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The groundwater circulation in the Finnsjö area – the impact of density gradients

PART A: Saline groundwater at the Finnsjö site and its surroundings
Kaj Ahlbom, CONTERRA AB

PART B: A numerical study of the combined effects of salinity gradients, temperature gradients and fracture zones
Urban Svensson, CFE AB

PART C: A three-dimensional numerical model of groundwater flow and salinity distribution in the Finnsjö area
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November 1991

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SALINE GROUNDWATER AT THE FINNSJÖN SITE AND ITS SURROUNDINGS

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CONTENTS

1. INTRODUCTION

Saline groundwater is found in many boreholes at the Finnsjön site. The occurrences and depths to the saline water vary however greatly between different boreholes. This report presents a conceptual model which can explain most of these differences. The model is based on several assumptions. The background and relevance for using these assumptions are discussed and estimated depths to the interface between non-saline and saline groundwater, based on the conceptual model, are presented.

2. SALINE GROUNDWATER IN UPPLAND

Saline groundwater is commonly found in deep wells in northeastern Uppland, where the Finnsjön site is located, Figure 1. It is estimated that at least 10 % of all wells (percussion drilled wells, 50–100 m in depth) in this region encounter saline water (T.Fagerlind, SGU, pers. comm). Unfortunately, only a few of these wells have been reported to the well archive of the Swedish Geological Survey (mainly because saline wells are regarded as failures by the drilling companies). As a result, data regarding saline wells in the vicinity of the Finnsjön site are scarce. However, the abundance of saline wells in the region is clearly shown on the nationwide compilation of saline wells shown in Figure 1. In this compilation wells are regarded saline if the chloride content of the groundwater exceeds 300 mg/l.

There are two underground constructions in the region, the Dannemora Mine and the SFR repository. Both have encountered saline groundwater. In the Dannemora Mine, 17 km south of the Finnsjön site, saline groundwater of 7000 mg/l of chloride occurs at 420 m depth (C. Müllern, SGU, pers. comm). In the SFR repository, located beneath the Baltic Sea, saline groundwater of up to 6000 mg/l of chloride (Smellie & Wikberg, 1989) have been sampled. For comparison, the chloride content of the brackish water of the Baltic Sea above SFR is 3000–4000 mg/l.

3. SALINE GROUNDWATER AT THE FINNSJÖN SITE

The Finnsjön site is located 13 km from the Baltic Sea. Despite the distance to the coast, saline groundwater is found in many boreholes at the site. The salinity of is about 0.8 %, or 5000–6000 mg/l of chloride (Smellie and Wikberg, 1989).

The Finnsjön site can be divided into a northern and a southern rock block (Figure 5), separated by a northeasterly trending fracture zone (Zone 1). For descriptions regarding these blocks and other structural features, see Ahlbom & Tirén (1989). In the northern block saline groundwater is found in all (9) boreholes at depths ranging from 90–300 m. For all boreholes the depths to the saline groundwater coincide with the upper boundary of the gently dipping and hydraulically active fracture zone (Zone 2).

In the southern rock block, south of Zone 1, four deep cored boreholes have been drilled to depths of 500–600 m. Although the borehole tests and groundwater sampling has not been as extensive in this block compared with the northern block, only non-saline waters have been reported from the boreholes. In both the northern and the southern blocks outcrops are common separated by minor deposits of morain.

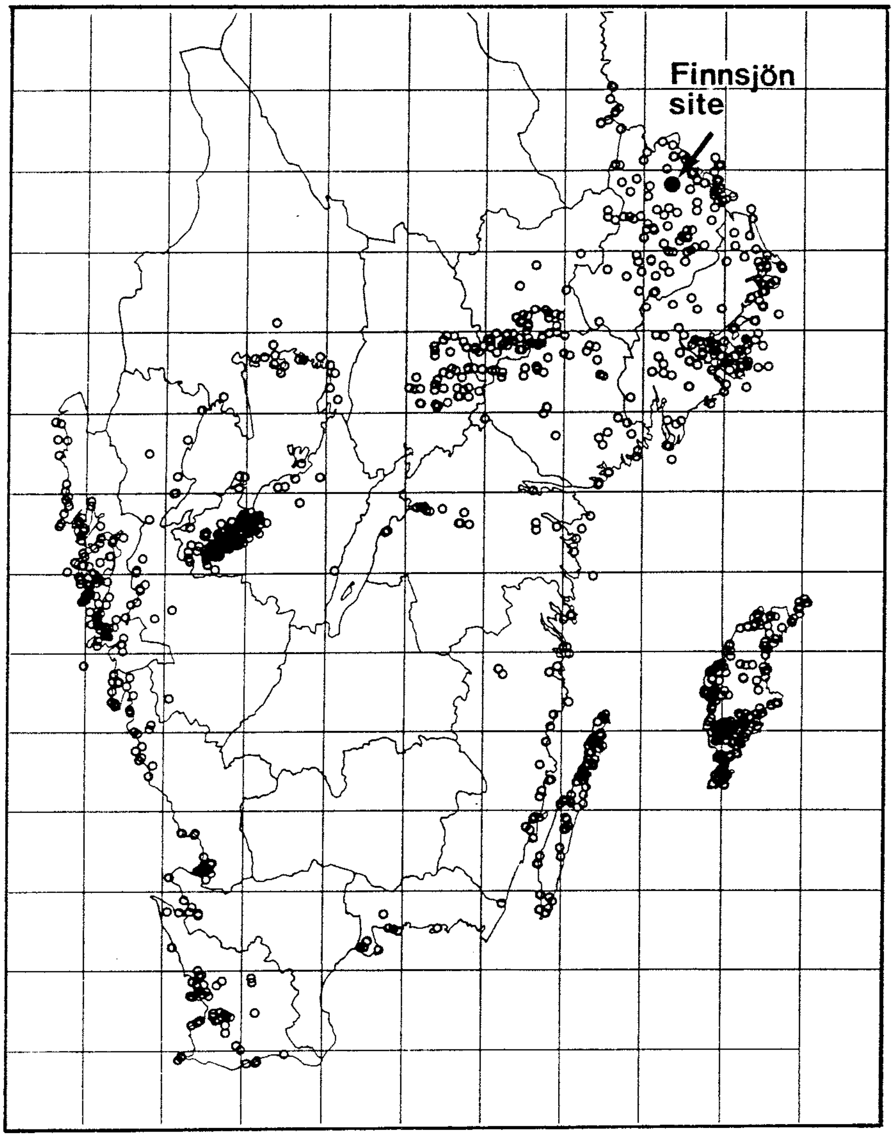

Figure 1. Wells with saline groundwater (after Lindewald, 1985).

Outside the site and to the east, the bedrock dips under a thick cover of glacial clay. The results from two soundings in this area show that the clay is 7–8 m thick (Jacobsson, 1980). Beneath the clay and overlying the bedrock there is a 1 m layer of morain. The topography of the ground surface is flat and the area is used for farming.

One borehole, KFi 8, has been drilled into this area. The location of the borehole is shown in Figure 5. This borehole is 464 m in length (c. 400 in depth) and drilled inclined 60° eastwards. It starts from the southern block, penetrating a north–south and steeply dipping fracture zone (Zone 3), and continuing under the farmland. Geophysical logging (Figure 2) shows that groundwater is non–saline in the upper part of the borehole (southern rock block and Zone 3) but saline (equivalent to 6000 mg/l of chloride) under the farmland. The borehole depth at which Zone 3 is more or less penetrated and saline water is encountered is c. 120 m (Figure 2).

To the west the Finnsjön site is bounded by a lake (Finnsjön).

4. POSTGLACIAL MARINE TRANSGRESSIONS

The load of the last inland ice resulted in a crustal downwarping of 500 m at the Finnsjön region. Immediately after deglacation, and as a result of the downwarping, the Finnsjön site was covered by the brackish Yoldia Sea about 9 600 years BP (Eronen, 1988, Figure 3). The continuous crustal uplift closed the connection to the Atlantic and a non–saline water covered the area (Ancylus Lake at 9000 years BP). Between 7500–7000 years BP the sea water become saline (Litorina Sea). This sea was then gradually transformed into the present brackish Baltic Sea. The Finnsjön site was lifted up above the sea level between the years 5000–3000 BP (Almén et al, 1978). The present crustal rebound at the Finnsjön site is 5.5 mm/year (Ekman, 1987).

Smellie and Wikberg (1989) compared the Finnsjön saline groundwater with other saline environments. They concluded that the Finnsjön saline water is dominantly marine in origin, probably originated from the Yoldia and Litorina sea waters, but with clear modifications resulting from water/rock interaction processes.

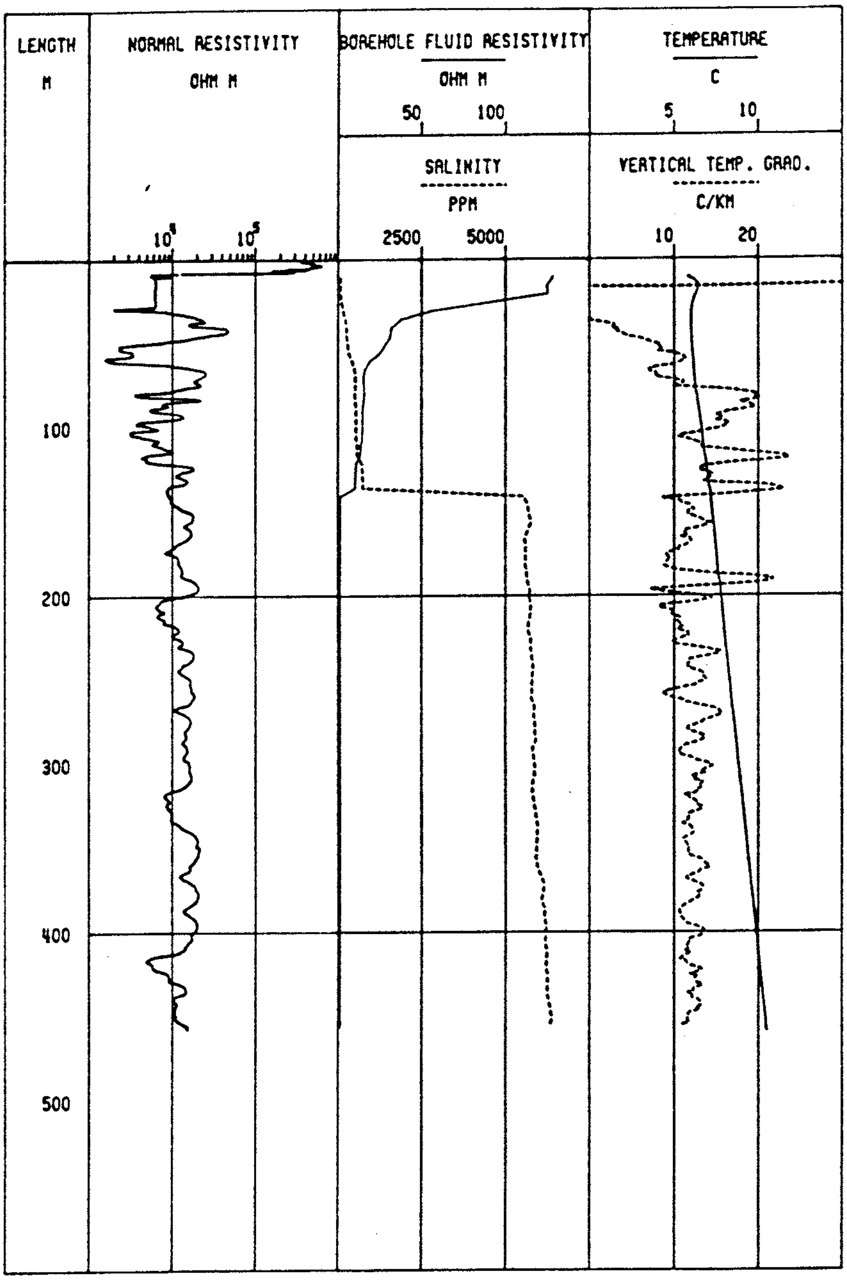

Figure 2. Geophysical logging of borehole KFI08. Observe that the measurements relate to borehole length (the borehole is drilled inclined 60°). Location of the borehole is shown in Figure 5.

Resistivity measurements (left) indicate that the borehole penetrates fractured rock (Zone 3) down to 140 m borehole length (120 m depth). Below this depth the groundwater is saline (center) and only minor fractured sections are indicated. Disturbances in the temperature log (right) indicate natural occurring groundwater flow across the borehole, primarily within Zone 3.

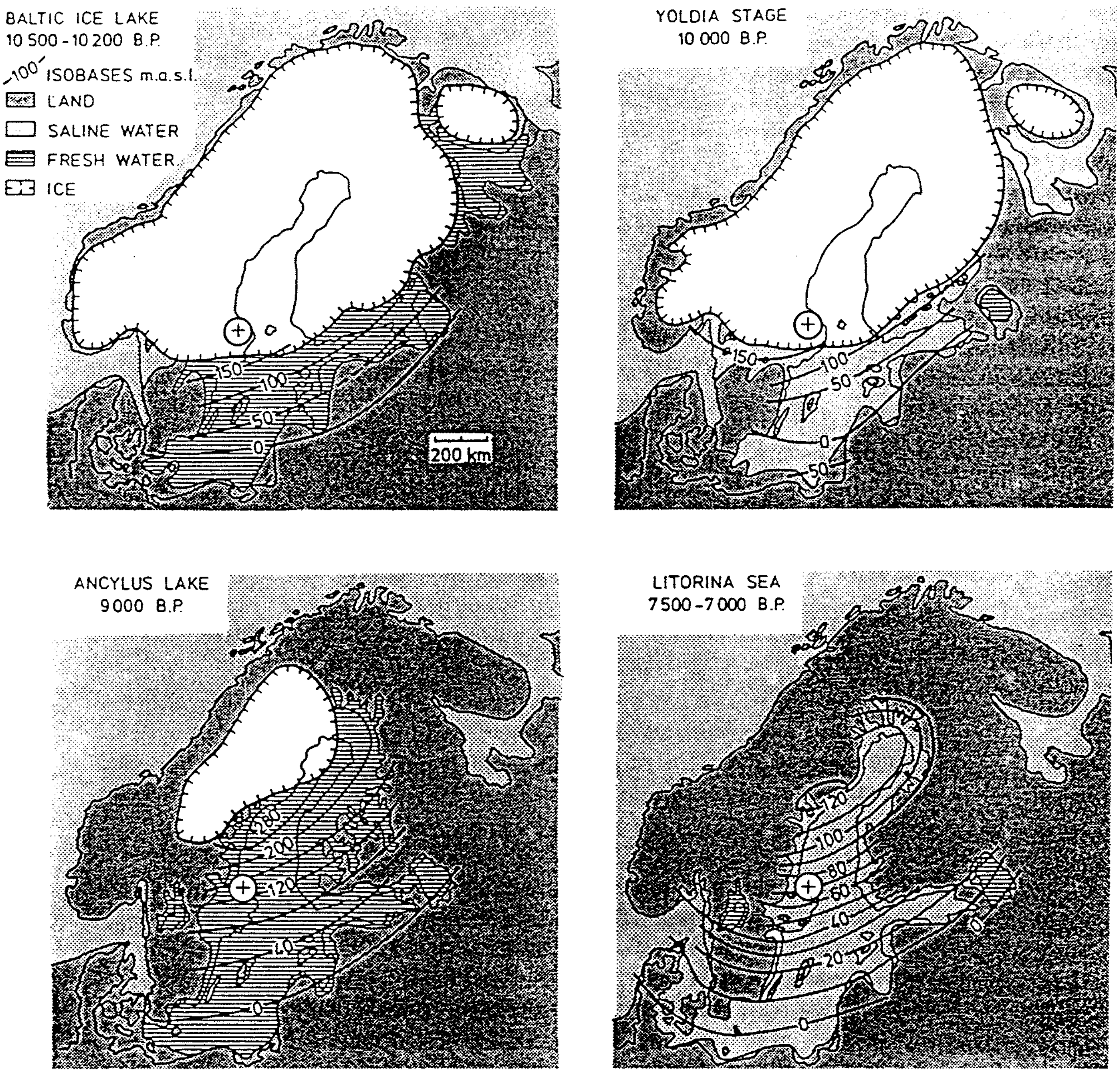

Figure 3. Maps showing four stages of the history of the Baltic Sea (after Eronen, 1988). The Finnsjön site is marked with a ⊕.

5. CONCEPTUAL MODEL

It is here assumed that saline sea water, from the time before 3000 years BP, has been "trapped" beneath the clay deposit in the flat farmland to the east of the site. The reasons for this assumption are: 1) the area was "recently" covered by the sea, 2) almost no infiltration of meteoric water will occur through the clays and, 3) a very small regional hydraulic gradient (in the order of 0.002 %) will delay the exchange of saline groundwater by regional groundwater flow of non-saline meteoric water. As discussed earlier, this assumption is supported by the occurrence of saline water in borehole KFi 8, and also by the common occurrences of saline waters in wells in the region.

If the above assumption is true, the present situation regarding the occurrence of saline groundwater at the Finnsjön site, can be conceptualized as a coastal environment. The flat farmland to the east of the site will in this conceptualization be regarded as a "conceptualized sea" (Figure 5). The outcropping of the Zone 3 would constitute the "coast line" and the Finnsjön rock block "the land".

In descriptions of coastal aquifers the interface between non-saline and saline waters in the steady state follows the so-called Ghyben-Hertzberg relation, where the interface occurs as an "enhanced mirror" to the variation in the groundwater table, Figure 4.

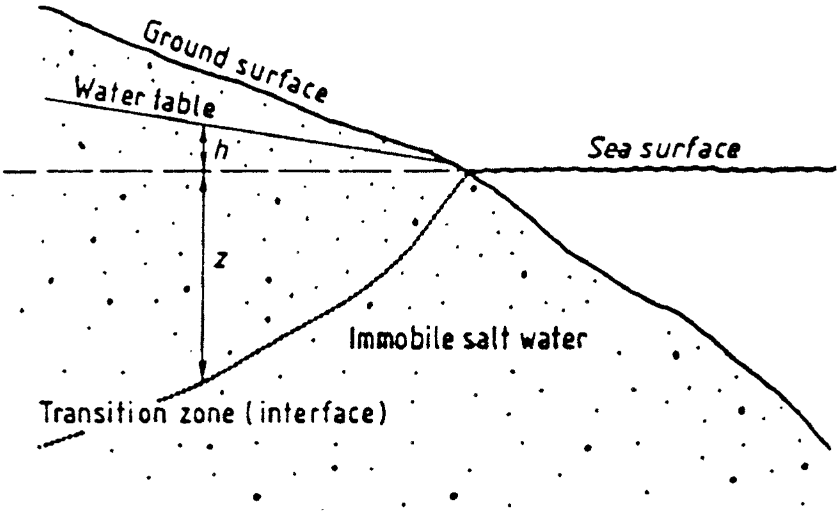

Figure 4. Idealized picture of fresh – salt water interface in a coastal environment.

With a normal contrast in density between ocean water and fresh water, the interface will follow the relation $z \approx 40\ h$. However, at the Finnsjön site the contrast between non-saline and saline water is much smaller (0.0083). The relation is therefore changed to $z \approx 120\ h$.

In a coastal environment, assuming porous homogeneous conditions, the variation in the groundwater table will thus govern the depth to the interface between non–saline and saline water in the steady state. As will be discussed in chapter 6 this might not be the case for structural inhomogeneous rock.

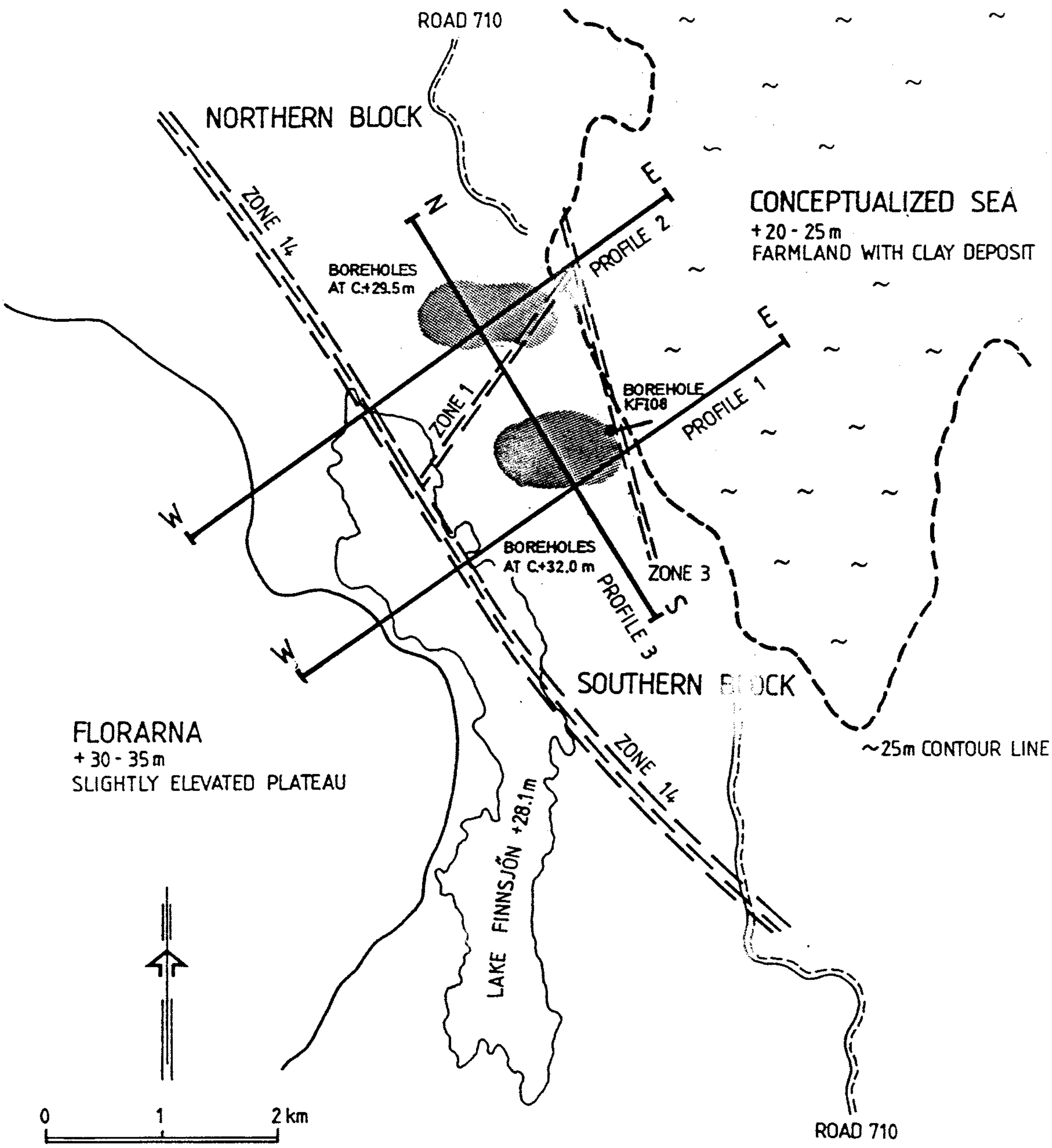

Figure 5. Schematic illustration of features related to the occurrence of saline groundwater in the Finnsjön area. Profiles 1–3 refer to cross–sections presented in Figure 7.

6. GROUNDWATER TABLE

The map of the groundwater table (Figure 6) by Andersson et al (1989) have been used to estimate the depths to the non-saline/saline interface (Figure 7). This map concerns the Finnsjön site only. For areas outside the site the groundwater table was assumed to more or less follow the topography.

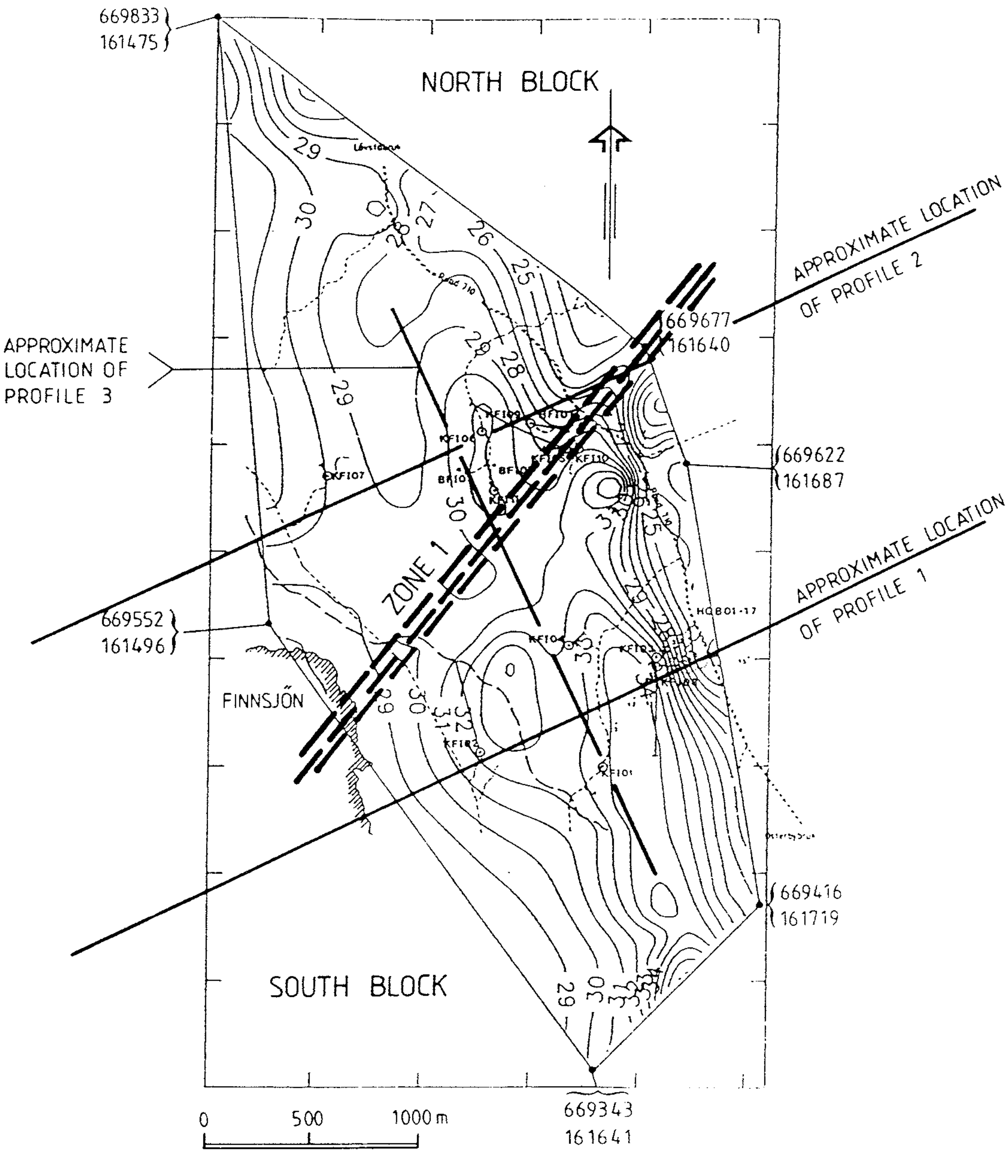

Figure 6. Map of the groundwater table at the Finnsjön site (from Andersson et al., 1989). Profiles 1–3 refer to cross-sections presented in Figure 7.

7. INTERFACE BETWEEN SALINE AND NON-SALINE WATER

Based on the conceptual model discussed earlier the depths to the interface between non-saline and saline waters within the Finnsjön site and its surroundings have been estimated along three schematic cross-sections, Figure 7. These depths should only be regarded as rough estimates as they represent 2-D cross-sections and are based on, to some extent, non-tested assumptions. They also assume steady state conditions. In reality, the on-going crustal rebound imply transient conditions.

The cross-sections 1 and 2 are oriented VSV-ENE, that is, they cross the Lake Finnsjön and extends across the farmland to the east. The cross-section 3 is located within the Finnsjön site, from the northern block to the southern block, and is perpendicular to the other profiles.

Southern block

In the southern cross-section (profile 1) homogeneous bedrock conditions is assumed. To the east, at the "conceptualized sea", the groundwater is saline from the bedrock surface and downwards (in accordance with borehole KFI08). At the Finnsjön site and to the west the non-saline/saline interface occurs as an inverse mirror to the groundwater table (compare Figure 4). In the central part of the southern rock block the depth to the interface is 700-1000 m, that is below the 500-600 m deep boreholes drilled in this block (in which no saline water was found).

Northern block

In the northern cross-section (profile 2), the gently dipping Zone 2 will have an strong effect on the interface between non-saline and saline groundwater. This zone is highly hydraulically conductive. Also, borehole measurements show a high natural flow (c. 100 $m^3/m^2 \cdot yr$) at the uppermost part of the zone. This indicates that the zone is continuous and that water mainly is transported by regional groundwater flow from the area west of the site to east of the site. The water probably infiltrates from the Lake Finnsjön via the steeply dipping Zone 14 (see Figures 5 and 7). The discharge probably occurs in the steeply dipping Zone 3 or some other vertical zone at the eastern border of the site.

There is a 3 m difference in groundwater head between the Lake Finnsjön (28 m) and the groundwater table in the discharge area (25 m) This head difference is here assumed to be linearly distributed along Zone 2. The groundwater table in the overlying "tight" rock of the northern block is assumed to have no, or only minor, influence on the distribution of groundwater head in Zone 2. With these assumptions, the 3 m of head difference between the eastern and the western parts of the Finnsjön site will influence the interface of the saline water to dip from 10 m under the "conceptualized sea" to 370 m under Lake Finnsjön. The interface will thus follow the dip of Zone 2, which also is in accordance with the borehole results.

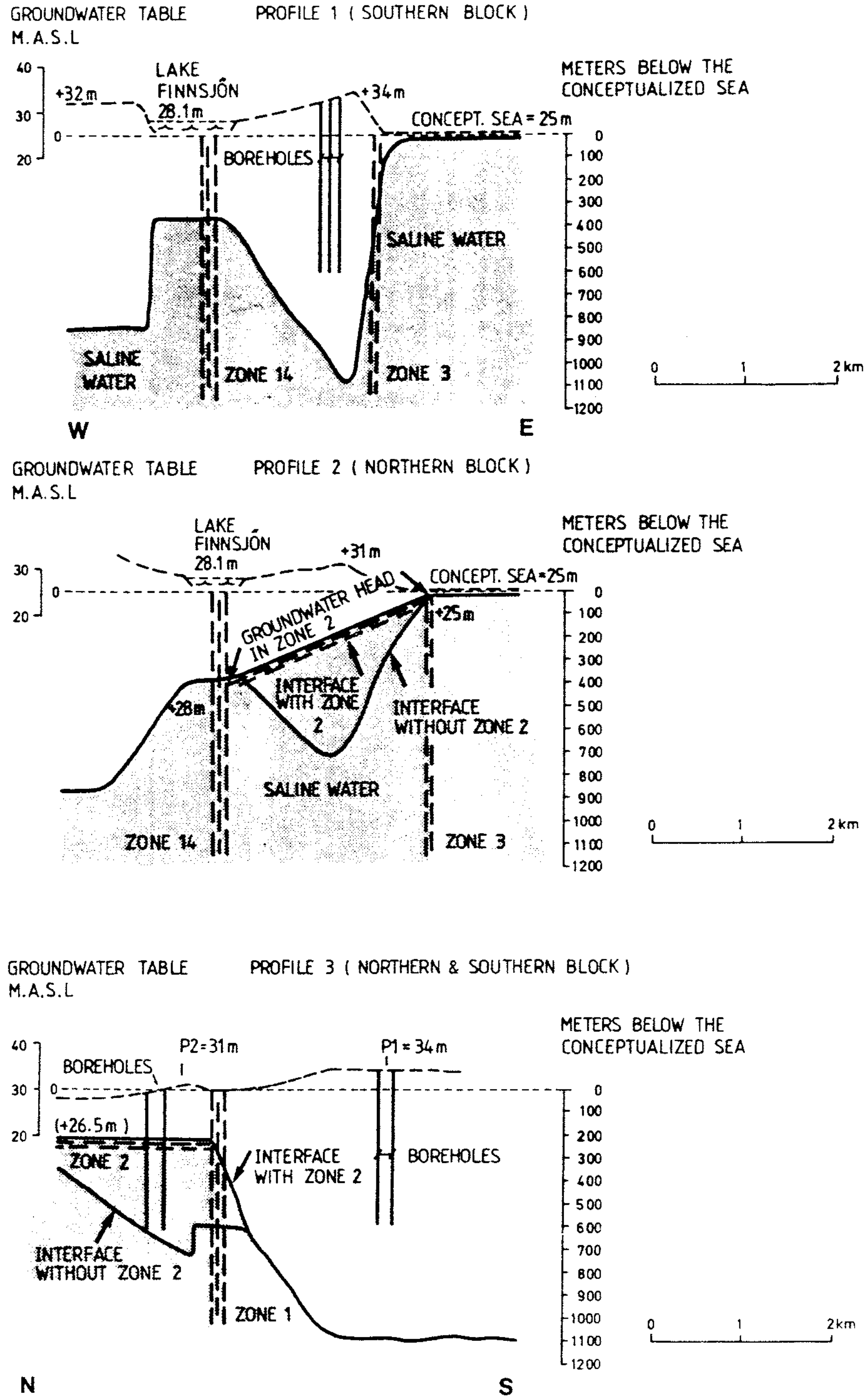

Figure 7. Schematic cross–sections 1–3 with estimated depths to the non–saline/saline interface at the Finnsjön site and its surroundings. Locations of cross–sections are shown in Figure 5.

The cross–section 3 shows the estimated depths to the non–saline/saline interface between the northern and the southern block based on the results presented in cross–sections 1 and 2.

In the case that Zone 2 would not have been present in the northern block, the saline interface would have mirrored the groundwater table (as for the southern block). The depths to the saline interface in this case is also indicated in Figure 7 (cross–sections 2 and 3).

8. CONCLUSIONS

Based on the assumptions presented earlier, a simple steady state model can explain why saline groundwater is encountered in all boreholes at the uppermost part of Zone 2 in the northern block (in spite of the varying depths to this zone). The model can also explain why saline groundwater is not encountered in boreholes in the southern rock block of the Finnsjön site. These results are partly based on non–tested assumptions and on rough estimates. Drilling a borehole and groundwater sampling at the "conceptualized sea" to the east of the site would be one way to test the assumptions. Another possibility is to test and improve the conceptual model by numerical modelling.

REFERENCES

Ahlbom K. and Tirén S., 1989: Overview of geologic and hydrogeologic character of the Finnsjön site and its surroundings. SKB Progress report 89–08.

Almén, K–E., Ekman, L., Olkiewicz, A., 1978: Försöksområdet vid Finnsjön. Beskrivning till berggrunds- och jordartskartor.

Andersson J–E, Nordqvist R., Nyberg G., Smellie J. and Tirén S., 1989: Hydrogeological conditions in the Finnsjön area. SKB AR 89–24.

Ekman M., 1987: Postglacial uplift of the crust in Fennoscandia and some related phenomena. International Association of Geodesy. Section V: Geodynamics. IXX General Assembly. Vancouver.

Eronen M., 1988: A scrutiny of the late Quaternary history of the Baltic Sea. Geological Survey of Finland. Special Paper 6, 11–18.

Jackobsson, J–Å., 1980: Resultat av kompletterande jordartssonderingar i Finnsjöns undersökningsområde 1979. SGU. SKBF/KBS AR 80–12.

Lindewald H., 1985: Salt grundvatten i Sverige. SGU, Rapporter och Meddelanden nr 39.

Smellie J.A.T. and Wikberg P., 1989: Characterization of fracture zone 2, Finnsjön study site (Ahlbom & Smellie editors). SKB TR 89–19.

Groundwater circulation in the Finnsjö area.

- A numerical study of the combined effects of salinity gradients, temperature gradients and fracture zones.

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TABLE OF CONTENTS.

1. INTRODUCTION.

The Finnsjö area, in the north-eastern part of Uppland Sweden, has been subject to comprehensive field studies. Reviews of these studies can be found in Ahlbom and Tirén /1-1/ and Andersson et al /1-2/. One striking result of these field measurements is that the depth to the salinity interface varies significantly. In the studied area,called the Finnsjö Rock Block, salt water is sometimes found 100 meters below the surface while in other areas no salt water has been encountered in boreholes at a depth of 700 meters.

It is the purpose of the present report to explain some of the complex interactions which are due to fracture zones, salinity gradients and temperature gradients from a potential repository. The study is carried out with idealized conditions but the reference to the Finnsjö Rock Block is clear. As the study is two-dimensional it is however not to be expected that we can simulate the Finnsjö Rock Block in detail, as strong three-dimensional effects can be expected in the area.

2. MATHEMATICAL MODEL.

The mathematical model used has previously been introduced by the author, see Svensson /2-1/, and will only be outlined in the present context.

2.1 BASIC EQUATIONS

The basic equations are the same as used in most other ground water models:

x-momentum: $$0 = -\frac{\partial p}{\partial x} - F_x \rho_0 u - (\rho - \rho_0)\, g \qquad (2.1)$$

y-momentum: $$0 = -\frac{\partial p}{\partial y} - F_y \rho_0 v \qquad (2.2)$$

Salinity: $$\frac{\partial us}{\partial x} + \frac{\partial vs}{\partial y} = \frac{\partial}{\partial x}\left(Dn\,\frac{\partial s}{\partial x}\right) + \frac{\partial}{\partial y}\left(Dn\,\frac{\partial s}{\partial y}\right) \qquad (2.3)$$

Temperature: $$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda\,\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\,\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda\,\frac{\partial T}{\partial z}\right) + \frac{S}{\rho_r C_p} \qquad (2.4)$$

Conservation of mass: $$\frac{\partial\, \rho u}{\partial x} + \frac{\partial\, \rho v}{\partial y} = 0 \qquad (2.5)$$

Equation of state: $$\rho = \rho_0\,(1 + \alpha_1 s - \alpha_2 T^2) \qquad (2.6)$$

Were u and v are velocities ("Darcy velocities"), α_1 (=8.0x10^{-3}) and α_2 (= 4.67 x 10^{-6}) expansion coefficients, ρ density, ρ_0 (= 1 000 kg/m^3) a reference density, ρ_r(= 2700 kg/m^3) rock density, F_x and F_y friction coefficients, p pressure, g acceleration due to gravity, s salinity, D dispersion coefficient, n porosity, T temperature, λ (= 1.5 x $10^{-6}m^2/s$) thermal diffusivity, S heat source and C_p (=3.0 W/m, K) specific heat of rock. The coordinate directions are denoted x (vertical), y and z.

2.2 DISCUSSION.

In the momentum equations the friction coefficients are related to the hydraulic conductivity and the equations may thus be interpreted as the Darcy law.

The salinity equation involves the dispersion coefficient, D. In the present study D is put to zero as we, as it is an idealized study, want to reduce dispersion as much of possible. The salinity interface will anyway be smeared by numerical diffusion. As a test the relation for the dispersion coefficient used in Svensson /2-1/ was employed. This relation reads:

$$D = k l_f V_p \qquad (2.7)$$

where l_f is fracture length, put to 1 meter, and V_p the pore velocity. The numerical coefficient was put to 2.0. Using equation (2.7) or putting D = 0 gave almost identical results, which shows that the numerical diffusion dominates physical dispersion. It is however believed that the numerical diffusion does not have a major influence on the results to be presented.

The temperature equation is written in a three-dimensional transient form. The reason for this is that the heat conduction problem, with the planned repository as the heat source, will be solved separately in a three-dimensional and transient mode. Predicted temperature fields, taken after 100 and 1000 years, will then be imposed on the salinity and circulation calculation.

The equation of state will be sensitive to variations in both salinity and temperature. The expansion coefficient α_2 has been chosen to give a fair approximation of the temperature dependence in the interval $0 < T < 40\ ^{0}C$.

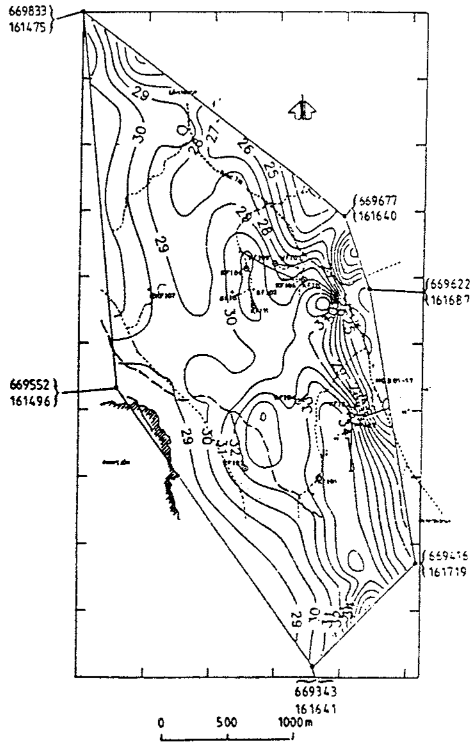
Boundary conditions are generally prescribed as a zero flux condition. Pressure is however prescribed at ground-level to simulate a variation in ground water head. Salinity is fixed at one of the two vertical boundaries and inflow at the upper boundary carries water with zero salinity.

The set of equations is solved using the general purpose equation solver PHOENICS, Spalding /2-2/. A grid with 40 cells a' 50 meters in the horizontal and 20 cells a' 50 meters in the vertical direction was used. No tests for grid independence were done.

3. RESULTS.

3.1 INTRODUCTION.

This study is, as already stated, somewhat idealized but has, however, a clear reference to the conditions encountered at the Finnsjö site. The Finnsjö Rock Block is shown in Figure 3-1 together with the idealized two-dimensional situation considered in the numerical model. This section may be typical for the northern part of the Rock Block and should run in the east-west direction. The sub-horizontal fracture zone, called zone 2, shown in Figure 1 has been extensively studied, see Ahlbom et al /3-1/. It has a transmissivity of 10^{-3} m^2/s and has also been found to separate fresh water above the zone from saltier water, salinity of about 0,8 %, below the zone. The salinity is also found to be high in the low area, right boundary in Figure 3-1, while boreholes as deep as 300 meters in the higher area, left boundary in Figure 3-1, have not encountered salt water. Thus we fix salinity to 0,8 % at the right boundary. The hydraulic conductivity of the rock is assumed to decay with depth as shown in Figure 3-1.



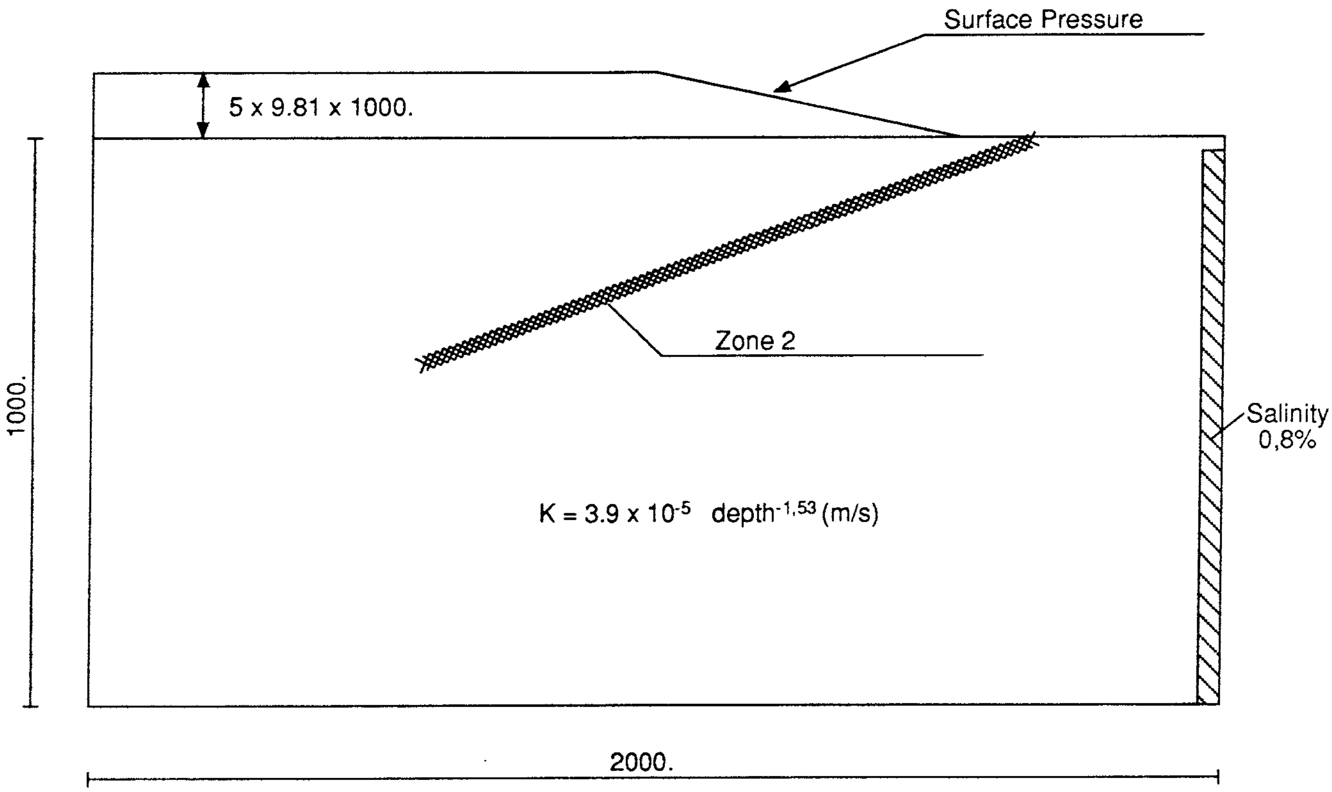


Figure 3-1. Ground water Table at the Finnsjön Rock Block (top) and schematic figure of calculation domain (bottom).

3.2 ZONE 2 AND SALINITY DISTRIBUTION.

The first question to be addressed is why zone 2 separates fresh and salt water. Figures /3-2/ a, b, c and d show a sequence of calculations which will give the answer. Without salinity or a fracture, see Figure /3-2/ a, the pressure drops linearly (from red to blue) according to expectations. If salinity is introduced, by a fixed salinity at the right boundary, a sharp interface will form, see Figure /3-2/ b. The shape is due to hydrostatics as a slope in ground water head of s will give an interface slope of $-s\rho_0/\Delta\rho$. The case of fracture zone 2 included but not salinity is shown in Figure /3-2/c. We see that the fracture, due to its high transmissivity, will have a more or less constant pressure, which is the pressure it has in contact with ground. The combined effect of zone 2 and salt is shown in Figure /3-2/ d. We can now formulate an explanation why salt water is found directly below zone 2: The salt water interface will have a slope which is governed by the pressure gradient in the fresh water. With fracture zone 2 low surface pressure (blue) is found all along zone 2 and the salinity interface strives to be horizontal. Zone 2 limits this upward movement. The high slope of the salinity interface is instead found at the end of zone 2, where large pressure gradients in the fresh water are concentrated.

3.3. SENSITIVITY TESTS.

The above explanation is probably correct for the idealized situation studied. The Finnsjö Rock Block, with its fracture system, does however constitute a three-dimensional problem. It is not possible to take this fracture system into account properly in a two-dimensional study; we can however study the sensitivity to some minor modifications. In particular we want to see if salt water will be found below zone 2 if various conditions are modified.

In Figure /3-3/ three such cases are presented. The first one, Figure /3-3/ a, illustrates the result if salinity is fixed at the bottom left boundary. As can be seen a more continuous salinity distribution results but it is evident that salt water will be found below zone 2. Figure /3-3/ b has a vertical fracture, called zone 14 ($T = 10^{-4} m^2/s$) added in contact with the bottom of zone 2. This will affect the pressure distribution in zone 2, but the salinity distribution is only slightly affected. Figure /3-3/ c shows the effect of adding two fractures, called zone 1 and 3 (both with $T = 10^{-4}\ m^2/s$).Note the higher surface pressure prescribed between zone 1 and 3. The higher pressure between and the strong circulation in zones 1 and 3 could be expected to act as an barrier for the salt water. But the salt water will find its way up to zone 2 also for this situation.

The conclusion from this sensitivity test is that the presence of salt water below zone 2 is not critically dependent on the conditions assumed. However, a full analysis of the situation needs to be three-dimensional.

3.4. IMPOSED TEMPERATURE FIELD.

Next we will consider the effect of a repository, which acts as a heat source. To this end, the three-dimensional transient heat conduction problem is first solved. The calculated temperature distributions after 100 and 1000 years are shown in Figure /3-4/. These two times were selected because the maximum repository temperature is found after 100 years and the "heat pulse" has reached the ground after 1000 years. The heat source, given as W/m^2 over the repository area shown in the figure, has an exponential decay starting at about 4.5 W/m^2, 1.5W/m^2 after 100 years, 0,35W/m^2 after 1000 years and less than 0,1W/m^2 after 10 000 years. These values are adopted from Håkansson /3-2/. As can be seen the maximum temperature is about $31^{0}C$ after 100 years and $22^{0}C$ after 1000 years; at this time the heat wave has also reached the ground level.

The mid section temperature fields for the two times shown were stored and imposed on the situation with salinity distribution and fracture zone 2. As can be seen in Figure /3-5/ no dramatic changes are obtained. Looking at the density distribution it is however clear that unstable stratification will result. This is also indicated by the salinity isolines. In order to explore this particles were released from three different positions and tracked. The result is shown in Figure /3-6/. In " natural " conditions, i.e. no temperature field imposed, the tracks are converging to zone 2 directly.The corresponding Darcian flow times, from left particle to right, are 220 000, 3 200 000 and 9 000 000 years. The actual flow time can be obtained if the effective porosity can be estimated. If, as an example, the effective porosity is 10^{-4} the flow times are 22, 320 and 900 years respectively. With the temperature field after 1000 years imposed the particle tracks are about the same as for natural conditions. The Darcian flow times can for this case be estimated as 180 000, 3 000 000 and 6 300 000 years.

4. DISCUSSION AND CONCLUSIONS.

The present study has attempted to explain why zone 2 in the Finnsjö Rock Block separates fresh water from saltier water below the zone. Results, from a numerical model, have been obtained which give an answer to this question. It is however important to keep in mind that the calculations are two-dimensional and steady. The three-dimensional nature of the fracture system has already been mentioned, but it may also be worthwhile to consider possible transient effects. It is known that the whole area has been covered by brackish water, which gives an initial condition with salt water up to ground level. Precipitation and runoff will then replace the salt water with fresh water in areas with high recharge. However, in more stagnant areas, like the region below zone 2, one can expect that this exchange process is quite slow and one may need to consider transient effects. As a numerical illustration, we can estimate the typical velocity required to move a particle 1000 meters under 1000 years, which is approximately the time since the area was covered with salt water. This velocity is about $3.0\ 10^{-8}$ m/s. We will not in the present context discuss effective porosities and Darcy velocities, but only note that this is a typical pore velocity in the deeper parts of the calculation domain. In Figure 4.1 the darcian flow velocities below zone 2 can be studied, both with and without salinity gradients. As can be seen the velocity field is sensitive to the salinity field, but 10^{-12}m/s is a typical darcian flow velocity for both situations shown. Transient effects may hence be needed to be considered when explaining the salt water distribution in the Finnsjö Rock Block.

The main conclusions emerging from this study can be summarized as:

- The saltwater below zone 2 can be explained by noting that zone 2 redistributes the pressure and that the salinity interface responds to pressure gradients in the fresh water.
- Three-dimensional and transient effects need to be considered before a close comparison with field data is carried out.
- A heat source, with a prescribed strength, at a depth of 500 meters will not affect the salinity distribution significantly.

5. <u>REFERENCES.</u>

1-1 Ahlbom, K. and S. Tirén. " Overview of geologic and hydrologic character of the Finnsjön site and its surroundings ". SKB, AR 89-08, 1989.

1-2 Andersson, J., Nordqvist, R., Nyberg, G., Smellie, J. and S. Tirén. " Hydrogeological conditions in the Finnsjön area ". SKB, AR 89-24, 1989.

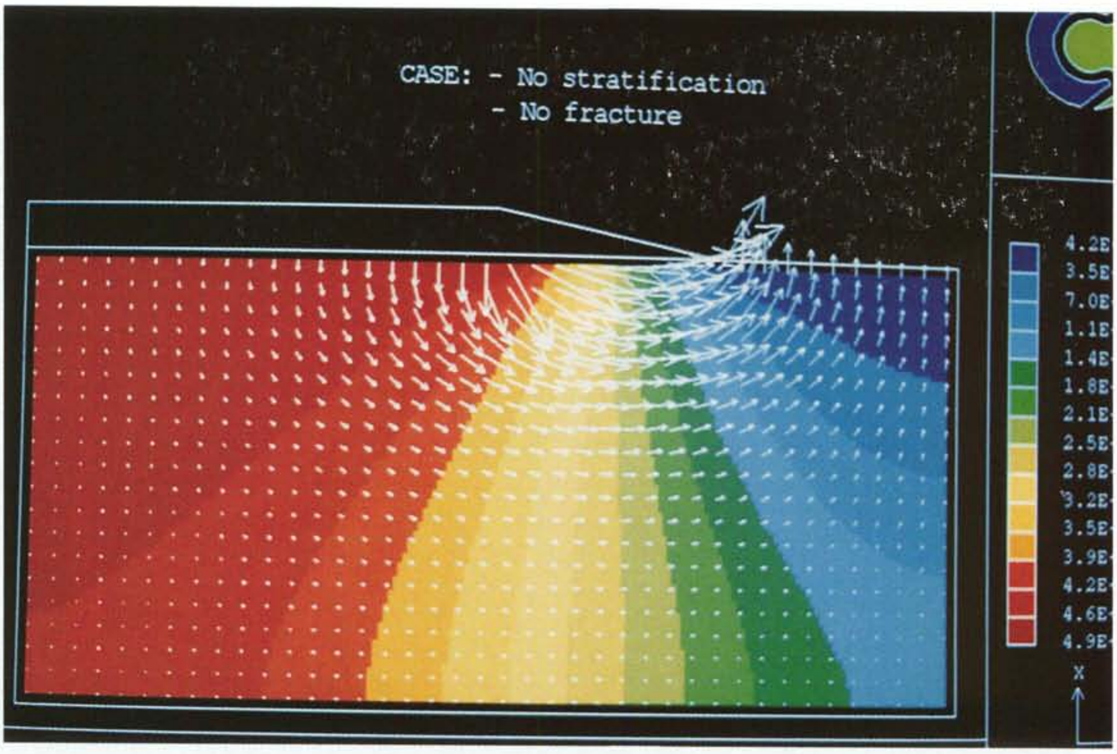
2-1 Svensson, U. " The Island of Äspö. - Numerical predictions of leakage to a planned tunnel ". SKB, Draft dated 1990-05-18.

2-2 Spalding, D.B. " A general purpose computer program for multidimensional one- and two-phase flow ". Math. Comp.Sim., 8, 267-276, 1981.

3-1 Ahlbom, K. and J.A.T. Smellie. "Characterization of fracture zone 2, Finnsjö study-site ". SKB, TR 89-19, 1989.

4-1 Håkansson, R. SKB AR 90-17, 1990.

6-1 Jun, L. and D.B. Spalding. Numerical Simulation of Flows with Moving Interfaces. CHAM report 1988/28.



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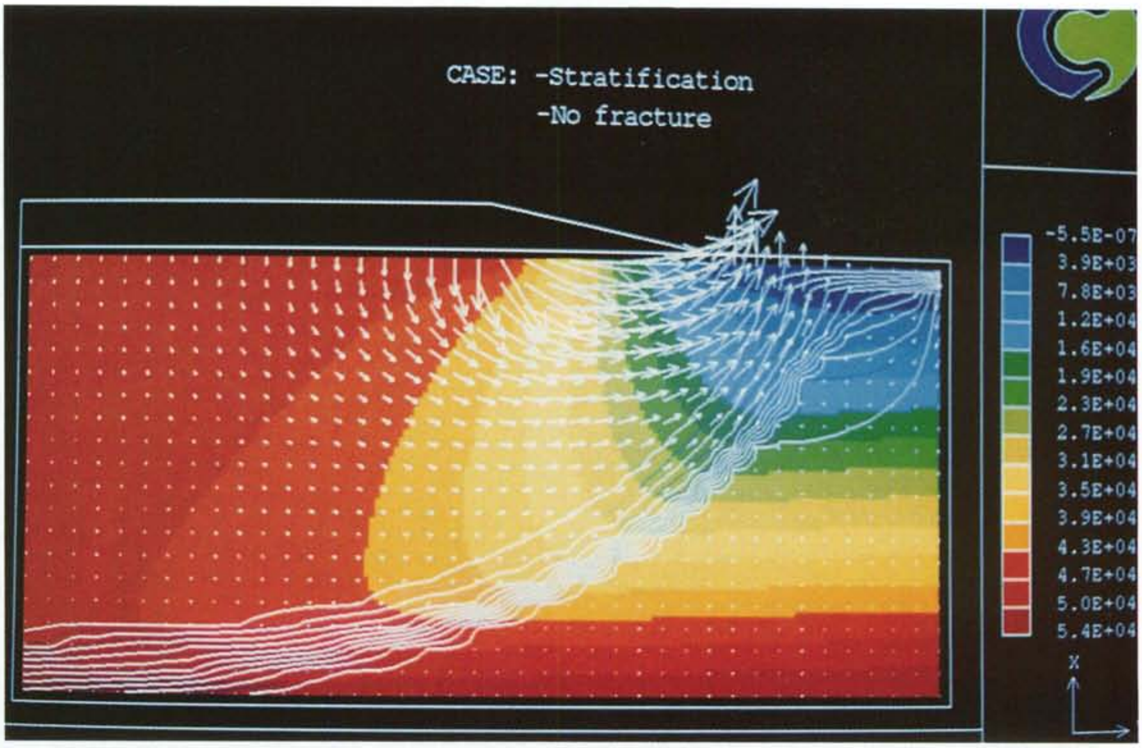
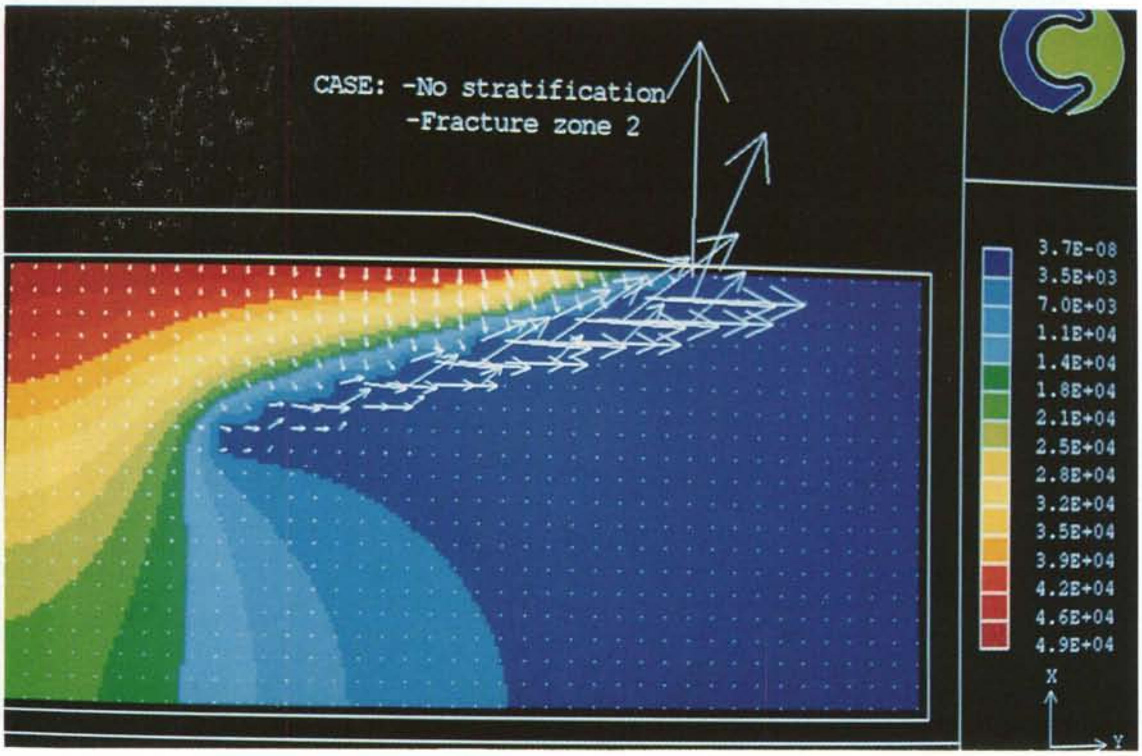


b

Figure 3-2. Zone 2 and the salinity distribution.

A sequence, a to d, of calculation results. ⟶ 10^{-10} m/s



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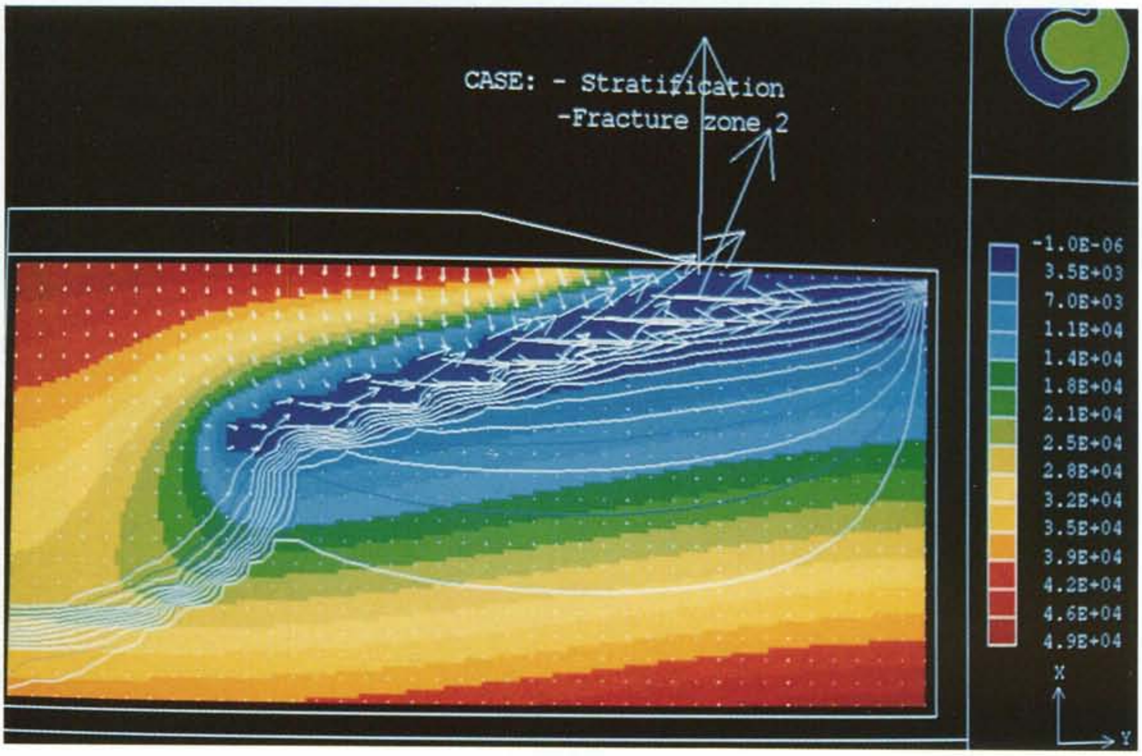
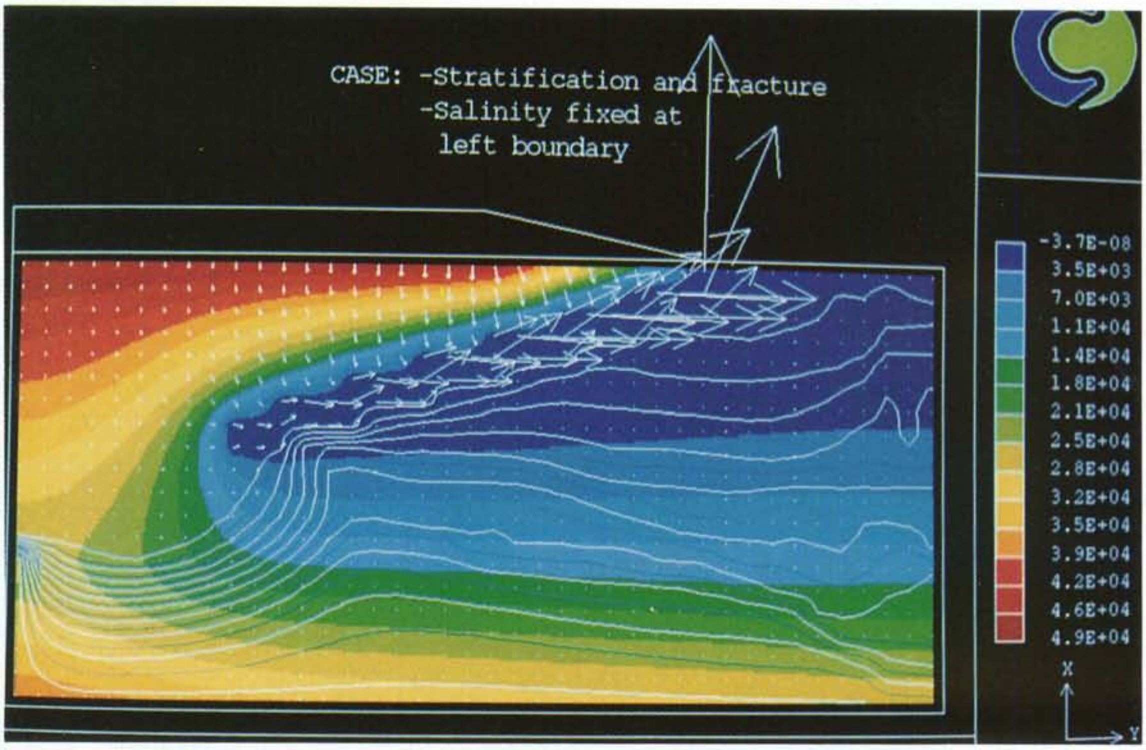


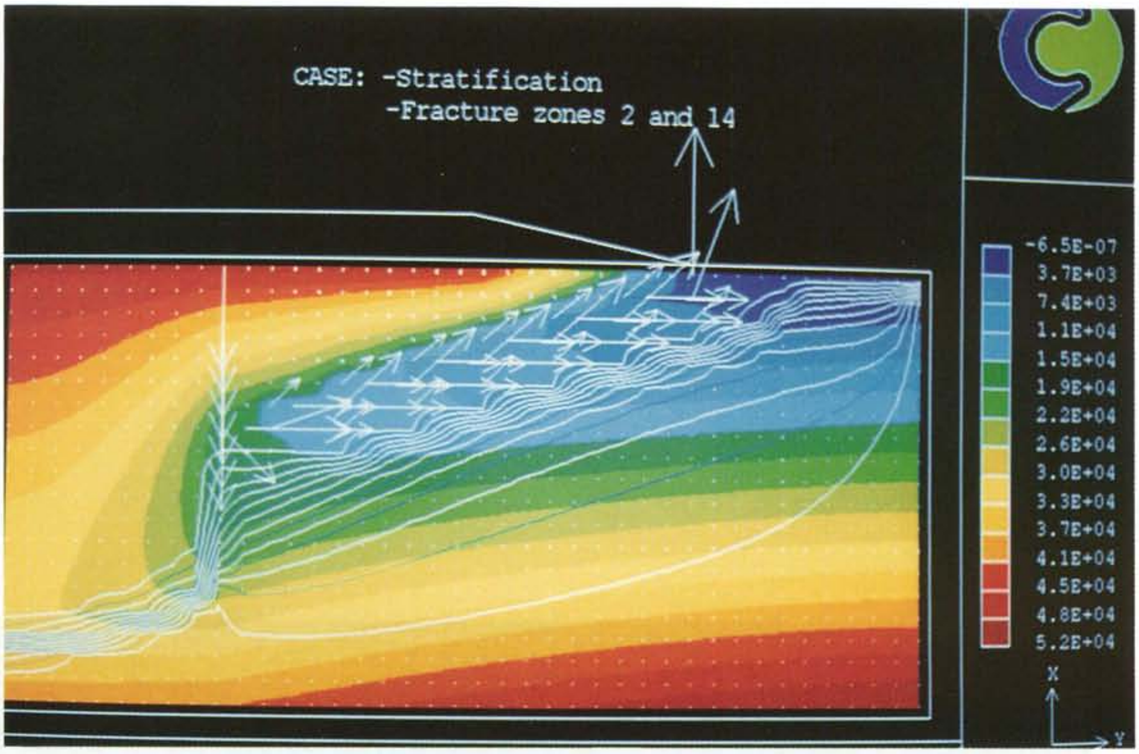
d

Figure 3-2, Continued. ⟶ $2 \cdot 10^{-9}$ m/s



a

Figure 3-3. Sensitivity tests. Salinity fixed at left boundary (a), zone 14 (b) and zones 1 and 3 (c). ⟶ $2 \cdot 10^{-9}$ m/s



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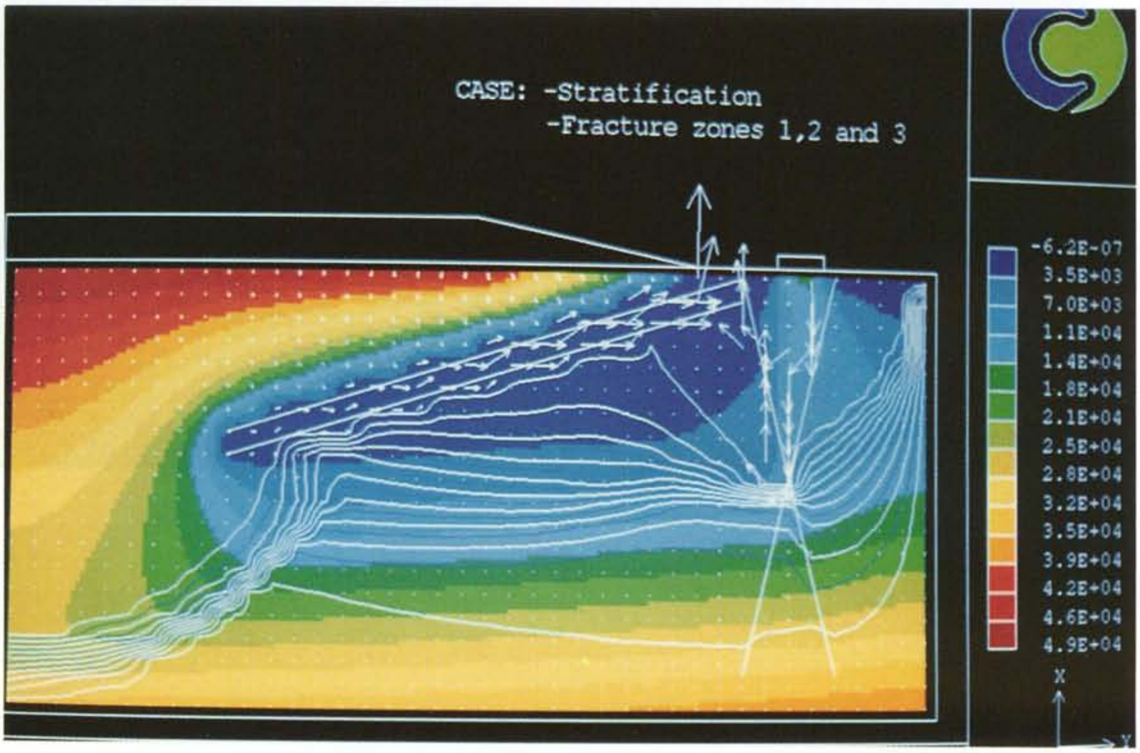

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Figure 3-3, Continued. ⟶ 6.10^{-9} m/s

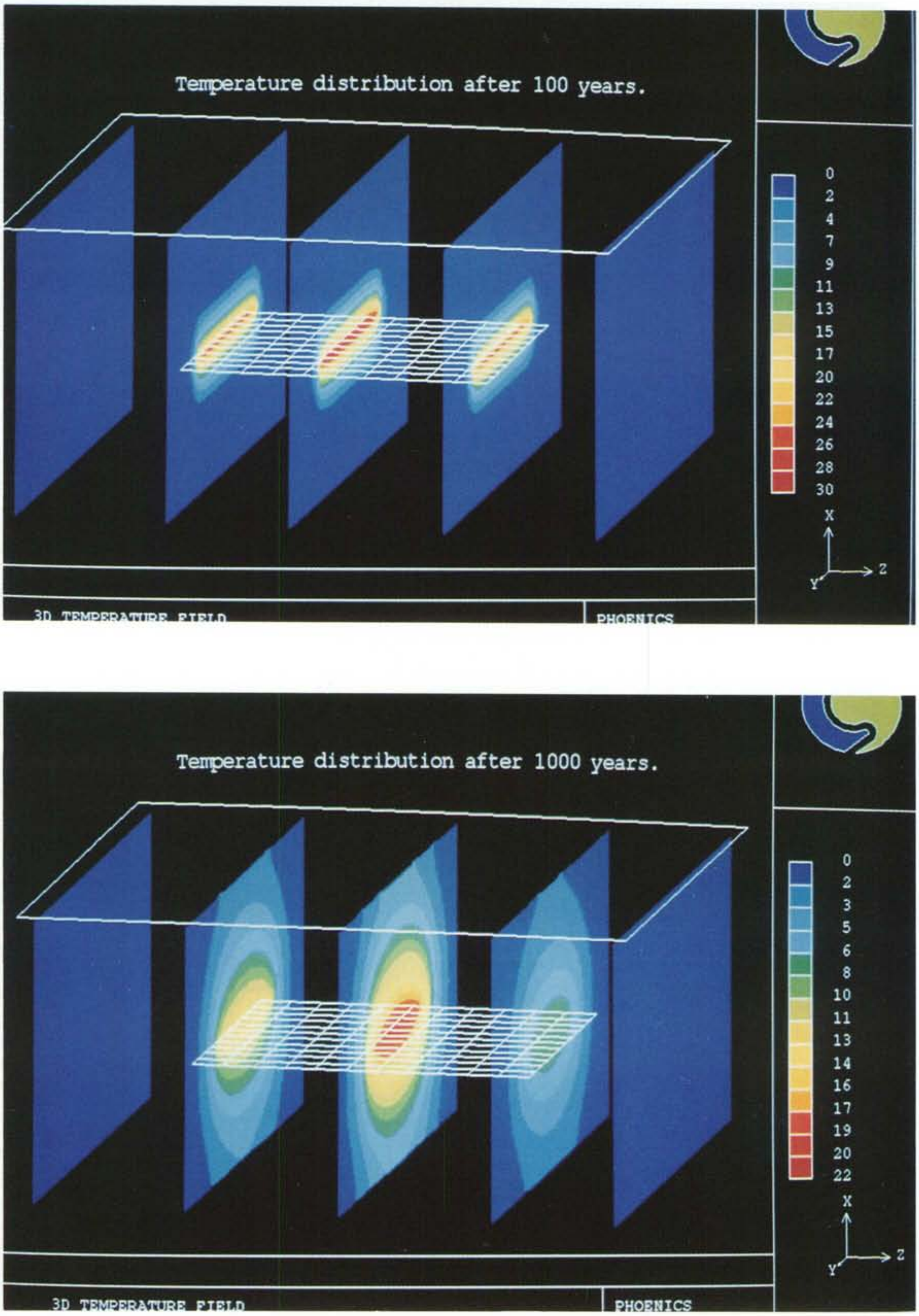


Figure 3-4. Predicted temperature fields after 100 (a) and 1000 (b) years respectively.

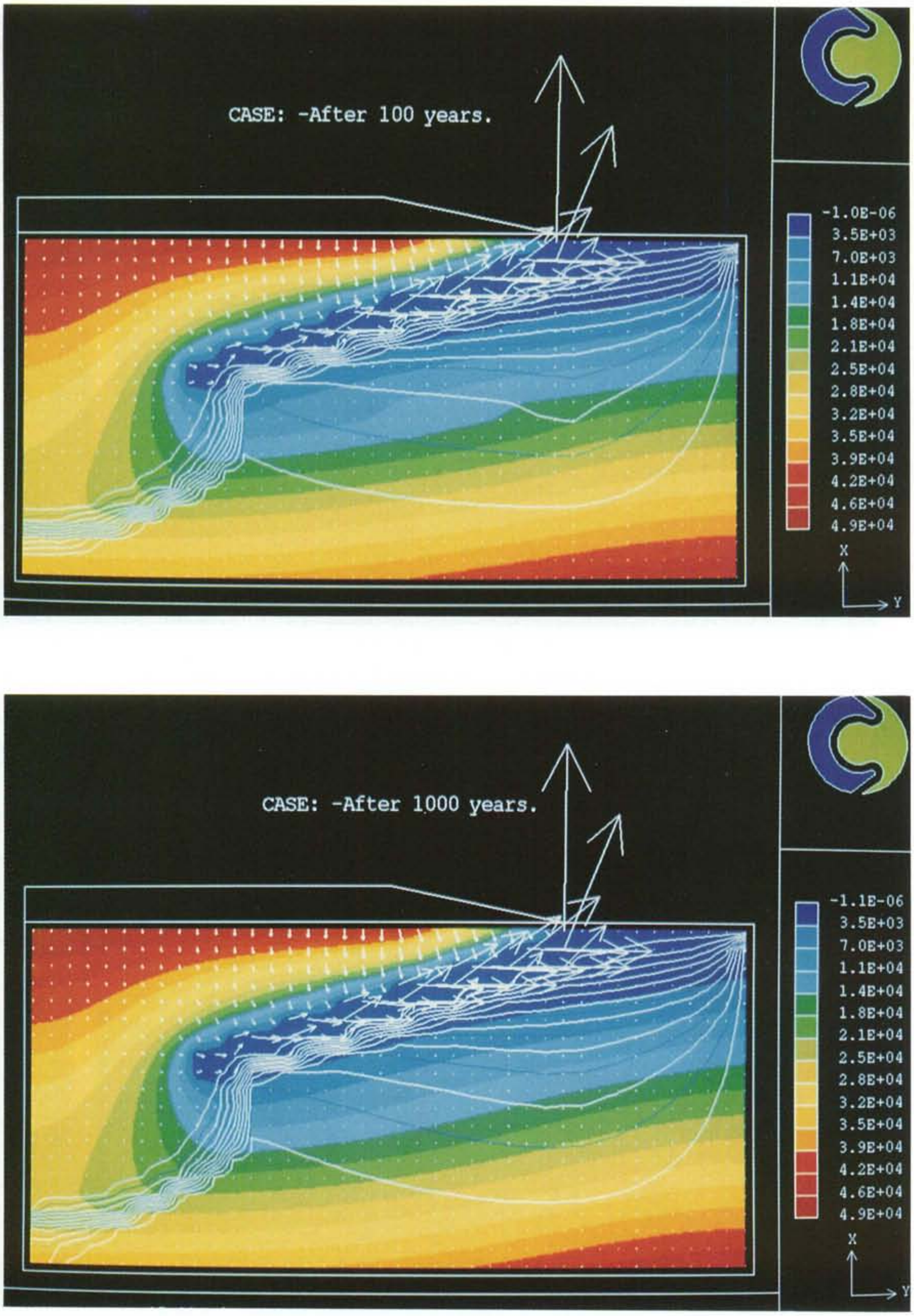
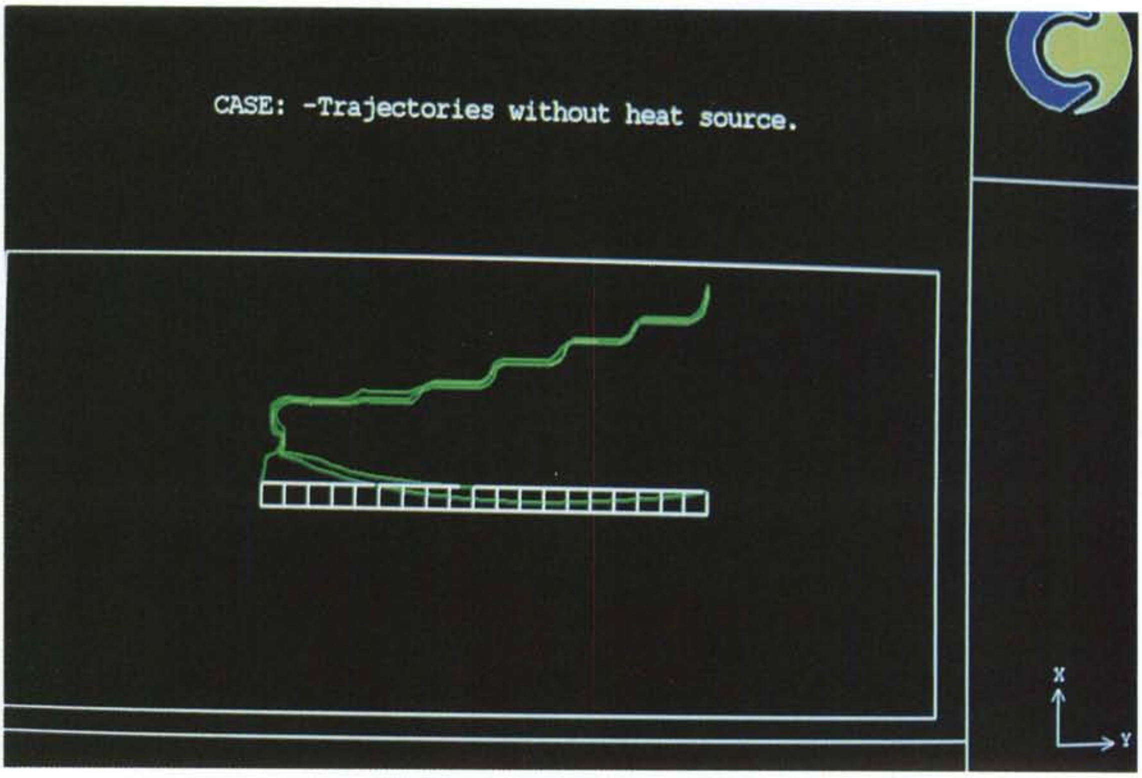


Figure 3-5. Temperature fields after 100 (a) and 1000 (b) years imposed on two-dimensional steady calculation.



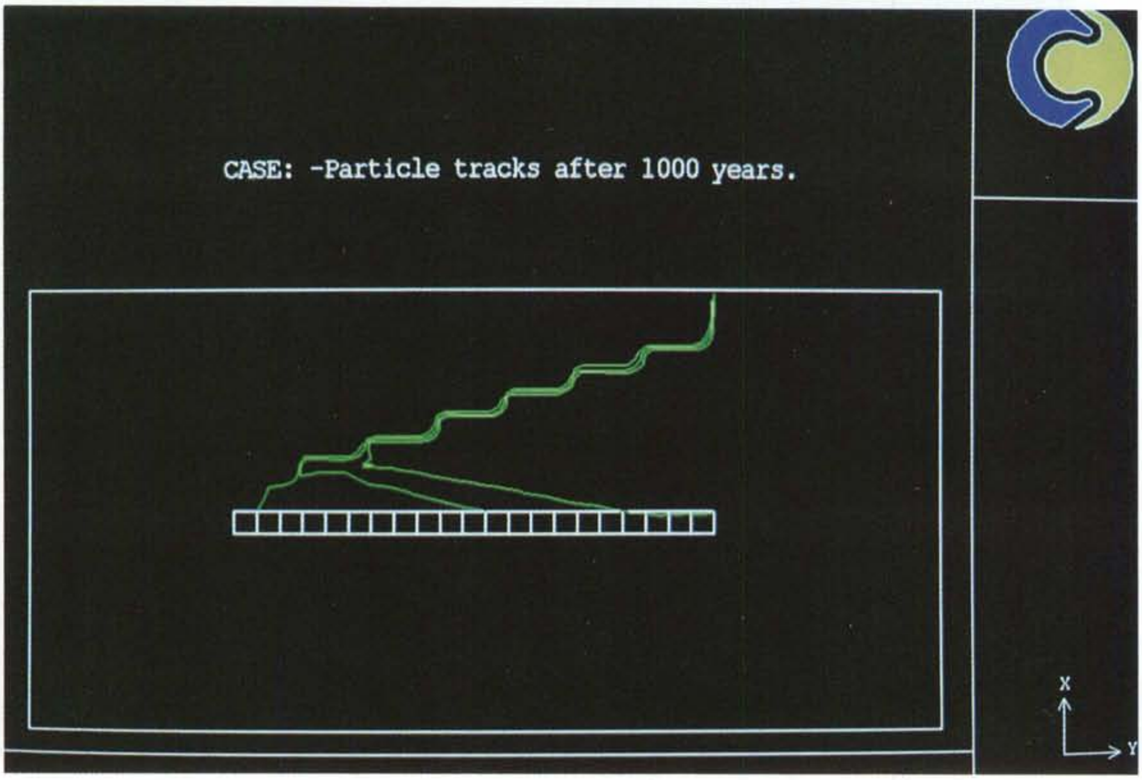


Figure 3-6. Particle tracks for natural (a) and "repository" (b) conditions.

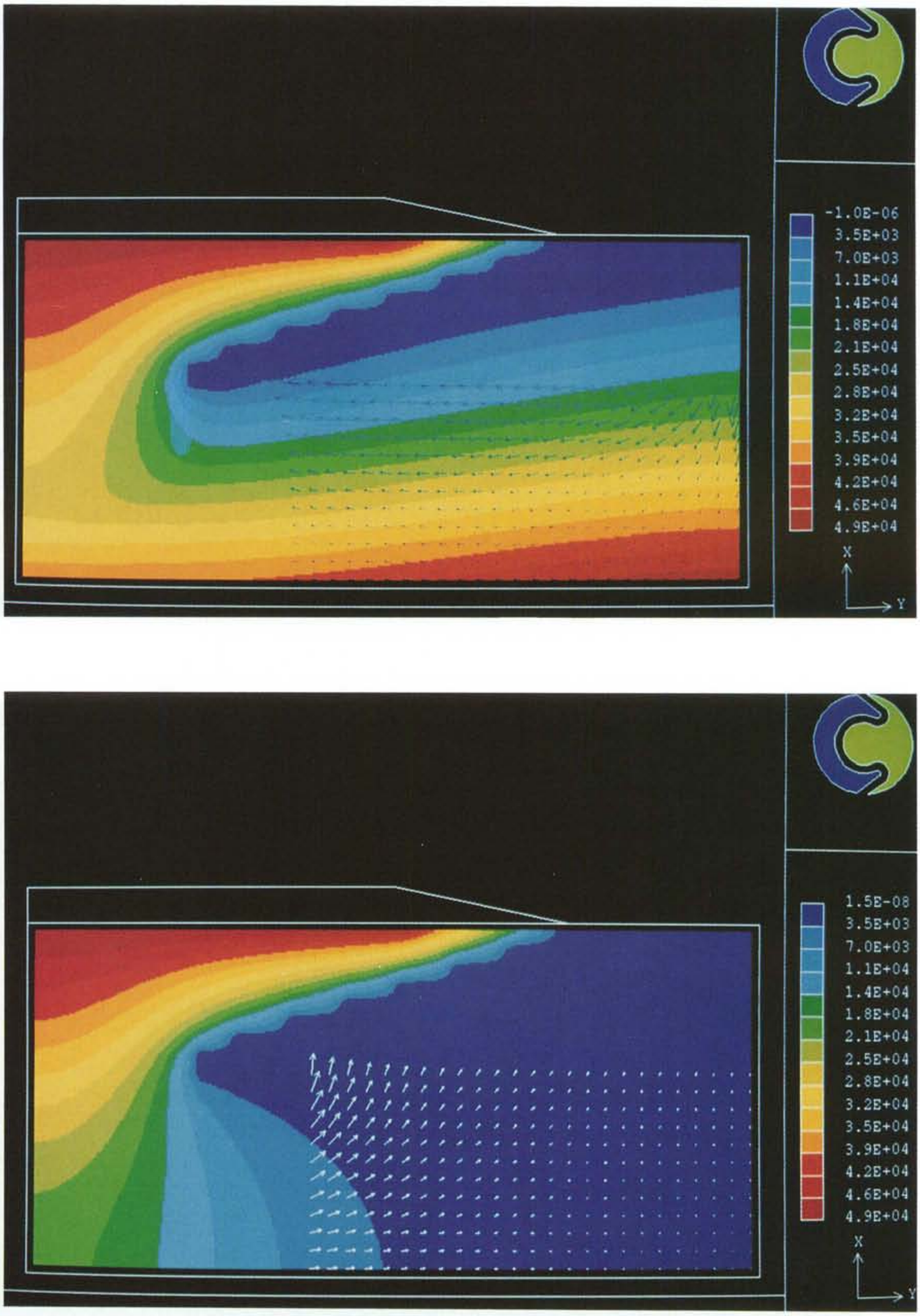


Figure 4-1. Darcy-velocity field under zone 2. With (top) and without salinity field. ⟶ 1. 10^{-11} m/s

6. APPENDIX A. A TWO-FLUID ANALYSIS.

Within the project an alternative numerical method has been evaluated. The method starts from the assumption that the salt- and fresh water are immiscible and thus solves the problem with the uncontrolled mixing of the salinity interface due to numerical diffusion. A full account of the method is given in Jun and Spalding /6-1/.

A simple test-problem is defined in Figure /6-1/.The test-problem will also be solved with the method used for other predictions presented in order to get a reference solution. The two-fluid method is based on a transient solution (due to a higher order explicit numerical scheme used) which hence requires that initial conditions are set. As the volumes of fresh and salt water are conserved it is understood that the initial conditions set will influence the solution at all later times. The method is developed with transient wave-phenomenon in mind but in the present study only the final steady solution will be presented.

Results of calculations are presented in Figure /6-2/. The two-fluid case was initialized with the lower half of the domain filled with salt water and with a horizontal salinity interface. The "standard method" has a fixed salinity at the right boundary; from the bottom up to a level specified from the two-fluid solution. This makes the two solutions comparable in at least a qualitative way. In general, see Figure /6-2/, the two methods give a similar result but, as expected, a sharper interface is obtained with the two-fluid method. One can also note that the salinity boundary condition in the standard method gives a small local disturbance.

This preliminary study of the two-fluid method shows, in the author's view, that the method is applicable in ground water contexts. The method is however about 10 times slower, as compared to the standard method, if only the steady state solution is of interest. The two-fluid method should thus preferably be used when transient phenomenon are to be solved and/or when a sharp interface between salt and fresh water is essential for the solution. For these types of problems the method is promising.

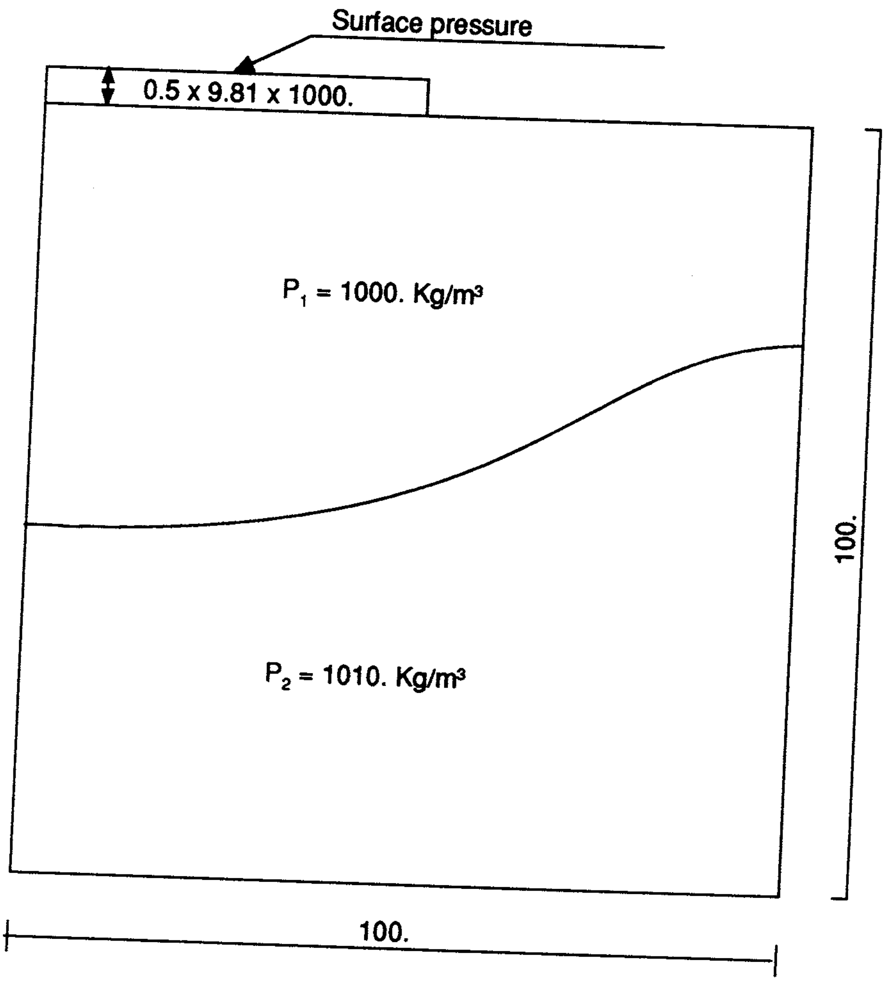
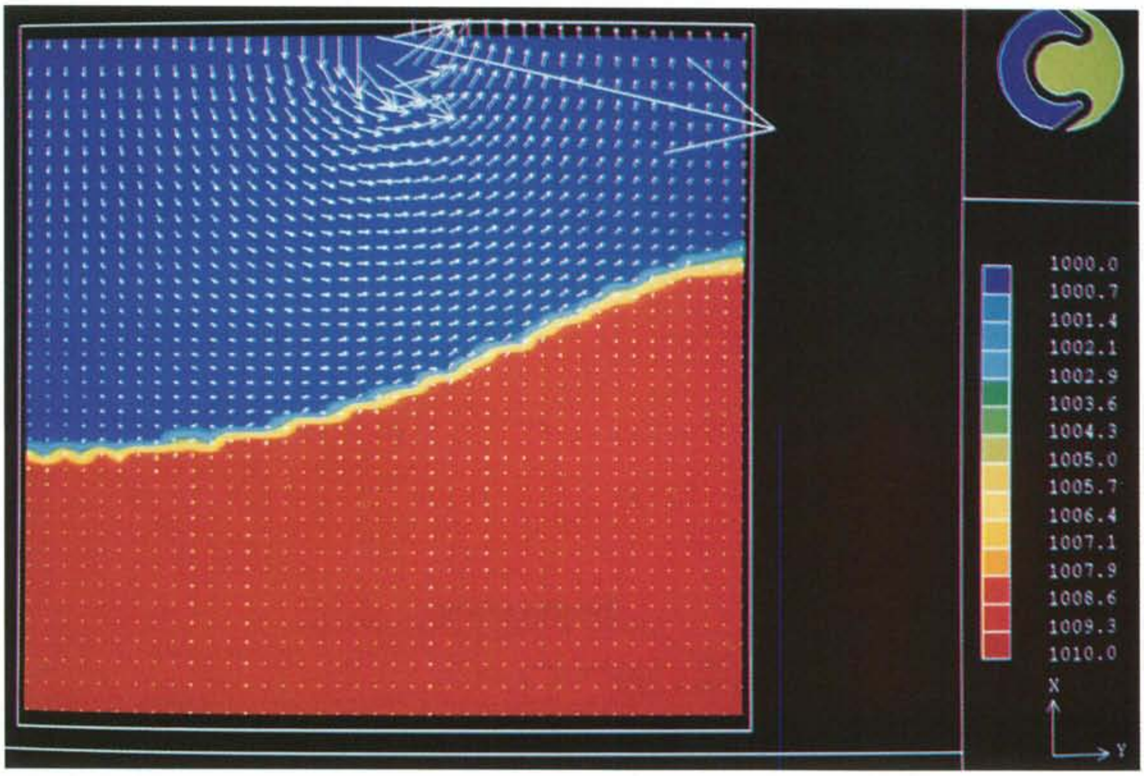


Figure 6-1. Definition of a test-problem for the two-fluid method.



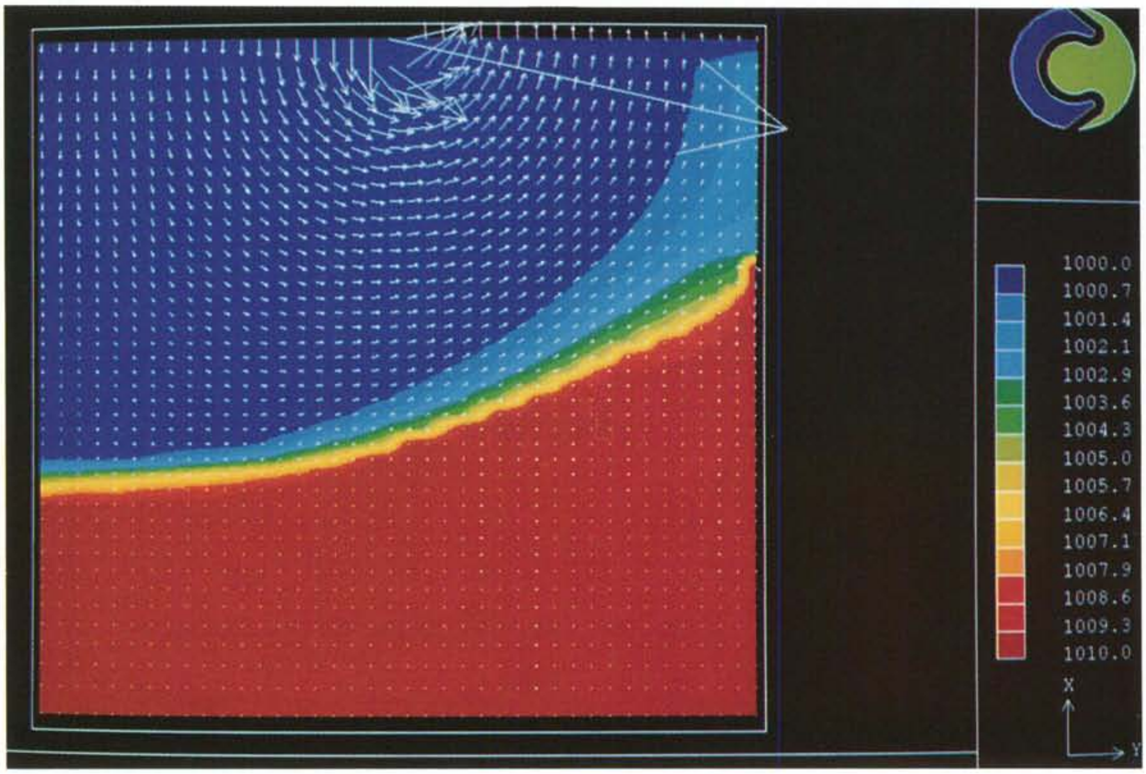


Figure 6-2. Results of calculation. The two-fluid method (top) and the standard method. Filled areas show the density distribution ($\Delta\rho$ = 10 kg/m^3)

A THREE-DIMENSIONAL NUMERICAL MODEL OF GROUNDWATER FLOW AND SALINITY DISTRIBUTION IN THE FINNSJÖ AREA.

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ABSTRACT/SUMMARY.

A numerical simulation model of the groundwater flow and salinity distribution in the Finnsjö Rock Block is presented. The model is three-dimensional and includes, in addition to the Darcy equations, the salinity equation and gravitational forces.

A conceptual model is first discussed in order to provide likely boundary conditions and motivate why a steady state analysis can be used.

The main result of the study is that the circulation below zone 2, at a depth of a hypothetical repository (500 or alternatively 600 meters), is strongly influenced by the presence of salt water. Typically the salt makes the water more stagnant.

1. INTRODUCTION.

The Finnsjö area, in the north-eastern part of Uppland Sweden, has been subject to comprehensive field studies. Reviews of these studies can be found in Ahlbom and Tire'n /1-1/ and Andersson et al /1-2/. One striking result of these field measurements is that the depth to the salinity interface varies significantly. In the studied area, called the Finnsjö Rock Block, salt water is sometimes found 100 meters below the ground surface while in other areas no salt water has been encountered in boreholes at a depth of 700 meters.

The Finnsjö Rock Block is introduced in Figure /1-1/, where both the fracture zones and the groundwater table are shown. The salt water is encountered below zone 2, which is a sub-horizontal zone limited by zones 4, 12, 1 and 7. Zone 2 is found at a depth of about 100 meters close to zone 5 and about 300 meters at zone 7, see Figure /1-1/. The Finnsjö Rock Block can be divided into a northern and southern block separated by the northeasterly trending fracture zone 1. It is in the northern block saltwater is found, at depths ranging from 90-300 meters, while in the southern block fresh water is found in boreholes drilled to depths of up to 700 meters.

It is presently not understood why salt water is found below zone 2. Ahlbom /1-3/ reviews the postglacial marine transgressions and from this review it is clear that the area has been covered with salt water, the Litorina Sea 7500-7000 BP, which is of marine origin. The Litorina Sea was gradually transformed into the present brackish Baltic Sea. The continued crustal uplift resulted in the emergence of the Finnsjö site above the sea between the years 5000-3000 BP. Why fresh water has replaced the salt water in the southern block but not below zone 2 in the northern block is however not clear. Ahlbom /1-3/ noted that the area east of the Finnsjö Rock Block is covered with clay and argued that the salt water may have been trapped below the clay. This assumption, combined with a modified Ghyben-Hertzberg relation, can then explain why salt water is found below zone 2. The assumption of "trapped salt water" has however not been verified, due to lack of field measurements.

The purpose of the present work is to analyze the distribution of salt water in the Finnsjö Rock Block using a three-dimensional numerical model. In particular it is of interest to study the influence of the saltwater on the circulation in the vicinity of a hypothetical repository at a depth of 500 meters.

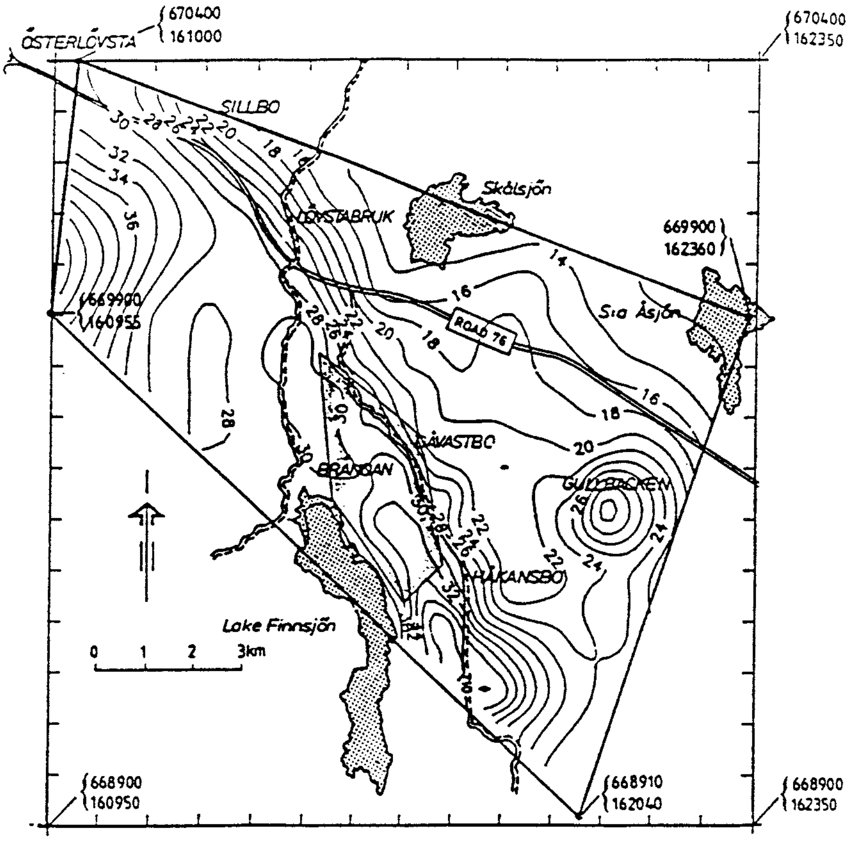
The outline of the report is as follows: Next a conceptual model is presented. Based on this conceptual model a mathematical/numerical model is formulated. Then results are presented and finally some concluding remarks are given.

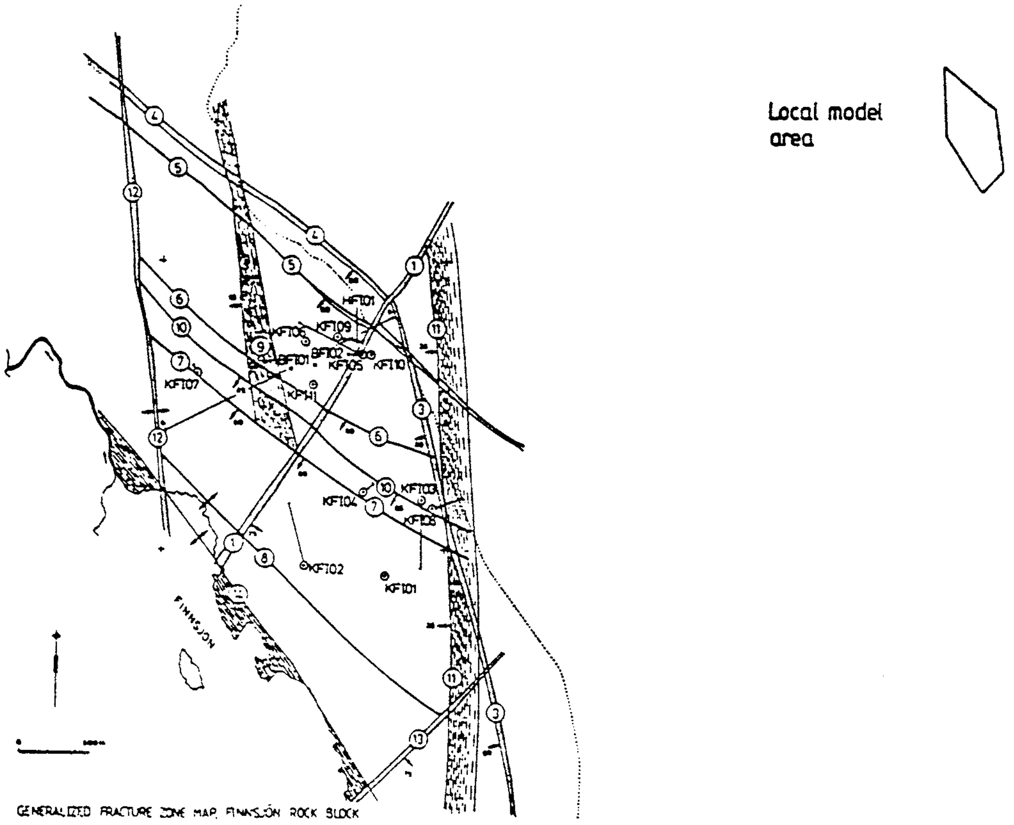
2. CONCEPTUAL MODEL

As mentioned it is not understood why salt water is present below zone 2. A mathematical model does however require a conceptual model and we thus need to introduce some assumptions and idealizations that "sets the scene" for the mathematical model. This will be done by discussing a two-dimensional vertical section running in the east-west direction through the northern block, introducing a number of features one by one.

Let us first introduce the classical Ghyben-Hertzberg relation, see Figure /2-1 a/. If we assume that the ground surface can be idealized as a high flat area, a slope and a low flat area the replacement of salt water by fresh water will be halted at a certain stage. The starting point of the anticipated process is thus that the whole area is covered by salt water. The position of the halted interface is given by the Ghyben-Hertzberg relation and is for the present conditions given by $h_2 = 120h_1$.

Next we introduce a sub-horizontal fracture zone which of course is assumed to give the principal effect of zone 2, see Figure /2-1 b/. This situation has been analyzed in Svensson /2-1/ and only the main conclusions will be repeated here. If the hydrostatic component, $-\rho_0 gz$, is subtracted from the pressure field we may use pressure gradients as the "driving force" for the circulation. If further the atmospheric pressure is used as a reference, p = 0, it is found, see Svensson /2-1/, that the pressure in the zone is close to zero. In the low flat area we have a pressure that increases with depth, due to the presence of salt, and the pressure gradient thus drives the water towards the zone. The ground surface slope is not felt below the zone; instead the sloping interface is found where the zone ends. The essential effect of the zone is thus to eliminate the effect of the ground slope below the zone.





Figure/1-1/. Fracture zones and groundwater table in the Finnsjö Rock Block.

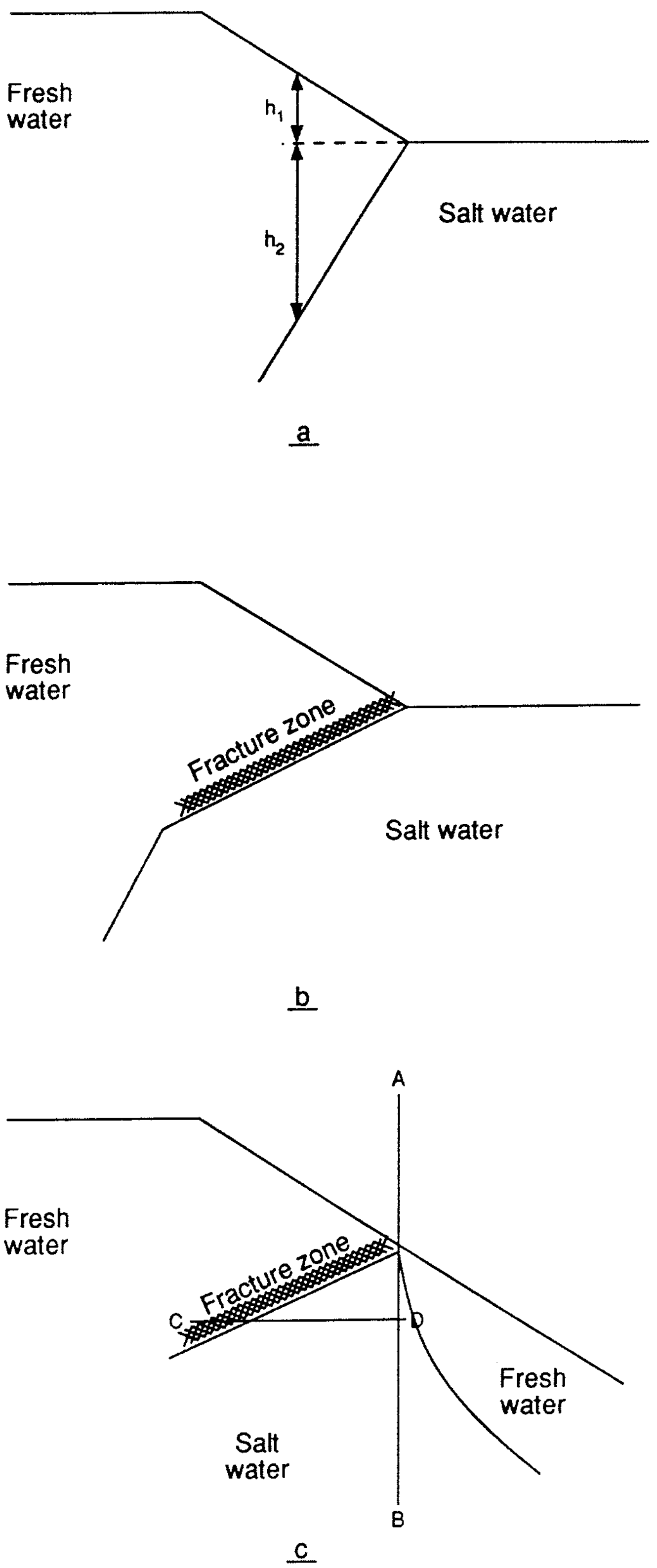


Figure /2-1/. Illustrations of conceptual model.

From Figure /1-1/ it is clear that a flat region is not found directly east of the Finnsjö Rock Block. It is thus of interest to analyze the situation with a continuous slope, see Figure /2-1 c/. As above, it is assumed that the domain is initially filled with salt water. Precipitation will then cause the salt water to be replaced with fresh water. If it is assumed that the pressure in the zone is determined by the contact with the atmosphere it is anticipated from Figure /2-1 c/ that we initially have a zero horizontal pressure gradient along the line C-D. Above the zone and east of the line A-B the fresh water will replace the salt water quite readily as the pressure gradient is significant. However below the zone the salt water will be trapped as the pressure gradient is close to zero. In fact, when fresh water has replaced the salt water in the zone the pressure gradient may even be towards the zone.

At this stage it is of interest to make reference to the conceptual model presented by Ahlbom /1-3/. He assumed that the area east of the block is covered by clay and that this was the reason why the salt water is trapped. The present analysis indicates that the clay cover is not necessary. However, if present it will make the replacement with fresh water east of line A-B in Figure /2-1c/ much slower and salt water will be found also east of line A-B.

The numerical model will utilize the conceptual model presented in the following way. The quasi-steady situation with salt water along the line A-B is prescribed as a boundary condition. To achieve this the salinity is prescribed east of the line A-B to the values expected at A-B. Also a zero flux condition at ground level is used east of the line A-B. This will not describe the conditions east of the block correctly, but will provide the desired conditions at the line A-B.

3. MATHEMATICAL FORMULATION.

3.1 BASIC EQUATIONS.

The basic mathematical formulation is the same as used in most other models. The following set of equations is used:

x-momentum: $$0 = - \frac{\partial p}{\partial x} - F_x \rho_o u - (\rho - \rho_o) g \qquad (3.1)$$

y-momentum: $$0 = - \frac{\partial p}{\partial y} - F_y \rho_o v \qquad (3.2)$$

z-momentum: $$0 = - \frac{\partial p}{\partial z} - F_z \rho_o w \qquad (3.3)$$

Salinity: $$\frac{\partial us}{\partial x} + \frac{\partial vs}{\partial y} + \frac{\partial ws}{\partial z} = \frac{\partial}{\partial x}(Dn \frac{\partial s}{\partial x}) + \frac{\partial}{\partial y}(Dn \frac{\partial s}{\partial y}) + \frac{\partial}{\partial z}(Dn \frac{\partial s}{\partial z}) \qquad (3.4)$$

Equation of state: $$\rho = \rho_o (1 + \alpha s) \qquad (3.5)$$

Conservation of mass: $$\frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0 \qquad (3.6)$$

Where u, v, w are velocities (= Q/A, "Darcy velocities"), α (= 0.008) an expansion coefficient, ρ_o (= 1000 kg/m^3) a reference density, F_x, F_y and F_z friction coefficients, p pressure, g acceleration due to gravity, s salinity, D dispersion coefficient and n porosity. The coordinate directions are denoted x (vertical), y and z. As the friction coefficients are related to the hydraulic conductivity, the momentum equations may be interpreted as the Darcy law.

3.2. BOUNDARY CONDITIONS.

Boundary conditions can generally be specified either as a fixed value condition or a specified flux condition.

At the upper boundary a fixed pressure, based on the groundwater table, is prescribed except for the region east of the block where zero flux is prescribed.

At the vertical boundaries and the lower boundary a zero flux condition is used for all variables. East of the Block the vertical salinity distribution is prescribed with a ground level value of 0.8% and an increase with depth of 0.8% per 1 400 meters.

3.3. HYDRAULIC CONDUCTIVITIES.

In the computational grid the velocities are evaluated at cell walls and conductivities are hence required at cell walls. For each cell three conductivities are needed (x, y and z-direction) as the other three cell walls may be considered as belonging to the neighbouring cells.

A quite elaborate method has been developed for the calculation of hydraulic conductivities. For each cell in the grid a conductivity is calculated as follows:

- A mean conductivity is given as input; this conductivity has a given variation in the domain,obtained from field measurements.
- A standard deviation, with a variation with depth, is given as input. A transformation to the cell-size scale is then performed.
- With a random number a log-normally distributed conductivity, with the specified mean value and standard deviation, is then generated.

This conductivity is representative for a cell, but we need a conductivity at a cell-wall. In each coordinate direction, giving an anisotropic conductivity field, a cell-wall conductivity is calculated as the harmonic mean of the two cell conductivities. The identified major fracture zones also need to be considered in the conductivity fields. An algorithm has been developed that determines the fracture length in each cell wall. Knowing this fracture length and the transmissivity of the fracture a modified cell wall conductivity can be determined; for details see Svensson /3-1/. The mean conductivity field and the standard deviation distribution are given in Andersson et al /1-2/ as follows:

Mean conductivity:

Southern block: $K = 1.04 \times 10^{-6}\ \text{depth}^{-1.10}\ \left[m/s \right]$ (3.7)

Northern block: $K = 3.90 \times 10^{-5}\ \text{depth}^{-1.53}\ \left[m/s \right]$ (3.8)

Standard deviation:

std = max (0.1, 1.28 - 0.83 x depth/550) (3.9)

The formula for the standard deviation is based on Table 1, p A26, in Andersson et al /1-2/. Equation (3.9) gives the standard deviation in the 3-meters scale. The following formula was used to transform the value to the actual cellsize, CLSIZE:

$std = std_3 \times 0.64 / Log (CLSIZE)$ (3.10)

3.4 DISPERSION.

The dispersion coefficient is known to be related to the fracture length and the pore velocity, i.e.:

$$D = k\ l_f\ V_p \qquad (3.11)$$

In the present calculations, see Svensson and Hemström /3-2/ for details, the fracture length was assumed to be 1 meter and the coefficient, k, equal to 2.0. The porosity, which multiplies the dispersion coefficient in equation (3.4), will eliminate the need to estimate the pore velocity as nV_p is taken as the Darcy velocity.

3.5 FRACTURE ZONES.

The fracture zones are introduced in Figure /1-1/. The transmissivities assigned to these are primarily based on values given by Andersson et al /1-2/. The following values were used:

Fracture	Transmissivity x 10^5
1	20
2	300
3	10
4	2
5	1
6,7	0.001
8,9,10	0.1
11	1
12	20
13	2
14	20

3.6. NUMERICAL SOLUTION.

The set of equations formulated was solved using the general equation solver PHOENICS, Spalding /3-3/. In order to avoid the extremely low velocities found in fractured rock, the conductivities and transmissivities were increased by a factor of 10^{10}. This scaling of the velocity does of course not influence the solution of the problem. Also the vertical pressure distribution was rescaled by subtracting the hydrostatic component ρ_o x g x depth from the pressure field.

Using 75600 cells (30x70x36) in a cartesian grid a converged solution was obtained in typically 5 hours on a SUN SPARC stn 1.

4. RESULTS

The computational grid and some lines along which sections will be presented are shown in Figure /4-1/. The typical gridspacing in the Block area is 87 meters in the horizontal and 40 meters in the vertical direction.

In this chapter results from the numerical model will be presented including: conductivity fields, salinity distributions, circulation patterns and particle tracks.

4.1 CONDUCTIVITY DISTRIBUTIONS

As an illustration the distribution of the vertical conductivity , calculated according to the method described in chapter 3, will be presented, see Figure /4-2/. When studying this figure one should note the following:

- Fracture zones are included in the conductivity fields.
- The mean conductivity decreases with depth and is different for the southern and northern blocks.
- The standard deviation decreases with depth and scale of the computational cell.
- It is the inverse of the conductivity that is plotted (for graphical reasons). This "resistance" does not resolve the difference between the conditions close to the surface as compared to the fracture zones.

The figure does nevertheless give an illustration of the conductivity fields used in the calculations.

4.2 SALINITY DISTRIBUTION

The vertical salinity distribution has been measured in several of the boreholes shown in Figure /1-1/. Three of these profiles are used for a comparison with the calculated salinity distributions, see Figure /4-3/. A general agreement is found; it is probably out of reach to get a closer agreement as the local variations in the profiles are due to stochastic variations.

Horizontal sections of the salinity distribution at the depths of 420 and 500 meters are shown in Figure /4-4/ and a perspective view is given in Figure /4-5/. The main impression of these figures is that the depth to the salinity interface is less in the northern block as compared to the southern block. From the figures it is also seen that the salinity distribution is fixed east of the block.

4.3 CIRCULATION

Two horizontal views of the circulation are shown in Figure /4-6/. The figure showing the flow in zone 2 is included for verification purposes as field measurements (Andersson et al /1-2/) have established that "the natural groundwater flow rate through a 1000 meter wide vertical section of zone 2 is in the order of 150 000-370 000 m^3/year". A typical calculated velocity in the south-east part of zone 2 is 1.5×10^{-7} m/s which, with a cell height of 40 meters, gives 180 000 m^3/year for a 1000 meter wide section. The horizontal view at 500 meters depth show that Darcy velocities at this depth is about two orders of magnitude smaller, i.e. 10^{-9} m/s.

Two vertical sections are shown in Figure /4-7/. It is once again confirmed that the high flow rates are found in zone 2.

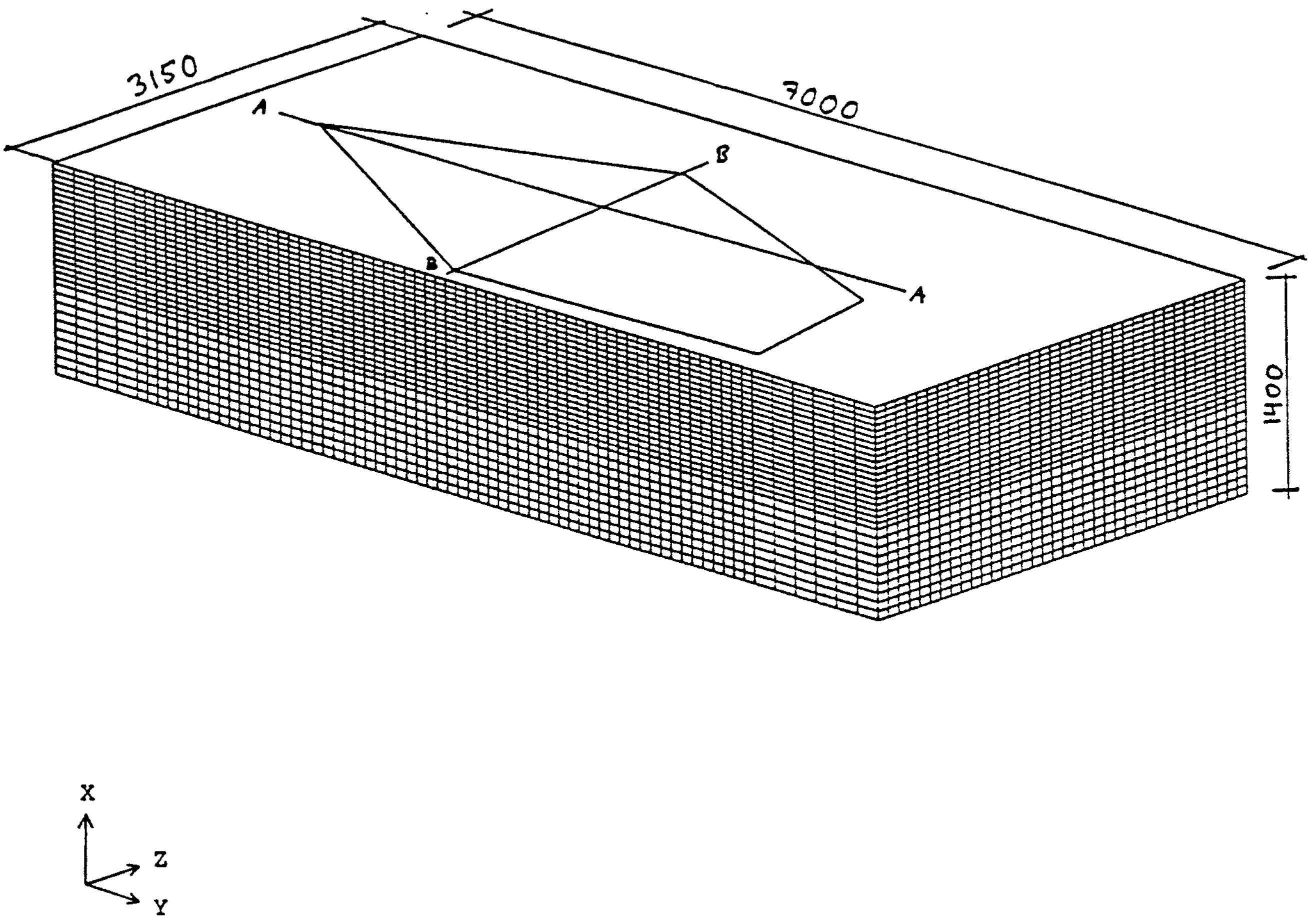


Figure /4-1/. Computational grid, dimensions and section lines.

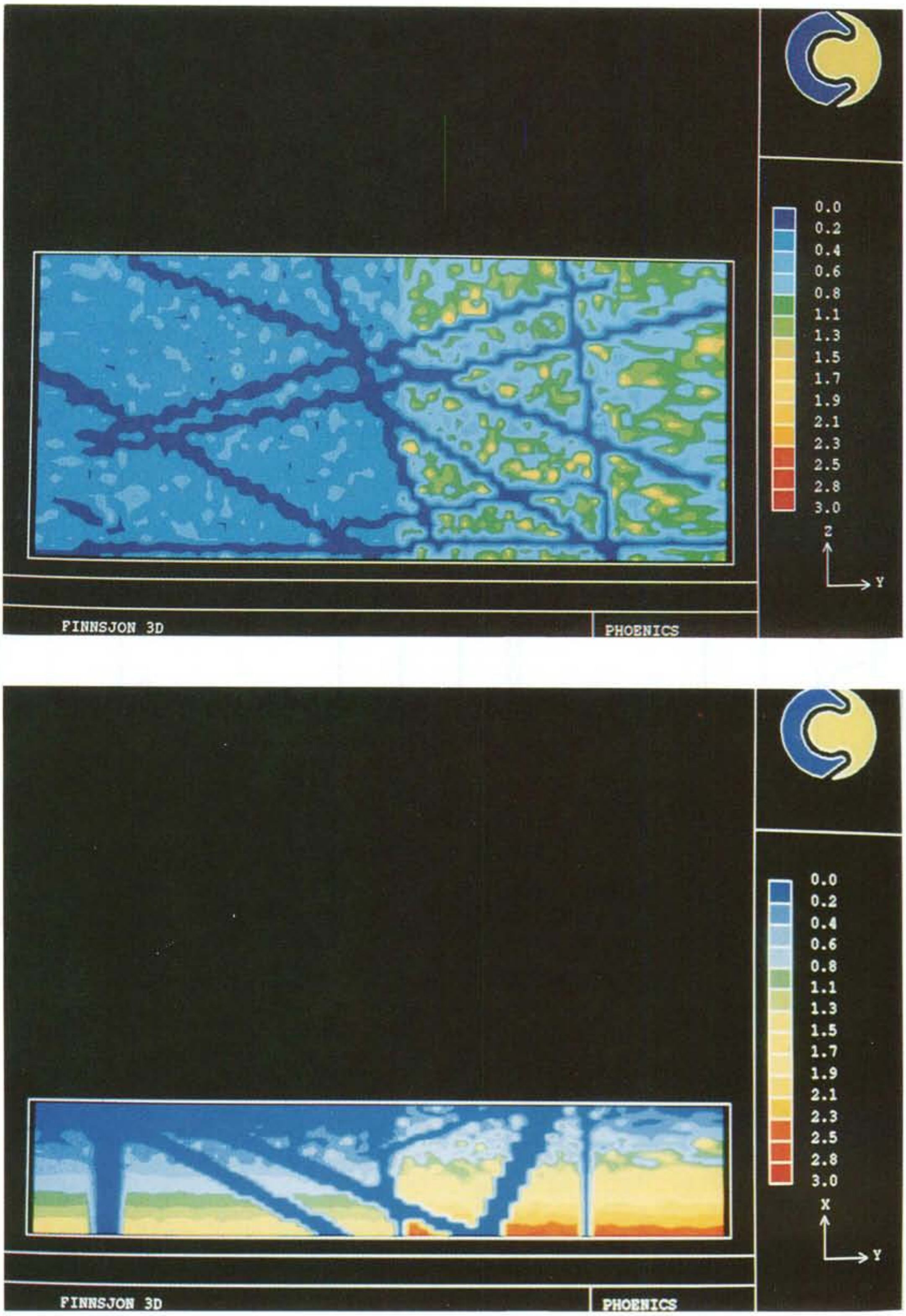


Figure /4-2/ Distribution of vertical conductivity. Horizontal section (top) at a depth of 500 meters and vertical section along line B-B.

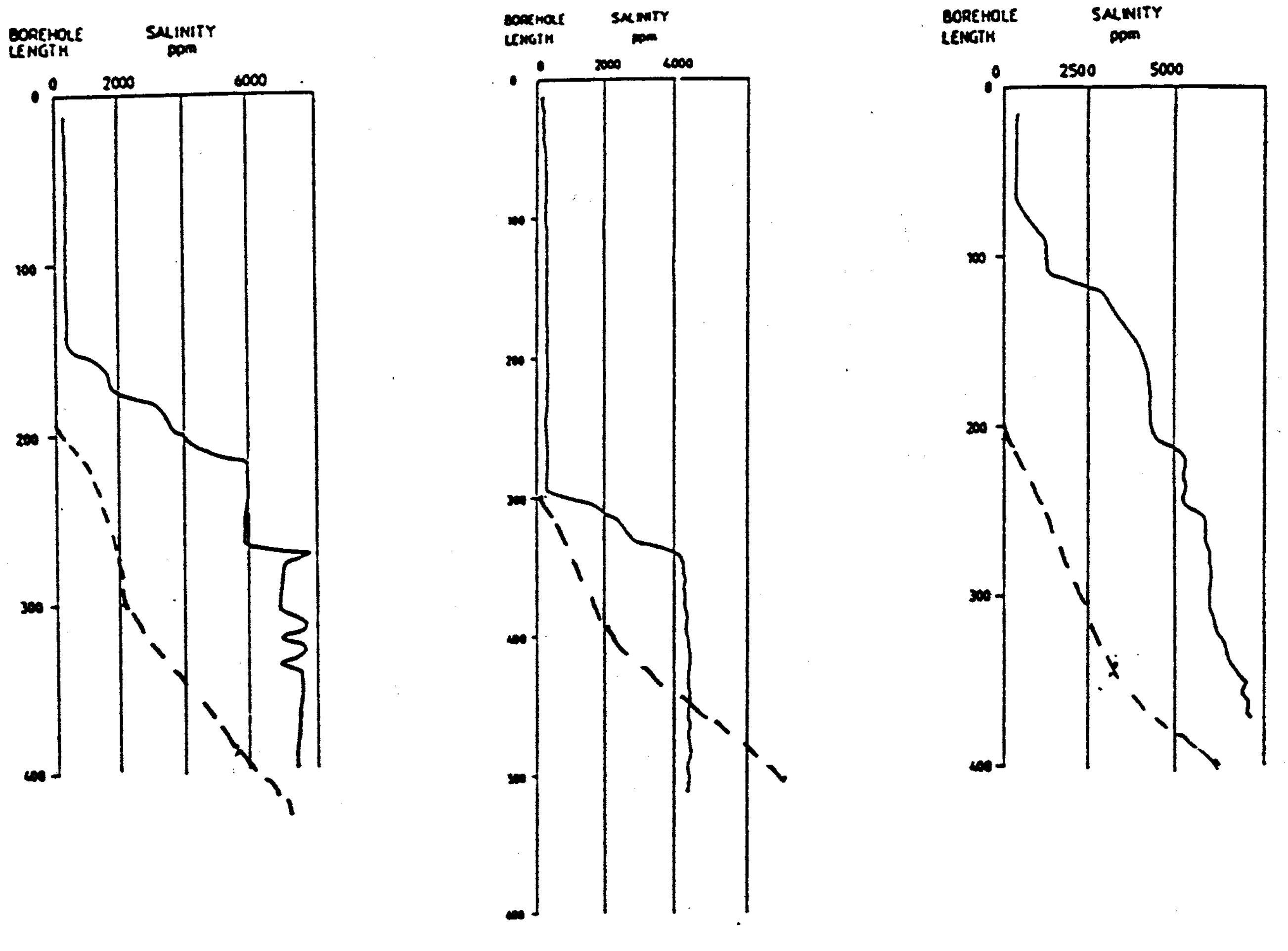
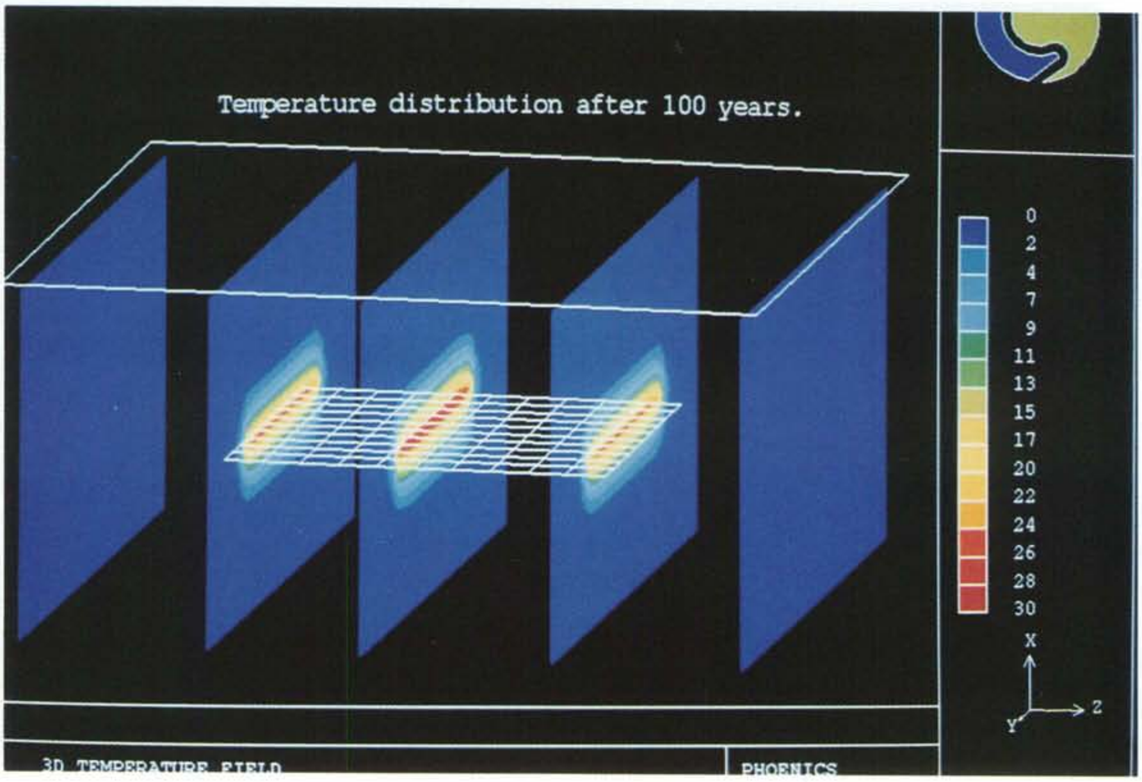


Figure /4-3/. Salinity distributions in boreholes KFI06, KFI07 and KFI09. Measurements (-) and calculations (- - -).



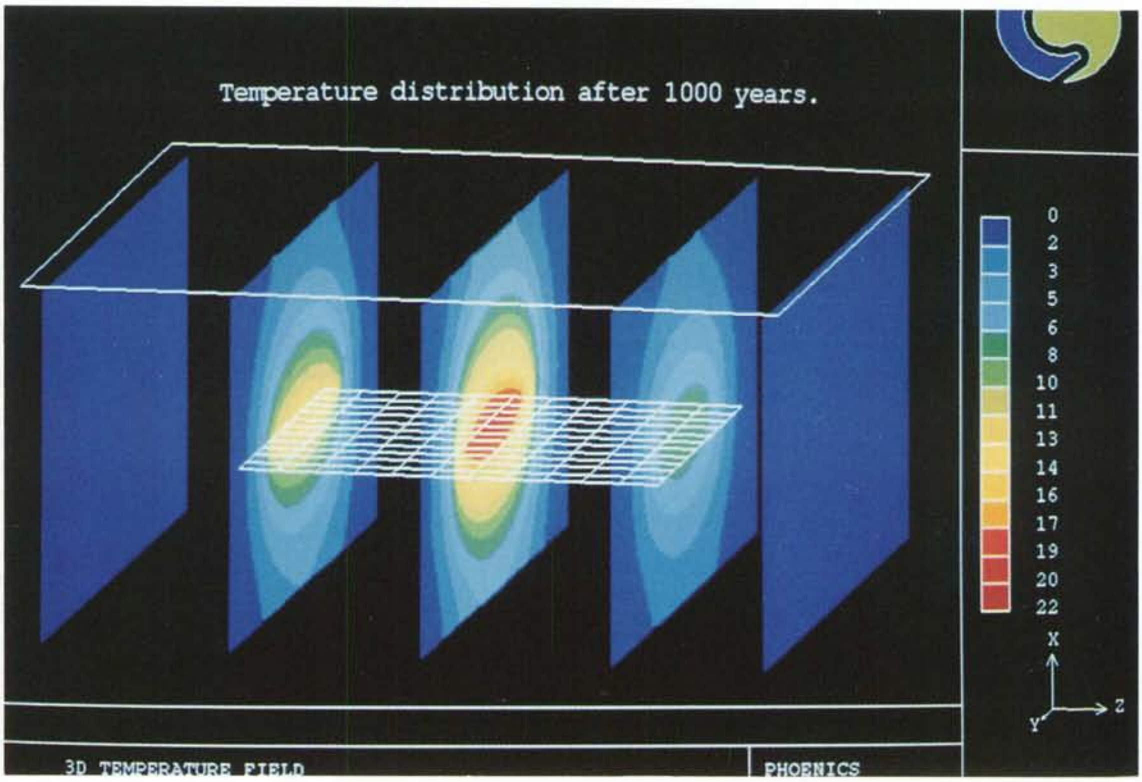


Figure 3-4. Predicted temperature fields after 100 (a) and 1000 (b) years respectively.

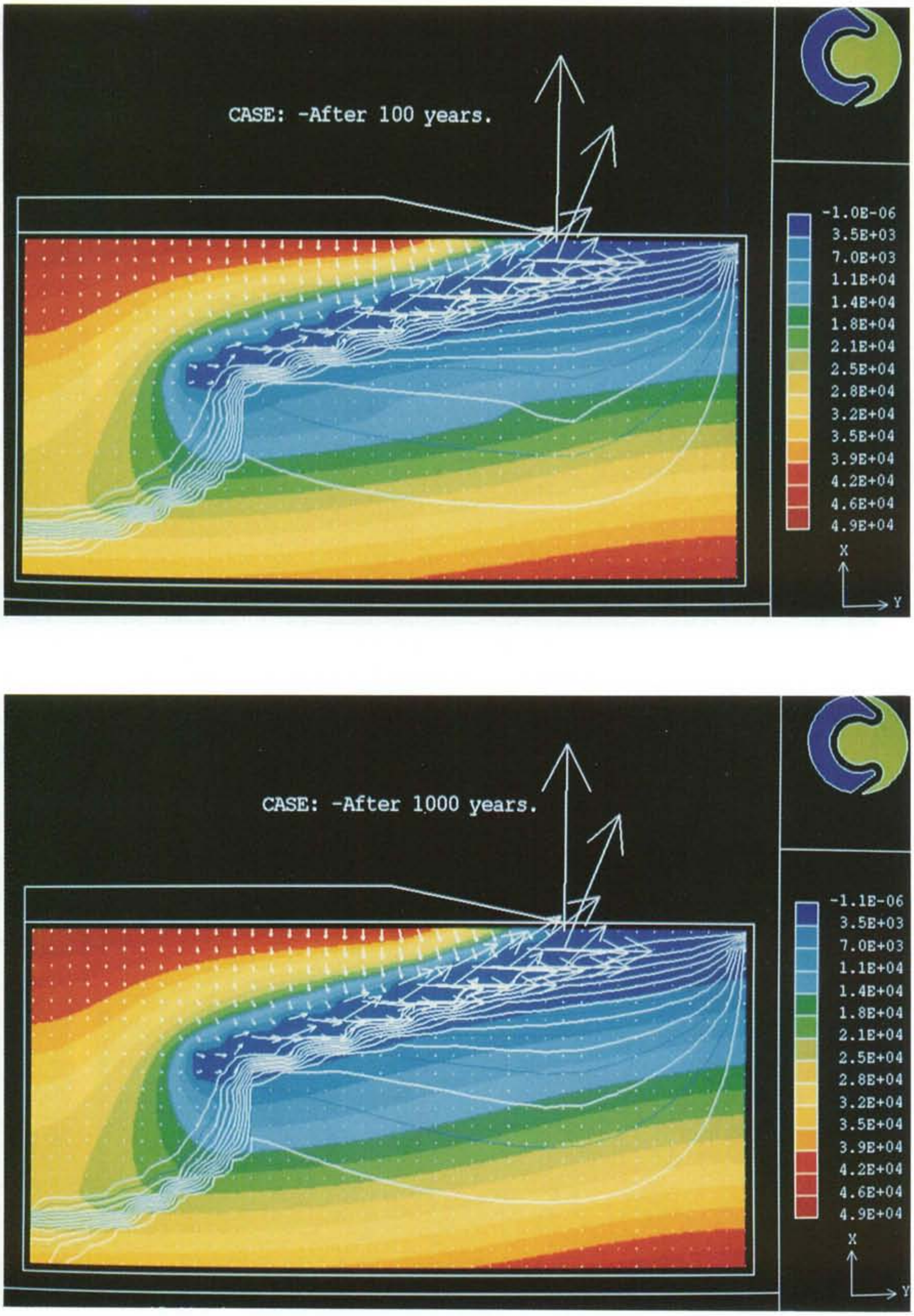
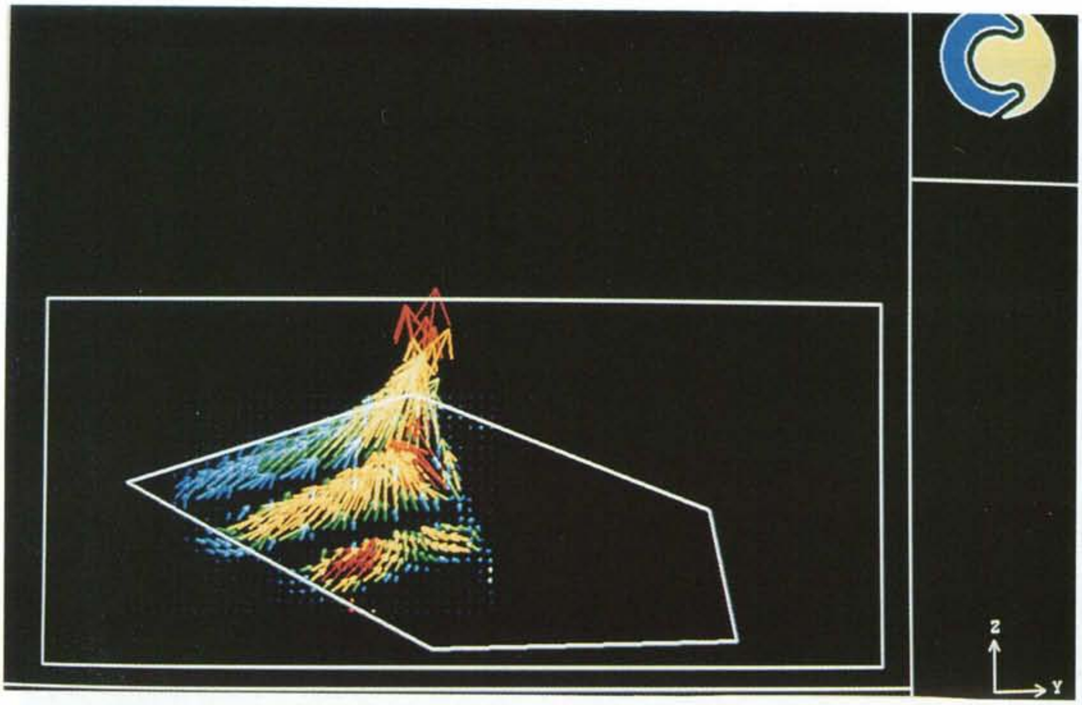
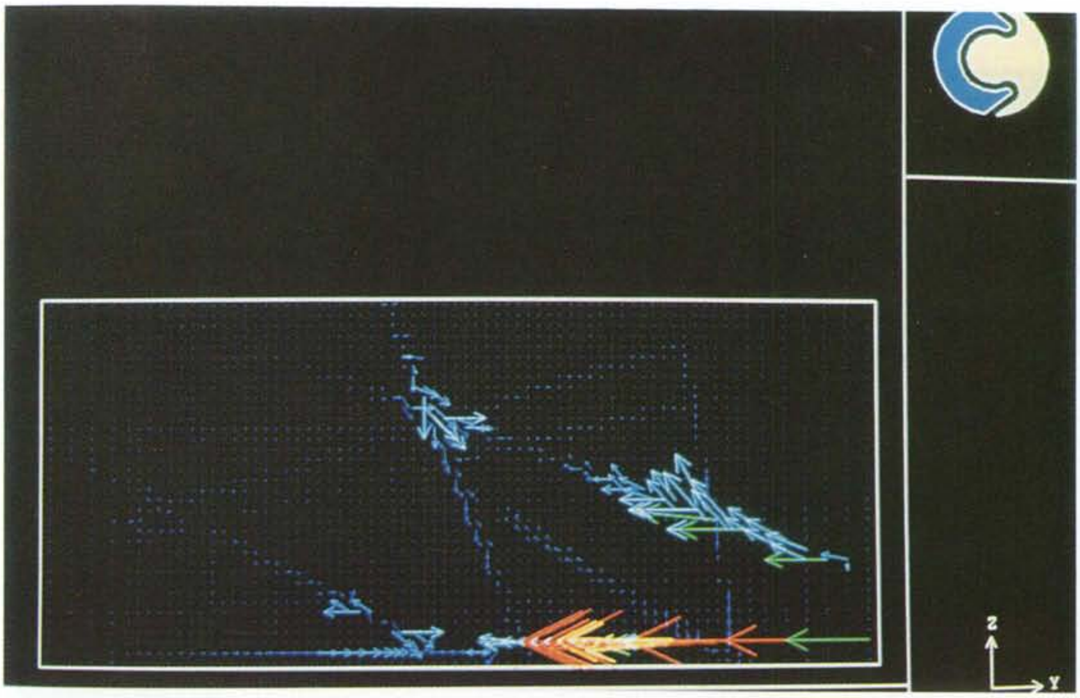


Figure 3-5. Temperature fields after 100 (a) and 1000 (b) years imposed on two-dimensional steady calculation.

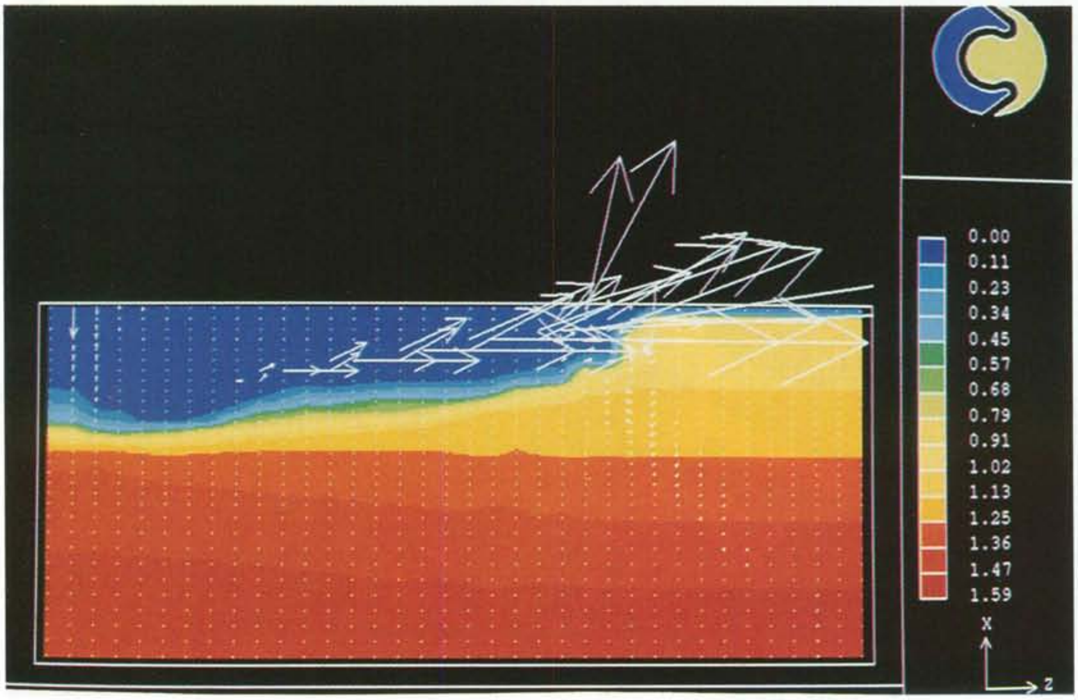


⟶ 10^{-7}m/s



⟶ 2 x 10^{-9}m/s

Figure /4-6/. Two horizontal views of the circulation. In zone 2 (top) and at a depth of 500 meters.



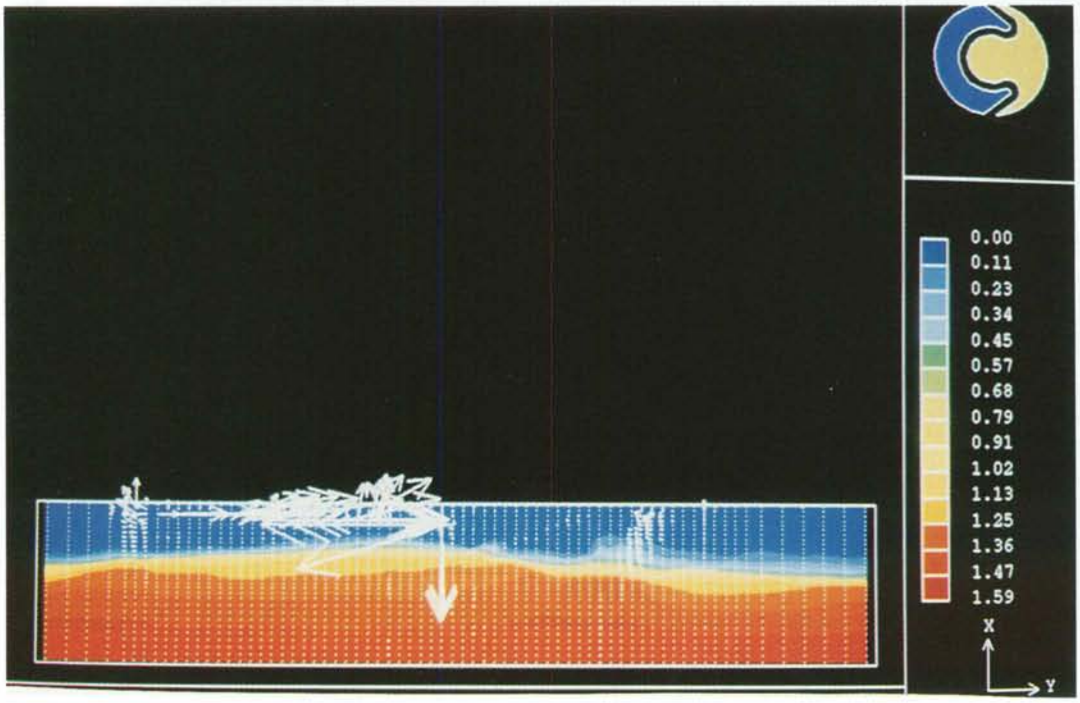


Figure /4-7/. Two vertical sections, A-A (top) and B-B showing the circulation and salinity distribution.

⟶ 2.5×10^{-8} m/s

4.4 HYPOTHETICAL REPOSITORY SITE

Finally some illustrations of the circulation at a hypothetical repository site will be presented. Figure /4-8/ shows the site; it is located below zone 2 at a depth of 500 meters. Five points are also marked in the figure. These are the starting positions for mass-less particles that are to be tracked.

The particle tracks have been calculated with a homogeneous model, i.e. no salinity, as well as with the basic model with salt. The results are shown in Figures /4-9/ and /4-10/. An examination shows that the tracks are sensible to the presence of salt. In fact, both the paths and the travel times are quite different. As an example one may study the x-z sections in the two figures. Without salt the tracks go more or less straight to the surface while the salt changes the paths completely. The tracks for the homogeneous case are quite similar to the ones presented by Lindbom et al /4-1/, who used the FEM-code NAMMU for the circulation predictions. A magnified view which also includes velocity vectors is shown in Figure /4-11/.Without salt the flow is eastward, driven by the mean slope of the ground water surface. With salt the flow pattern is similar to what is found in seawater intrusion situations, i.e. the salt water flows towards the freshwater below the salinity interface.

The travel times in years, assuming a porosity of 10^{-4}, are presented in Table 4-1. As expected, the travel times are longer for the situation with salt.

Particle	Travel times (years).	
	with salt	without salt
1	280	83
2	5720	48
3	2480	270
4	2300	1100
5	1420	880

Table 4-1. Travel times in years for five particles assuming a porosity of 10^{-4}.

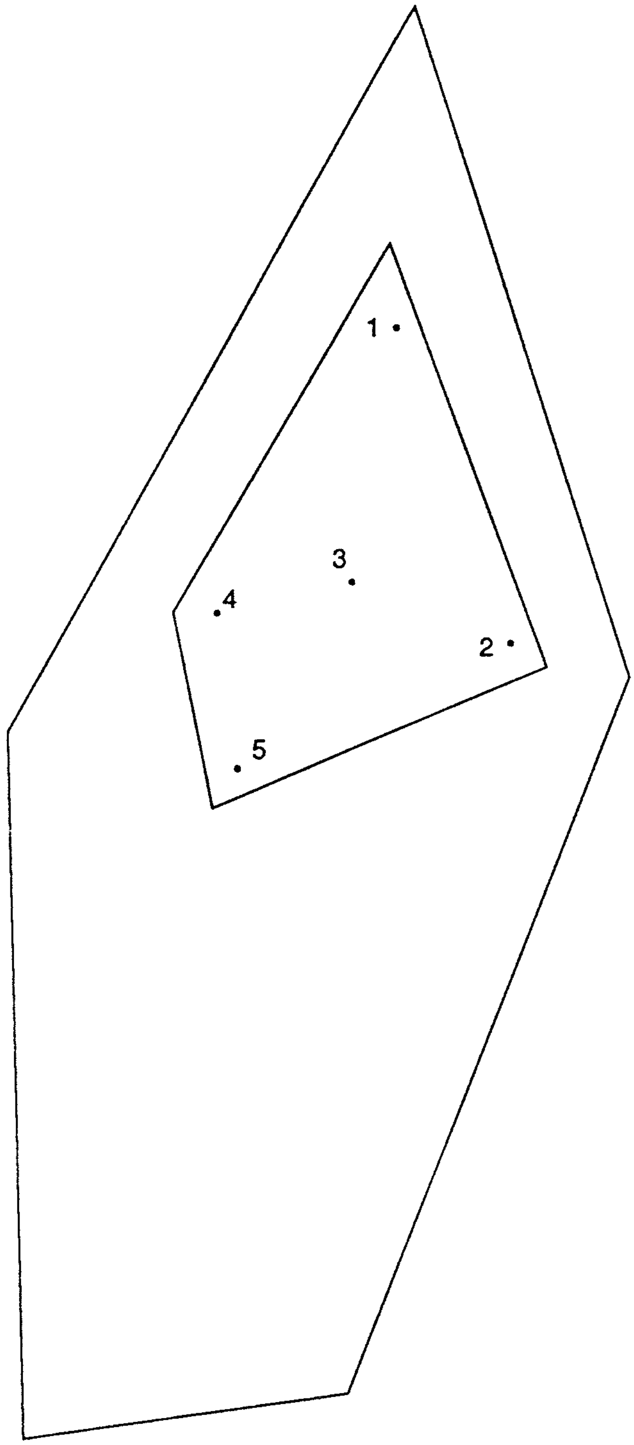


Figure /4-8/. Hypothetical repository site and start positions for particle tracks.

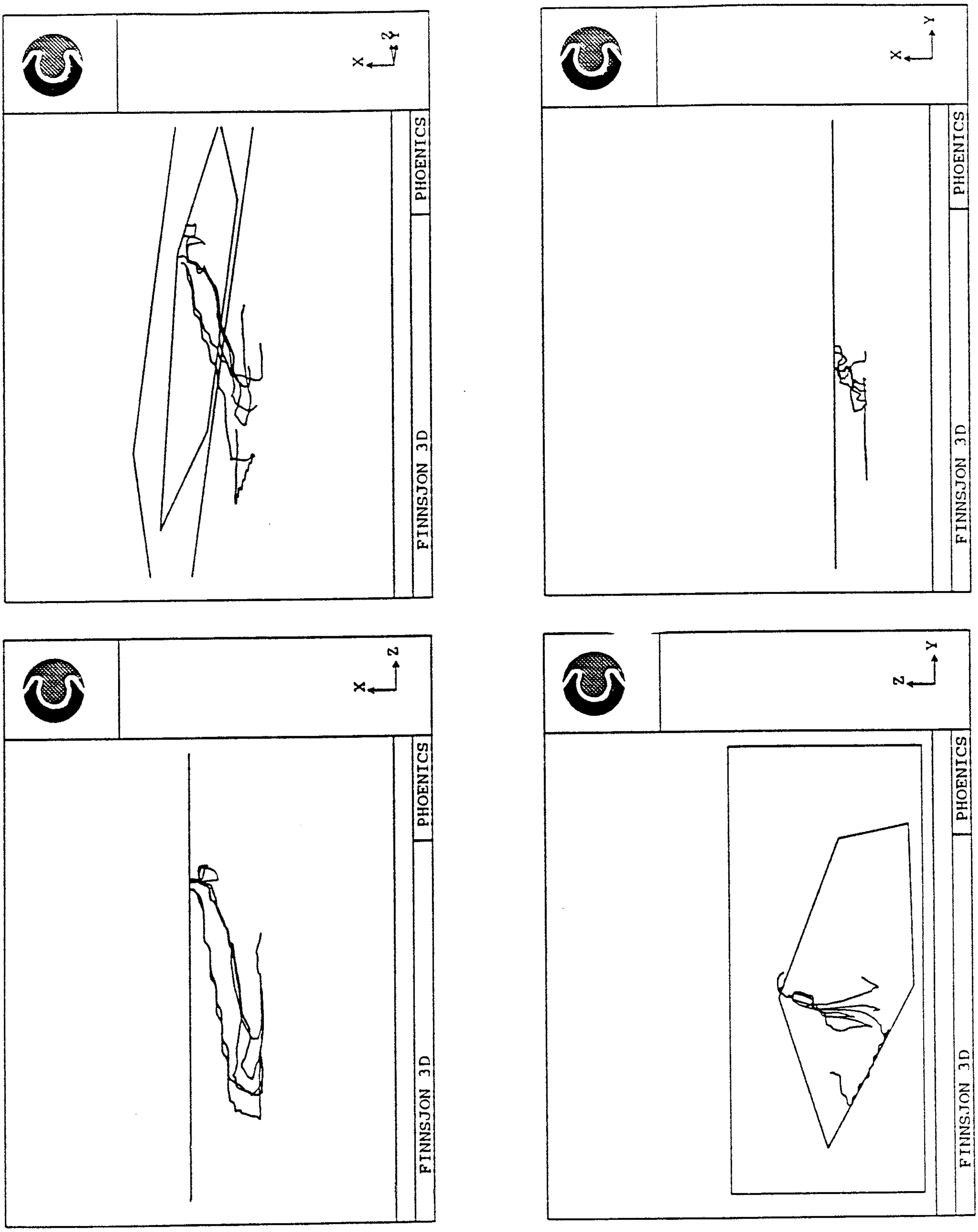


Figure /4-9/. Particle tracks for model with salt.

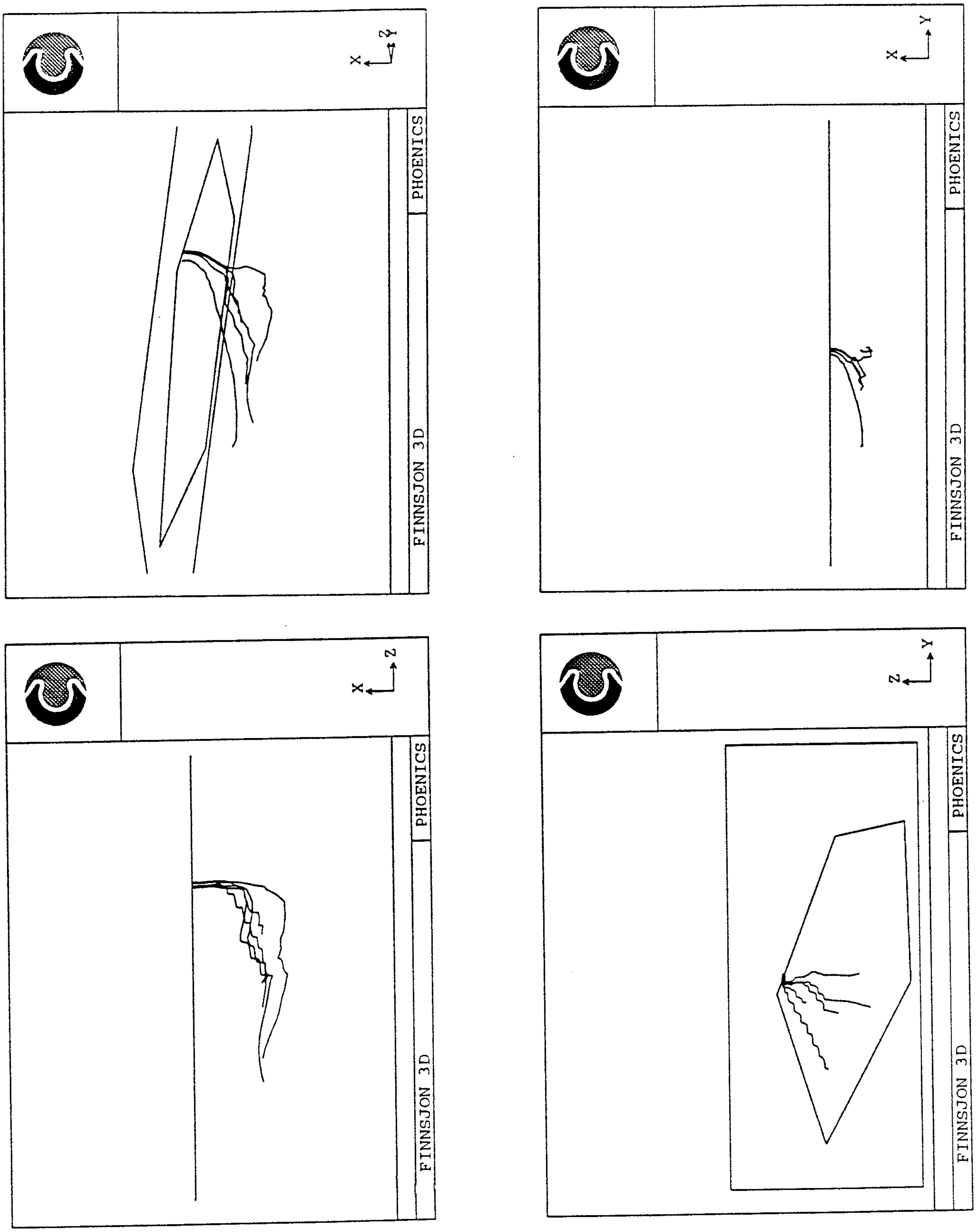


Figure /4-10/. Particle tracks for model without salt.

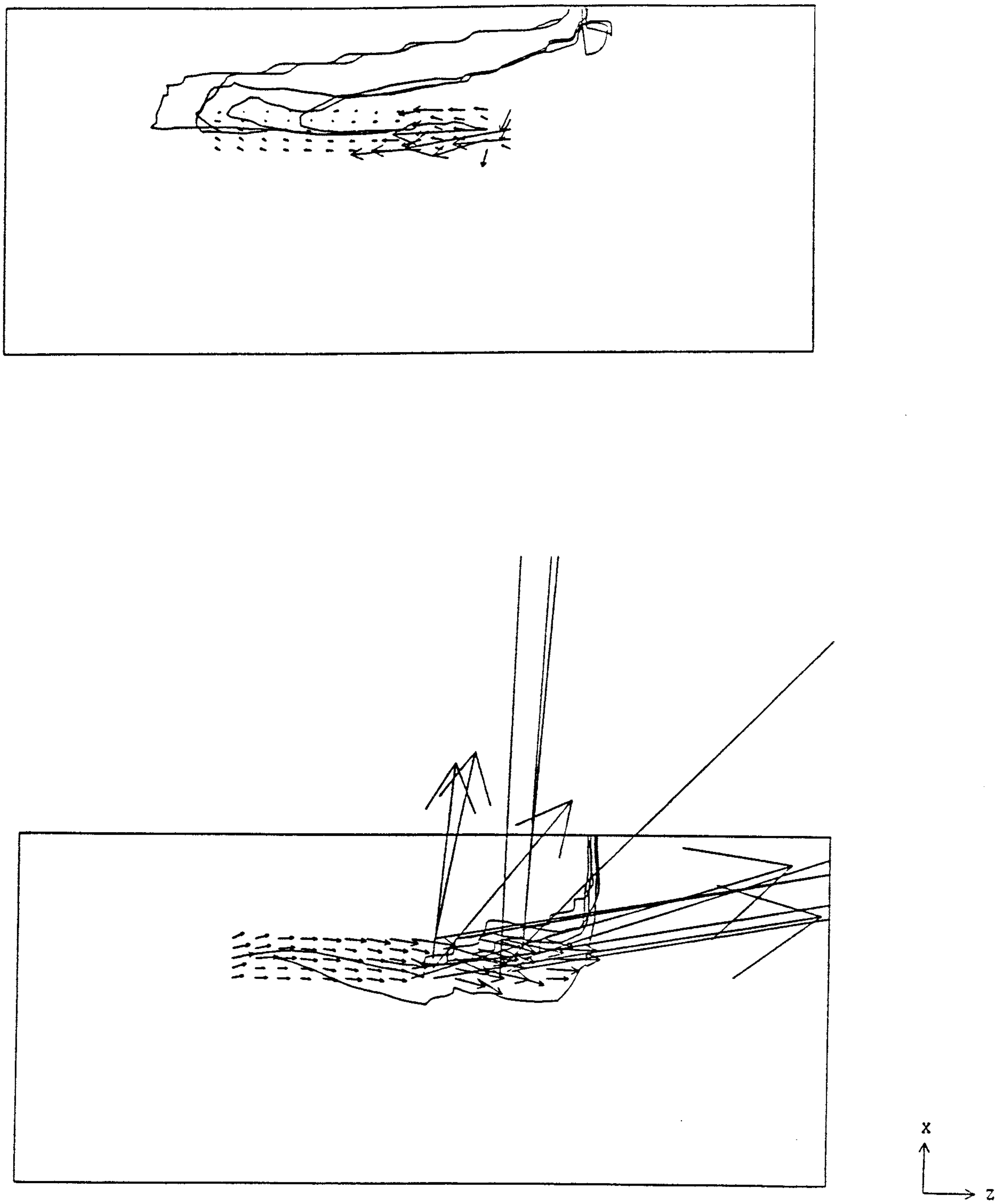


Figure /4-11/. Magnified view of particle tracks and velocity fields for model with salt (top) and without salt.

⟶ 10^{-11} m/s

Care should be taken when interpreting the travel times. One reason for this is that the times are critically dependent on the presence of fracture zones, i.e. if a fracture zone is present at or near the release point the travel time may decrease with orders of magnitude. The estimated time is also proportional to the assumed porosity, which also may vary with an order of magnitude.

One of the reviewers of a draft version of this report suggested an alternative analysis: "Locate the repository at a depth of 600 meters and release about 100 particles at this depth, with and without the presence of salt". This analysis is presented in Appendix A.

5. CONCLUDING REMARKS.

As mentioned in the introduction it is presently not understood why salt water is trapped below zone 2. Ahlbom /1-3/ has presented one explanation, another is suggested in the present report. The numerical model requires a reliable conceptual model if the simulations are to be accepted and trusted. For the present problem it is suggested that the following questions should be addressed if an improved conceptual model is to be established.

- Is it correct to assume that the area has been covered with salt water at one stage and start the analysis from there or do we need to consider several stages with salt and brackish water?
- The conceptual model presented in the present report assumes that a quasi-steady situation can be defined. Is this correct or do we need to consider a transient process?
- What are the conditions east of the Rock Block? Is the clay cover continuous and of low conductivity? Is the groundwater of high salinity?

In additions to these basic issues there is of course also a need for improved knowledge about fracture zones, conductivities, groundwater table, etc. Regarding the conductivity field, this was generated by a stochastic method in this work. The field used should thus be regarded as one realization of several possible. It was decided not to test the sensivity of the results to the sequence of random numbers used for two reasons. Firstly it has been shown previously, see Svensson /3-1/, that the predicted gross features will not change and, secondly, given the above uncertainties of the conceptual model it does not seem motivated.

The results obtained in the present report do not rest on a firm ground, due to the conditions just discussed, and all conclusions have to be tentative in nature. It does however seem likely that the presence of salt water makes the water below zone 2 more stagnant. This is indicated by the travel times for the particles. At the hypothetical repository site depth it was further found that the flow direction is towards the east without salt but towards the west with salt.

The main conclusion of the report is thus that the circulation pattern seems to be significantly changed, due to the presence of salt, both in magnitude and direction.

6. REFERENCES

1-1 Ahlbom, K. and S. Tirén. "Overview of geologic and hydrologic character of the Finnsjö site and its surroundings". SKB, TR 91-08, 1989.

1-2 Andersson, J., Nordqvist, R., Nyberg, G., Smellie, J. and S. Tirén."Hydrogeological conditions in the Finnsjön area". SKB, AR 89-24, 1989.

1-3 Ahlbom, K. "The groundwater circulation in the Finnsjö area - The impact of density gradients". Part A. SKB, AR 90-42, 1990.

2-1 Svensson, U. "The groundwater circulation in the Finnsjö area - The impact of density gradients". Part B. SKB, AR 90-42, 1990.

3-1 Svensson, U. "The Island of Äspö. -Numerical predictions of leakage to a planned tunnel". SKB, Draft dated 1991-03-11.

3-2 Svensson, U. and Hemström, B. "The penetration of sea water into a fresh-water aquifer. A numerical study". SKB, Progress report 25-88-2.

3-3 Spalding, D.B. "A general purpose computer program for multidimensional one- and two-phase flow". Math. Comp. Sim., 8, 267-276, 1981.

4-1 Lindbom, B., Boghammar, A., Lindberg, H. and Bjelkås, J. "Numerical groundwater flow calculations at the Finnsjö site". SKB, Technical report 91-12.

A-1 Ageskog, L., Sjödin, K. Tentative outline and siting of a repository for spent nuclear fuel at the Finnsjön site. SKB, Technical report 91-36.

APPENDIX A

1. INTRODUCTION

The objective of this appendix is to analyze travelling times for marked fluid elements released 600 meters below the ground surface. The particles are to be released within a specified area, called the deposition area in Figure A1, in the northern block. Travelling times will be calculated for 108 particles, with starting positions given in Figure A2. Predictions will be carried out both for the stratified case, i.e. salt is present, and the homogeneous case.

2. RESULTS

Travelling times are summarized in Table A1. The times are given in years, for convenience. A flow porosity of 10^{-4} has been assumed, when estimating the pore velocity from the Darcian velocity. The line numbers in Table A1 refer to the lines shown in Figure A2.

Starting with the homogeneous case one can find a trend on each line, with longer travelling times the further west the particle starts. The average travelling time is about 450 years.

The presence of salt make the travelling times considerably longer as can be seen. Predicted times range from 761 to 27 672 years with an average of about 13 500 years.

3. DISCUSSION

The pore velocities for the stratified case are exceedingly small. If we assume that a particle has to travel 300 meters, on an average, before it finds a fracture zone one may calculate a typical velocity as: 300/10 000 = 0.03 m/year. We can assume that the travelling time in the fracture zone is small compared to the time to reach the zone. It is thus crucial to determine the smallest velocities with high accuracy. In the numerical model it was hence found essential to calculate pore velocites ranging from

10^{-10} m/s to 10^{-3} m/s (in zone 2).

As it is the smallest velocities that determine the travelling times it is of relevance to question how accurate these are. It is believed that the numerical model determines the velocities accurately enough for the conditions given. One can however not exclude that other mechanisms can generate transport of similar, or larger, magnitude. Molecular diffusion is one such mechanism, oscillations generated by yearly ground water variations another. It is outside the scope of the present report to evaluate these.

4. CONCLUDING REMARKS

The general discussion in the concluding remarks of the main report applies also to the results presented in this Appendix. The insight added by the relase of 108 particles at a depth of 600 meters can be summarized as:

- It is crucial to determine the smallest velocities with high accurancy in order to get correct travelling times, in particular for the stratified case.
- The average travelling time, based on a porosity of 10^{-4} and 108 particles, is 450 years for the homogeneous case and 13 500 years for the stratified case.

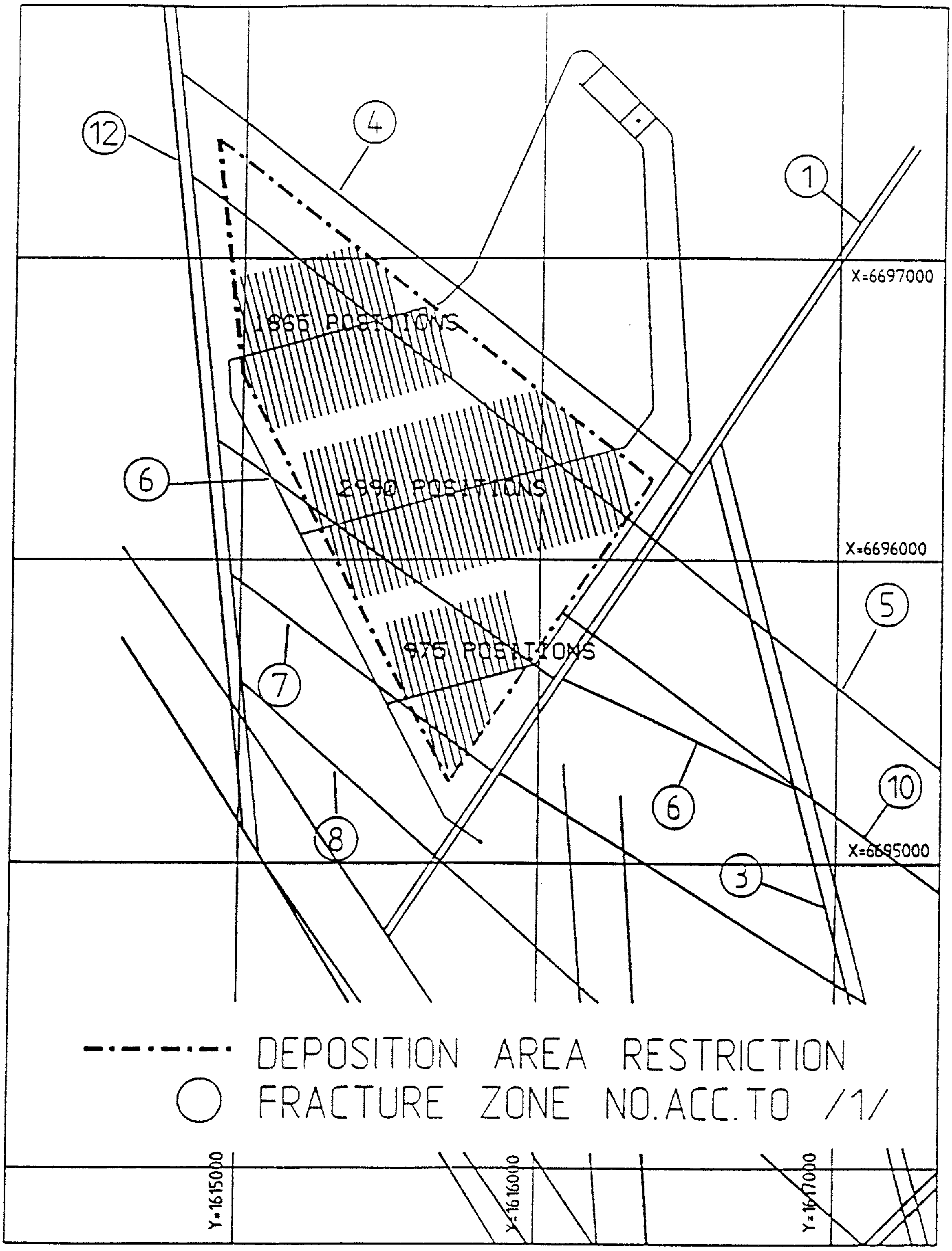


Figure A1. Repository layout. Fracture zones at a depth of 600 meters. Basic figure from Ageskog and Sjöden /A-1/

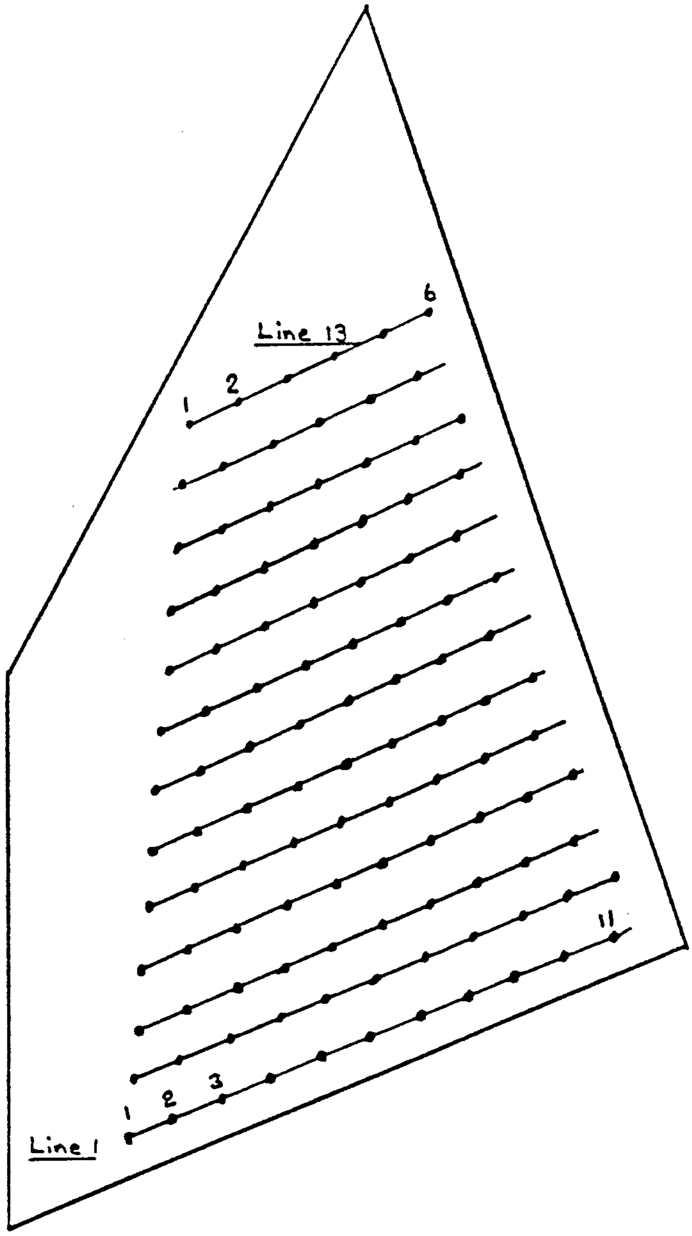


Figure A2. Release points for 108 particles at a depth of 600 meters.

LINE NUMBER = 1

PARTICLE	STRATIFIED	HOMOGENEOUS
1	2693.	941.
2	2860.	302.
3	5141.	159.
4	8339.	148.
5	2265.	26.
6	2308.	26.
7	4878.	178.
8	13238.	145.
9	21312.	6.
10	26536.	146.
11	2417.	38.

LINE NUMBER = 2

PARTICLE	STRATIFIED	HOMOGENEOUS
1	13904.	816.
2	15689.	500.
3	16195.	815.
4	21774.	669.
5	17520.	470.
6	13947.	249.
7	15438.	152.
8	16245.	31.
9	23287.	9.
10	24287.	113.
11	6642.	24.

LINE NUMBER = 3

PARTICLE	STRATIFIED	HOMOGENEOUS
1	19022.	1343.
2	19317.	1246.
3	14558.	911.
4	16369.	872.
5	17758.	625.
6	19694.	306.
7	27672.	145.
8	27079.	17.
9	16776.	127.
10	30703.	26.

LINE NUMBER = 4

PARTICLE	STRATIFIED	HOMOGENEOUS
1	14015.	1299.
2	16041.	1110.
3	21313.	817.
4	17297.	634.
5	18937.	433.
6	21042.	265.
7	26763.	148.
8	26603.	18.
9	17267.	129.
10	12452.	19.

Table A1. Travelling times in years for stratified, i.e. salt present, and homogeneous case.

LINE NUMBER = 5

PARTICLE	STRATIFIED	HOMOGENEOUS
1	14191.	1252.
2	15901.	981.
3	16552.	759.
4	15480.	493.
5	19135.	306.
6	19876.	180.
7	21496.	107.
8	24449.	23.
9	5791.	90.

LINE NUMBER = 6

PARTICLE	STRATIFIED	HOMOGENEOUS
1	9942.	1256.
2	9897.	874.
3	13922.	694.
4	14428.	519.
5	16765.	344.
6	14434.	167.
7	12231.	111.
8	12940.	133.
9	18543.	29.

LINE NUMBER = 7

PARTICLE	STRATIFIED	HOMOGENEOUS
1	8844.	1083.
2	10715.	859.
3	9681.	729.
4	13116.	546.
5	14564.	342.
6	13737.	197.
7	10857.	37.
8	17493.	165.

LINE NUMBER = 8

PARTICLE	STRATIFIED	HOMOGENEOUS
1	19466.	1113.
2	9207.	1015.
3	8406.	759.
4	10616.	491.
5	11805.	270.
6	12631.	127.
7	13290.	160.
8	11254.	32.

LINE NUMBER = 9

PARTICLE	STRATIFIED	HOMOGENEOUS
1	13930.	1235.
2	15499.	929.
3	7595.	696.
4	22161.	490.
5	12105.	291.
6	6328.	150.
7	4481.	132.

Table A1. Continued.

LINE NUMBER = 10

PARTICLE	STRATIFIED	HOMOGENEOUS
1	5725.	1017.
2	4449.	1060.
3	5953.	607.
4	8707.	362.
5	9548.	265.
6	26128.	72.
7	3577.	163.

LINE NUMBER = 11

PARTICLE	STRATIFIED	HOMOGENEOUS
1	20123.	1030.
2	12581.	862.
3	12885.	586.
4	6751.	253.
5	9469.	70.
6	5170.	172.

LINE NUMBER = 12

PARTICLE	STRATIFIED	HOMOGENEOUS
1	8564.	1079.
2	10020.	681.
3	5622.	465.
4	6364.	184.
5	761.	170.
6	3976.	106.

LINE NUMBER = 13

PARTICLE	STRATIFIED	HOMOGENEOUS
1	7015.	911.
2	8612.	646.
3	9561.	405.
4	11915.	200.
5	11527.	113.
6	9774.	52.

Table A1. Continued.

List of SKB reports

Annual Reports

1977-78
TR 121
KBS Technical Reports 1 – 120
Summaries
Stockholm, May 1979

1979
TR 79-28
The KBS Annual Report 1979
KBS Technical Reports 79-01 – 79-27
Summaries
Stockholm, March 1980

1980
TR 80-26
The KBS Annual Report 1980
KBS Technical Reports 80-01 – 80-25
Summaries
Stockholm, March 1981

1981
TR 81-17
The KBS Annual Report 1981
KBS Technical Reports 81-01 – 81-16
Summaries
Stockholm, April 1982

1982
TR 82-28
The KBS Annual Report 1982
KBS Technical Reports 82-01 – 82-27
Summaries
Stockholm, July 1983

1983
TR 83-77
The KBS Annual Report 1983
KBS Technical Reports 83-01 – 83-76
Summaries
Stockholm, June 1984

1984
TR 85-01
Annual Research and Development Report 1984
Including Summaries of Technical Reports Issued during 1984. (Technical Reports 84-01 – 84-19)
Stockholm, June 1985

1985
TR 85-20
Annual Research and Development Report 1985
Including Summaries of Technical Reports Issued during 1985. (Technical Reports 85-01 – 85-19)
Stockholm, May 1986

1986
TR 86-31
SKB Annual Report 1986
Including Summaries of Technical Reports Issued during 1986
Stockholm, May 1987

1987
TR 87-33
SKB Annual Report 1987
Including Summaries of Technical Reports Issued during 1987
Stockholm, May 1988

1988
TR 88-32
SKB Annual Report 1988
Including Summaries of Technical Reports Issued during 1988
Stockholm, May 1989

1989
TR 89-40
SKB Annual Report 1989
Including Summaries of Technical Reports Issued during 1989
Stockholm, May 1990

1990
TR 90-46
SKB Annual Report 1990
Including Summaries of Technical Reports Issued during 1990
Stockholm, May 1991

Technical Reports

List of SKB Technical Reports 1991

TR 91-01
Description of geological data in SKB's database GEOTAB Version 2
Stefan Sehlstedt, Tomas Stark
SGAB, Luleå
January 1991

TR 91-02
Description of geophysical data in SKB database GEOTAB Version 2
Stefan Sehlstedt
SGAB, Luleå
January 1991

TR 91-03
1. The application of PIE techniques to the study of the corrosion of spent oxide fuel in deep-rock ground waters
2. Spent fuel degradation
R S Forsyth
Studsvik Nuclear
January 1991

TR 91-04
Plutonium solubilities
I Puigdomènech[1], J Bruno[2]
[1]Enviromental Services, Studsvik Nuclear, Nyköping, Sweden
[2]MBT Tecnologia Ambiental, CENT, Cerdanyola, Spain
February 1991

TR 91-05
Description of tracer data in the SKB database GEOTAB
SGAB, Luleå
April, 1991

TR 91-06
Description of background data in the SKB database GEOTAB
Version 2
Ebbe Eriksson, Stefan Sehlstedt
SGAB, Luleå
March 1991

TR 91-07
Description of hydrogeological data in the SKB's database GEOTAB
Version 2
Margareta Gerlach (ed.)
Mark Radon Miljö MRM Konsult AB, Luleå
December 1991

TR 91-08
Overview of geologic and geohydrologic conditions at the Finnsjön site and its surroundings
Kaj Ahlbom[1], Sven Tirén[2]
[1]Conterra AB
[2]Sveriges Geologiska AB
January 1991

TR 91-09
Long term sampling and measuring program. Joint report for 1987, 1988 and 1989. Within the project: Fallout studies in the Gideå and Finnsjö areas after the Chernobyl accident in 1986
Thomas Ittner
SGAB, Uppsala
December 1990

TR 91-10
Sealing of rock joints by induced calcite precipitation. A case study from Bergeforsen hydro power plant
Eva Hakami[1], Anders Ekstav[2], Ulf Qvarfort[2]
[1]Vattenfall HydroPower AB
[2]Golder Geosystem AB
January 1991

TR 91-11
Impact from the disturbed zone on nuclide migration – a radioactive waste repository study
Akke Bengtsson[1], Bertil Grundfelt[1], Anders Markström[1], Anders Rasmuson[2]
[1]KEMAKTA Konsult AB
[2]Chalmers Institute of Technology
January 1991

TR 91-12
Numerical groundwater flow calculations at the Finnsjön site
Björn Lindbom, Anders Boghammar, Hans Lindberg, Jan Bjelkås
KEMAKTA Consultants Co, Stockholm
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TR 91-13
Discrete fracture modelling of the Finnsjön rock mass
Phase 1 feasibility study
J E Geier, C-L Axelsson
Golder Geosystem AB, Uppsala
March 1991

TR 91-14
Channel widths
Kai Palmqvist, Marianne Lindström
BERGAB-Berggeologiska Undersökningar AB
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TR 91-15
Uraninite alteration in an oxidizing environment and its relevance to the disposal of spent nuclear fuel
Robert Finch, Rodney Ewing
Department of Geology, University of New Mexico
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Porosity, sorption and diffusivity data compiled for the SKB 91 study
Fredrik Brandberg, Kristina Skagius
Kemakta Consultants Co, Stockholm
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Seismically deformed sediments in the Lansjärv area, Northern Sweden
Robert Lagerbäck
May 1991

TR 91-18
Numerical inversion of Laplace transforms using integration and convergence acceleration
Sven-Åke Gustafson
Rogaland University, Stavanger, Norway
May 1991

TR 91-19
NEAR21 - A near field radionuclide migration code for use with the PROPER package
Sven Norman[1], Nils Kjellbert[2]
[1]Starprog AB
[2]SKB AB
April 1991

TR 91-20
Äspö Hard Rock Laboratory. Overview of the investigations 1986-1990
R Stanfors, M Erlström, I Markström
June 1991

TR 91-21
Äspö Hard Rock Laboratory. Field investigation methodology and instruments used in the pre-investigation phase, 1986-1990
K-E Almén, O Zellman
June 1991

TR 91-22
Äspö Hard Rock Laboratory. Evaluation and conceptual modelling based on the pre-investigations 1986-1990
P Wikberg, G Gustafson, I Rhén, R Stanfors
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TR 91-23
Äspö Hard Rock Laboratory. Predictions prior to excavation and the process of their validation
Gunnar Gustafson, Magnus Liedholm, Ingvar Rhén, Roy Stanfors, Peter Wikberg
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TR 91-24
Hydrogeological conditions in the Finnsjön area. Compilation of data and conceptual model
Jan-Erik Andersson, Rune Nordqvist, Göran Nyberg, John Smellie, Sven Tirén
February 1991

TR 91-25
The role of the disturbed rock zone in radioactive waste repository safety and performance assessment. A topical discussion and international overview.
Anders Winberg
June 1991

TR 91-26
Testing of parameter averaging techniques for far-field migration calculations using FARF31 with varying velocity.
Akke Bengtsson[1], Anders Boghammar[1], Bertil Grundfelt[1], Anders Rasmuson[2]
[1]KEMAKTA Consultants Co
[2]Chalmers Institute of Technology

TR 91-27
Verification of HYDRASTAR. A code for stochastic continuum simulation of groundwater flow
Sven Norman
Starprog AB
July 1991

TR 91-28
Radionuclide content in surface and groundwater transformed into breakthrough curves. A Chernobyl fallout study in an forested area in Northern Sweden
Thomas Ittner, Erik Gustafsson, Rune Nordqvist
SGAB, Uppsala
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TR 91-29
Soil map, area and volume calculations in Orrmyrberget catchment basin at Gideå, Northern Sweden
Thomas Ittner, P-T Tammela, Erik Gustafsson
SGAB, Uppsala
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A resistance network model for radionuclide transport into the near field surrounding a repository for nuclear waste (SKB, Near Field Model 91)
Lennart Nilsson, Luis Moreno, Ivars Neretnieks, Leonardo Romero
Department of Chemical Engineering, Royal Institute of Technology, Stockholm
June 1991

TR 91-31
Near field studies within the SKB 91 project
Hans Widén, Akke Bengtsson, Bertil Grundfelt
Kemakta Consultants AB, Stockholm
June 1991

TR 91-32
SKB/TVO Ice age scenario
Kaj Ahlbom[1], Timo Äikäs[2], Lars O. Ericsson[3]
[1]Conterra AB
[2]Teollisuuden Voima Oy (TVO)
[3]Svensk Kärnbränslehantering AB (SKB)
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TR 91-33
Transient nuclide release through the bentonite barrier - SKB 91
Akke Bengtsson, Hans Widén
Kemakta Konsult AB
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SIMFUEL dissolution studies in granitic groundwater
I Casas[1], A Sandino[2], M S Caceci[1], J Bruno[1], K Ollila[3]
[1]MBT Tecnologia Ambiental, CENT, Cerdanyola, Spain
[2]KTH, Dpt. of Inorganic Chemistry, Stockholm, Sweden
[3]VTT, Tech. Res. Center of Finland, Espoo, Finland
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TR 91-35
Storage of nuclear waste in long boreholes
Håkan Sandstedt[1], Curt Wichmann[1], Roland Pusch[2], Lennart Börgesson[2], Bengt Lönnerberg[3]
[1]Tyréns
[2]Clay Technology AB
[3]ABB Atom
August 1991

TR 91-36
Tentative outline and siting of a repository for spent nuclear fuel at the Finnsjön site. SKB 91 reference concept
Lars Ageskog, Kjell Sjödin
VBB VIAK
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Pertti Auerkari, Heikki Leinonen, Stefan Sandlin
VTT, Metals Laboratory, Finland
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Dept. Land and Water Resources, Royal Institute of Technology, Stockholm, Sweden
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MBT Tecnologìa Ambiental, Cerdanyola, Spain
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Leonardo Romero, Luis Moreno, Ivars Neretnieks
Department of Chemical Engineering, Royal Institute of Technology, Stockholm, Sweden
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TR 91-49
Description of transport pathways in a KBS-3 type repository
Roland Pusch[1], Ivars Neretnieks[2], Patrik Sellin[3]
[1] Clay Technology AB. Lund
[2] The Royal institue of Techonology Department of Chemical Engineering, Stockholm
[3] Swedisch Nueclear Fuel and Waste Management Co (SKB), Stockholm
December 1991

TR 91-50
Concentrations of particulate matter and humic substances in deep groundwaters and estimated effects on the adsorption and transport of radionuclides
Bert Allard[1], Fred Karlsson[2], Ivars Neretnieks[3]
[1]Department of Water and Environmental Studies, University of Linköping, Sweden
[2]Swedish Nuclear Fuel and Waste Management Company, SKB, Stockholm, Sweden
[3]Department of Chemical Engineering, Royal Institute of Technology, Stockholm, Sweden
November 1991

TR 91-51
Gideå study site. Scope of activities and main results
Kaj Ahlbom[1], Jan-Erik Andersson[2],
Rune Nordqvist[2], Christer Ljunggren[2], Sven Tirén[2],
Clifford Voss[3]
[1]Conterra AB
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October 1991

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Fjällveden study site. Scope of activities and main results
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