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Predictive geology in nuclear waste management

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PREDICTIVE GEOLOGY IN NUCLEAR WASTE MANAGEMENT

O Brotzen, Sweden

Revised version
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ABSTRACT

The present situation at a specific site in the Baltic Shield is viewed in the light of its geologic history. Prediction, at a given level of confidence and from a limited number of drillholes, of the minimum average spacing of conductive zones in subsurface rocks of low hydraulic conductivity is based on a combination of the binomial and Poisson distributions, regarding the holes as a profile sampling and assuming a cubic pattern of fractures.

The data provide an empirical basis for linking the nature and frequency of past geologic events to their local effects. Special attention is given to the preservation of tectonic blocks of large rock-volumes with very low hydraulic conductivity throughout the present cratonic stage, during which intermittent movement took place in marked fault-zones bordering the Shield, and three different orogenies affected the surrounding regions. Rock-mechanical, stochastic and deterministic approaches are utilized to predict future effects from this basis.

KEY WORDS: Site evaluation, prediction, Baltic Shield, hydraulic conductivity, conductive zones, spacing, profile sampling, binomial, Poisson, finite-element, geo-chronology, Precambrian, Caledonian, Hercynian, Variscan, Alpine, post-Alpine, Quaternary, fracture, fault, volcanism, seismicity, peneplain, climate, weathering, glaciation.

INTRODUCTION

Geological work concerning nuclear waste in Sweden is at present mainly directed towards preliminary site investigations and their evaluation. Two questions are often asked in this context:

1 How can the presence of large volumes of rock of low hydraulic conductivity at depth be predicted from a limited number of narrow drillholes?

2 How will future geologic events and climatic changes affect conditions at depth?

Attempts to answer these questions in relation to one specific site will be reviewed here.

THE STERNÖ SITE

This site is situated on the Sternö peninsula at $56^{o}09'$N and $14^{o}50'$E of Greenwich, about 2 km south of the town of Karlshamn, on the southeastern coast of Sweden. It is located near the margin of a Precambrian gneiss complex in the Baltic Shield. The choice of the marginal location was dictated by the fact that permission to drill here was granted by the landowner, Sydkraft AB. The area was suggested for investigation by Professor I. Larsson on the basis of its structural geology, the notoriously low yield of water from wells in this rock and his experience from large storage facilities here. This suggestion was shown to be fully justified by the very first drillhole, KBS 1977, and this evaluation has been further substantiated by subsequent drilling, KBS 1979, Ahlbom et al 1979. This series of steps in itself represents a successful case of a well established type of geological prediction, which is of great practical importance in the management of nuclear waste.

The investigations of the Sternö site were made by the Geological Survey of Sweden. The results are available as follows:

- A map (1:10 000) of the bedrock at the surface, together with brief descriptions and detailed logs (1:100) of the cores from five drillholes, Olkiewicz and others, 1979.
- Results of water-injection tests in the drillholes, employing both single and double packer equipment, to establish the hydraulic conductivity of the bedrock, Ekman and others 1980.
- Model calculations on ground water conditions, Axelsson and Carlsson, 1979.
- General evaluation of the site, Ahlbom and others, 1979.

A separate presentation of the investigations has been prepared by the staff of the KBS-project, KBS 1979, see also KBS 1978.

An additional evaluation of the site by a group of geological consultants has been presented by SKI, 1979. The possible role of suspected fracture zones as derived from topographical features at the site is especially emphasized by this group, which, however, did not inspect the drillcores, nor accept values of hydraulic conductivity below 10^{-7} m/s. Therefore the presence and significance of long sections of very low conductivity at depth, which is the subject of the present analysis, was entirely overlooked. The westernmost fracture zone on Sternö, as shown in Fig 1, is taken from this report.

The geological situation at Sternö may briefly be described in the following way:

The northern part of the peninsula, where the drillholes are located, is roughly conical in shape, with a maximum elevation of 50 m above SL. It is made up of a grey complex of quartzo-feldspathic para- and orthogneisses, showing weak foliation, occasional banding and a varying migmatitization and development of irregular pegmatites. Precrystalline deformation is strong; the axial planes and the foliation predominantly dip around 15° to the North. To the South the gneiss borders on a younger, reddish granite, which also is predominant at depth in the drillholes. The contact between gneiss and granite is complex in detail, showing interfingering and gradations. Yet on a larger scale it appears to conform approximately to the attitude of the gneiss. The fracturing at the surface is limited both in extent and intensity. Generally no displacement along individual fractures is seen in outcrop, a reported maximum value is 2 cm. Furthermore, this displacement is suspected to be due to surface blasting. Later work has disclosed a horizontal displacement of 7.3 cm along a fracture entirely outside the realm of blasting activities.

Five inclined drillholes (56 mm diam, fully cored) to vertical depths between 500 and 775 m have been drilled at the site (Fig 1). Fig 2 and 3 represent the hydraulic conductivities obtained by water injection tests in these holes. It is seen that the upper part of the bedrock is characterized by average values around 10^{-9} m/s, whereas the deeper sections consistently show much lower values. Table 1 summarizes the results on the low-conductivity sections.

Table 1

Deep sections with low hydraulic conductivity, Sternö

Drill-hole	Inclination	total length	upper limit	length	hydraulic conductivity
Ka	degrees	m	m	m	m/s
1	80	778.5	199.5	579	1.0×10^{-12}
2	75	575.8	350.0	226	3.1×10^{-12}
3	50	764.6	400	365	6.6×10^{-11}
4	75	580	452	128	5.0×10^{-11}
5	60	577.8	300	278	2.4×10^{-12}

The transition between the upper, conductive, and the lower, practically non-conductive sections, is remarkably distinct. Comparison with the core-logs indicates that the transition is independent of the gneiss/granite interface, but appears to reflect, to some extent, the distance to larger fracture zones. Thus the transition is found at the greatest depth in drillholes 4 and 3, which both are close to such zones. In contrast it is found at a more shallow depth in drillhole 1, which is at a greater distance from the known or indicated major fractures. Drillholes 2 and 5 take intermediate positions in this respect.

The results from Sternö appear to be significant in different respects:

1. The rapid change in hydraulic conductivity indicates that the cumulative fracturing by near-surface processes, including repeated quaternary glaciations, did not reach technically prohibitive depths.

2. The rapid change casts doubt on the prevalence of a continuously decreasing conductivity with depth. Such a decrease might be expected from the increasing overburden pressure and a laboratory demonstration of the validity of the cubic law for fluid flow down to very small fracture apertures, Witherspoon and others 1979. The rapid change might instead suggest that the length and connectivity of fractures must enter hydrogeological predictions, and perhaps also that under natural gradients, which are much smaller than those employed in most experiments, narrow fractures become non-transmissive due to electrical double layers, as demonstrated by Cherskiy and others, 1977, for small pores in fine-grained sandstones.

3. The continuous lengths of low-conductive bedrock found in the deeper parts of the drillholes permit prediction of the average spacing between the more conductive zones that may occur at these depths at Sternö.

Analysis of the spacing starts from the finding that all five drillholes end in sound rock of very low conductivity and that the deeper sections of the holes show no single subsection with a conductivity of 10^{-8} m/s or higher over a length of 3 m or more. (Such a zone is here called a conductive zone).

In spite of this favourable result the occurrence of such conductive zones at depths well below the general upper boundary of the low-conductivity part of the bedrock must be expected. This follows from the great length of some of the fracture zones traced at the surface, indicating a corresponding, great persistence in depth.

A limiting statistical estimate of the frequency of conductive zones at depth may be obtained from considering the drillholes as a kind of profile sampling of the bedrock. The limited width of the holes and of the zone of influence in the injection tests is obviously of little relevance in this context. Furthermore, the spread of the drillholes over the site, and the difficulty to predict from the surface, and without extensive geophysical investigations , where conductive zones may be found at depth, justify acceptance of this sampling as essentially random in nature.

The total length drilled below the upper boundary of the low-conductive part of the bedrock thus approximates a random sample of this rock volume. The length may be divided into a given number N of subsections (sampling units) of length s. Each sampling unit may then be referred to one of two alternative classes according to whether it includes or does not include any conductive zone. In cases like this a binomial distribution may be applied to estimate from the observed frequency in the sample (X:N) of one of the two classes, and at a desired level of confidence, limiting values of its proportion p in the population being sampled. Clopper and Pearson, 1934.

At the Sternö site the total length drilled below the conductive part of the bedrock, 1576 m, may for instance be divided into 30 subsections 52.5 m in length, N=30, s=52.5. The number of subsections without conductive zones also is 30, X= 30. For X and N= 30 the limiting values of p at 90% confidence are 0.9 and 1.0. Other combinations of s, N and p pertaining to the Sternö site are listed in Table 2.

Table 2

Number and length of hypothetical subsections, total length 1576 m, p, z, and S at 90% confidence.

N number	s (m) length	p lowest proportion of subsections without high-cond. zones	z=s/S average number of conductive zones/subsec.	S (m) smallest spacing
100	15.8	0.97	0.030	519
50	31.5	0.94	0.062	509
30	52.5	0.90	0.105	499
20	78.8	0.86	0.15	525
15	105	0.82	0.20	529
10	157.6	0.74	0.30	523
5	315	0.55	0.60	527

Snow, 1968, has pointed out that the number of fractures intersected by equal lengths of random drillholes should obey a Poisson distribution, and that drillhole-sections showing zero-discharges in water-injection tests give evidence of the number of water-conducting fractures. The frequency of zero-discharges, i e the proportion of subsections without conductive zones, is related by the Poisson distribution to the average spacing (S) between conductive zones in the drillholes in the following way:

$$z = s/S = \mathrm{Ln}\ 1/p;$$

where s, as before, is the length of the subsections considered, S is the average spacing between conductive zones in the holes, and p is the proportion of sub-sections without conductive zones. The lower limits of p as earlier obtained from the binomial distribution thus define the lower limits of S. Both p and S are listed in Table 2 for various values of s and N. The minimum average spacing, at a confidence level of 90%, is seen to be around 500 m, and independent of the lengths of the subsections used in its calculation. Therefore this applies also if they are of unequal length, such as the complete lengths of low-conductive rock from Sternö listed in Table 1.

Snow, loc.cit, further cites the common occurrence of three mutually orthogonal and similar sets of fractures as justification for a statistically cubic fracture model. If a drillhole is normal to one of the fracture-sets in such a cubic pattern it will not intersect the other two sets. The average distance between the fractures is then equal to S, as observed in the drillhole. If the direction of a drillhole is along the diagonal of the cubic pattern, it will intersect all three sets, and the average spacing between fractures is 1.7 S. From this follows that the minimum average spacing of conductive zones as calculated for the drillholes at a given level of confidence also represents at the same level of confidence the minimum average distance between conductive zones in a cubic pattern.

A cubic model is only an approximation of the true situation. The value of 500 m for the minimum average distance therefore is not a fully accurate estimate, but it certainly indicates in what range the separation between conductive zones can be expected to fall. In this case it obviously justifies the conclusion that the separation is of the order of several hundred metres. In combination with a separate evaluation of the possible effects of individual fracture-zones on the pattern of groundwater flow at Sternö, Axelsson and Carlsson 1979, it may further be concluded that large volumes of rock with low hydraulic conductivity would here be available for the storage of high-level nuclear waste.

EFFECTS OF FUTURE EVENTS

Predictions in many branches of engineering are based on actual tests of the material or structure in question. In a similar way a specific geologic situation, such as the one described above, may be regarded as the result of a natural testing procedure, represented by its geologic history. This provides an empirical basis for linking the nature and frequency of geologic events to their effects in the bedrock. For this purpose a brief review will be given of the available geological evidence bearing on the present situation at Sternö.

A special study by Larsson and others, 1977, has shown that the area surrounding and including Sternö was pervasively fractured already in Precambrian time. A set of dilation dykes of dolerites striking NNE occupy the tensional fractures of a final disruptive phase, which also gave rise to a complete array of hkO- and hO1-shears. One of these dykes, between 100 and 250 m wide, is found about 300 m to the east of the end of drillhole Ka 3 at Sternö. Two samples define its age as 870 and 940 Ma (million years, Rb-Sr) respectively. (The ages of Swedish rocks given here are quoted from a compilation by Welin, 1980).

No younger volcanic rocks are known in the area, and the dolerites are non-metamorphic and practically undeformed. They therefore show that this part of the Shield had reached its present cratonic stage already 900 million years ago. Also, the regional fracturing, and its associated volcanic activity at the very margin of the Sternö site must here mark the most important event contributing to the present hydraulic conductivity in the deeper parts of the bedrock. The dyke itself has probably brought about a local heating, followed in turn by a period of cooling. It may also be connected with the deposition of fissure-filling minerals, such as chlorite, calcite, gypsum, quartz and pyrite, seen in the drillcores and reducing the conductivity created by the preceeding fracturing.

No observations indicating a later fracturing was reported in these studies. Very recently, however, a discovery of Quaternary fault-movements, from between 10 000 and 12 500 years ago, has been announced by Mörner, 1980 a, b. The postglacial vertical displacement is reported to amount to about 7 m, and the fault is alleged to cross the site at Sternö although its actual course has not yet been disclosed.

Other parts of the Baltic shield show very much a similar picture. A pioneering study by Asklund, 1923, established that the fracture-pattern in another area further to the north was formed in connection with the emplacement of different generations of basic dykes, all Precambrian in age. Later geochronological work has so far shown that such regionally distributed dykes represent volcano-tectonic episodes between 900 and 1500 Ma ago.

The regional preservation and distribution of sub-Cambrian, sub-Mesozoic and sub-Cretaceous peneplains respectively, cf Rudberg 1970 and Kumpas 1980, show that the rocks of the Shield exposed today attained near-surface conditions about 600 Ma ago, and that their deformation since then has been generally very limited. What is left of Phanerozoic cover rocks indicates that later burial, which occurred during some periods only, amounted to around one kilometre or less, except near the southern margin of the Shield.

Deformation during the last 600 Ma involved both local block-movements and a systematic uplift along a long train of individual faults and flexures, which form the western, topographic limit of the sub-Cambrian peneplain, as preserved today. The course of this limit seems to coincide rather well with the main linear belt of increased seismicity in Sweden. This "seismic" step marks an uplift of the western part of Sweden of around 150 m.

Individual faults bordering subsided blocks with preserved cover rocks represent total vertical displacements of a few hundred metres at most during the last 600 Ma. Smaller displacements, of the order of 30 m, are rather common in many parts of the Shield. The largest known faults are found near the southern margin of the Shield, and are indirectly related to the Tornquist line. Here the total vertical displacement during the last 600 Ma at individual faults reached two kilometres, and it can be shown that the average rate of absolute vertical displacement over the last 600 Ma was approximately the same as over the last 400, 200 and 65 Ma, Röshoff and Lagerlund 1977, KBS 2, 1977. It is recognized, of course, that these averages represent episodes of tectonic activity separated by periods of relative tranquility.

The following episodes of tectonic activity, with or without associated volcanism, are known to have affected the Shield or parts thereof during the last 600 Ma (in contrast very little is known of the time between 600 and 900 Ma ago):

1 Tectonic activity associated with alkaline volcanism at Alnö and Åviken, age 550 Ma (Cambrian);

2 Silurian subsidence at the southern margin of the Shield (Scania, Colonous-shale);

3 Dolerite emplacement, NW dykes in Scania, horizontal sill at Billingen (plus alkaline complex at Särna) age 280 - 305 Ma (Carboniferous);

4 Basalt volcanism in Scania, age 170 Ma (Jurassic);

5 Basalt volcanism in Scania (plus Mien rhyolite/impact), age 110 Ma (Cretaceous);

6 Post-Campanian tectonism and possible volcanic or intrusive activity in the Hanö bay area (Kumpas 1980);

7 Tertiary subsidence of formerly forested (Amber) areas now at the bottom of the Baltic Sea. Probably the relative uplift of western Scandinavia and formation of the central "seismic" step in Sweden also took place at this time;

8 Quaternary and neotectonic activity.

This localized evidence may be compared to the tectonic manifestations on a much grander scale simultaneously taking place in the less stable regions surrounding the Shield, as recently summarized in a special issue of Episodes, vol. 1980 No 1.

The Alnö activity may reflect Cadomian or early Caledonian disturbances and the Silurian subsidence is part of the Rügen-Pommeranian Caledonian activity.

The Carboniferous dolerites in southern Sweden are contemporaneous with Variscan-Hercynian activity in Europe, also represented by large-scale rifting and volcanism in the Oslo area.

Jurassic basalt volcanism in Scania (Kimmerian) is simultaneous with the creation of the Alpine geosyncline and may be regarded as an early outlier of the Brito-Arctic volcanic province,heralding the opening of the Atlantic Ocean. Its actual opening may in a similar way be reflected in the Cretaceous basalts, whereas post-Campanian activity, the subsidence of the Baltic and even the Neotectonic events in the Shield would correspond to intense faulting in Central Europe and the North Sea, reflecting and following the main Alpine folding in upper Eocene time. The newly discovered signs of sub-marine post-Campanian volcanism may thus mark a Baltic representative of the post-Alpine volcanism of Central Europe, active into the late Quaternary.

Prediction based on this combined evidence may proceed along several lines. A structural and rock-mechanical approach may first consider the demonstrated preservation, throughout this long-continued series of deformations and varying stress orientations, of large blocks with limited fracturing and very low hydraulic conductivity, situated between marked fracture-zones of higher conductivity and reduced shearing strength, some of which have been intermittently mobile for the last 600 million years.

This long-lasting contrast betwwen stable blocks and mobile fracture-zones provides empirical confirmation of finite-element calculations which show that a fracture-pattern of the existing type will accommodate future deformations with only insignificant new fracturing, Stephansson and others 1979. This is further supported by field evidence of repeated reactivation of individual fractures, Samuelsson 1975, and of the role of older fracture-zones in neotectonic activity, Stephansson 1979, Röshoff 1979, Lagerbäck 1979, Henkel 1979 and Mörner 1979. Also the alignment of the present seismic activity in the Shield along very old NW-striking fracture-zones, Strömberg 1976, Båth 1978, Talvitie 1979, confirms this approach. Recognition of the decisive role of the pervasive Precambrian fracturing, and the limited effects of later tectonic events obviously leads to the prediction that present low-conductivity volumes will remain intact also for the next few million years. Actual verification of Quaternary faulting crossing the Sternö site would naturally provide most convincing evidence in this respect, because here its effects on the hydraulic conductivity in large volumes of rock at depth can be shown to be below the limits of detection of presently available measurements of hydraulic conductivity.

On the other hand it is not possible to establish for each individual fracture at what point in time it was formed. It may therefore be prudent to assume that each tectonic episode adds to the total fracturing and hydraulic conductivity in the bedrock. The contribution to the present situation from each episode in the past cannot at present be estimated,nor can future contributions be predicted. It is possible, however, to consider a set of equivalent episodes of equal number as in the past,the effects of which would add up to the situation as presently found at the Sternö site. It may then be predicted that a similar set of tectonic episodes in future would approximately double the number of fracture-zones, and also the amount of fracturing between them, and hence the hydraulic conductivity of the intervening rock masses. If such episodes are randomly distributed in time, then the probability that this will happen in a given span of time can be calculated by the Poisson distribution.

By this approach the present situation at the Sternö site may in an extreme case be regarded as the result of the tectonic episodes listed above, during the time after the 900 Ma dolerite. Perhaps the last three of them are simply different manifestations of the same (post-Alpine) phase of tectonism. Although the Quaternary includes repeated glaciations and deglaciations, Hays and others 1976, it is in the present time-perspective better considered as only one part of a single post-Alpine episode. This leaves a total of six known episodes, with an average frequency of 7 x 10^{-3} per Ma. The probability that six equivalent episodes will occur in the next one million years, and thus within this time cause a doubling of the fracturing at the Sternö site is

$$(7 \times 10^{-3})^{6}/6! \; e^{\,7 \times 10^{-3}} = 1.6 \times 10^{-16}$$

This, of course, is an approximation only, just indicating the order of magnitude. The estimate neglects the pervasive fracturing preceeding dolerite intrusion. Inclusion of one additional episode in the past which has affected the site but so far remained undetected, would decrease the probability by a factor of 400.

A stochastic approach may, however, be unrealistic because the episodes in question cannot for physical reasons be compressed into one million years, furthermore they are not randomly distributed in time. They appear instead to be connected to an orderly succession of orogenies, each of a duration of 50-100 Ma. It may further be noted that each new orogeny developed further out from the Shield than the preceeding one, and that the known volcanic manifestations in the Shield show a similar displacement towards its southern margin. From the present geologic situation it may thus be predicted that the next orogeny of concern would perhaps develop south of the Alps or west of the Caledonides. Its development would be such a slow process, that the first million years from now represent only an insignificant fraction thereof. More likely Northern Europe is still in a waning post-Alpine stage of faulting and volcanism, the decline of which is evidenced by the much reduced volcanism in the Quaternary as compared to the Tertiary. The effects of one million years in such a period of relative tranquility thus must represent only a completely negligible fraction of a fraction of the combined effects of earlier orogenies.

EFFECTS OF CLIMATIC EVENTS

In the Baltic Shield the geologic record of climatic events includes extensive Jotnian redbeds in central Sweden, widespread sub-Cretaceous kaolinite deposits in Scania, local fossil evidence of subtropic humid conditions in the Tertiary with deep local weathering in the crystalline rocks tentatively correlated with it, and repeated glaciations in the Quaternary.

The effects of these events in the bedrock at depth at Sternö are absent or barely traceable.

Montmorillonitic weathering along fracture-zones at shallow depth has been reported, Larsson 1977, Pusch 1979, but at depth this has not been observed, and supergene effects are only represented by gypsum and rare limonite-stains in individual fissures. Chlorite and biotite with ferrous iron prevail throughout the bedrock, demonstrating its unoxidized condition, and pyrite is frequently found in its fractures. The local limitation of oxidation even in cases of extreme and deep weathering is described from adjacent parts of the Shield, Geijer and Magnusson, 1926. It is therefore concluded that even extreme climatic events will not affect the redox-conditions in the rock away from major fractures at depth.

The effects of repeated glaciations and deglaciations, which occurred in the Pleistocene, have been shown to be limited to the upper parts of the bedrock. An additional glaciation cycle in future may conceivably deepen this limit of influence somewhat, but the evidence from the Sternö site shows that in the flat country of the Shield this is irrelevant in comparison to depths attainable in modern mining. It is therefore concluded that the hydraulic conductivity and reducing conditions at depth at Sternö will remain practically unaffected by climatic changes and geologic events even beyond the next one million years.

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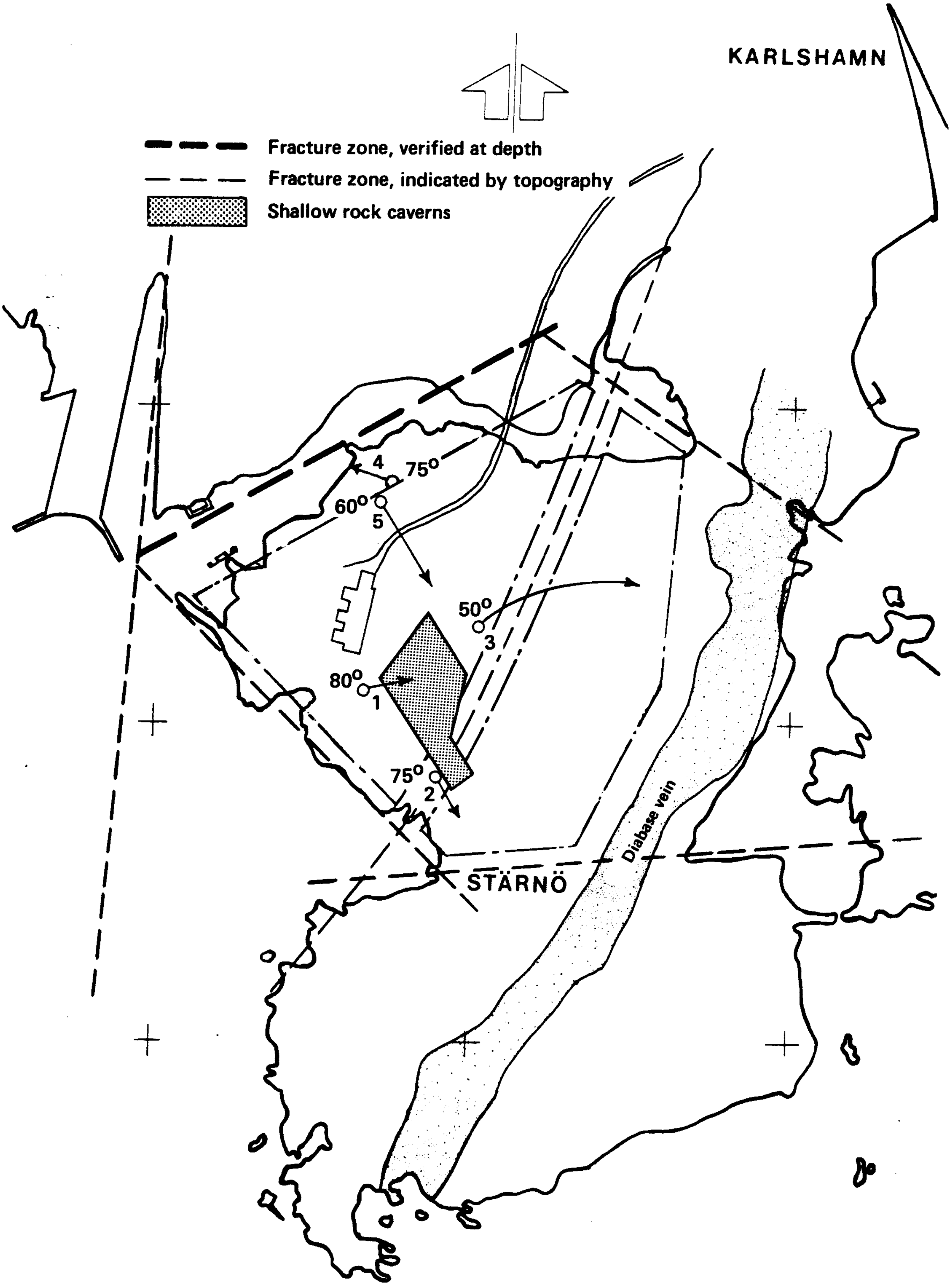

Figure 1. Map of Sternö Peninsula with location of drillholes.

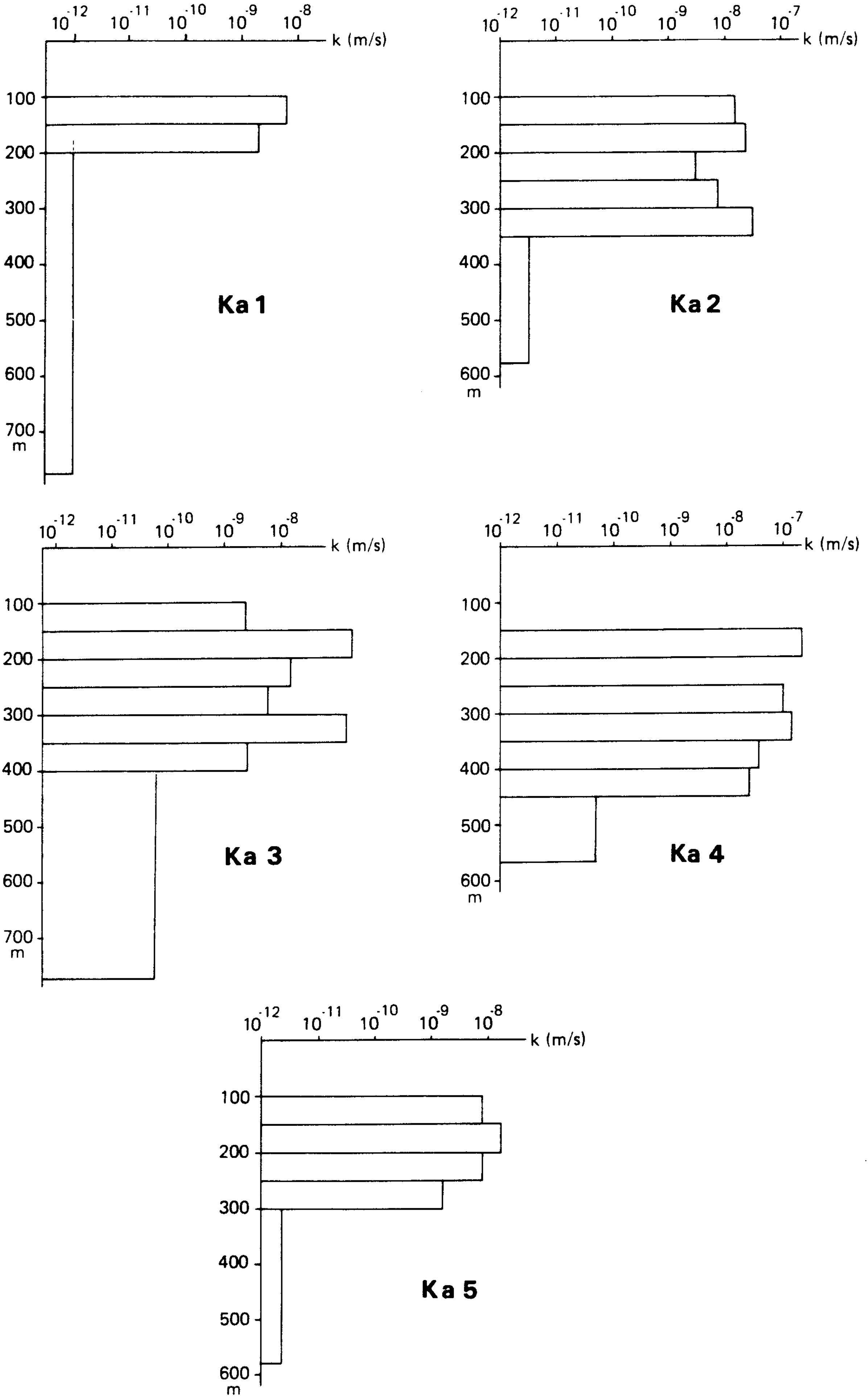

Figure 2. Hydraulic conductivity in drillholes by single-packer water injection tests. Distance between packers, and also between measuring points, 50 m.

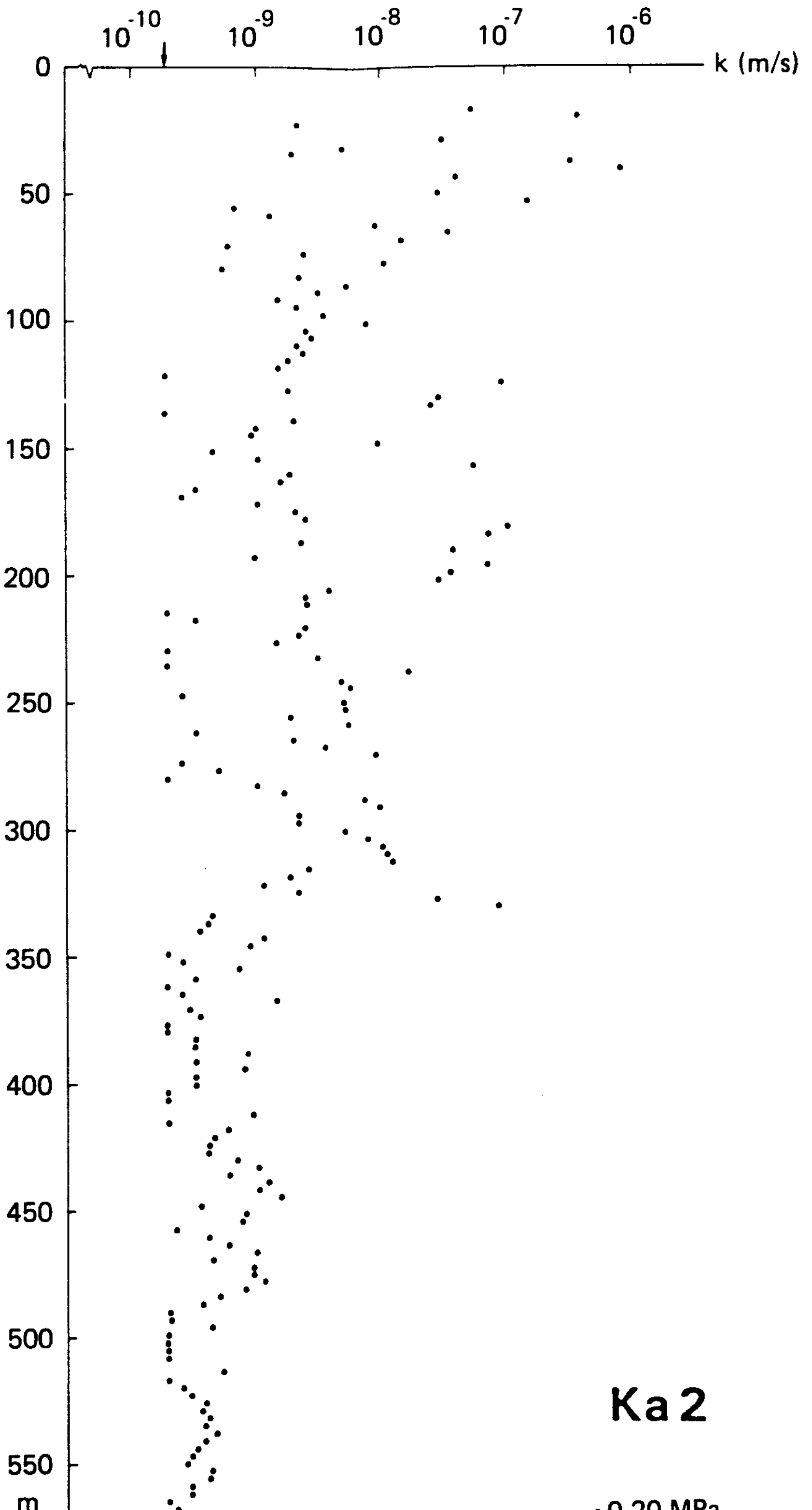

Figure 3. Hydraulic conductivity in drillhole Ka2 by straddle-packer water-injection tests. Distance between packers 3.0 m. Injection pressure 0.20 MPa.

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