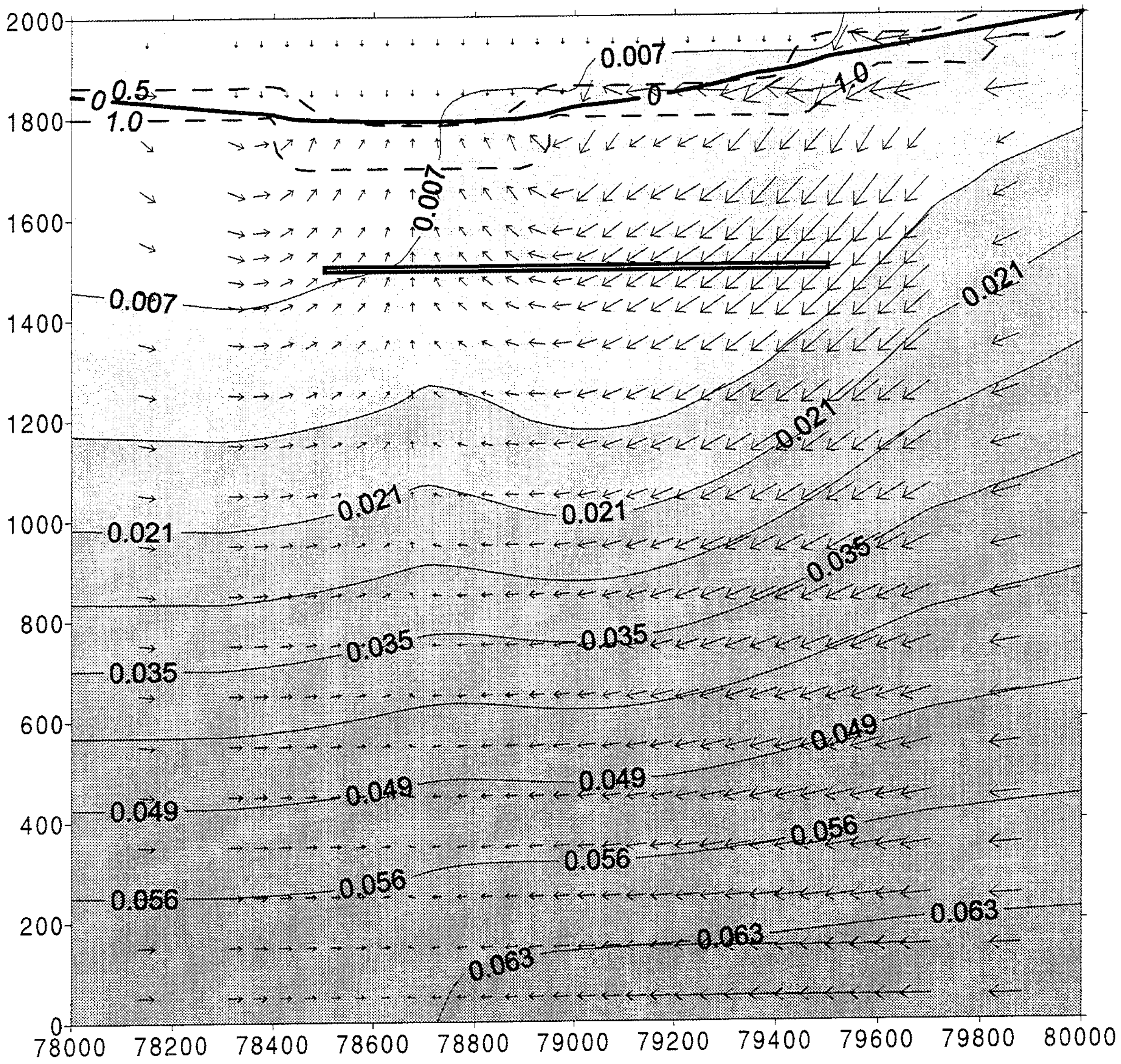

**Figure 16** Repository-scale situation after 50 years of resaturation of case A. The location of the closed repository is indicated with rectangle.

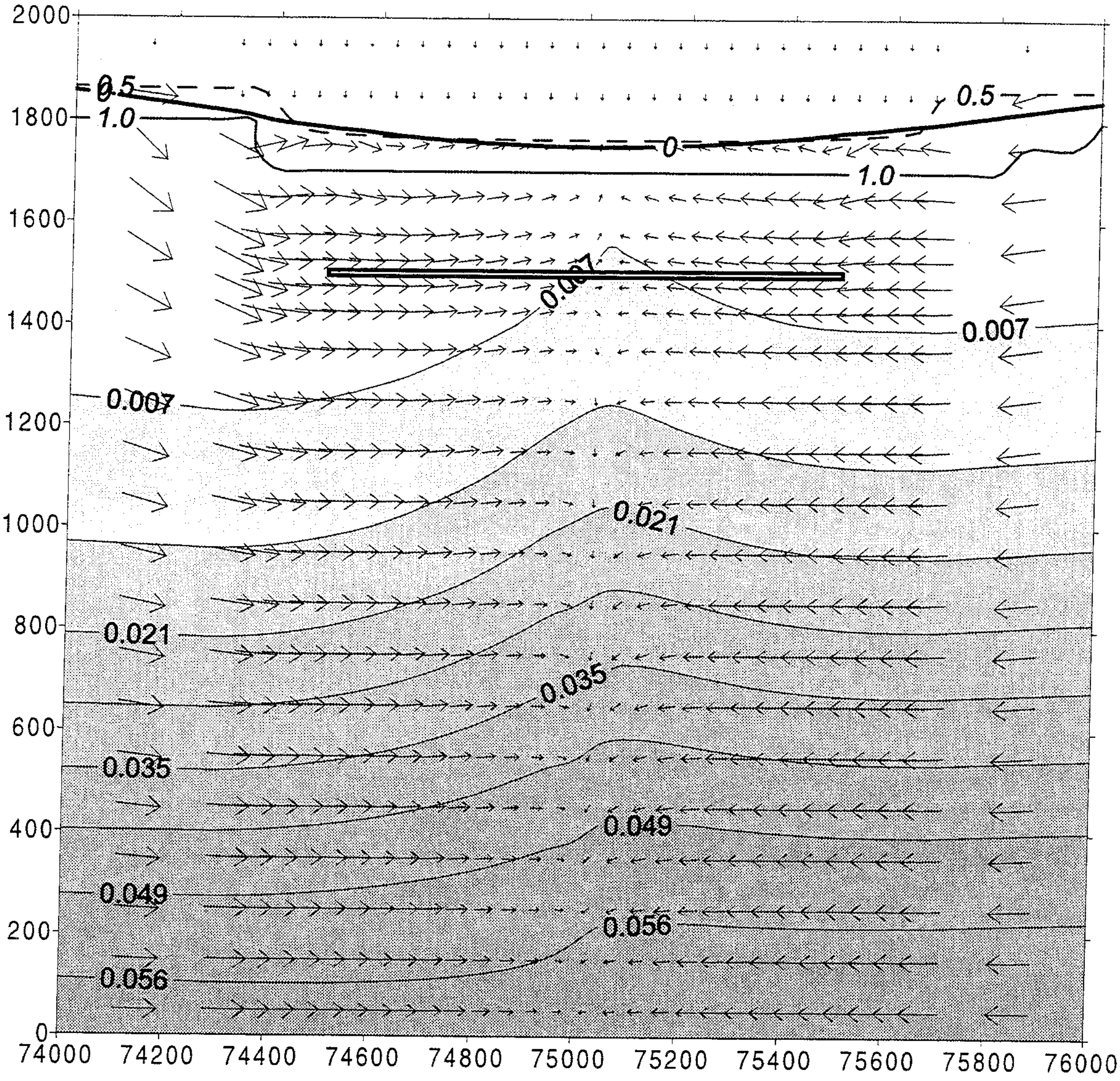

Figure 17 Repository-scale situation after 50 years of resaturation of case C. The location of the closed repository is indicated with a rectangle.

# 4. Conclusions

This conceptual-numerical study treats the dewatering and resaturation phases associated with the construction, use and closure of a coastal nuclear waste repository located at depth in sparsely fractured Baltic Shield rocks. The main objective of the study is to simulate the extent and duration of saline intrusion for a reasonable set of geohydrological assumptions. Long-term changes in the chemical environment associated with saline intrusion may affect the properties of the buffer zone material (bentonite).

The study consists of two parts. Part 1 deals with history matching of a simple model geometry. Part 2 simulates the dewatering and resaturation phases. The purpose of Part 1 is to provide reasonable initial geohydrological conditions for the simulation in Part 2. The numerical simulations use the US Geological Survey computer code SUTRA (Voss, 1984).

The history matching of the adopted simple model geometry is made against the concentration profiles of two deep core boreholes located close to the seashore. The simulation results support the standpoint of Voss and Andersson (1993) that the occurrence of saline ground water reflects an ongoing but incomplete Holocene flushing of the Baltic Shield. In conclusion, the position of the interface between fresh and saline ground waters is time dependent from a historical viewpoint. This study assumes that the flushing passes through the seaward side of the modeled cross section, i.e., beyond the seashore and in under the Baltic Sea.

For the purpose of this study, the simulation of unsaturated flow is accomplished by using an empirical model for unsaturated flow through porous media provided by van Genuchten (1980). An excavated damaged zone around the repository is tentatively simulated by decreasing the effective permeability of the model elements adjacent to the repository two orders of magnitude.

The drawdown after fifty years of dewatering is highly dependent on the permeability of the excavated damaged zone. If the permeability close the repository is unaltered the entire region between the top side of the model and the repository is more or less partially saturated at the end of the simulation period. To some extent this is may be due to the assumption of a fixed infiltration rate at the top side of the model. However, field data from Äspö Hard Rock Laboratory suggest that the permeability of the excavated damaged zone is more important than a correct top boundary condition.

The simulations suggest that the question of saline intrusion may be a phenomenon that is dominated by vertical upconing rather than lateral infiltration.

The simulations of a fifty year long recovery period suggest an extensive residual drawdown. To some extent this result is caused by the small infiltration rate prescribed at the top side of the model. Notwithstanding, the distribution between fresh and saline ground waters is quite close to the conditions prior to the dewatering phase already after fifty years of closure despite the incomplete pressure recovery. This result suggests that the infiltration rate at the top side of the model does not have major impact on the recovery of the concentration profile, which is an interesting result considering the objective of the study. Moreover, an incomplete pressure recovery implies a downward flow gradient at the depth of the simulated repository for the first couple of decades after the closure.

*1994*
TR 94-33
**SKB Annual Report 1994**
Including Summaries of Technical Reports Issued during 1994.
Stockholm, May 1995

## List of SKB Technical Reports 1995

TR 95-01
**Biotite and chlorite weathering at 25°C. The dependence of pH and (bi) carbonate on weathering kinetics, dissolution stoichiometry, and solubility; and the relation to redox conditions in granitic aquifers**
Maria Malmström[1], Steven Banwart[1], Lara Duro[2], Paul Wersin[3], Jordi Bruno[3]
[1] Royal Institute of Technology, Department of Inorganic Chemistry, Stockholm, Sweden
[2] Universidad Politécnica de Cataluña, Departmento de Inginería Química, Barcelona, Spain
[3] MBT Tecnología Ambiental, Cerdanyola, Spain
January 1995

TR 95-02
**Copper canister with cast inner component. Amendment to project on Alternative Systems Study (PASS), SKB TR 93-04**
Lars Werme, Joachim Eriksson
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[1] Itasca Geomekanik AB
[2] Itasca Consulting Group Inc.
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