Handling of Spent Nuclear Fuel and Final Storage of Vitrified High Level Reprocessing Waste

Supplementary Geological Studies

KÄRN - BRÄNSLE - SÄKERHET

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Stockholm, February 1979
The Nuclear Fuel Safety Project

1 PREFACE

Government Resolution 78-10-05 concerning application for permission to fuel the Ringhals 3 and Forsmark 1 reactors requires that certain supplementary geological studies be carried out in order to ensure that all of the provisions of the Nuclear Power Stipulations Act are completely fulfilled. KBS has therefore carried out additional drillings and measurements within the previously studied areas at Karlshamn and Finnsjö Lake. Four new holes have been drilled at both Karlshamn and Finnsjö Lake. In addition, a previous hole at Karlshamn has been drilled deeper.

The purpose has been to supplement the data which will comprise a basis for determining whether rock formations exist which are of sufficient size and which possess the characteristics on which the safety analysis previously published by KBS is based.

The supplementary studies confirm the picture of the geological situation which was presented in the previous analysis.

The previous KBS report concluded that the studies within the three areas at Karlshamn, Finnsjö Lake and Kråkemåla showed that the first-named area was the most attractive. This conclusion has been supported by the new investigations. Furthermore, results from the Karlshamn area are more consistent than those from the Finnsjö area and show in a simple and clear manner that the premises of the safety analysis are fulfilled with ample margin within a sufficiently large area. The Karlshamn area has therefore been chosen in this report as an example of an area which fulfills the requirements of the Stipulations Act.

The Stipulations Act requires only that the existence of a sufficiently large rock formation possessing the required characteristics be demonstrated and not that a specific site for a final repository be selected or proposed. Prior to the final selection of the site of a final repository some time around the turn of the century, comprehensive studies of various possible areas will be conducted. This work has been started within the National Council for Radioactive Waste Management (Prav). Reconnaissance work during the course of the KBS studies has revealed the existence of several rock formations which appear to fulfill the necessary conditions for a final repository and which are also of considerable size. Primarily because the owners of this land would not consent to drilling, it has not been possible to study these areas more closely.

In the following, Chapter 2 presents a general background to the questions which were brought up as a result of the Government Resolution of 78-10-05. The size and geometric configuration of a final repository as well as ways of increasing safety margins in the final repository are discussed in this chapter.

Chapter 3 gives an account of the supplementary geological studies and their results.

Chapter 4 deals with the geological premises on which the safety analysis was based while Chapter 5 includes a summary and the conclusions drawn by KBS.

2 BACKGROUND

2.1 Fuelling applications for Ringhals 3 and Forsmark 1

The law concerning special permission for charging nuclear reactors with fuel etc. (SFS 1977: 140), known as the Nuclear Power Stipulations Act, lays down the requirements on the handling and final storage of high-level waste which must be fulfilled in order for the Government to be able to grant permission to charge new nuclear power reactors with nuclear fuel.

On December 6, 1977, the State Power Board submitted an application for such permission in accordance with Section 2, paragraph 2 of the Stipulations Act for unit 3 of the Ringhals power station. On April 6, 1978, Forsmarks Kraftgrupp AB submitted a similar application for unit 1 of the Forsmark power station.

Both applications referred to agreements concerning the reprosessing of nuclear fuel and a report on how safe terminal storage of high-level waste from the reprocessing of spent nuclear fuel can be effected, as described in KBS report "Handling of Spent Nuclear Fuel and Final Storage of Vitrified High Level Reprocessing Waste".

2.2 Government Resolution of 78-10-05 and its implications

On October 5, 1978, the Swedish Government passed a resolution concerning applications for the fuelling of Ringhals 3 and Forsmark 1. The Resolution included the following:

> "The Government considers the reprocessing agreement referred to in the application to be in compliance with the requirements of the Nuclear Power Stipulations Act. However, in assessing whether the prerequisites for an absolutely safe storage of the high-level waste have been fulfilled, the Government finds that certain supplementary geological studies are required for full compliance with the provisions of the Act.
>
> The Nuclear Power Stipulations Act does not require the applicant to specify the precise location of the site intended for the terminal storage. However, in the present case, the Act must be interpreted as requiring the applicant

> to show the existence in Sweden of a site or sites possessing such characteristics that terminal storage can be effected in compliance with the provisions of the Act.
>
> The supplementary geological studies should therefore demonstrate the existence of a sufficiently large rock formation at the depth in question and possessing the other characteristics stipulated by the KBS safety analysis. In this connection, the Government wishes to emphasize that the requirements which must be made on the volume and configuration of the rock formation depend upon the quantity of radioactive waste and on the geometric parameters of the terminal storage facility. The design of the rock repository originally described in the KBS report may have to be modified in accordance herewith.
>
> Accordingly, the Government finds that further exploratory drillings are necessary, as well as measurements occasioned by such drillings, in districts which, in the opinion of the applicant, display the above-mentioned geological characteristics.
>
> For these reasons, permission cannot be granted at the present time".

It is evident from the passages quoted that the Government considers the storage method proposed by KBS as such to be absolutely safe in the meaning intended by the law. But the Government has also found that KBS has not submitted sufficient geological study data in order to demonstrate convincingly that one or more areas of sufficient size exist in Sweden which possess the characteristics set forth as premises in the safety analysis.

2.3 Sizing premises for a final repository

In the KBS report concerning vitrified reprocessing waste, the various facilities for the handling and final storage of high-level waste have been designed and sized for the quantity of waste produced by 13 reactors, each with an operating life of 30 years. This quantity of waste corresponds to about 9000 tonnes of uranium in the form of 9000 cylinders containing vitrified high-level waste. This capacity is based on a decision of the Swedish Parliament in the year of 1975 that the Swedish nuclear power programme should be oriented towards 13 reactors, pending further consideration. This means that capacity must be provided for the amount of waste which is equivalent to 9000 tonnes of uranium or an equal number of waste canisters.

With a strict interpretation of the provisions of the Stipulations Act, it would be sufficient here to describe the terminal storage possibilities for the quantity of high-level waste produced by the two reactors with which the present fuelling application is concerned, namely Ringhals 3 and Forsmark 1. This would define the lower limit for the capacity of the final repository at about 1500 tonnes of uranium or an equal number of waste canisters. However, this lower limit is of no practical interest, since the supplementary geological studies have demonstrated that considerable rock volumes with satisfactory characteristics exist in the Karlshamn area.

2.4 Geometric configuration of the final repository

In the previous KBS report, the final repository was designed as a system of tunnels at a depth of about 500 m. The primary reason why it was proposed that the final repository be limited to one level and not divided into several levels was to obtain a dispersal of the heat-generating waste over a large area and thereby limit the temperature increase. The requirement which was imposed was that the highest surface temperature on the hottest waste canister should be well below 100°C. As is evident from /1/, the surface temperature of the hottest canister is about 65°C. A final repository for 9000 canisters would be contained in half as large an area if the canisters were distributed equally between two levels. With a vertical distance of 100 m, there would be no increase of the maximum temperature of the canisters and the rock, and the margin to the specified upper limit of 100°C would remain unchanged. However, the temperature would drop at a much slower rate in a two-level than in a single-level repository, see Fig. 1.

A suitably arranged final repository divided into two or more levels would not seem to entail any significant alteration of the conditions which determine the safety of the repository. In this report, however, the alternative with all canisters located on one level is described.

2.5 Some possibilities for affecting the safety margins in the final repository

It is evident from the investigations so far carried out within the KBS project that the safety margins in a final repository can be affected to a great extent by the design of certain technical barriers. Thus, the release of the various elements from the high-level waste is dependent upon

- the canister material and the design of the canister
- the buffer material
- the properties of the waste glass

The safety margins, which are dependent upon natural barriers, can be affected by

- the choice of site for the waste storage
- the depth of the repository

If a final repository is designed in accordance with the proposal described by KBS for vitrified waste, a large margin of safety is obtained against the harmful release of radioactive elements. Continued KBS studies have shown that the safety margin is unnecessarily great in many respects and that simplifications in design are possible without jeopardizing the required level of safety.

On the other hand, it is also possible to increase the safety margin in various ways. Thus, substituting a copper canister for the lead-titanium canister and highly-compacted bentonite for the sand-bentonite buffer material /2/ would both substantially increase the service life of the canister. The radioactivity of the encapsulated waste would probably have decreased to such a low level before any glass leaching could start that the function of any other barriers would be of secondary importance.

The composition and leaching properties of the waste glass are currently being intensively investigated in a number of countries. It can be assumed that these studies will enable a more leaching-resistant glass to be devised.

The shortest transit time of the groundwater can be extended by locating the repository deeper than 500 m. Such an extension of the water transit time in combination with retardation of the radioactive elements, due to chemical reactions and their decay while migrating through the fissures in the rock, will lead to a considerable reduction of the amount of radioactive elements which can reach the biosphere.

Thus, by means of a suitable choice of technical measures and technical design, the margins of safety can be varied within relatively wide limits. In this report, however, it is assumed that the final repository is designed entirely in accordance with the principles described in the KBS report entitled "Handling of Spent Nuclear Fuel and Final Storage of Vitrified High Level Reprocessing Waste".

3 SUPPLEMENTARY GEOLOGICAL STUDIES

3.1 Scope of the studies

The supplementary studies were begun in October 1978 within the previously studied areas east of Finnsjö Lake and at Karlshamn. Fig. 2. The studies include supplementary geological mapping, the drilling of four new holes within each of the areas, mapping of drill cores, mineralogical investigations and permeability determinations. Certain supplementary geophysical measurements and groundwater analyses have also been carried out.

It is known from previous studies that the rock nearer the surface can have a higher frequency of open fractures. But the nature of the surface rock only affects the safety of the final repository to a slight degree. It has therefore not been considered necessary to report the results of permeability determinations for the upper 250 m of the bore holes here. However, core mapping has been carried out and is reported for the full length of the boreholes.

As was mentioned in Chapter 1, the Karlshamn area has been selected as an example of an area which fulfills the requirements of the Stipulations Act. Therefore, only the results from Karlshamn are presented in this report. However, the technical reports, which present the study results in detail, cover both the Finnsjö and Karlshamn areas.

3.2 Study programme for the Karlshamn area

The observations which were previously made at Karlshamn in a deep borehole and in adjacent rock caverns have shown that the bedrock there, owing to the generally low frequency of fractures, offers good conditions for a final repository for high-level waste. The investigations at the Karlshamn plant have therefore been supplemented by four new boreholes. In response to criticism that the previous studies do not extend deeper than 500 m, it was decided that the new holes would be drilled to vertical depths varying between 522 m and 595 m. In addition, the previous borehole has been drilled deeper from 500 m to 790 m. The locations of the holes which have been drilled within the Karlshamn area are shown in Fig. 3.

The holes were located to achieve the following objectives:

Ka 1, the first hole which was drilled, has been deepened in order to obtain further information on the nature of the rock at great depth,

Ka 2, has been drilled southward to explore a presumed east-west zone of weakness at the transition to the southern part of the Sternö Peninsula,

Ka 3, has been directed eastward in order to investigate the eastern parts of the area,

Ka 4, in the northern part of the Sternö Peninsula, has been drilled in direct connection to a fracture zone in Munkahus Bay in order to determine the effects on the surrounding rock,

Ka 5 has been located near Ka 4, but directed southward from the fracture zone. This location is intended to shed light on conditions at the border between the fracture zone and less disturbed bedrock.

3.3 Study results from the Karlshamn area

3.3.1 Core examination

The results of the examination of cores from the boreholes within the Karlshamn area have been summarized by the Geological Survey of Sweden (SGU) as follows /3/.

"The drilling which was carried out on Sternö, Ka 1, produced a core with an extremely low fracture frequency. The rock was primarily of the coastal gneiss type with some increase in coarseness towards greater depth. KBS Technical Report No. 60 reports the suspicion that a rock contact was probably approached at the end of this hole (owing to an increase in conductivity and a structural change in the core).

The new drillings confirmed this suspicion, since the extension of Ka 1 descended into granite of the Karlshamn type. However, this does not seem to have any appreciable effect on fracture frequency.

The results from the new boreholes Ka 2, Ka 3 and Ka 5 are only slightly worse than those from Ka 1. Scattered fracture zones were found in Ka 5 down to about 200 m. The coastal gneiss has changed character and become migmatized and coarsened by the influence of granites. Gneissic granite with augen ("eyes") of potash feldspar is common in the transition zone to more granitic material. The contact, however, is not of a tectonic nature; instead, the different rock types appear to intercalate with one another.

Borehole Ka 4, which is directly adjacent to Munkahus Bay, exhibited sections of intensive fracturing and reveals the existence of a shear zone bordering Sternö on the northwest.

The conclusions which can be drawn from the borehole studies on the Sternö Peninsula can be summarized as follows:

- Except for borehole Ka 4, the cores exhibit a low fracture frequency.

- The dominant rock species are coastal gneiss (mainly at the surface), gneissic granite and granite. No difference in the macrofracturing of these rock species has been recorded.

- Fracture fillers occur, mainly in the form of calcite, with some gypsum. Chlorite is found as a deposit on the fracture surfaces.

The fracture lines which have been found or can be presumed to exist within the area are illustrated in Fig. 4.

3.3.2 Measurements of hydraulic conductivity

The results of conductivity measurements at 3-metre intervals in the Ka 1, Ka 2, Ka 3 and Ka 5 boreholes are shown in Fig. 5a-d. No conductivity measurements were performed in the Ka 4 borehole, since the hole was drilled with the sole purpose of ascertaining the location of and conditions around a crush zone.

The results of measurements with two packer seals spaced relatively closely are influenced by certain sources of error which are dealt with in /4/. During two-packer measurements in the Ka 5 borehole, it was also found that a leak had occurred in the equipment which led to excessively high flow values being recorded. For these reasons, single-packer measurements have also been carried out, whereby average conductivity was determined over fairly long sections from the bottom of the holes up to various levels. The results of these measurements are reported in the tables in Figs 5a, 5b and 5d. Single-packer measurements were carried out at different pressures, whereby some variation was obtained in calculated conductivities. The values given in the tables apply at a pressure of 0.6 MPa.

An average conductivity of 2×10^{-12} m/s was obtained in the Ka 1 borehole between 199.5 m and 778.5 m. If this average value was attributable to an outflow in the rock in only one three-metre section, the conductivity there would be 4×10^{-10} m/s. If there is leakage in several sections, the conductivity in each one of these is lower.

An average conductivity of 5×10^{-12} m/s was obtained in the Ka 2 borehole between 350 m and 576 m. In the same manner as described above for borehole Ka 1, the maximum conductivity of an individual three-metre section can be calculated to be 4×10^{-10} m/s.

The measurements in the Ka 3 borehole indicate a fracture zone between about 300 and 350 m. Below this level, conductivities measured in three-metre sections vary between 10^{-9} and 10^{-10} m/s. Single-packer measurements have not been carried out in Ka 3, but it can be assumed that they would give fundamentally the same results as those obtained in Ka 1, Ka 2 and Ka 5. The core examination shows that the deeper parts of Ka 3 have a very low fracture frequency.

As was mentioned above, it was found after the measurements in Ka 5 that a leak had occurred in the equipment. The conductivity values for three-metre sections which are given in Fig. 5d are therefore incorrect. An average conductivity of 4×10^{-12} m/s was obtained from single-packer measurement between 300 m and 578 m. If the entire measured flow is attributable to a single three-metre section, this section would have conductivity of 4×10^{-10} m/s.

The single-packer measurements show that the conductivity of the rock below the 200-350 m level lies within the interval 10^{-11} to 10^{-12} m/s. However, the possibility of individual values around 10^{-10} m/s in certain three-metre sections cannot be entirely excluded. The very similar results which were obtained from the different boreholes would indicate that these conductivity conditions are characteristics for most of the rock mass within the areas which have been identified as being suitable for the location of the repository.

3.3.3 Groundwater chemistry

The nature of the groundwater is determined by reactions between the infiltrating precipitation on the one hand, and the soil layers and the bedrock on the other.

In the particular infiltration area in question, the bedrock consists of gneissic and granitic rocks of similar mineral composition. Owing to the slow movement of the groundwater, it is in near-equilibrium with the minerals which occur at the 500 m level. These minerals constitute a buffer system which prevents changes in the amount or composition of the precipitation causing any major changes in the groundwater chemistry.

The supplementary studies have included analyses of water samples from relatively shallow depth in the Ka 1 borehole, in two observation holes from the surface of the ground near the rock caverns and from a tunnel which connects the rock caverns. In addition, an analysis of Baltic seawater has been carried out. The results are presented and discussed in /5/. Analyses of groundwater in the Karlshamn district and other parts of Blekinge are also reported there.

In certain respects, the results of the new analyses lie outside of the interval which was previously deemed probable for groundwater and rock at a depth of 500 m /2, Vol. II, page 112/. This applies particularly to the SO_4^{2-}concentration, which is between 56 and 250 mg/l, in comparison with the previous estimate of 1-15 mg/l. This decrepancy can be explained by the fact that the samples were taken at shallow depth, and perhaps by a nearly completed washing-out of old seawater.

The presence of Fe^{2+} in the water samples shows that the samples come from a reducing environment.

Resistivity logging at a number of levels in the Ka 4 and Ka 5 boreholes does not reveal any appreciable salt content.

3.3.4 Groundwater movements

The topography of the area in question around the Karlshamn plant is such that the horizontal component of the groundwater movement is more or less radial from the highest point in the area, which is about 50 m above sea level, cf. Fig. 6. The groundwater movements can therefore be described by means of a radially symmetric two-dimensional model, which is described in /6/.

Calculations /7/ have been carried out concerning direction of movement, flow times and gradients in the profiles A-C shown in Fig. 6. The proposed site of the final repository has been marked in the figure. The premises postulated for the calculation have been a permeability of 10^{-9} m/s, a porosity of 10^{-3} and water tables which follow the terrain and the surface of the sea.

Fig. 7a-c shows flow lines in the different sections. For section A, it is assumed that an unlimited sea extends from the southern shore of Munkahus Bay. For section B, the actual topographic conditions apply. For section C, the existence of any sea at all has been disregarded, i.e. it has been assumed that the sea bottom is exposed.

Fig. 8 shows the calculated times for the transport of the groundwater from the final repository up to the surface of the ground or the sea bottom. The shortest calculated transit time is approximately 1000 years. This time applies to a limited area in the northern part of the repository. Considerably lower transit times are obtained for the rest of the repository. Since the measured permeability is considerably less than 10^{-9} m/s, the actual transit times are also considerably longer than that shown in Fig. 8.

The properties of the rock which immediately surrounds the storage holes are of special interest. On the basis of measurements, this rock can be assumed to have a conductivity of no more than 10^{-11} m/s. The gradient within the repository area at a depth of 500 m has been estimated to be between 0.009 and 0.02. At a porosity of 10^{-3} /2, Vol. II:3.4.5/, Darcy's Law then gives a transport distance for the groundwater of 1.0 - 2.4 m in 400 years.

4 GEOLOGICAL PREMISES FOR THE SAFETY ANALYSIS

4.1 General

The Government Resolution of October 5, 1978, specifies the purpose of the supplementary report: "... the study should therefore demonstrate the existence of a sufficiently large rock formation at the depth in question and possessing the other characteristics stipulated by the KBS safety analysis".

This means that the properties of the rock on which the safety analysis included in the previous report was premised are now to be used as criteria in evaluating whether the geological studies demonstrate the existence of acceptable rock or not.

The radiaiton doses to which the environment can be subjected are decisive for the safety assessment of a final repository for vitrified high-level waste. The factors in the safety analysis which are dependent upon geological input data are the time of canister penetration, the leaching rate of the waste glass and the transit time of the groundwater and the waste elements in the rock. By "geological data" is also meant here data which are based on geochemical and hydrogeological conditions.

In view of the uncertainties in available data and methods of calculation, the input data for the safety analysis were selected throughout so that the results would represent an upper limit for possible consequences.

In the time which has passed since the safety analysis for vitrified waste was carried out, considerable new knowledge has been brought to light, especially as a result of the work which lies behind the KBS report on the final storage of unreprocessed spent nuclear fuel /2/. This work has further verified the fact that the safety analysis of the final storage of vitrified high-level radioactive waste contains large margins of safety on vital points.

The following sections deal with the importance of the geological input data which have been used in the safety analysis and the degree to which the results of the supplementary studies could possibly influence the choice of these data. In connection herewith, the safety margins are discussed in the light of the new information which is available.

4.2 Groundwater chemistry

The amount of corrosive substances which come into contact with the waste canisters influences the time during which the canisters will remain intact and the waste glass inaccessible for leaching. The rate at which the waste glass will then be leached is influenced by the chemical composition of the groundwater. Groundwater chemistry will also influence the retardation effects which appear when the substances dissolved from the waste glass are transported with the groundwater through the fissures in the rock.

The chemical environment around the final repository is dealt with in /2, Vol. II:3.5/.

Canister corrosion

The KBS study proposes that the waste cylinders be enclosed in a canister of lead and titanium.

In their final evaluation of the lead-titanium canister /8/, the Swedish Corrosion Institute and its reference group have estimated the probable service life of the canister to be tens of thousands of years. Even if it is assumed that the titanium will be damaged within a relatively short period of time by delayed fracture, the service life of the canister is nevertheless estimated to be at least 1000 years. The estimated minimum service life is based on the conservative assumption that all accessible oxidants contribute towards the corrosion attacks to which the lead lining can be subjected.

The importance accorded to the chloride content of the groundwater in assessing the service life of the canister is based on the pitting and crevice corrosion of unalloyed titanium which can occur under certain conditions in hot chloride solution.

By far the most important oxidant for lead is the maximum quantity of oxygen which can remain after the tunnels have been filled with buffer material. The quantity of oxidants which can be supplied via the groundwater is insignificant in comparison. It is assumed that the groundwater can contain a maximum of 0.1 mg O_2 per litre /2, Vol. II, page 112/, the additional amount which is obtained from this source is completely negligible compared to the amount of oxygen which diffuses into the canister from the air entrained in the buffer material. In reality, however, the fact that the groundwater at the depth in question is reducing should entail that the water flow through the repository will decrease rather than increase the available supply of oxygen in the repository.

The choice of 1000 years as the minimum service life of the canister is thus not influenced by normal variations in the chemical composition of the groundwater.

Leaching of the glass

The values for the leaching rate of the waste glass used in the safety analysis are based on the results of leaching tests performed with tap water, seawater and distilled water where the supply of water has been unlimited. The capacity of the groundwater to dissolve the silicic acid in the glass under the conditions prevailing in a final repository will be considerably lower, since the flow rates in question are so low that the scarcity of water limits leaching and since the dissolving capacity of the water has already been largely exhausted in dissolving the silicic acid in the rock and in the fracture-filling minerals. The difference between the dissolution rate assumed in the safety analysis and the much lower actual rate of dissolution of the glass has been discussed in connection with the review of the KBS report by various domestic and foreign authorities and agencies.

The other variations in the chemical composition of the groundwater, i.e. aside from the silicic acid content, dealt with in /5/ are of secondary importance for the glass dissolution rate and do not influence the choice of glass dissolution data in the safety analysis.

Retention factors

The retention factors for various elements used in the previous KBS safety analysis were calculated on the basis of experiments with aearated water (oxidizing environment) and short contact times between the elements dissolved in the groundwater and the rock surface. In connection with KBS studies concerning the final storage of unreprocessed spent nuclear fuel, extensive tests have also been carried out with oxygen-free water (reducing environment). This corresponds to the chemical environment which will prevail in a final repository, as has been verified by measurements of the redox potential and oxygen content of groundwater from boreholes and by data in the literature referred to in /2, Vol. II:3.5/. Considerably greater retardation is obtained for many of the important nuclides in a reducing environment than in an oxidizing environment /9/. The same reference also shows that the long contact times which result from slow groundwater movements lead to increased retardation effects.

Of the chemical factors which can influence retardation, the redox potential is of crucial importance. Since the actual environment in the final repository will be reducing, the retention factors which were used in the safety analysis and which were based on an oxidizing environment contain very large margins of safety for certain important radioactive elements. In comparison with this, the observed variation in the composition of the groundwater has a negligible influence on the retardation effects. Thus, the chemistry of the groundwater does not affect the choice of retention factors in the safety analysis.

4.3 Hydraulic conductivity

At a given hydraulic gradient, the conductivity of the rock determines the groundwater's transit time as well as the amount of groundwater which passes the canister and also constitutes an input parameter in calculating the retardation of the waste elements.

Transit time of the groundwater

The transit time of the groundwater from the repository to the surface of the ground was calculated in the previous KBS report concerning vitrified waste on the basis of model studies employing a two-dimensional flow model and age determinations employing the carbon-14 method performed on groundwater from deep boreholes. 400 years was chosen as a conservative value for the shortest water transit time from any part of the repository up to the surface of the ground.

The results of calculations for the Karlshamn area based on the same model, actual topography and an assumed conductivity of 10^{-9} m/s are presented in section 3.3.4. These results show that the transit time of the groundwater in the Karlshamn area is considerably longer than the 400 years which was assumed in the previous KBS safety analysis.

In addition, the fact that the storage holes in the Karlshamn area can be located in rock with a conductivity of 10^{-11} to 10^{-12} m/s means that a transit time of 400 years is obtained within only a few metres of the holes.

Groundwater flow

The groundwater flow rate in rock with a conductivity of 10^{-9} m/s and with the hydraulic gradients in the Karlshamn area was found in the KBS report on vitrified waste to be 0.2 l/m^2 and year. A considerable increase of this value would not affect the premises and results of the safety analysis.

Moreover, the results of the supplementary conductivity measurements show that the actual groundwater flow can be expected to be considerably less than that previously reported.

Retardation calculations

The dispersal calculations in the KBS safety analysis have been based on a residence time for groundwater of 400 years in rock with a conductivity of 10^{-9} m/s. The results of conductivity measurements show that the study area at Karlshamn is dominated by rock with considerably lower conductivity. In such rock, the retardation of radioactive elements is greater than in rock with a conductivity of 10^{-9} m/s. Thus, the premises of the safety analysis are met in the Karlshamn area with a large margin.

5 SUMMARY AND CONCLUSIONS

Bedrock conditions

The geological make-up of the study area at Karlshamn has been investigated by surface mapping and observations in boreholes and rock caverns. With increasing depth, there is a transition from coastal gneiss and gneissic granite to Karlshamn granite. It has been found that the points of contact between different rock species are not associated with zones of weakness or higher fracture frequencies.

Surface indications and observations in drill cores are the basis for the map of established or presumed fracture lines which is shown in Fig. 4. The fracture zones are steeply inclined.

Hydraulic conductivity

The borehole loggings show that almost all of the bedrock within the studied area has very low hydraulic conductivity. Below the 200-350 m level, average conductivity has been determined by means of single-packer measurements to be around 5×10^{-12} m/s over sections 230-580 metres in length. Thus, as is noted in Chapter 4, the premises of the safety analysis regarding the conductivity of the bedrock are met with ample margins.

Water chemistry

Analyses have been carried out on the groundwater from the study area at Karlshamn and from other sites near the Blekinge coast. The results of the analyses show that the chemical properties of the groundwater which are of importance for the safety of the final repository lie within the range of variations given in previous KBS reports. The premises of the safety analysis are thereby fulfilled.

Rock volumes

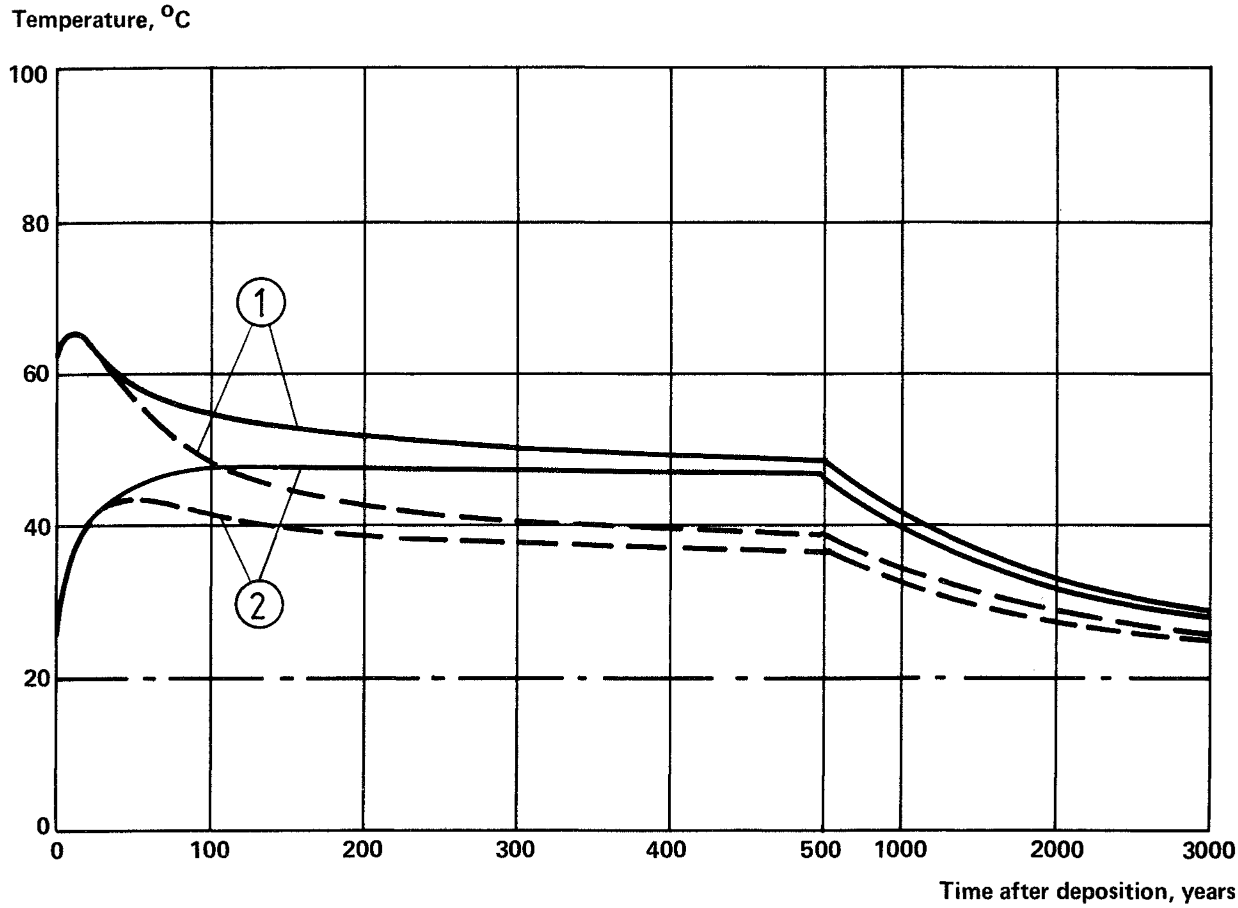
The fracture lines in Fig. 4 border on the area which possesses the characteristics necessary for a final repository.

According to section 3.3.4, the groundwater is transported 1.0 - 2.4 m in 400 years in the impervious rock which is characteristic of most of the study area. Theoretically, this would mean that the requirement for a transit time of at least 400 years would be fulfilled if each storage hole were surrounded by 2.5 m of rock with these characteristics. If this "400-year condition" is applied to the storage holes immediately adjacent to a fracture zone, it would be theoretically required that at least 2.4 m of rock with a conductivity of 10^{-11} m/s should separate the storage hole from the face of the fracture zone. In order to guarantee this, it has been assumed here that a zone of adequate width up to proven or presumed fracture lines will be left undisturbed and not be used for waste storage. The same applies with respect to the diabase vein in the eastern part of the area.

The areas which would thus be suitable for use for waste disposal are shown in Fig. 9. The areas cover a total surface area of 1.2 km^2. An area of just under 1 km^2 is required for 9000 canisters deposited on the same level. The possibility that local defects will render certain storage positions unsuitable for use cannot be excluded. However, in view of the highly uniform properties of the rock which have been found by borehole studies, it can be assumed that such local defects will be very rare.

Conclusions

The supplementary geological studies within the area at the Karlshamn plant have demonstrated the existence there of rock volumes possessing the required characteristics and of sufficient size for the terminal disposal of high-level waste equivalent to approximately 9000 tonnes of uranium. This is considerably more waste than the amount which is produced over a period of 30 years in the nuclear reactors in question here, which are subject to the provisions of the Nuclear Power Stipulations Act.



— — — — Single-level repository, ~1000 x 1000 m. Ref. report KBS-45.

———— Two-level repository, ~700 x 700 m. Distance between levels 100 m. Repository otherwise as described in KBS-45.

— · — · — Temperature of undisturbed rock.

1 Temperature at titanium surface for hottest canisters in repository, i.e. hottest canisters at centre of each level.

2 Macroscopic temperature profile at centre of level.

Fig. 1. Temperature profiles in single-level and two-level final repository.

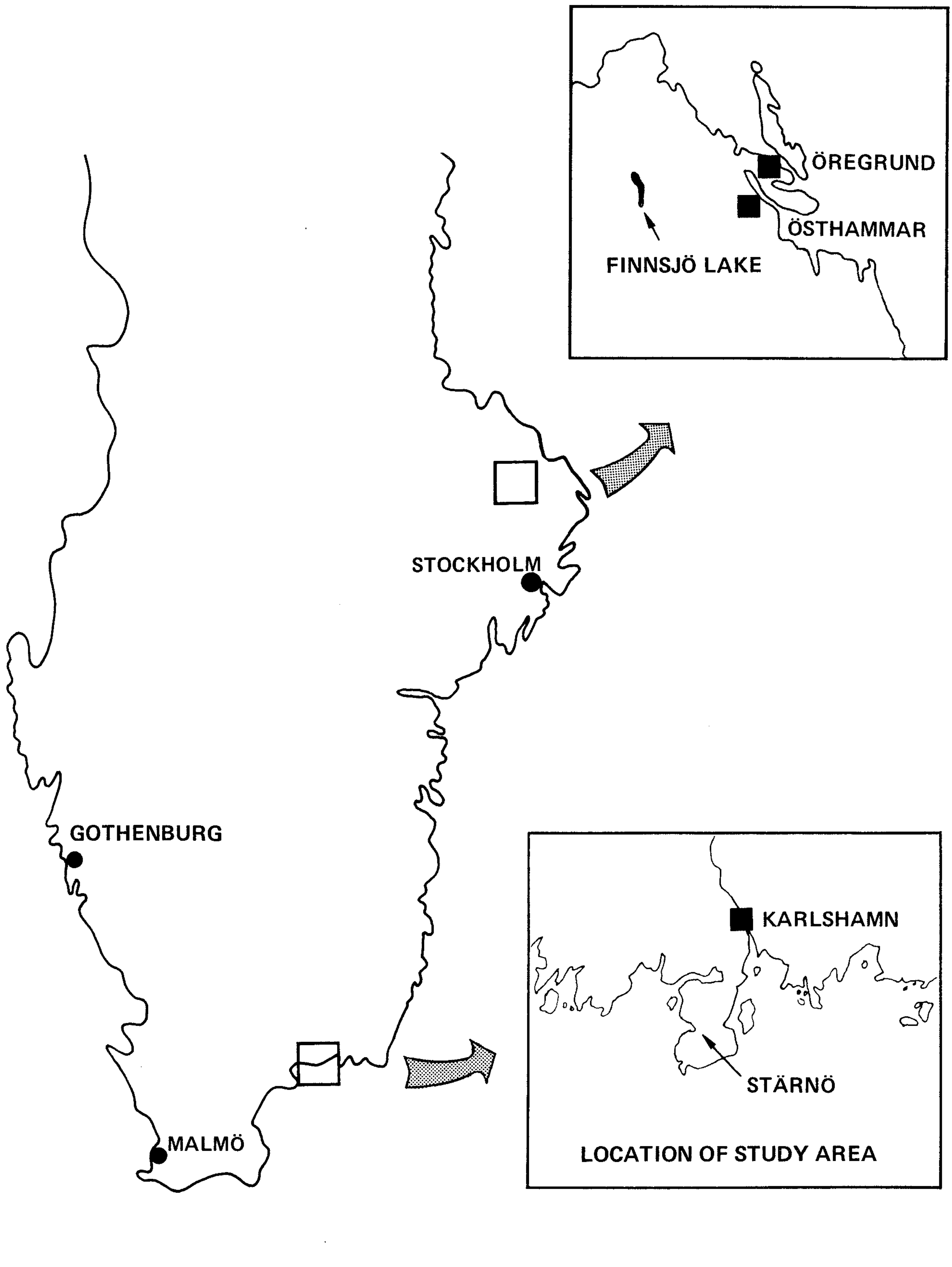


Fig. 2. Supplementary geological studies have been carried out at Finnsjö Lake and Karlshamn.

Fig. 3. Earlier (Ka 1) and new (Ka 2 – Ka 5) boreholes at the Karlshamn plant. Arrow marks direction of drilling and length in horizontal plane. Figures within parentheses indicate the angle of the boreholes in relation to the horizontal plane.

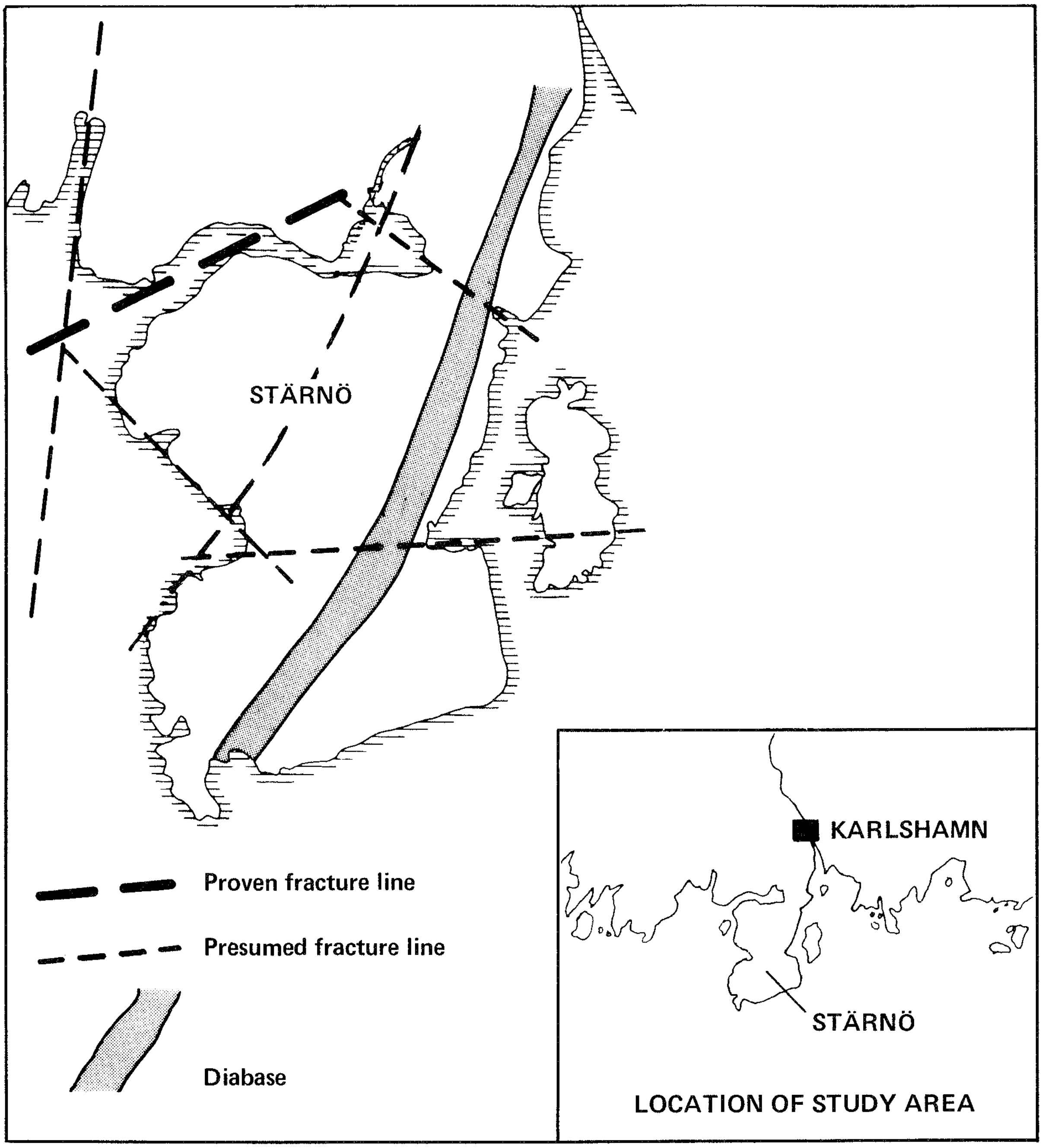
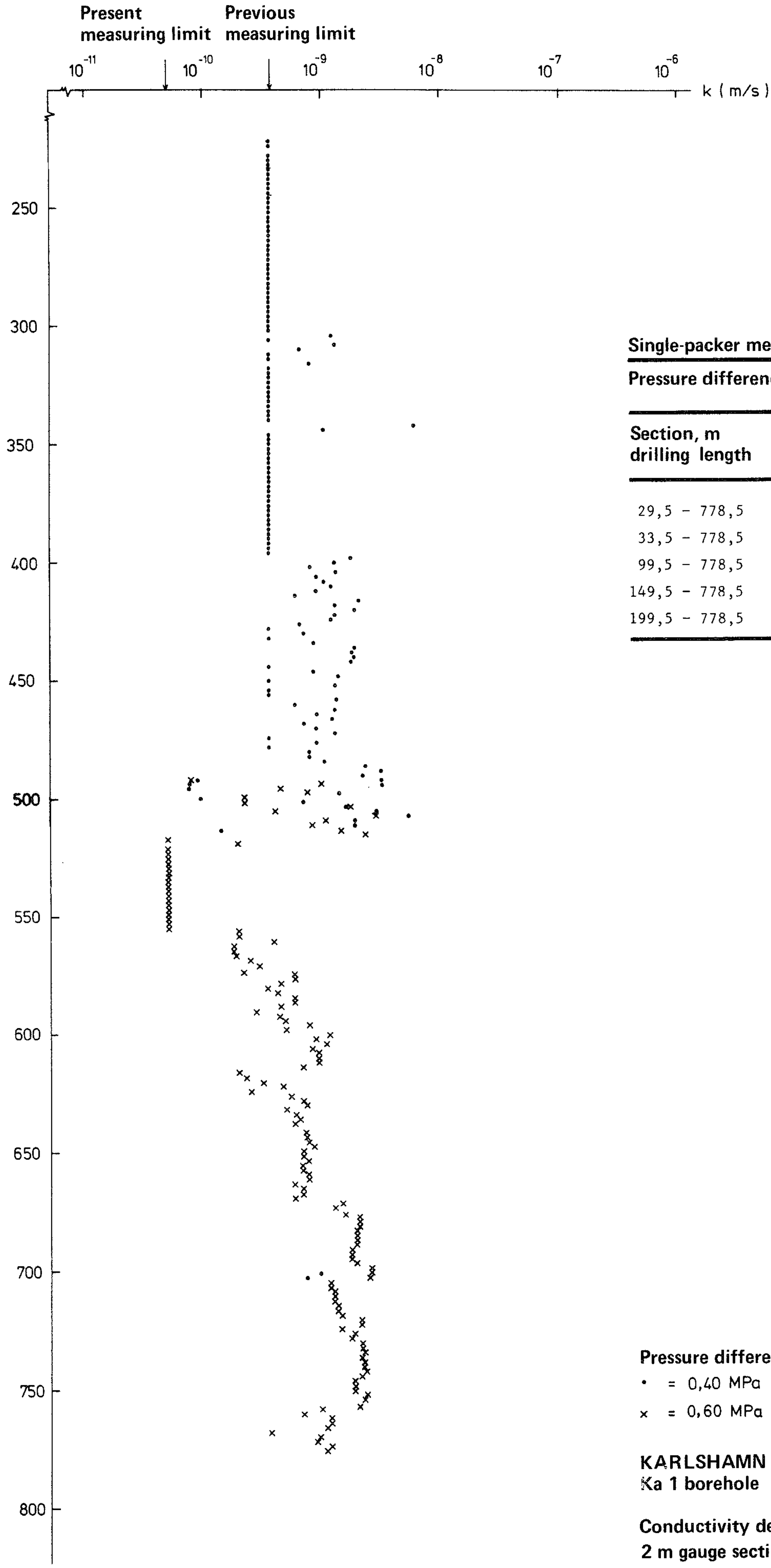


Fig. 4. Lineament map of study area at Karlshamn plant.



Single-packer measurements, Ka 1

Pressure difference 0.6 MPa

Section, m drilling length	Conductivity m/s
29,5 - 778,5	$4{,}0\times10^{-10}$
33,5 - 778,5	$4{,}0\times10^{-10}$
99,5 - 778,5	$1{,}4\times10^{-10}$
149,5 - 778,5	$8{,}7\times10^{-11}$
199,5 - 778,5	$2{,}0\times10^{-12}$

Pressure difference

• = 0,40 MPa

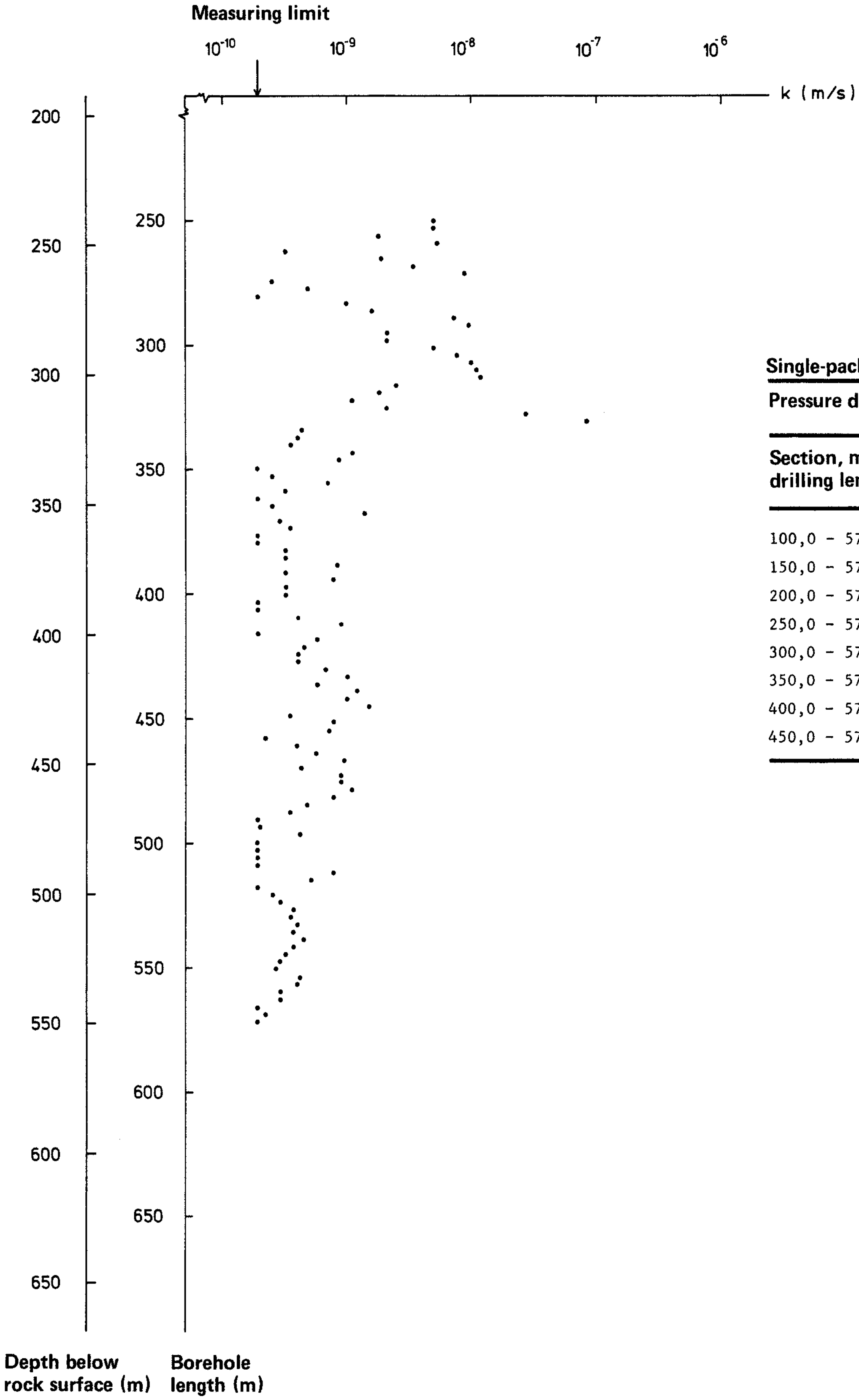
× = 0,60 MPa

KARLSHAMN
Ka 1 borehole

Conductivity determination
2 m gauge section

Geological Survey of Sweden
Bedrock Bureau
1978

Fig. 5 a.



Single-packer measurements, Ka 2

Pressure difference 0.6 MPa

Section, m drilling length	Conductivity m/s
100,0 - 575,8	$4,1 \times 10^{-9}$
150,0 - 575,8	$4,2 \times 10^{-9}$
200,0 - 575,8	$3,3 \times 10^{-9}$
250,0 - 575,8	$3,6 \times 10^{-9}$
300,0 - 575,8	$3,4 \times 10^{-9}$
350,0 - 575,8	$5,0 \times 10^{-12}$
400,0 - 575,8	$4,1 \times 10^{-12}$
450,0 - 575,8	$1,9 \times 10^{-12}$

Pressure difference

• • 0,20 MPa

KARLSHAMN
Ka 2 borehole

Conductivity determination
3 m gauge section

Geological Survey of Sweden
Bedrock Bureau
1979

Fig. 5 b.

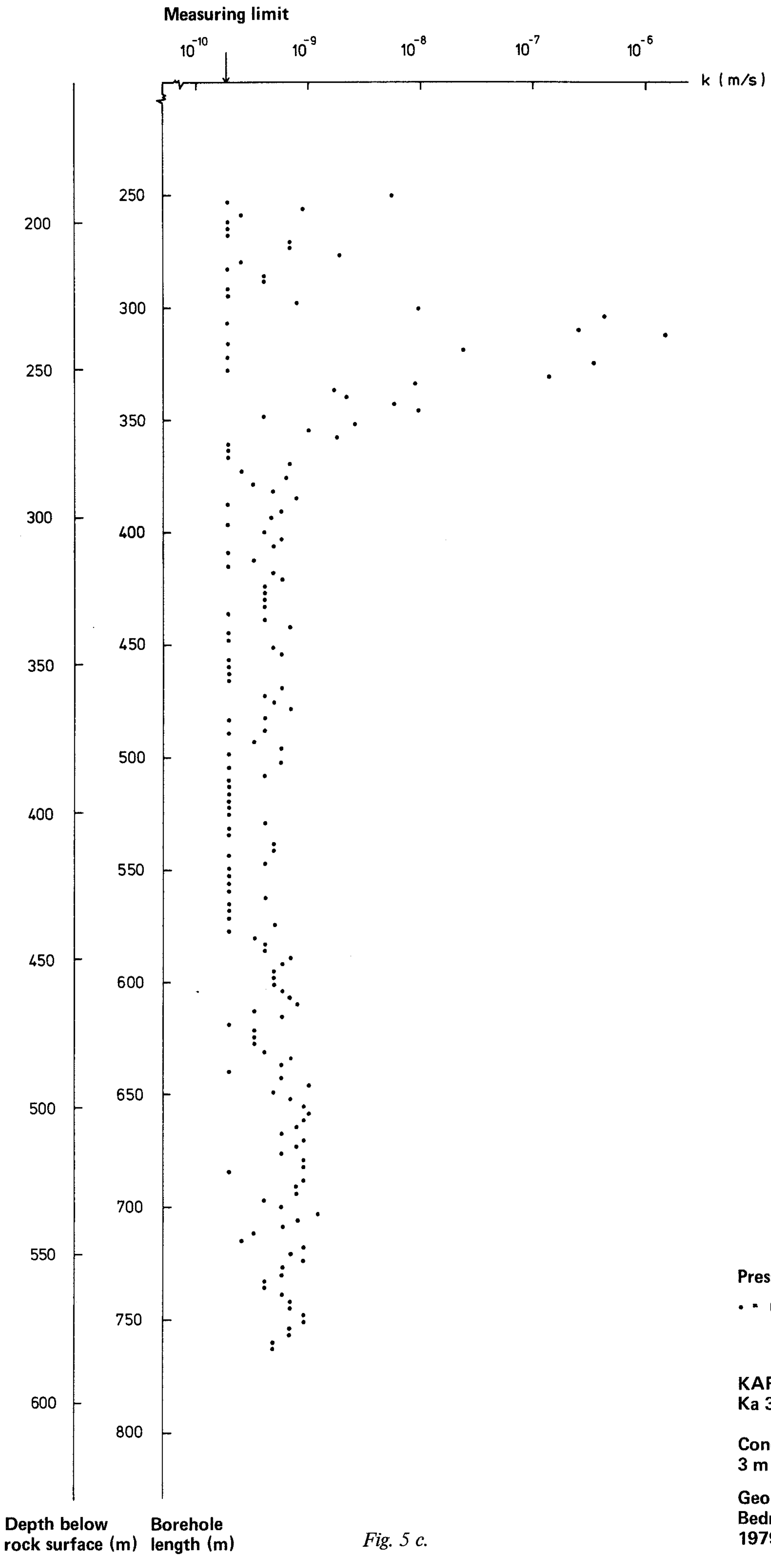


Fig. 5 c.

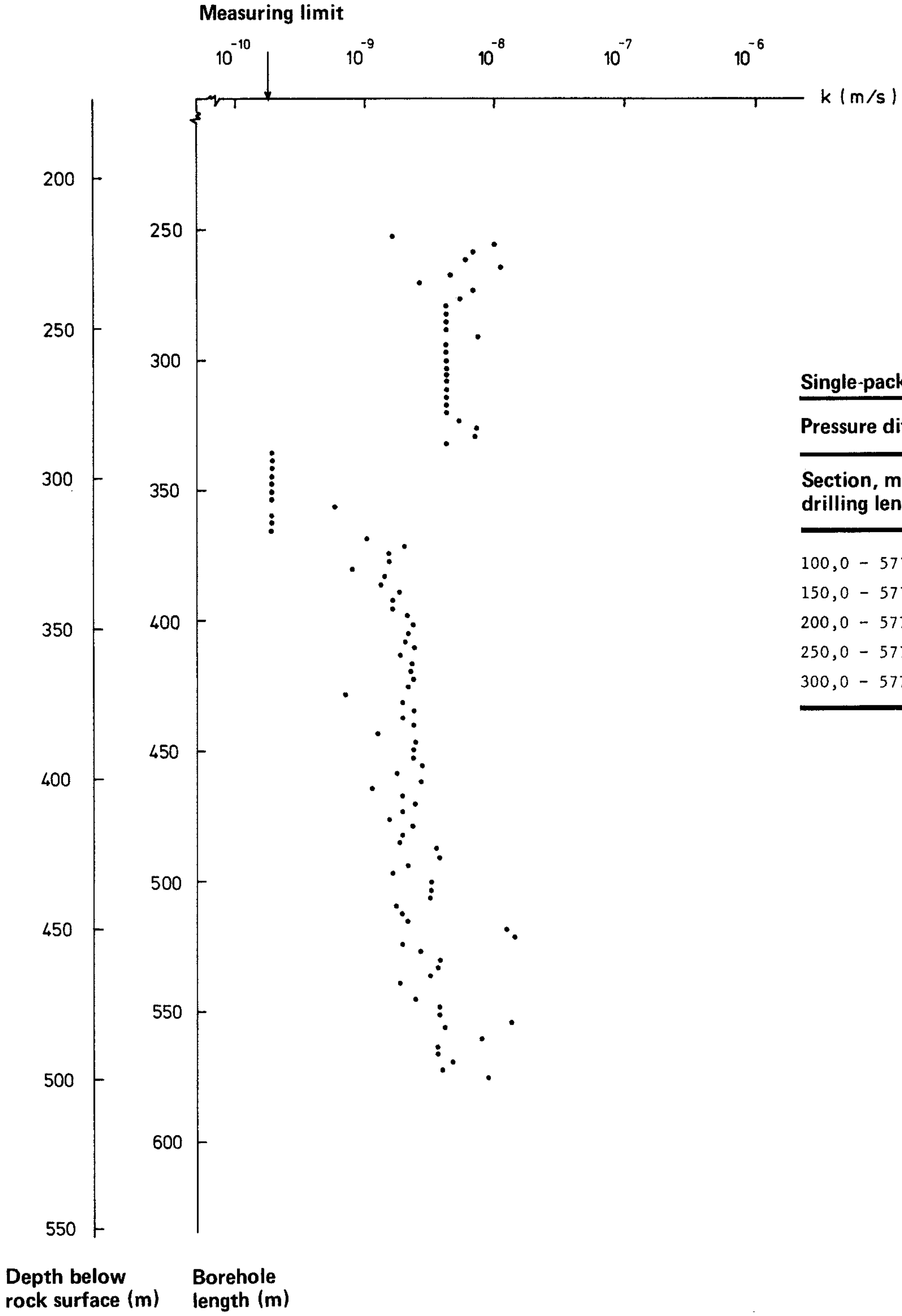
Pressure difference

• 0,20 MPa

KARLSHAMN
Ka 3 borehole

Conductivity determination
3 m gauge section

Geological Survey of Sweden
Bedrock Bureau
1979



Single-packer measurements, Ka 5

Pressure difference 0.6 MPa

Section, m drilling length	Conductivity m/s
100,0 - 577,8	$1{,}8 \times 10^{-9}$
150,0 - 577,8	$1{,}2 \times 10^{-9}$
200,0 - 577,8	$1{,}1 \times 10^{-9}$
250,0 - 577,8	$1{,}8 \times 10^{-10}$
300,0 - 577,8	$4{,}0 \times 10^{-12}$

Pressure difference

• ▪ 0,20 MPa

KARLSHAMN
Ka 5 borehole

Conductivity determination
3 m gauge section

Geological Survey of Sweden
Bedrock Bureau
1979

Fig. 5 d.

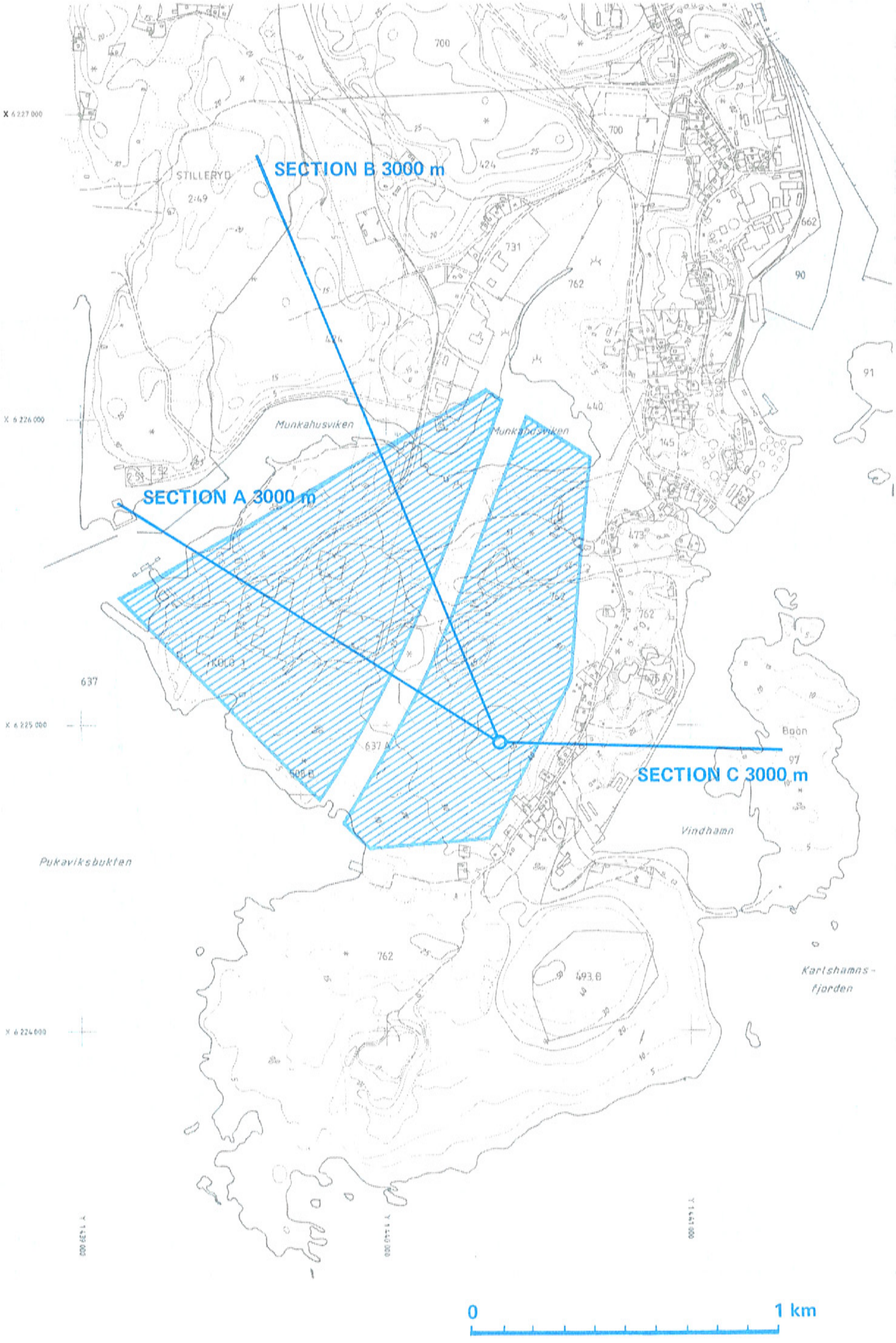


Fig. 6. Sections where groundwater flows have been calculated.

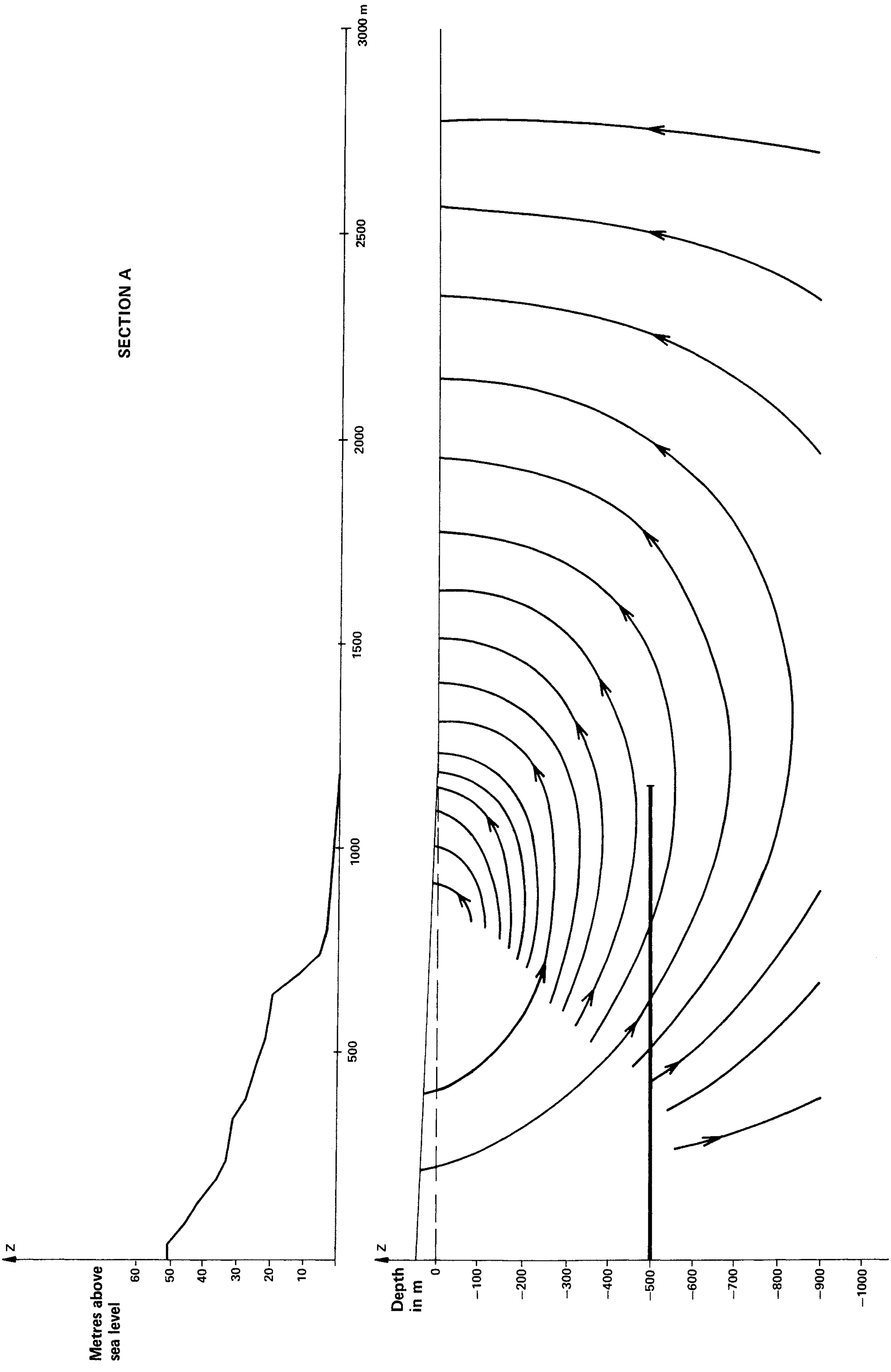


Fig. 7 a. Flow lines in section A. The groundwater flow between solid flow lines is equal everywhere.

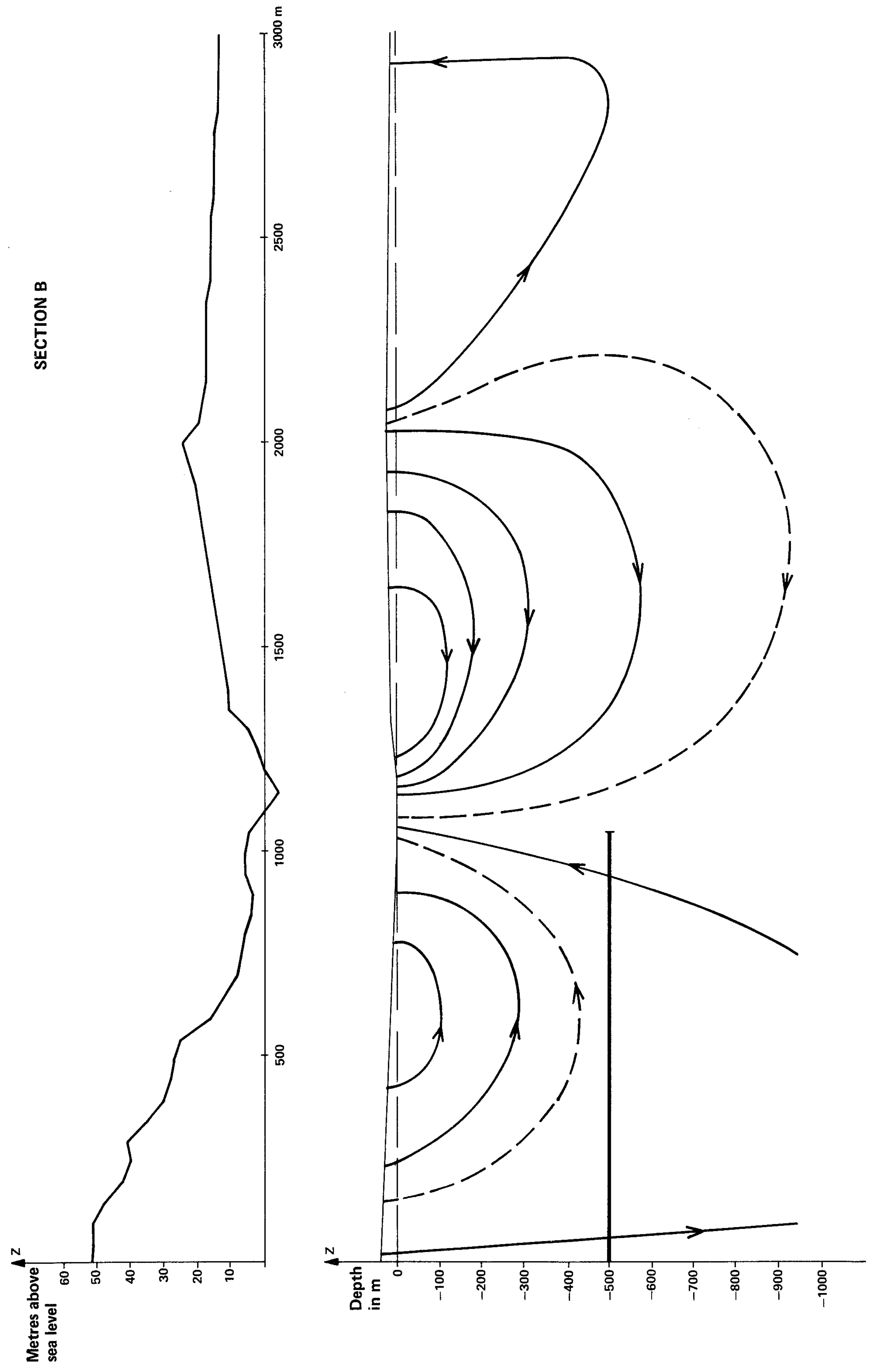


Fig. 7 b. Flow lines in section B. The groundwater flow between solid flow lines is equal everywhere.

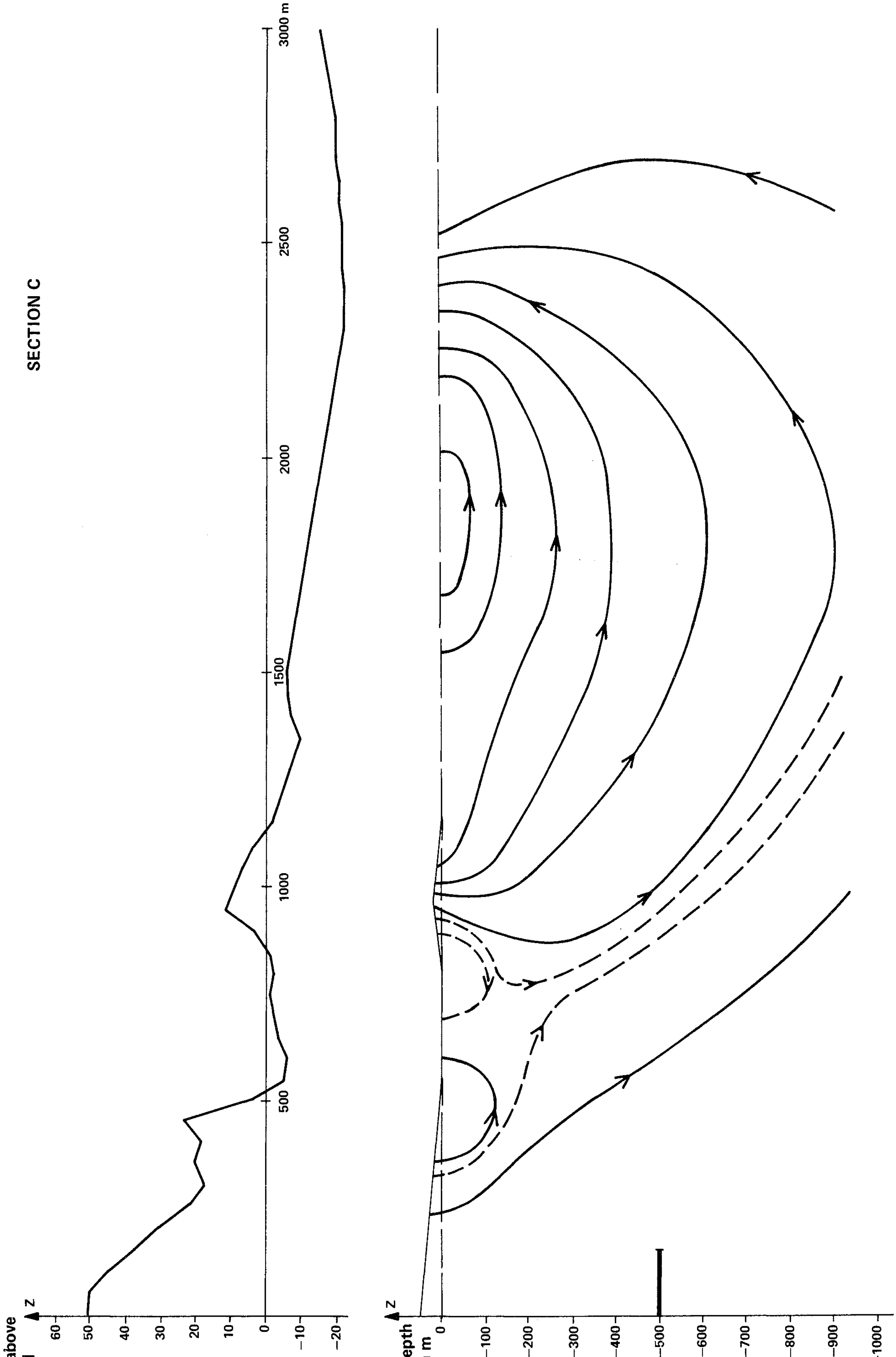


Fig. 7 c. Flow lines in section C. The groundwater flow between solid flow lines is equal everywhere.

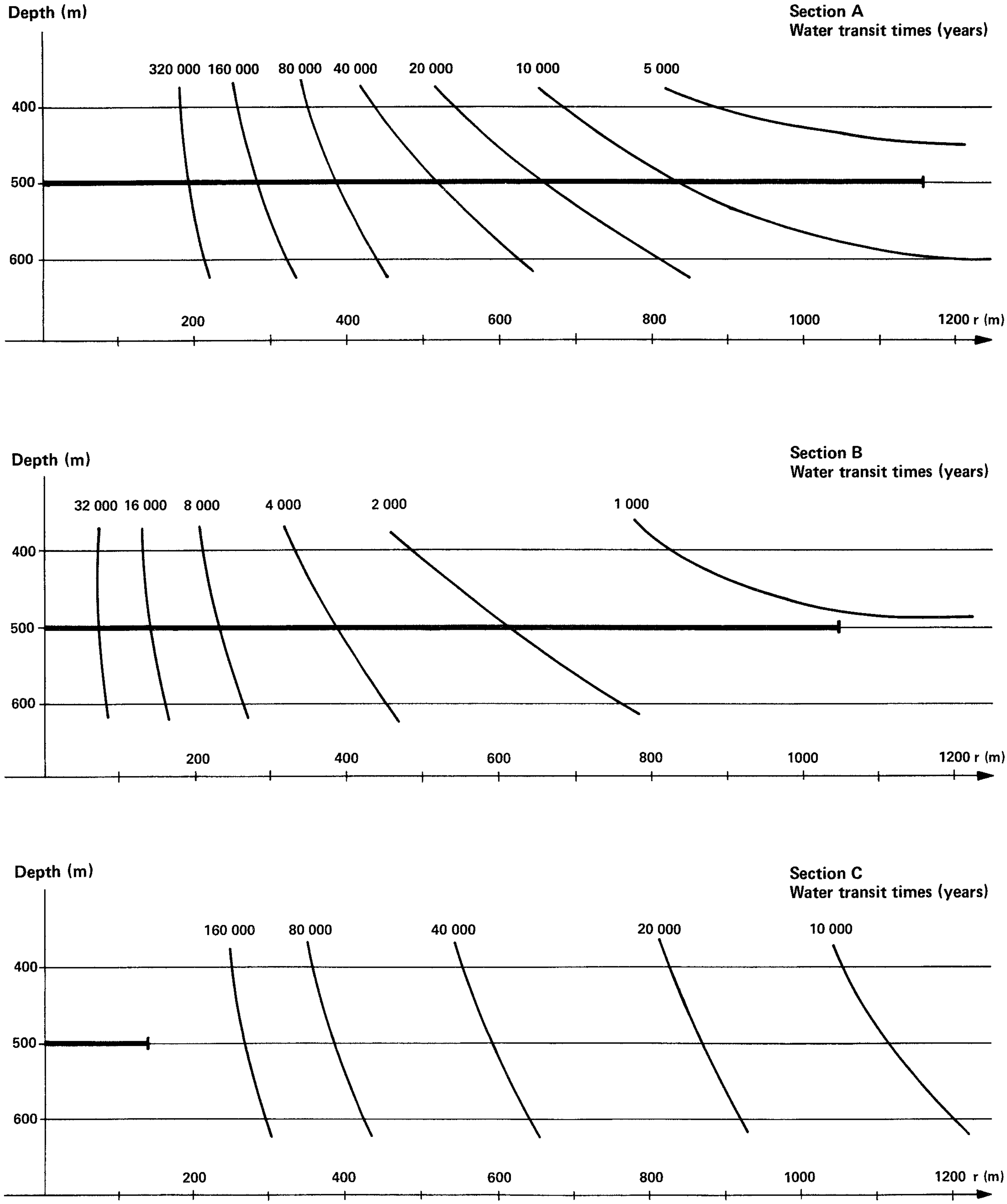


Fig. 8. Estimated time for groundwater flow to ground surface in section A–C.
Premises: $\kappa = 10^{-9}$, $\epsilon = 10^{-3}$

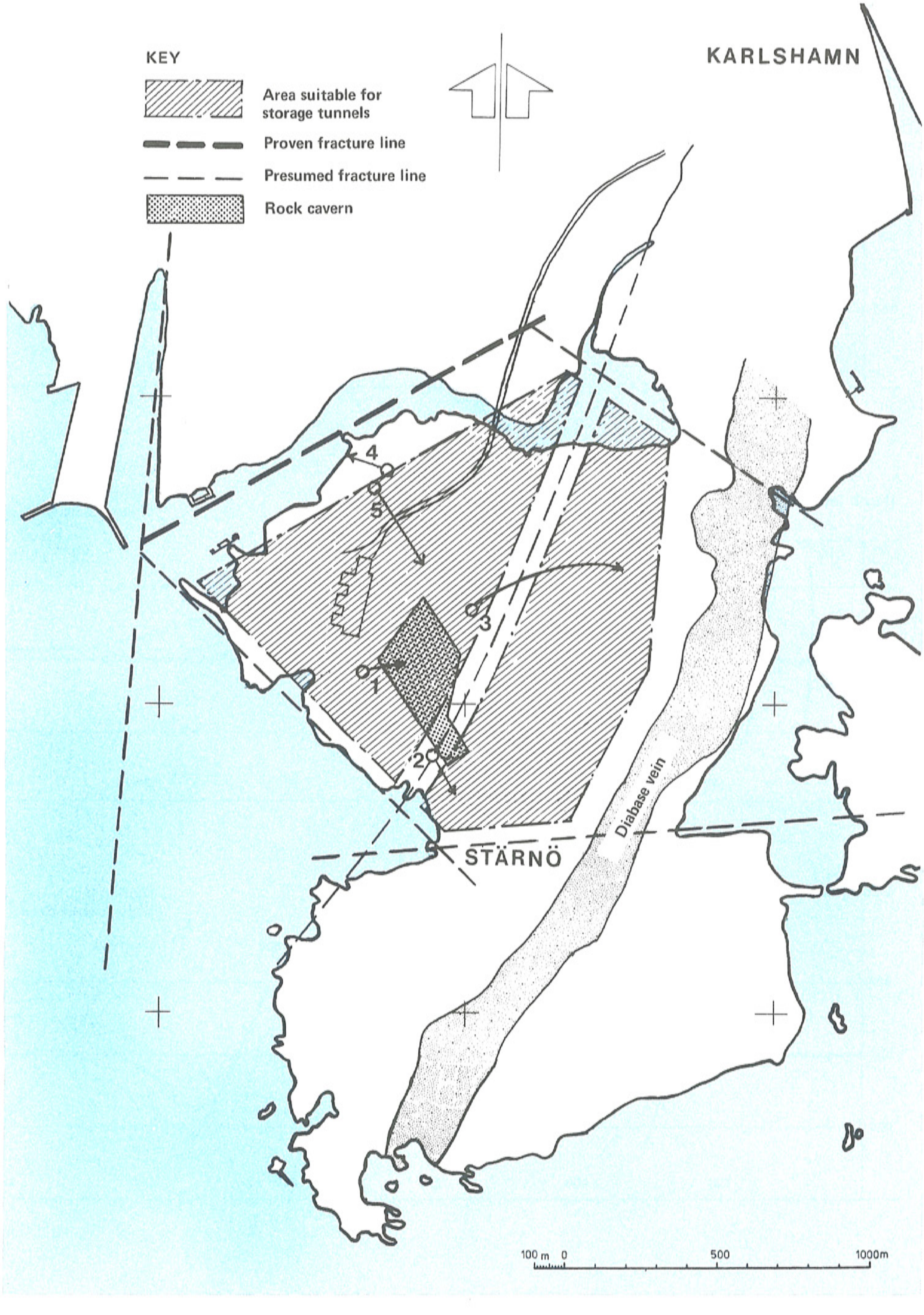


Fig. 9. Summary map of the area at the Karlshamn plant which has been found to fulfill the geological prerequisites for the construction of a final repository.

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