SKB TECHNICAL REPORT 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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SVENSK KÄRNBRÄNSLEHANTERING AB
SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT CO

BOX 5864 S-102 48 STOCKHOLM

TEL 08-665 28 00 TELEX 13108 SKB S
TELEFAX 08-661 57 19

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JUNE 1991

compiled by:

Kaj Ahlbom*

Timo Äikäs**

Lars O. Ericsson***

* Conterra AB
** Teollisuuden Voima Oy (TVO)
*** Svensk Kärnbränslehantering AB (SKB)

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FOREWORD

Ice ages have repeatedly occurred throughout geological history, and it is likely that they will also occur in the time-span considered for the disposal of spent nuclear fuel. Based on the present status of knowledge, this report discusses when future ice ages will occur and the possible changes in the geosphere that might be of importance for repository performance. The report is intended to be used as a basis when developing scenarios for safety analysis of a final repository for spent nuclear fuel.

The principal processes predicted to occur during future glaciations, and which are likely to be of importance for a repository, were initially formulated at working meetings and finally discussed at a seminar held in Helsinki, June 13, 1990. The state-of-the-art was compiled in two reports by Eronen & Olander (1990) and Björck & Svensson (1990). This report constitutes a synthesis of the results from the above-mentioned meetings and reports, together with other relevant data. During the spring of 1991, a draft version of this report was reviewed by Prof. G.S.Boulton and many of the improvements suggested by him have been implemented.

CONTENTS

1. GENERAL

The world's climate will be dominated by glaciations for the next 100 000 years in the same way as it has been over similar periods for the past million years. This forecast is based on the last 20 years of research which have clearly demonstrated that glaciations have occurred periodically for at least the last 900 000 years. There is also an overwhelming evidence that the time of occurrence of glaciations are triggered by small periodic changes in the earth's orbit around the sun (Milankovitch orbital parameters) resulting in changes in the solar radiation reaching earth. Since these periodic changes are possible to calculate for the future, also predictions of future glaciations can be made.

Astronomical data show that we are presently approaching the end of an interglacial (warm) period and the climate is slowly developing towards glacial conditions. Anthropogenic (human) effects, such as the greenhouse effect, might possibly delay the change-over to glacial conditions. This possibility is still difficult to assess quantitatively. The following scenario therefore chooses to consider climatic trends unaffected by human activities.

Future changes in the global climate are often thought to influence the long term performance of a final repository for spent nuclear fuel. Since there are great similarities in the geographic and geologic setting between Sweden and Finland, as well as similarities in the concepts for spent fuel repositories, it was decided by SKB and TVO to jointly develop a scenario for future glaciations.

2. THE GLACIATION SCENARIO

The aim of the SKB/TVO glaciation scenario is to identify and describe those conditions that during a glaciation cycle might have an influence on the performance of the repository. A realistic description of these conditions is aimed for in this report.

The means to achieve this are:

1 an overview over the various mechanisms and processes involved in a typical glaciation cycle (this report)

2 identification of those processes and mechanisms that might influence repository performance and

3 assessment of their influence on man and his environment.

This report concerns the first point in this listing. The scenario covers the time from today and to the next interglacial, i.e. the next time when climatic conditions will once again return to the present conditions, and thus make it possible for man to resettle. Such a warm climate is likely to occur at the interglacial period around 75 000 years from today. Only a brief description will be presented of the expected climatic conditions after that time.

It is recognized that the prediction of how a glaciation period will develop must be beset with substantial uncertainties. Since, however, any large glaciation, irrespective of the existence of a repository for radioactive waste, will substantially change most environmental conditions for man's existence, a detailed evaluation of possible future doses is not meaningful. The primary purpose is to see if the existence of a repository might in a substantial way restrict man's use of his natural environment in a period when the glaciated area once again is resettled.

3. FUTURE GLACIATIONS

3.1 General

This report describes timing, extent and duration of future glaciations. The chapter also discusses, for each glaciation cycle, the extent of permafrost, thickness of ice, downwarping of the crust and relative sea-level changes with mainly reference to the Stockholm-Helsinki region. The effect of a repository on man during a glaciation cycle will depend on the biosphere that can exist and on man's use of groundwater and land. The climatic situation during the "warm periods" (interglacials and interstadials) between the glaciations will be discussed from this point of view.

The term glacial or stadial denotes cold periods with large build-up of ice sheets. Interstadials are temporarily warmer periods, within a glacial cycle, with a climate similar to Greenland or Antarctica (periglacial conditions). Interglacials are major warmer periods with a climate similar to the present.

3.2 Climate models

In the development of the SKB/TVO glaciation scenario the ACLIN (Astronomical Climate Index, see Mattews in AECL-7822 and Kukla, 1979) and the Imbrie & Imbrie (1980) model of future climate has been considered. Although the ACLIN model is calibrated to past marine climatic record, the output from this model is mainly related to the Milankovich orbital parameters. In the Imbrie & Imbrie model the output from the orbital parameters has been tuned to six radiometrically dated events in the past.

3.2.1 ACLIN model

The output from the ACLIN model consist of indices (figure 1) where those exceeding 4.3 are judged to represent interglacial conditions. Values between 4.3 to 3.6 represent temperate interstadials, those between 2.5 to 3.6 represent interstadials and values less than 2.5 represent stadials. In figure 1 the output for the period - 1 million to + 1 million years is presented. As can be seen in the figure the model suggest regular occurring glaciations (about 40 stadials /million year).

The model output for the last interglacial-glacial cycle and the forecast for the next 60 000 years is shown in figure 2. The ACLIN curve suggests that we are now in the final stages of a true interglacial. Between now and the next interglacial, climate should remain predominantly cold, except for two temperate interstadials. The temperatures will gradually reach a first minimum around 5000 years from now. Considering the short time until this first cold period, it is not clear whether this period will actually result in major glaciation. There is however great probability that glaciation will occur at c. 23 000, 60 000 and 100 000 years from now. Interstadial conditions will prevail between these three glaciations. The next interglacial is expected at 125 000 years.

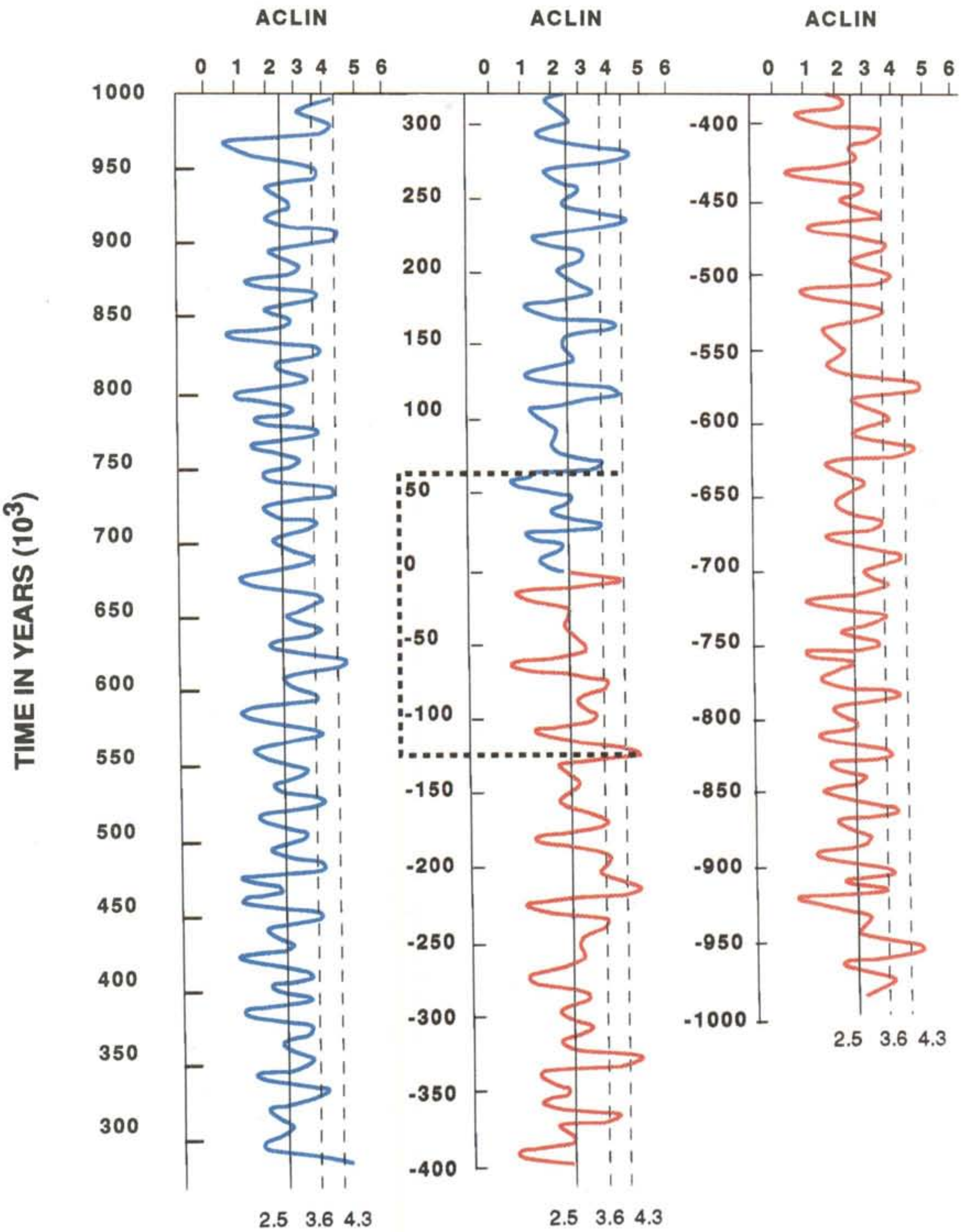

Figure 1. Astronomical Climate Index (ACLIN) for the period from -1 million years to +1 million years (from AECL 7822). The ACLIN curve within the dashed line represent the last glacial cycle and the next 60 000 years. This part is showed in detail in figure 2.

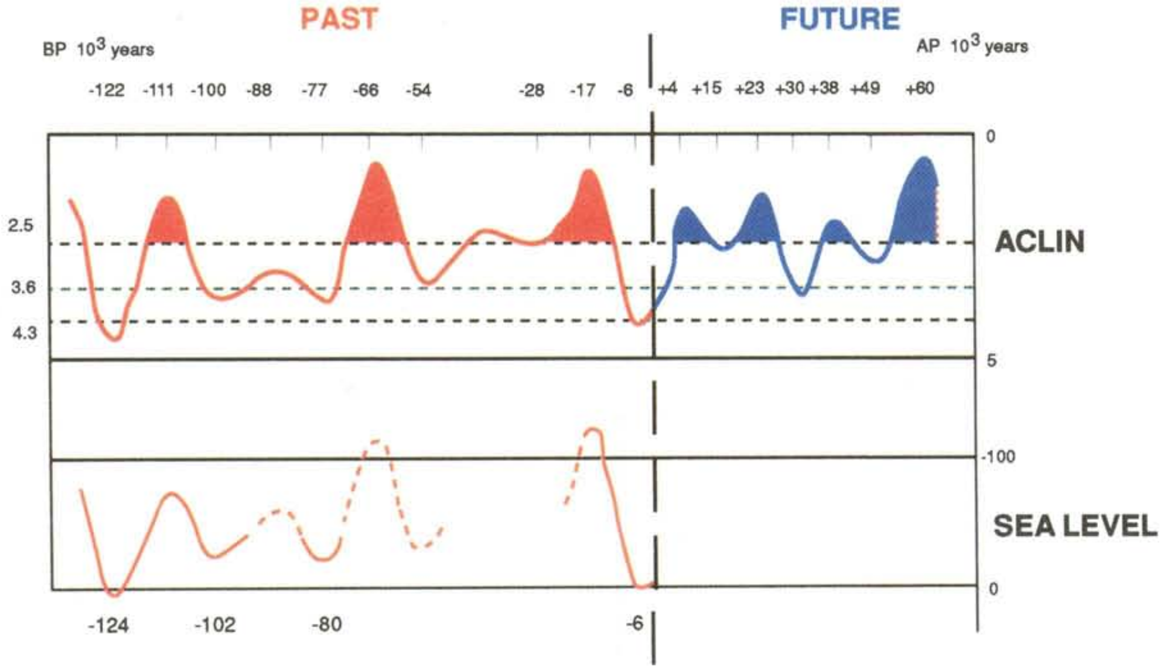

Figure 2. Above, the last glacial cycle and the ACLIN projected climate of the next 60 000 years. Below, the world sea-level (from AECL 7822).

3.2.2 Imbrie & Imbrie model

The output from the Imbrie & Imbrie (1980) model (figure 3) is the global variation of ^{18}O, which indirectly is a measure of the amount of water that is tied to continental ice sheets. This output can be used to predict the extent of future ice sheets by comparing the predicted ^{18}O values for future glaciations with known variations in ^{18}O values for past glaciations (with known extensions of ice sheets). Figure 3 shows that the Imbrie & Imbrie model is capable of simulating the last 350 000 years of climatic changes very well.

Similar to the ACLIN model the Imbrie & Imbrie model show that present day interglacial conditions are gradually changing to glacial conditions with a maximum occurring at 23 000 years. However, no "cold peak" at 5 000 years is predicted as in the ACLIN model. The next glaciations will occur at c. 63 000 years and 100 000 years.

The Imbrie & Imbrie model suggests that the amount of ice tied to continental ice-sheets during the 23 000 year glaciation will be similar to an early stage (the so called isotope stage 4, c. 60 000 BP) of the Weichselian glaciation when parts of Scandinavia and North America were glaciated. A probable extension of the ice sheet is down to the Stockholm-Helsinki region. For the glaciation 60 000 years ahead the ice sheet might extend down to northern Germany, thus covering the whole of Sweden and Finland.

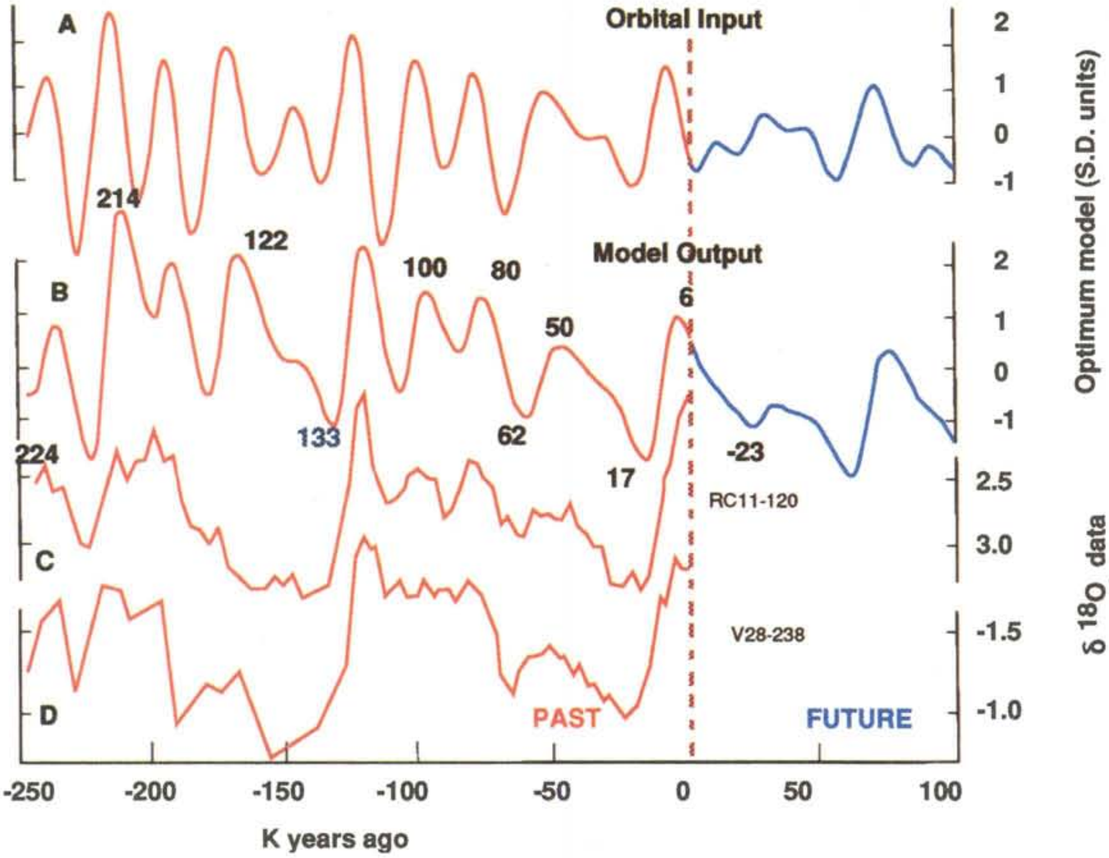

Figure 3. Input and output of Imbrie & Imbrie (1980) response model compared with isotopic data on climate of the past 250 000 years. A = orbital input, B = model output, C = oxygen isotope curve (Indian ocean), D = oxygen isotope curve (Pacific ocean).

3.2.3 Other models

Apart from the ACLIN and Imbrie & Imbrie models there are several other models of future climate (Calder, 1974, Weertman, 1976, Berger et al, 1981, Kukla et al, 1981 and Oerlemans & Van der Veen, 1984). All models show a basic similarity of output, reflecting characteristics both of the record of geological change and Milankovitch fluctuations. Most models predict a glacial phase at 60 000 years with a magnitude similar to the last glacial maximum, and with a duration of 20 000-25 000 years. Most models also support the 20 000 year glaciation, while only one model (Berger et al, 1981) support the 5000 year glaciation.

3.3 Future deglaciation periods

As discussed above, both the ACLIN and the Imbrie & Imbrie models shows that the present climate will gradually change into colder conditions until a full glaciation is reached after c. 23 000 years. The first somewhat "warmer" period (interstadial) will occur between c. 30 000-50 000 years. (The ACLIN model suggests a minor stadial within this period.) Both models suggest periglacial conditions during this period. This implies an extremely harsh climate in central and northern Sweden and the whole of Finland with conditions comparable to present day Greenland or Antarctica.

The next deglaciation period will according to both models occur between c. 70 000 to 80 000 years, with its optimum at c. 75 000 years. The Imbrie & Imbrie model indicates "moderate" interglacial conditions during this period (i.e. a climate in southern Sweden/Finland similar to present day northern Sweden/Finland). The ACLIN model indicates interstadial conditions at this period (similar to the conditions at the 30 000-50 000 interstadial) and not until 125 000 years ahead will the climate, according to this model, return to present day conditions.

3.4 Summary

Both the ACLIN and Imbrie & Imbrie models suggest stadials (glaciations) at c. 20 000, 60 000 and 100 000 years from now. The ACLIN model also suggests a glaciation period around 5000 years ahead. The next interglacial period will occur at c. 75 000 years, according to the Imbrie & Imbrie model, while the ACLIN model suggests that interglacial conditions will not appear until 125 000 years from now. Other models strongly support the 60 000 year glaciation event. To some extent there is also support for the 20 000 and 5000 year events.

For the purpose of the SKB/TVO scenario it is suggested that smaller or larger glaciations will occur at 5000, 20 000 and 60 000 years from now. Following the last glaciation, interglacial conditions will prevail at 75 000 years. Thus after the first glaciation (5000 years) this is the earliest time when most parts of Sweden and Finland will once again be resettled by man.

4. CONDITIONS DURING A GLACIATION CYCLE

4.1 General

This chapter presents some of the major characteristics and conditions of a "typical glaciation". The aim is to present a background for later conceptual modelling and evaluation of possible consequences for repository performance.

Each section is divided into two parts, overview and scenario description. The overview part summarizes the present knowledge, primarily based on the reports by Eronen & Olander (1990) and Björck & Svensson (1990), while the scenario part discusses what conditions should be assumed in the reference scenario.

4.2 Permafrost and subglacial temperatures

4.2.1 Overview

In general a glaciation is preceded by tundra and permafrost. However this is not always so. The formation of permafrost requires dry and cold conditions with mean annual temperatures colder than 2-3° C below zero. Contrasts in snow depth may significantly change the relative depth of permafrost when this is thin, but will be unimportant for deep permafrost. Water bodies (lakes, rivers, sea) are important for permafrost distribution as they have a large thermal capacity and both by conduction and groundwater advection, tend to melt permafrost. Also the length of the freezing period before the ice covers the area and local effects, such as topography and wind, influence the formation and distribution of permafrost. In general, permafrost will reduce the recharge of the groundwater.

During the last glacial maximum, about 18 000 BP, permafrost spread to extensive areas beyond those covered by the ice sheets, figure 4. During this time also the proportion of forest in central and southern Europe decreased, while that of tundra, steppes and deserts increased (CLIMAP, 1976).

As the continental ice sheet grows, and extends over a frozen ground, the base of the glacier will initially be cold. However, the geothermal heat will gradually raise the temperature at the base of the ice sheet. If permafrost has been buried beneath the glacier this will begin to melt gradually from the bottom and upwards. If the temperature at the base of the glacier reaches the pressure melting point (-1.6° C for a 2 km ice thickness) the permafrost will also melt. Thus glaciers can be either cold-based or warmed-based, i.e. with temperature at their base either below the temperature required for pressure melting or above that point. In the present-day ice sheets the cold-based type dominates (figure 5).

During the freezing process dissolved ions will be concentrated below the permafrost. If this process continues for a long time the salinity of the groundwater might raise due to the formation of ice.

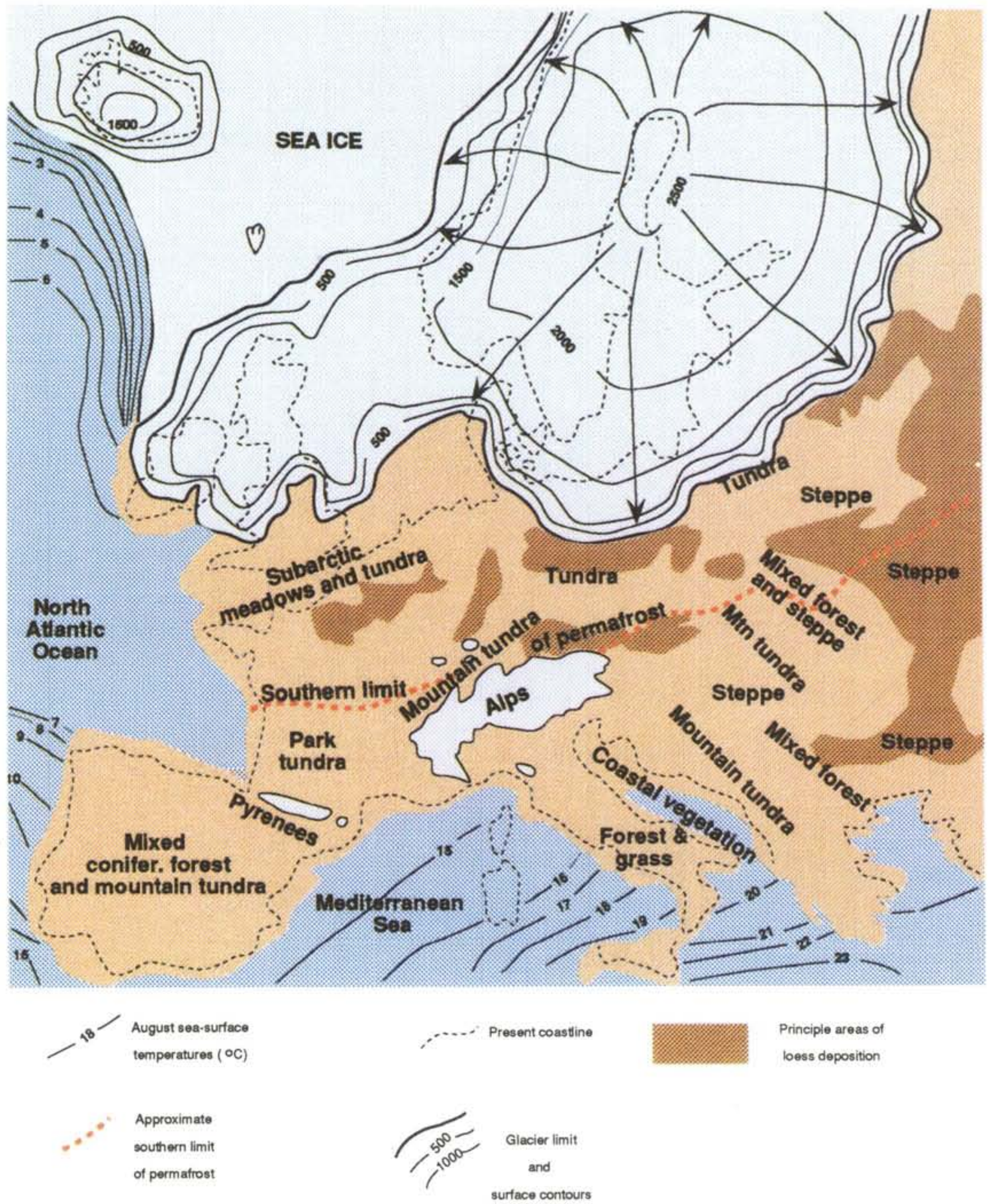

Figure 4. A reconstruction of the paleogeography of northern and western Europe during the last glacial maximum, about 18 000 B.P. (from Skinner & Porter, 1987).

4.2.2 Scenario

Permafrost occurs both during glaciation advance and during deglaciation. The extent and thickness of permafrost during a glaciation period could however vary considerable due to global as well as local conditions. It is therefore not at present possible to suggest probable maximum permafrost depth. Thus, for the purpose of the SKB/TVO scenario a wide range of permafrost depths should be considered, a possible variation could be from shallow to depths of more than 500 m.

Figure 5. Calculated basal temperatures for the Antarctic ice sheet, contoured for each 10° C below pressure melting-point. The blue areas are at pressure meltingpoint (from Embleton & King, 1975).

4.3 Ice sheet thickness and erosion

4.3.1 Overview

Today the largest ice sheet by far occurs over the Antarctic continent. Its ice sheet covers an area of one and a half times of the United States. The mean thickness of the Antarctic ice sheet is estimated to about 2 000 m and the maximum thickness to about 4 000 m. Several glaciological reconstructions of the last European ice sheet all produce centre-height estimates at the glacial maximum of the order of 2.5-3.0 km, with sub-ice depression between 900-500 m (Mörner, 1979, Boulton et al, 1985; Oerlemans, 1982; Lindstrom, 1989).

When consider erosion, recent calculations (Hindmarsh, Boulton and Hutter, 1989) indicate that the central part of the ice-sheet have basal temperatures beneath the melting point, and thus with no or very little erosion. This part is fringed by a broad zone of melting with associated erosion. Irregularities in the ice substrate in the melting zone will give rise to pressure variations, so that the temperature will drop below the pressure melting point at times, causing the base of the glacier to freeze temporarily and the ground surface to attach tightly to the basal ice in places, causing a powerful abrasion effect and detaching pieces of the underlying material, which are then carried away by the glacial flow.

The erosional effect of a continental ice sheet will vary greatly in time and from one place to another. It is therefore difficult to measure the extent of this erosion. Calculations on the extent on erosion have nevertheless been made from the amounts of sediments derived from ice erosion. For example, the mean depth of the mineral soil in Finland is 8.3 m (Okko, 1964). Although, this estimate of erosion is uncertain, there are other strong indications that erosion in bedrock during a single glacial cycle does not exceed 10 m. It could thus be concluded that erosion is not a significant process in regions of pre-glacial low relief, such as Finland or Sweden (outside the Caledonian mountains). Plucking is probably the most important erosional process related to ice sheets.

4.3.2 Scenario

For the three postulated future glaciations, discussed earlier, the ice thickness at the centre of the ice sheet is estimated to 1 000 m for the first (5 000 yr), 1 500 m for the second (20 000 yr) and 3 000 m for the third (60 000 yr). The centre of the ice sheet is assumed to be located at the Caledonian mountains for the first glaciation and at the Gulf of Bothnia (NE Sweden) for the second and third glaciation. The maximum thickness of the ice sheet at the Stockholm-Helsinki region for these three glaciations are 0 m, 800 m and 2000 m, respectively.

The average erosion during a glaciation cycle in the low relief areas of Finland and Sweden does not exceed 5-10 m.

4.4 Deflection of the crust, downwarping and rebound

4.4.1 Overview

Glacially induced downwarping and rebound is in fact the best understood large-scale crustal deformation process we know, and as such a key to the mechanics of other large-scale crustal deformations. Its basic principle is the application, and later removal, of an extra load of relatively low density, upon a denser crust in previously approximate isostatic equilibrium, and a viscoelastic response, involving both the crust and the mantle. In detail, of course, this is not a simple system to describe mechanically, and the processes are further complicated, for instance by considerable shifts in the location of the maximum load both during loading and deglaciation. They are produced by internal flowlike movements in the ice, reflecting major topography beneath the ice, and shifts in the location of maximum precipitation.

Ice sheets provide loads of relatively high magnitudes and of such short durations that they, in the geological time scale perspective, often do not achieve isostatic equilibrium. The time-lag involved in the process could be as much as 15 000 to 20 000 years. As a rule of thumb, the maximum crustal downwarping beneath a large ice sheet is estimated to about 25-30 per cent of the maximum ice thickness. However, for ice sheets of short duration the downwarping is considerable less.

The surface rebound decreases exponentially after the release of the ice-load on the bedrock. Just after the melting, and within the central parts of the glaciated area, the uplift rate may exceed 0,1 m per year. 10 000 years later the rate of uplift may be in the order of 0,01 m per year.

Different approaches have been used to determine the contours and the amount of the absolute downwarping or uplift due to the Late Weichselian (maximum extension at 18 000 years BP) ice sheet. Mörner (1979) estimates a maximum absolute uplift of 800 m (figure 6), based on ancient shorelines. According to this model the maximum surface gradient of the crust, within the central parts of the cone of depression, is estimated to c. 1 m/km.

On the sides of the ice-dependent central depression there will occur an arch formation. This arch is called a forebulge (figure 6). The absolute height of the forebulge is very uncertain because of the dynamic stress situation during the glaciation. However, at full extension of a major glaciation, the forebulge is not expected to exceed a height of 150 m.

4.4.2 Scenario

The crustal downwarpings presented below for the three postulated ice sheets are of course speculative. They are mainly based on the assumption of 25-30% maximum downwarping to the three postulated ice sheets. This will result in a maximum crustal downwarping at the glaciation centre of 300 m for the first (5 000 yr), 500 m for the second (20 000 yr) and 700 m for the third (60 000 yr).

The crustal downwarping at the Stockholm-Helsinki region for these ice sheets are assumed to be 0, 60 m and 600 m. The first ice sheet will not to reach the Stockholm-Helsinki region, thus no downwarping will occur. The downwarping of the second ice sheet will be limited because this ice sheet will not occupy this region long enough for maximum downwarping to occur. Maximum downwarping is however assumed for the extensive third ice sheet.

There is some doubt if a "migrating forebulge" exists during an ice advance. Still, if such a forebulge is considered it might have a maximum height of 50 m.

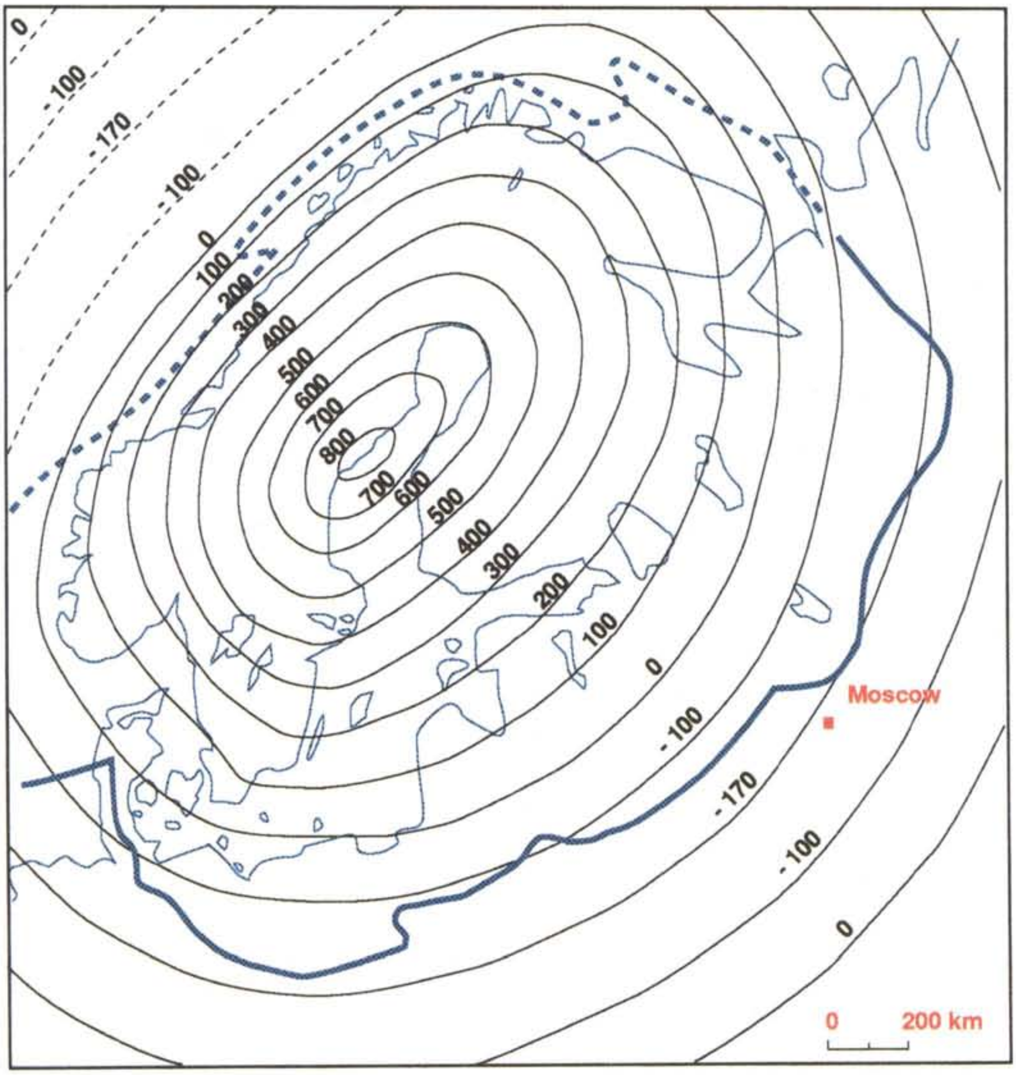

Figure 6. Contours of total absolute uplift and subsidence in relation to the last glaciation of the Fennoscandian Shield (modified after Mörner, 1979).

4.5 Sea-level changes

4.5.1 Overview

During continental glaciations an essential part of the water in the hydrosphere is successively stored in the glaciers which causes the global sea-level to descend. Sea-level changes are much dependent on the degree of glaciation. Due to the coupled effects of sea-level changes and crustal displacements in response to glacial loading and rebound, the global, as well as the local, sea-levels are complicated to predict.

The first order sea-level trends in Europe during a glacial cycle is controlled by global ice volume change. The largest component of which is the North American

(Laurentide) ice sheet. A glaciation down to the Stockholm-Helsinki region implies a global lowering of the sea-level of approximately 85 m. A maximum extension of a Fennoscandian ice sheet (ice sheet down to northern Germany) will imply a global sea-level lowering of 100-150 m. The ice/bedrock interface in the central part of the ice sheet will at this latter time be at 500-600 m below the sea-level (as is the case with present day Antarctica), if the maximum depression of the crust coincides in time with the maximum global lowering of the sea-level.

Generally, deglaciation implies a sea-level rise. However immediately after the commencement of the ice retreat the land uplift may exceed the sea-level rise. During a major deglaciation, one may assume that the sea-level in the Stockholm-Helsinki region would reach a level about 100 m higher then at present (highest shoreline). The relative sea-level changes of the Baltic Sea during deglaciation of the last (Weichselian) ice sheet is presented in figure 7. During periods of constant ice-masses the global sea-level is assumed constant and the relative changes are due to delayed isostatic crustal adjustments.

In the context of discussing relative sea-level changes also a rapid drainage of dammed extensive ice lakes (e.g. the Baltic Ice Lake type) may be considered. Sudden water level lowering of approximately 30 m may occur because of drainage through topographic passes.

4.5.2 Scenario

During the onset of a glaciation period a drawdown in the sea-level would occur. For the first glaciation (5000 year) the Scandinavian ice sheet is assumed small. However, the Laurentide ice might be considerable larger. It is therefore difficult to estimate global sea-level drawdown. Instead a range of values between 5-50 m should be considered. For the second and third glaciations (20 000 year resp. 60 000 year), when the ice sheet has moved almost down to the Stockholm-Helsinki region, a maximum global sea-level drawdown is estimated to 85 m. For the maximum extension of the third ice sheet a global drop of 150 m is assumed.

No estimates are presented on relative sea-level changes during the time when the ice sheet covers the region but in general, the downwarping of the crust under the central parts of the ice sheet results in a crustal position below sea-level.

During deglaciation the coupled effects of sea-level rise and the isostatic rebound makes it difficult to estimate relative sea-levels (relative to a given point at the ground). But generally speaking, for present day low elevated coastal regions that have been covered by a thick ice sheet for a long period of time, the isostatic downwarping would have been greater than the drawdown of the sea-level. Thus, for these regions the ice front would occur "at sea" (figure 7).

On the other hand, for areas close to the maximum ice front, sea-level drawdown could be greater than the isostatic downwarping and thus an ice front "on land" would be the result.

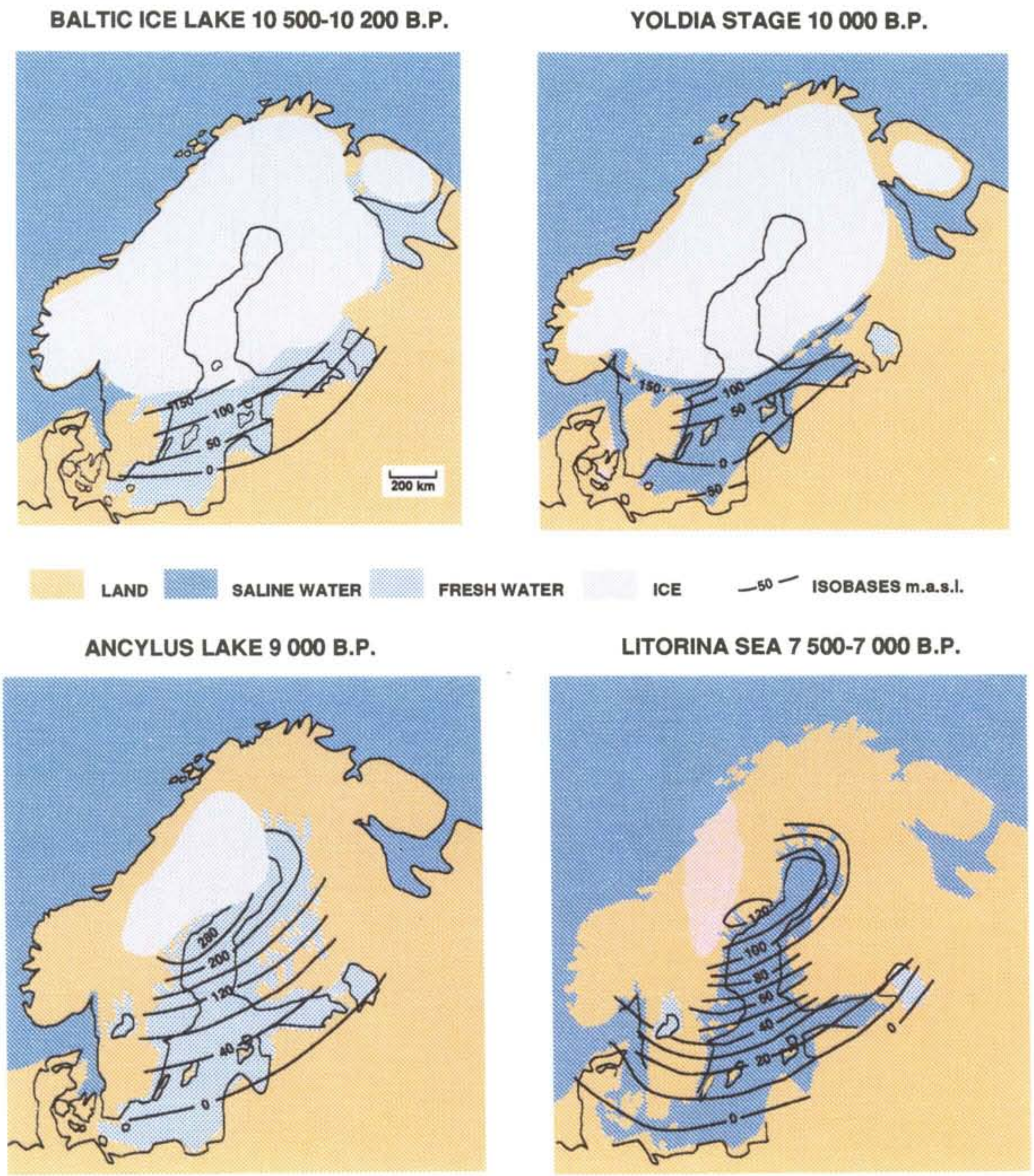

Figure 7. Maps showing four stages of the history of the Baltic Sea (after Eronen, 1988).

The first situation might apply to the deglaciation of the large 60 000 years ice sheet. The assumed downwarping of the Stockholm-Helsinki region during this glaciation is about 600 m. Although some isostatic uplift will have occurred before the ice front reaches the Stockholm-Helsinki region, the area will still be covered by the sea.

The second situation might apply to the deglaciation of the "moderate" ice sheet 20 000 years ahead. During this deglaciation the ice front is assumed to have covered the Stockholm-Helsinki region and slightly beyond. During this "moderate size" glaciation the sea-level will have dropped about 85 m. However, only a crustal downwarping of 60 m is assumed for the Stockholm - Helsinki region (ice thickness of 800 m and short duration at its maximum stage). The resulting sea-level at the ice front will therefore be at 25 m below present day coast line and the ice front will thus stand "on land".

In the continuing deglaciation process the global sea-level will rise until present day sea-level is reached. At the same time isostatic rebound will also occur. The latter process is however slower. For most coastal areas the resulting effect of these two processes will be submergence at first, followed by later emergence. This would continue until isostatic equilibrium is reached or interrupted by a new glaciation cycle.

It is estimated that during the cold interstadial period between the second (20 000 yr) glaciation and the third (60 000 yr) glaciation, the global sea-level will rise from - 85 m during the glaciation to - 60 m at the peak of the interstadial, i.e. the global sea-level will be 60 m below present due to the great amount of water still bounded into large ice sheets during this period.

The relative sea-level at the Stockholm-Helsinki region during this interstadial will be 50 m below the present coastline. This is a result of a residual downwarping of 10 m (i.e. from -60 m during the glaciation to -10 m during the interstadial) in combination with a global sea-level of 60 m below present.

4.6 Bedrock movements/reactivation of faults

4.6.1 Overview

Evidence of postglacial fault movements have been found in several parts of Sweden and Finland, notably in some northern regions. Extensive work regarding their recognition and location has been carried out over large areas, followed by special studies at interesting sites. The most comprehensive studies so far relates to the Lansjärv area (Bäckblom & Stanfors, 1989).

The overall result is that the postglacial fault movements have occurred within major zones of older faulting, that thus were reactivated. These faults would not escape detection in a "standard" site investigation.

The results of hydraulic tests and groundwater sampling in the Lansjärv area revealed that the hydraulic conductivity and groundwater chemistry in the surrounding bedrock are comparable to results from potential sites for a repository in Sweden (being sited more favorable). At Lansjärv the studies also showed that the fault movement occurred shortly after the ice sheet left the area. During this time the postglacial sea covered the area.

The cause(s) for the faulting is not clear. Both strong postglacial uplift or release of suppressed tectonic forces by the load and insulation of large ice sheets (see Talbot et al. in SKB TR 89-31) have been suggested. The latter suggestion is based on present-day lack of significant earthquakes beneath Greenland and Antarctica. It is suggested that the normal plate tectonic forces in these areas are suppressed and stored elastically by the load and insulation of the ice sheets (Johnston, 1987).

It is likely that similar reactivation of faults during deglaciation have occurred in other parts of Sweden and Finland. The occurrence of extensive new faults, from the bedrock surface and down to repository depth, has been suggested but no evidence has so far been demonstrated.

Numerical modelling of rock mass response to future glaciation at the Finnsjön site (Rosengren & Stephansson, 1990) also showed that future displacements due to glaciation and deglaciation will most likely occur in existing fracture zones. For example, when simulation isostatic movements in combination with ice loading and ice melting, stress discontinuities and large displacements occurred in the model at the major fracture zones. This was specially pronounced when simulating melting conditions during deglaciation.

4.6.2 Scenario

The scenario should include postglacial reactivation of some major, older fault outside the potential deposition area of a repository and without any significant effects on the hydraulic conductivity and geochemistry of the deposition area.

The postglacial reactivation of faults seems to occur at the early phase of rebound at, or shortly after, the ice front has left the area. Both of the above proposed causes for postglacial faulting imply that the region previously was covered by a thick ice sheet for a long time. This would have caused a major downwarping of the crust and thus, for low elevation coastal areas, the faulted area would at the time of faulting be covered by a postglacial sea.

4.7 Hydraulic conditions during glaciation/deglaciation

4.7.1 Overview

At the early stages of a glaciation cycle the temperature and precipitation decreases. If sufficient cold and dry conditions are present permafrost might form. In general, these conditions will to a great extent reduce the recharge of groundwater.

Field data on the hydraulic conditions at the base of the ice sheet or in the underlying bedrock during major glaciations and deglaciations are still mainly lacking. Only a few boreholes have penetrate the ice sheets of Antarctica and

Greenland. At least in one of these boreholes (Antarctica) water was found at the ice base at a depth of 2 164 m, possibly as a basal layer of the order of 1 mm thick (Embleton & King, 1975).

As described in section 4.3 calculations by Hindmarsh, Boulton and Hutter (1989) show that the basal temperature in the central part of an ice sheet will probably be beneath the melting point. Thus no groundwater recharge/flow will occur in this part (stagnant conditions). Outside this central part there will be a broad zone of melting (figure 8). Near the ice front, there might be a narrow subglacial frozen zone. Typical melting rates (at the base of the ice sheet) will be in the range 2 - 50 mm per year. The discharge will require a substantial piezometric gradient to drive it, and will tend to induce strong groundwater flow in any aquifers. It will also reduce the strength of subglacial rock joints by decreasing the effective pressure (G.S. Boulton, written comm, 1991).

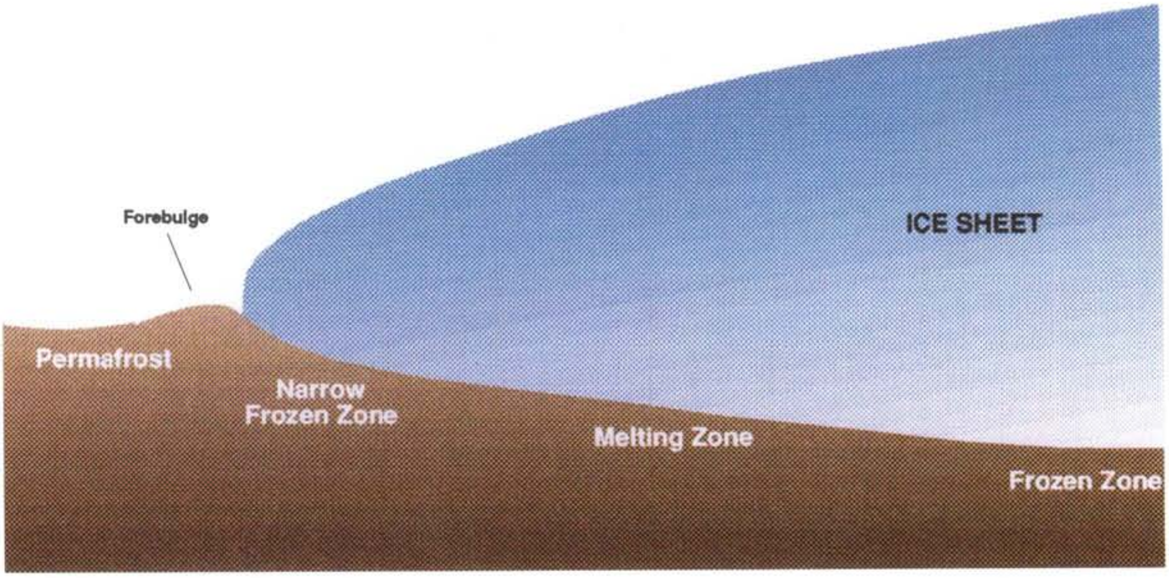

Figure 8. Principle drawing of hydraulic conditions beneath an ice sheet. Scale is not linear.

4.7.2 Scenario

(Most text in this section has been suggested by G.S.Boulton, written comm., 1991).

Conditions before glaciation, when tundra and steppe are prevailing, are quite stationary. Changes occur mostly in precipitation which decreases. Permafrost might form. The result will be a decrease in groundwater recharge.

During glaciation the ice sheet will advance over an area in which continuous or discontinuous permafrost may have taken hold. This will ensure that the terminal zone, at least of the advancing glacier, has a frozen base. It will warm up rapidly however, and give way to a zone of melting as the glacier advances. If subglacial rocks or sediments have a significant permeability, either because of intergranular voids or fractures, subglacial meltwater will be discharged as groundwater. The discharge will be driven by the slope of the glacier surface, and groundwater will therefore tend to be discharged parallel to glacier flow.

When subglacial transmissivity is low, the piezometric gradient will increase in order to maintain the discharge. If the potential pressure in subglacial water rises to equal the value of ice pressure, tunnels will form at the glacier/bed interface, through which water will be discharged. The "role" of these tunnels will be to ensure that groundwater pressures are less than ice pressures. Permafrost beneath the glacier terminus, or beyond the glacier, may seal off aquifers through which groundwater might otherwise be discharged. As a consequence, subglacial water pressures may progressively build up leading either to instability and surging of the ice sheet, or extensive hydrofracturing at the glacier/bed interface, in the ice, or deep in bedrock along zones of weakness, so as to permit meltwater to drain. As the ice sheet extends further, the cold central zone will expand, and subglacial meltwater will freeze.

Typical decay rates of Quaternary ice sheets in mid-latitudes will produce 0.2-0.5 $km^3/km/yr$ of meltwater in addition to normal runoff, significantly adding to river discharges.

4.8 Possible changes in groundwater chemistry

4.8.1 Overview

Very little is known about changes in groundwater chemistry at repository depth (500 m) that might occur during a glaciation cycle. However, one can envisage three major processes in which the groundwater chemistry at repository depth might be changed during a glaciation cycle.

Firstly, during the permafrost period (prior to the region being covered by the ice sheet) saline groundwater might form under a permafrost layer due to an increase of dissolved ions resulting from a fractionation-type freezing process (Boulton & Spring, 1986). This may produce a downward percolating saline front which could extend to greater depths, via density gradients, along large-scale penetrating fracture zones. Such a process might occur over thousands of years.

Secondly, under the ice sheet and mainly in the marginal ice or at the ice front, non-saline and oxidizing melt water might infiltrate the rock due to great differences in groundwater heads. These waters will probably be characterized by: a) low ionic strength, b) oxygen saturation because of the atmospheric pressure, and c) low carbonate content due to a virtual absence of microbial activity. In this case, deeply penetrating fracture zones would facilitate the downward infiltration of alkaline, highly oxidizing groundwaters to depth.

Thirdly, during the glaciation cycle with both lowering and rising of the relative sea-level, groundwater of both marine and non-marine origin might infiltrate the bedrock. The result will be a mixing of groundwater types.

During a lowering of the sea-level non-saline water will successively replace saline water. During this period an increased alkalinity is to be expected due to the influence of clay minerals previously in contact with seawater. This is accomplished by exchanging sodium ions with calcium, thereby increasing calcite solubility. Saline waters will still dominate at greater depths. During sea-level rise saline water will tend to successively replace non-saline types. Once again, deeply penetrating fractures would locally enhance such mixing processes to greater depths.

Glaciation will furthermore remove older oxidized surface deposits and leaves a fresh and unweathered rock surface. Glacial deposits after the removal of earlier oxidation products are generally unoxidized, and the preservation of sulphides, such as sphalerite, which is extremely sensitive to oxidation, in such deposits is well known. This has a direct bearing on the redox-potential of the groundwaters, which will tend to be more reducing at shallower depths.

Site-specific investigations on the Fennoscandian shield have shown the present state of groundwater mixing resulting from the last glaciation. Not only is it difficult to determine the origin of the various water compositions, which tend to be derived from several sources (e.g. marine, metamorphic, glacial melt, precipitation), but it is also difficult to determine how many glaciation cycles they represent. Furthermore, the depth to which mixing takes place will depend on the bedrock fracture frequency and depth of penetration. Studies of present-day systems indicate that within sufficiently conductive fracture zones localized in a recharge area, oxidizing groundwater can extend, although restricted, down to depths of 500 m, and perhaps more.

4.8.2 Scenario

The lack of data concerning possible changes in the groundwater chemistry makes it necessary to consider groundwater compositions caused by all of the above processes. Therefore, the scenario should include the possibility that the existing groundwater is to be exchanged with both saline and non-saline water during a glaciation cycle.

5. SKB/TVO SCENARIO

Even if reality turns out to deviate from the basic forecasts, the present scenario aims to provide examples of basically realistic developments, serving as illustrations of what may be expected. It should however be noted that these forecasts are made without consideration of human effects on the climate. Based on the output from the ACLIN and the Imbrie & Imbrie models (chapter 3) and the conditions during a glaciation cycle (chapter 4) the following climatic and other conditions has been selected as the SKB/TVO reference scenario. The maximum extensions of the postulated three future ice sheets are shown in figure 9 a-c.

0 - 10 000 years. The climate at Scandinavia will gradually become colder permitting the growth of an ice sheet at 5 000 years in the mountainous area of Sweden (figure 9a). Ice sheet thickness in the central mountainous part is 1 000 m. There will be no ice sheet at the Stockholm-Helsinki region. A crustal downwarping of 300 m is expected in the central mountainous part of the ice sheet. Sea-level will drop 5-50 m at the Stockholm-Helsinki region. During the main part of this period there will be permafrost in northern Sweden and Finland.

10 000 - 30 000 years. After a minor and somewhat warmer period the climate will again become colder and fully stadial conditions will occur sometimes around 20 000 years from now. The glacial peak will last about 5 000 years. The ice sheet will advance until it covers Sweden and Finland down to the Stockholm - Helsinki region (figure 9b). Ice sheet thickness in the central part of the ice sheet is 1 500 m, while ice sheet thickness at the Stockholm-Helsinki region is 800 m. A crustal downwarping of 500 m is expected in the central part of the ice sheet and 60 m at the Stockholm-Helsinki region. During deglaciation, when the ice front is located at the Stockholm-Helsinki region, the sea-level is estimated to 25 m below present day coastline. Permafrost in southern Sweden.

30 000 - 50 000 years. Interstadial with a dry and cold climate. Glaciers in the Swedish mountains and permafrost in northern Sweden and Finland. Uplift of 50 m in the Stockholm-Helsinki region and a 15 m rise of sea-level to - 60 m, resulting in a sea-level at 50 m below present coastline at the Stockholm-Helsinki region. Periglacial conditions similar to Greenland or Antarctic.

50 000 - 70 000 years. Full glaciation, stadial conditions. The previous period's cold climate will make the ice sheet respond more rapidly. The glaciation will culminate in around 60 000 years. The ice sheet will extend over the whole of Sweden and Finland and down to northern Germany (figure 9c). Ice sheet thickness in the central part is 3 000 m. Ice thickness at the Stockholm-Helsinki region is 2 500 m. Downwarping of 700 m in the central part of the ice sheet and 600 m at the Stockholm-Helsinki region. During deglaciation, when the ice front is located at the Stockholm-Helsinki region, the sea-level is estimated to 100 m above present day coastline.

A

0 - 10 000 YEARS

B

10 000 - 30 000 YEARS

C

50 000 - 70 000 YEARS

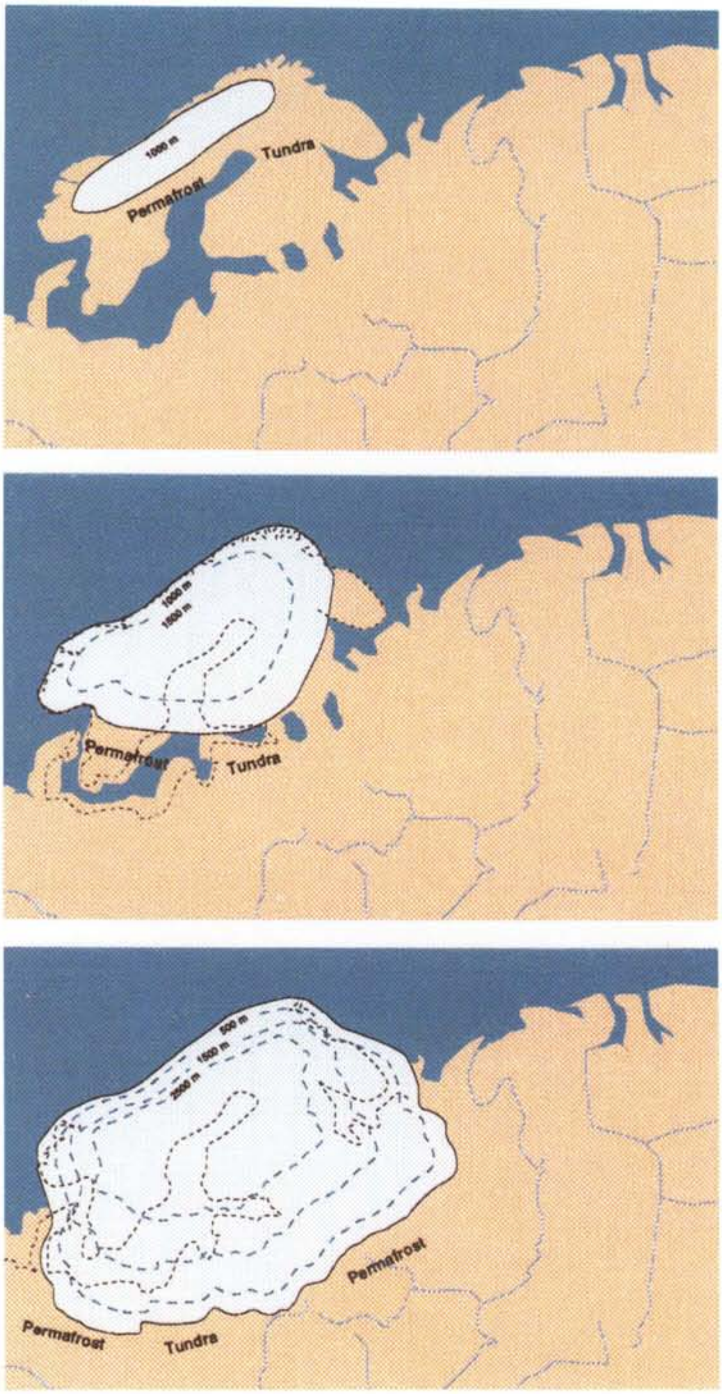

Figure 9. SKB/TVO scenario. Illustration of the stadial periods. A = glaciation around 5000 years from now, B = glaciation around20 000 years from now and C = glaciation around 60 000 years from now. Estimates of future shorelines are highly speculative.

70 000 - 80 000 years. A rapid deglaciation will lead to and culminate in interglacial conditions at 75 000 years. A crustal uplift of 700 m in the central part of the previous ice sheet and 600 m at the Stockholm-Helsinki region. This will be a relatively "warm" period with a climate at the Stockholm-Helsinki region similar to the present northern Sweden/Finland. Small mountain glaciers and permafrost in the very north. Parts of southern Sweden and Finland will be resettled and farming might be possible. Sea-level similar to the present.

80 000 - 120 000 years. The climate will gradually become colder with a maximum stadial conditions at 100 000 years. The ice sheet will be extensive.

120 000 - 130 000 years. Interglacial. The next warm period with a climate similar to the present.

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