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Swedish Hard Rock Laboratory First evalution of preinvestigations 1986-87 and target area characterization

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June 1988

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SWEDISH HARD ROCK LABORATORY
FIRST EVALUATION OF PREINVESTIGATIONS 1986-87
AND TARGET AREA CHARACTERIZATION

BY
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CONTENTS Page

	SUMMARY	i-iii
	ABSTRACT	iv
	ACKNOWLEDGEMENT	v
1	INTRODUCTION	1
2	GEOLOGY	5
2.1	GEOLOGICAL STUDIES	5
2.1.1	Bedrock geology	5
2.1.2	Geophysics	11
2.1.3	Structural geology	18
2.1.4	Fracture zones in the Simpevarp area	24
2.1.5	Fracture mapping	31
2.2	GEOLOGICAL-TECTONIC MODELS OF THE SIMPEVARP AREA	36
2.2.1	Regional scale	36
2.2.2	Site scale	42
2.2.3	Detailed scale	45
2.3	BOREHOLE SITING	60
2.3.1	Percussion boreholes at Äspö, first batch	60
2.3.2	Core boreholes KAS 02 and KAS 03	61
2.3.3	Percussion boreholes at Äspö, second batch	62
2.3.4	Core borehole KAS 4	62
2.3.5	Percussion boreholes in the Laxemar area	62
2.3.6	Core borehole KLX 01	63
3	GEOHYDROLOGY	64
3.1	GEOHYDROLOGICAL STUDIES	64
3.1.1	Hydrological conditions in the Simpevarp area	64
3.1.2	Regional Well Data Analysis	65
3.1.3	Geohydrological data from the Simpevarp Area	66
3.1.4	Hydraulic tests at Ävrö, Äspö and Laxemar	66
3.1.5	Generic modelling of the SKB rock laboratory	70
3.2	CONCEPTUAL MODELS OF THE GEOHYDROLOGY OF THE SIMPEVARP AREA	71
3.2.1	A conceptual regional model	71
3.2.2	Conceptual models on site scale	77
3.2.3	Conceptual models on detailed scale	80

		Page
4	CHEMISTRY	83
4.1	CHEMICAL STUDIES	83
4.1.1	Well Water Analysis	83
4.1.2	Shallow groundwater chemistry at Laxemar, Äspö and Ävrö	84
4.1.3	Surface waters from Laxemar, Äspö and Ävrö	86
4.2	CONCEPTUAL MODELS OF THE GROUNDWATER CHEMISTRY OF THE SIMPEVARP AREA	86
4.2.1	Regional model	87
4.2.2	Site models	87
4.2.3	Detailed scale models	89
5	EVALUATION OF THE INVESTIGATION METHODS	92
6	DISCUSSION OF THE RESULTS WITH RESPECT TO THE SITING OF THE HARD ROCK LABORATORY	95
	REFERENCES	97

SUMMARY

The site investigations for the Hard Rock Laboratory in the Simpevarp area were started in 1986 with an aerogeophysical survey, including magnetic, coaxial EM, radiometric and two-station VLF measurements. All the aerogeophysical results have been processed using the EBBA image system. A gravity measurement net has been made with a density of about one station per square kilometre.

Ground geophysical profiles (magnetic and VLF) complemented the aerogeophysical survey on the islands of Ävrö and Äspö and in the Laxemar area.

Lineaments in the Simpevarp area have been interpreted from four different digital terrain models and compared with the topographic expressions of aeromagnetic lineaments.

The solid rock has been mapped to a scale of 1:10 000 in an area nearest to Simpevarp and to a scale of 1:50 000 in the larger outer area.

Fracture mapping and special tectonic studies were carried out with the main goal of describing the geometry of the fractures and of characterizing the main sets of tectonic zones identified as lineaments in the area.

A first attempt to make rock mass description to different scales was based on the results of the investigations mentioned above.

A rock mass description on a regional scale shows that the Simpevarp area is mainly of granitic composition (Småland granite) with inclusions of E-W elongated massifs of basic rock, greenstone, which are indicated by positive magnetic and gravimetric anomalies. Some circular structures have been interpreted as anorogenic granite diapirs (the Götemar and Uthammar granites). They are represented by a more or less round nonmagnetic pattern and positive Bouger anamalies.

Information from all geological and geophysical investigations support a tectonic picture of the Simpevarp area dominated by one almost orthogonal system of 1st order fracture zones running N-S and E-W. According to coincident magnetic and VLF indications, the zones trending N-S are probably more permeable than those trending E-W. Besides the system of 1st order fracture zones there are also 2nd order zones trending NW and NE forming another

almost orthogonal system. Most of the regional fracture zones in the Simpevarp area have been preliminaryly interpreted as vertical or sub-vertical, but both geological and geophysical indications point to the possibility of fracture zones that are flatter or dipless.

Rock mass descriptions to a more detailed scale were concentrated to the Laxemar area and to the island of Äspö, where more detailed investigations were performed. These two areas will be the target areas for further site investigations - especially core drilling.

The geohydrological investigations performed within the first phase has comprised of analyses of existing data from different aspects and hydraulic tests in percussion boreholes.

An analysis of data from water wells in the area shows a significant difference of the hydraulic conductivity for different rock types. The most pervious unit is the granites of Götemar-Uthammar type, the abundant Småland granite has intermediate conductivity and least pervious are the greenstones of the area.

An attempt to correlate the hydraulic conductivity to tectonic features has had little succes but a weak tendency for increased conductivity parallell to NW-SE and NE-SW lineaments and fractures was found. This was later confirmed by the pumping tests in the percussion boreholes.

Some fracture zones, very distinct with a few open fractures and a high transmissitivity were found in the Småland granite area. The areas of greenstone and with greenstone lenses were found to be the less pervious. The mylonite zone, crossing Äspö from NE to SW was found to be moderately pervious.

The geohydrological investigations have shown that suitable target areas for the Hard Rock Laboratory are likely to be found on Äspö and in the Laxemar area.

Chemical studies have been made on existing well water analyses from Kalmar county, on surface waters and on shallow groundwaters from percussion boreholes at Laxemar, Ävrö and Äspö. These studies indicate that the investigated area is a characteristic part of the Kalmar county. Furthermore, the shallow groundwaters at Äspö are of different types: present freshwater, mixed fresh-saline water and relict seawater with a higher chloride content than the present Baltic Sea. This indicates that there are parts of the rock mass with a rapid water flow but also parts with stagnant water.

The chemistry of the Äspö water is also expected to vary with the bedrock type. The water in contact with the greenstones are expected to have a higher pH and a more reducing character than the water in contact with the granitic rocks.

Chemical models are given on the areal and site scales. Chemical block scale models based on the geological and hydrogeological block scale models are presented.

ABSTRACT

SKB plans to site an underground research laboratory in the Simpevarp area. A regional survey started in 1986 and an extensive programme for geology, geohydrology and hydrochemistry was carried through. This report gives an evaluation of all available data gathered from the start of the project up to the drilling of core boreholes in some target areas in the autumn of 1987. A descriptive geological-tectonic model on a regional scale is presented that is intended to constitute a basis for the hydrogeological modelling work. Preliminary rock mass descriptions are also presented on a more detailed scale for some minor parts of the area.

It is recommended that the island Äspö is the principal target area for the continued work on the Swedish Hard Rock Laboratory.

ACKNOWLEDGEMENT

This report is based on the work of many people involved in different investigations. They have performed their tasks with great enthusiasm often under strict time limits. Data have been served promptly to the authors of this report both during the progress of the work and as final reports of high quality. We owe them all a great thanks.

A special thanks is also given to Göran Bäckblom, SKB's project leader, whose enthusiasm and positive questioning of our results significantly have improved the quality of our work.

1 INTRODUCTION

SKB presented in the autumn of 1986 a comprehensive R&D - programme (SKB 1986)

The highlight of the programme was the planned underground research laboratory - the Swedish Hard Rock Laboratory - to be sited close to the CLAB-facility in the southeast of Sweden.

The primary objectives of the laboratory are to:

- Demonstrate that the site-dependent factors that control the safety of a final repository are understood and can be quantified or delimited.
- Validate the models and assumptions included in the safety analyses.
- Develop methods for the construction and quality assurance of a final repository for spent fuel.

The activities can be grouped into three separate phases.

The current phase - Pre-investigation - is aimed at siting the laboratory, describing the natural conditions in the bedrock and predicting the changes that will occur during construction of the laboratory.

Phase 2 - Construction - is planned to start in the autumn of 1990. A tunnel will be blasted to about 500 m below ground level. The predictions from the previous phase will be checked and discrepancies explained.

The experience gained from the Pre-investigation and Construction Phases is proposed to be used on two sites in Sweden before selection of the final site for a repository.

The last phase of the laboratory - Operation - is planned to commence in 1993 and may last until the year 2050.

By the end of the period up to 1993 it is expected that the following objectives will have been achieved:

- Selection of a suitable site for the laboratory
- Preparation of a detailed description of the natural conditions around the site

- Preparation of a detailed prediction of the disturbances that will be caused by construction

- Achievement of small discrepancies between measured and predicted responses

- Establishment of a relevant and practical methodology for detailed characterization of a rock mass, to be used for detailed investigation on two sites in Sweden

- Completion of the Construction Phase

- Planning of relevant activities for the Operation Phase of the project

This report is the first summarized technical evaluation of all geological, geophysical, geohydrological and chemical data that has been gathered since the project commenced in late 1986.

Site investigations for the Swedish Hard Rock Laboratory are currently being conducted in the Simpevarp area (Fig. 1.1). The regional investigation area is about 25 km x 35 km. More detailed investigations have been performed in the close vicinity of Simpevarp.

Lineaments in the Simpevarp area have been interpreted from four different digital terrain models processed by EBBA II image analysis techniques. The topographic expression of aeromagnetic lineaments has been compared with the results from the digital terrain models. Detailed structural analysis of terrain features in the area close to Simpevarp has been performed on topographical maps to the scale of 1:4 000 (Tirén et al, 1987).

A fracture mapping programme has been carried out. The main goal was to make a geometric description of the fractures with respect to strikes, dips, fracture densities and fracture lengths (Ericsson, 1987).

The solid rock in the central area nearest to Simpevarp was mapped to the scale of 1:10 000. A map covering a greater, outer area was compiled to the scale of 1:50 000. The description that accompanies the maps is based on fieldwork and studies of the mineralogy in thin sections and the chemistry of representative samples of the different kinds of rock in the area (Kornfält et al. 1987).

Talbot et al, 1988, presented a tectonic study based on some weeks of fieldwork in the Simpevarp area. The main aim of the study was to characterize the main sets of tectonic zones identified as lineaments in the region. The fieldwork also comprised a study of the fracture zones on the islands Ävrö and Äspö.

Airial geophysical surveys, ground geophysical measurements and petrophysical measurements on rock samples were performed in the region around Simpevarp to locate and characterize rock bodies and fracture zones on a regional scale.

The airial geophysical surveys included aero-magnetic measurements, coaxial EM (Slingram), radiometric (U, TH, K) and two-station VLF (GQD and JXZ) studies. The flight altitude was 30 metres, the spacing between the flight lines was 200 metres and flight lines were in the east-west direction. The gravity measurements at an intensity of about one station per square kilometre.

All the aerogeophysical measurements were processed using the EBBA image system (Nisca, 1987). Ground geophysical profile measurements were performed on the islands Ävrö and Äspö and over the Bussvik and Laxemar areas (Stenberg, 1987).

The surface hydrology of the Simpevarp region was compiled to provide basic input (Svensson 1987).

In order to make use of existing geohydrological data an analysis was made of regional well data from the SGU Well Records (Liedholm, 1987) and a compilation made of geohydrological data from the Simpevarp area, where results from the pre-investigations and construction works for the power plants and CLAB were also used (Rhén, 1987).

Pumping tests were performed in the boreholes drilled in 1987 and evaluated (Nilsson, 1987, Nilsson, 1988).

In order to assess the influence of the Hardrock Laboratory on the geohydrological conditions a generic modell was made of two layout alternatives (Axelsson, 1987).

The existing data on well water chemistry in Kalmar county was evaluated statistically by Liedholm (1987). Water samples from percussion holes and surface water at Laxemar, Äspö and Ävrö were analysed by Laaksoharjo (1988).

The results of the site investigations have been compiled in a large number of reports. A summary of these reports is presented in this report. The report consists also of the conceptual models set up by the principal investigators based on all gathered material.

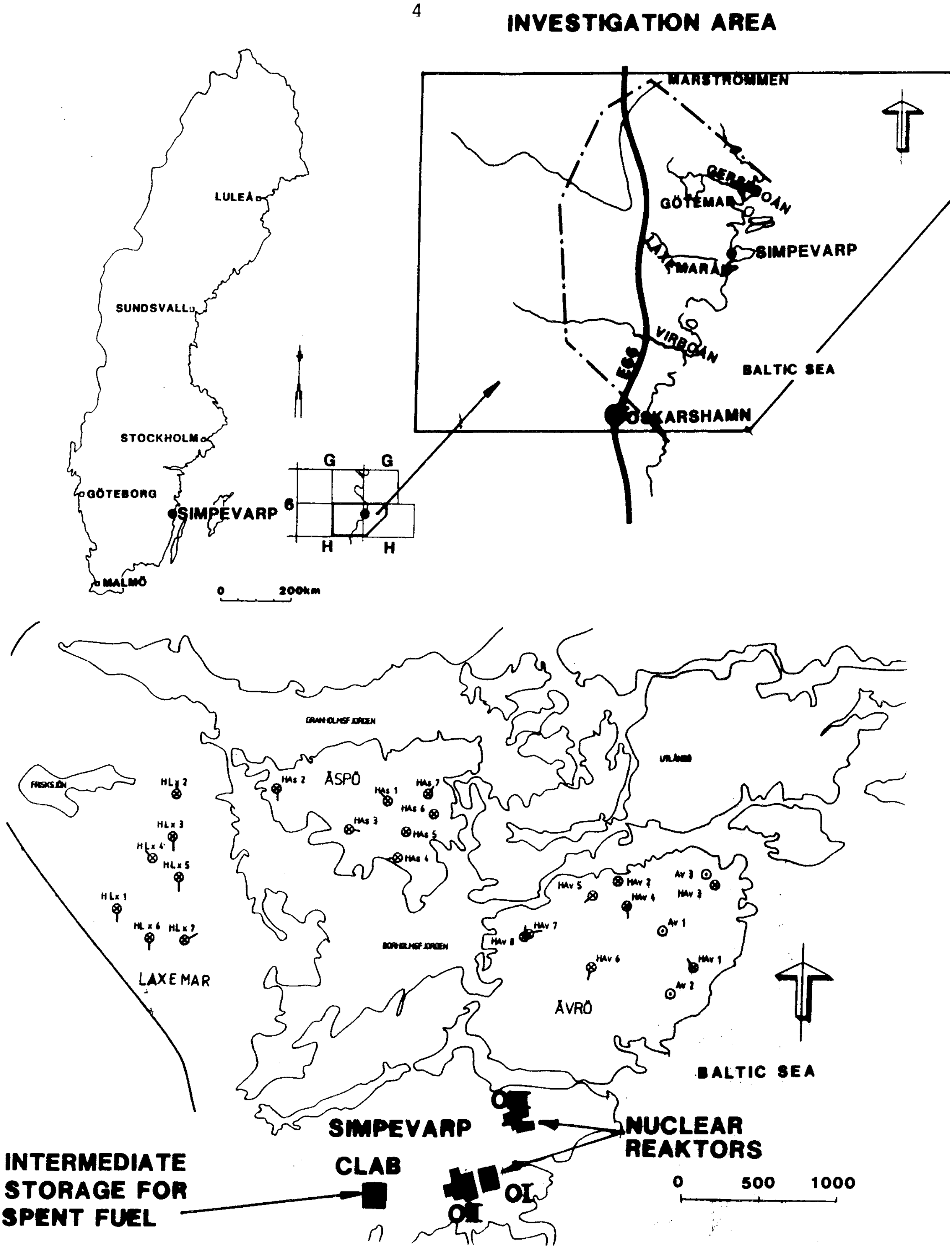


Fig. 1.1 Investigation area and the vicinity of Simpevarp.

2 GEOLOGY

Sections 2.1.1 to 5 contain an extract of 5 reports on the site investigations.

2.1 GEOLOGICAL STUDIES

2.1.1 Bedrock geology

Kornfält-Wikman (1987) presented a description of the bedrock in the Simpevarp area. This area is a part of the Precambrian bedrock in SE Sweden, where the Småland-Värmland intrusions (Småland granites) predominate the older, Svecokarelian complexes, including both metasediments, metavolcanics and gneissgranite. Acidic volcanic rocks (Småland porphyries) are closely related to the Småland granites. The Småland-Värmland intrusions are post-orogenic in relation to the Svecokarelian folding. There are also intrusions of younger (anorogenic granites forming circular massifs in the older bedrock (e.g. the Götemar granite).

Among the oldest rocks in the Simpevarp area supracrustals of sedimentary origin are not very common. Within the inner area (Fig. 2.1) small gneissic remnants, which constitute metasediments, are sometimes found. The best preserved metavolcanics are grey to dark grey very fine-grained rocks, which are encountered mainly on the Simpevarp peninsula and the island of Ävrö. They are often penetrated by granites and the boundaries of the volcanic bodies are often irregular and therefore very difficult to map in detail. Especially on Ävrö the metavolcanics are in part brecciated by granites. The metavolcanics show no prominent foliation but are on the whole strongly affected by younger granites. Compared with the intrusive rocks, the metavolcanics show more intense and closely spaced jointing. Close to the joints the metavolcanics are usually red-brown in colour and the joints are sometimes filled with quartz and epidote. Calcite is also common as joint filling. In the area nearest to Simpevarp there are only a few small outcrops of greenstone. On the northeastern island of Äspö and on the small islands to the east of it a dark grey, fine-grained, rather homogeneous greenstone is found, which is probably a metabasalt. The rock has often been intruded by a fine-grained, greyish-red granite. When the granite occurs as dykes in the greenstone they generally run in an ENE direction. Brecciated greenstone is also found at some other places in the Simpevarp area. There are also areas with greenstone xenoliths.

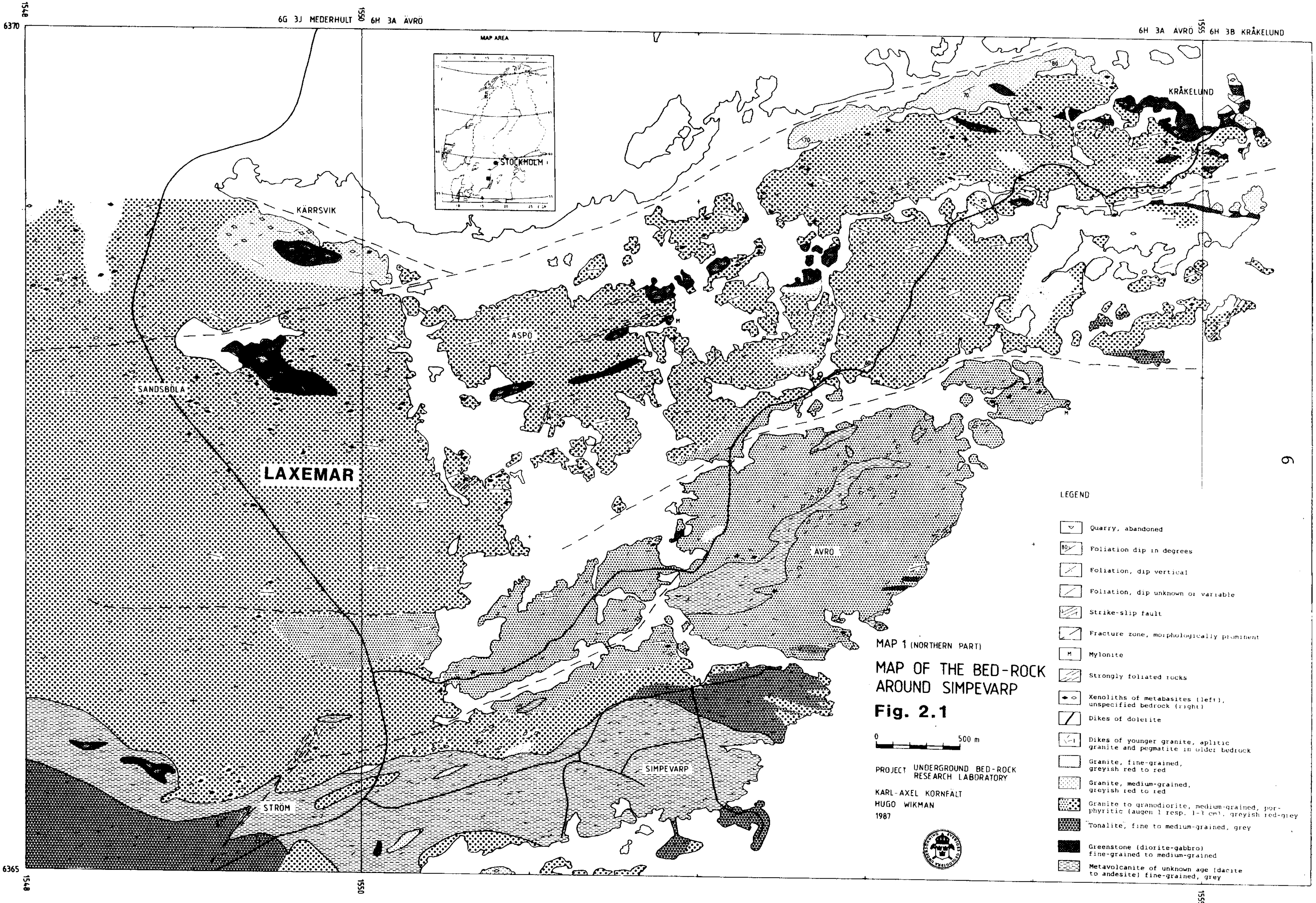

6G 3J MEDERHULT
6H 3A ÄVRÖ
6H 3A ÄVRÖ
6H 3B KRÅKELUND
MAP AREA
STOCKHOLM
KÄRRSVIK
KRÅKELUND
ÄSPÖ
SANDSBÖLA
LAXEMAR
ÄVRÖ
SIMPEVARP
STRÖM
6370
6365
1548
1550
1555
LEGEND
Quarry, abandoned
Foliation dip in degrees
Foliation, dip vertical
Foliation, dip unknown or variable
Strike-slip fault
Fracture zone, morphologically prominent
Mylonite
Strongly foliated rocks
Xenoliths of metabasites (left), unspecified bedrock (right)
Dikes of dolerite
Dikes of younger granite, aplitic granite and pegmatite in older bedrock
Granite, fine-grained, greyish red to red
Granite, medium-grained, greyish red to red
Granite to granodiorite, medium-grained, porphyritic (augen 1 resp. 1-3 cm), greyish red-grey
Tonalite, fine to medium-grained, grey
Greenstone (diorite-gabbro) fine-grained to medium-grained
Metavolcanite of unknown age (dacite to andesite) fine-grained, grey
MAP 1 (NORTHERN PART)
MAP OF THE BED-ROCK AROUND SIMPEVARP
0
500 m
PROJECT UNDERGROUND BED-ROCK RESEARCH LABORATORY
KARL-AXEL KORNFÄLT
HUGO WIKMAN
1987

Fig. 2.1

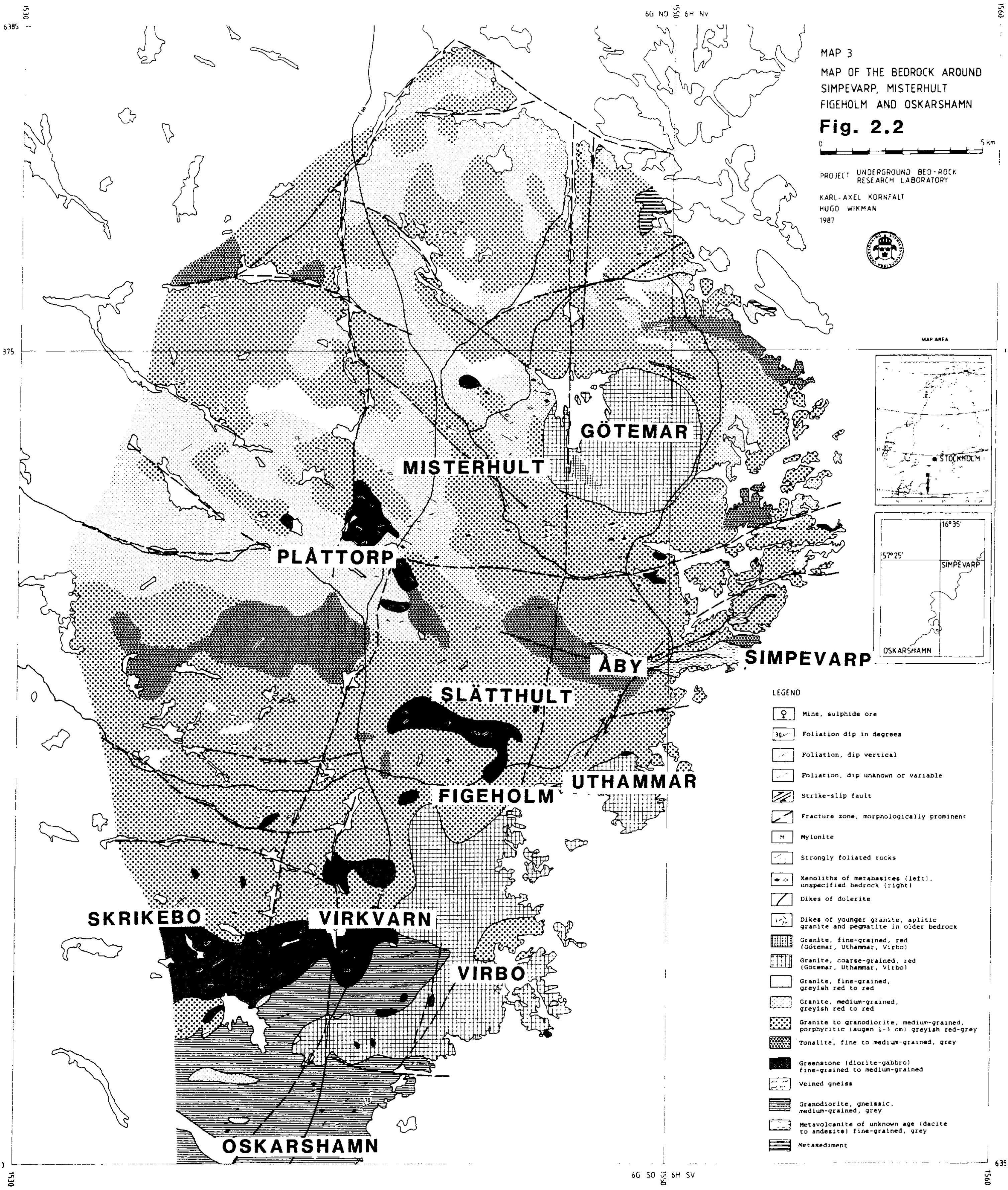
It should, in this connection, be observed that some of the rocks designated as metavolcanics on the map may actually be greenstone. These two rocks can be very difficult to separate macroscopically. In the outer area (Fig. 2.2) there are larger massifs of greenstone. The largest runs east-west in the area between Virkvarn and Skrikebo. Here the greenstone is generally fine-grained, often intruded by fine-grained or medium-grained, red granite.

Another greenstone massif occurs to the north of Figeholm. Here the greenstone is more coarse-grained and has also a gabbroid composition. Among the postorogenic intrusions the designation "tonalite" has been used for a group of grey-reddish, generally medium-grained rocks which, according to macroscopic assessment, were supposed to be more basic than the common reddish, porphyritic Småland granites, but not as basic as the greenstones in the area. Along the road, south of Åby, there occurs a dark grey rock with sparse megacrysts of red microcline. This rock probably represents an altered variety belonging to the "tonalite" group.

About 300 m SE of Åby the "tonalite" is strongly foliated in N55°E, 90°, probably due to a later deformation along a strike-slip fault.

The porphyritic granites (Småland granites) within the area studied comprise very different types. The colour, grainsize and the frequency and size of the potash megacrysts vary. These rocks can as a rule be classified as granites, but there are also a few granodiorites and one quartz monzodiorite among the samples studied in thin sections. The porphyritic granites within the area mapped are thus rather heterogenous. They are also as a rule weakly foliated. The greyish-red granite on the island of Ävrö is an example of a more acid variety, with only sparse and rather small (approx. 1 cm) potash megacrysts. In the northern part of the inner area there is a reddish-grey granite, generally with large and rather closely spaced megacrysts (2-4 cm) frequently intruded by a greyish-red granite with smaller megacrysts.

The porphyritic granites within the area mapped are always intruded by a fine-grained (sometimes medium-grained), greyish-red granite, presumably representing a later differentiation phase of the postorogenic, granite magma. An anorogenic origin is, however, a possibility that cannot be ruled out.


MAP 3
MAP OF THE BEDROCK AROUND SIMPEVARP, MISTERHULT FIGEHOLM AND OSKARSHAMN
Fig. 2.2
0
5 km
PROJECT UNDERGROUND BED-ROCK RESEARCH LABORATORY
KARL-AXEL KORNFALT
HUGO WIKMAN
1987
MAP AREA
STOCKHOLM
16°35'
57°25'
SIMPEVARP
OSKARSHAMN
GÖTEMAR
MISTERHULT
PLÅTTORP
ÅBY
SIMPEVARP
SLÄTTHULT
UTHAMMAR
FIGEHOLM
SKRIKEBO
VIRKVARN
VIRBO
OSKARSHAMN
6G NO 1550 6H NV
6G SO 1550 6H SV
1530
1560
6385
375
LEGEND
Mine, sulphide ore
Foliation dip in degrees
Foliation, dip vertical
Foliation, dip unknown or variable
Strike-slip fault
Fracture zone, morphologically prominent
Mylonite
Strongly foliated rocks
Xenoliths of metabasites (left), unspecified bedrock (right)
Dikes of dolerite
Dikes of younger granite, aplitic granite and pegmatite in older bedrock
Granite, fine-grained, red (Götemar, Uthammar, Virbo)
Granite, coarse-grained, red (Götemar, Uthammar, Virbo)
Granite, fine-grained, greyish red to red
Granite, medium-grained, greyish red to red
Granite to granodiorite, medium-grained, porphyritic (augen 1-3 cm) greyish red-grey
Tonalite, fine to medium-grained, grey
Greenstone (diorite-gabbro) fine-grained to medium-grained
Veined gneiss
Granodiorite, gneissic, medium-grained, grey
Metavolcanite of unknown age (dacite to andesite) fine-grained, grey
Metasediment

The fine-grained greyish-red granite is common in the whole area. In the inner area, which has been mapped in detail, the fine-grained granite occurs both in smaller massifs and in dykes in the older rocks. Often the direction of the dykes follow the foliation in roughly the direction E-W to NE-SW.

The dykes are usually about 0.5-5 metres thick, but some measuring 30 metres across have also been found.

The age of the fine-grained granites is uncertain. We know that the anorogenic Uthammar granite is accompanied by a fine-grained granite, but that is a common feature of granite plutons of different ages. Thus, the postorogenic Småland granite is also accompanied by fine-grained granite.

It is clear from the modal analyses that fluorite occurs in the anorogenic granites, but not in the postorogenic, fine-grained granites. The fluorite content is lower in the postorogenic granite than in the anorogenic one.

It is typical of the dykes of fine-grained granite that some of them are strongly deformed. Some are porphyritic and similar to metavolcanic rocks. Such dykes could perhaps have been feeder-dykes of metavolcanic rocks.

The deformation of the rock may be interpreted in the following way. After the emplacement of the granite dykes along fracture planes, the block movements must have continued, resulting in a brittle deformation of the fine-grained granite in the dykes and in the country rock next to them. In thin sections this is illustrated by bands of granulated quartz and a streaky pattern of elongated clusters of mafic minerals.

Common to the younger (anorogenic) (Götemar, Uthammar granites) is their red colour, coarse grainsize and presence of relatively abundant fluorite. In other respects, such as mineral contents, they are fairly different. The colour is red on fresh surfaces but more greyish-red with greyish-white quartz on weathered surfaces. The age of the Götemar granite has been estimated to 1350-1400 Ma. (Åberg et al, 1985). The Uthammar granite has not yet been dated, but is supposed to be of a similar age. Thus, these granites are definitely younger than the other granites in the area.

At Uthammar village, a dyke of fine-grained granite has intruded into the coarse-grained granite. This fine-grained granite must therefore be younger than the Uthammar granite and, thus, represents the youngest granite in the area. To the north of Uthammar, bordering on the massif, is a fine-grained granite with a streaky pattern of mafic minerals. This is supposed to be a mechanically deformed Uthammar granite.

The Götemar granite forms an almost circular intrusion just to the northwest of the area investigated. A red granite is the most common variety. The mineralogical and chemical compositions are relatively uniform throughout the whole massif. All varieties are very alkali-rich granites with quartz and feldspar making up about 95 per cent of the rock by volume. As characteristic accessories fluorite and topaz should be mentioned. The flourite often occurs as a coating on the joints in the granite.

The joints in and around the granite body are of several types but especially notable are the flat joints that can be seen in the quarries, and above, all to the north of the massif. This type of jointing has given rise to very flat and gently dipping outcrops, the surfaces of which are often coated with aplite granite or pegmatite that have intruded into the joints. The fine-grained porphyritic dyke of granite just to the north of the massif can also be shown to dip very gently. Very low dipping pegmatites and, to a lesser degree, aplite granite are characteristic of the area around the massif and can be studied in many roadcuts. This feature of granite tectonics may indicate that the Götemar granite is a rather extensive body below the Småland granites which tries to open up like the skin of an onion. The intrusion may also have caused not only joints but also gently dipping shear-zones not visible at the present bedrock surface.

Pegmatite and aplite dykes are not at all as common as the dykes of fine-grained granites, but are still a very interesting element in the bedrock. Unlike the fine-grained granite dykes, dipping more or less vertically, the pegmatites dip more gently. The pegmatites and aplites form narrow dykes and small massifs, above all in the northern part of the area investigated. As the dip of the pegmatites and aplites is low, the surface of an outcrop could be coated with pegmatite and aplite, making it easy to be mistaken, the whole outcrop being mapped as pegmatite.

Younger dolerites are also encountered at quite a few places. These dykes are only a few decimetres thick and constitute probably apophyses to somewhat broader dykes running roughly in a N-S direction. One of these has been noticed in the Götemar massif. The age of the dolerites is not known, but it is probably approx. 960- 980 m.y.

2.1.2 Geophysics

The aerogeophysical measurements were performed in 1986. The direction of the flight lines was east-west. The measuring altitude was about 30 metres and the spacing between the lines 200 metres. The low-altitude airial survey has included magnetic, AEM, radiometric and two series of VLF measurements. The two VLF transmitters (GQD and JXN) are on lines at almost right angles from the site, which means that it is possible to detect almost all conductive zones in respect of the strike direction. Readings of the magnetic field have been made every 0.1 seconds, which represents a measurement taken every 7 metres, with a resolution of 0.1 nT. The VLF, EM and radiometric measurements were made every 0.3 seconds, corresponding to every 22 metres. The gravity measurements are at an overall density of about one station per square kilometre. A total of 257 petrophysical samples were taken. Most of the samples were taken in the vicinity of Simpevarp.

The aerogeophysical results are reported and interpreted on a lot of maps of which many are of excellent quality such as the coloured aeromagnetic map in Fig. 2.3.

According to the geophysical interpretation, (Nisca, 1987), the Götemar and Uthammar granites (Fig. 2.4) coincide with two distinct negative Bouguer anomalies. These two granites are of leucocratic mineral composition, with a silicate density of 2.62 g/m3. Gravity and magnetic modelling of these granites strongly suggests an outward dip, that is, the granites become larger with depth. These granites can be regarded as "true" diapirs. The estimated depths of the Götemar and Uthammar granites are about five kilometres. These granites have been classified in the geological mapping as anorogenic granites. A north-south gravity interpretation profile from the Götemar granite to the Uthammar granite is presented in Fig. 2.5.

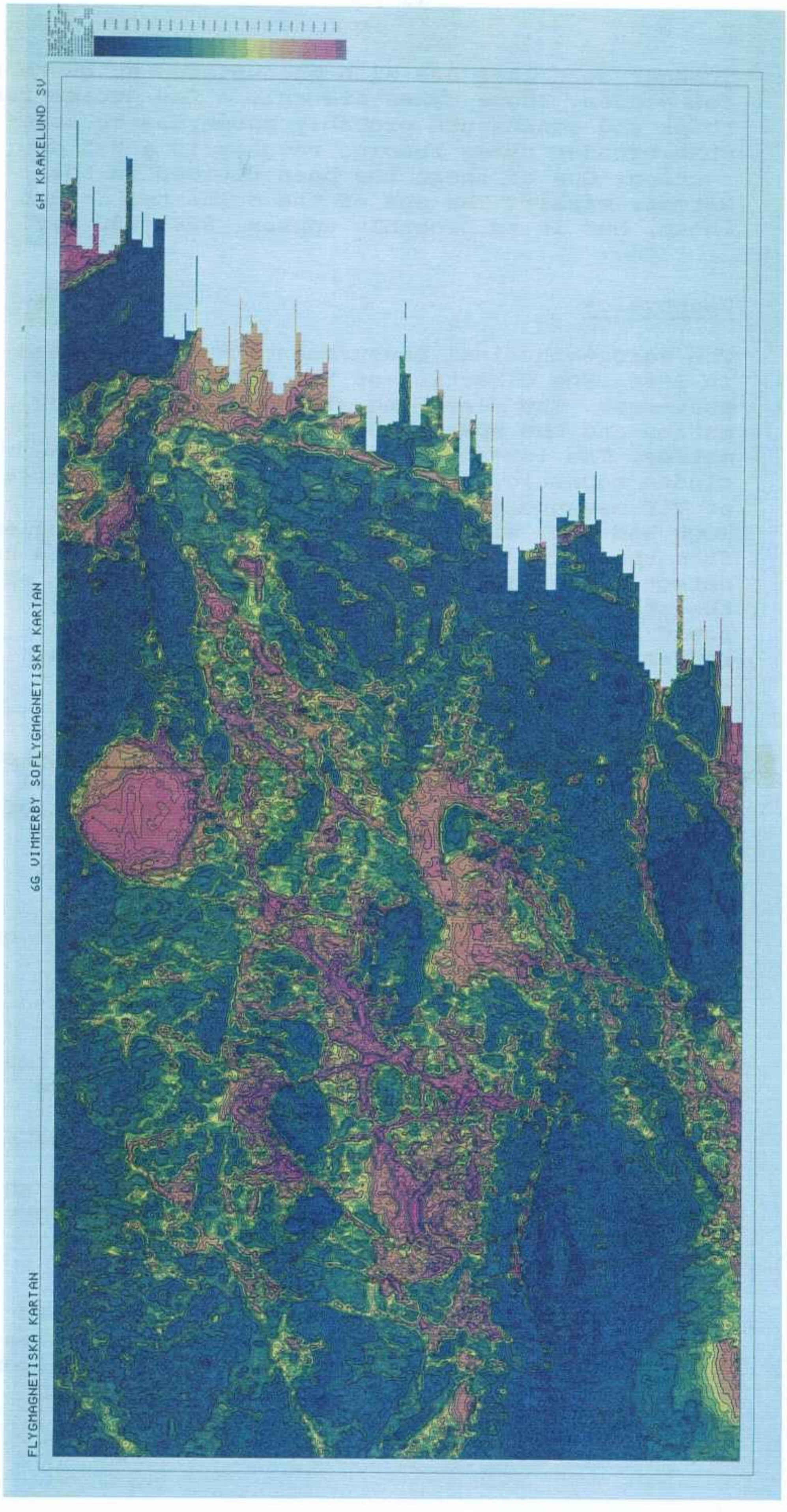


Fig. 2.3 Aeromagnetic map of the Simpevarp area.

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According to the geological mapping the Virbo granite also belongs to the anorogen granites. However, the Virbo granite has lower uranium and potash contents and also a higher susceptibility and silicate density than the three granites mentioned above. Furthermore, no clear negative Bouguer anomaly corresponds to the Virbo granite. This granite can probably be interpreted as an older member in the anorogen granite suite. Several circular magnetic structures were observed in the underwater area east of the Götemar granite. The magnetic structures are similar to the Götemar granite diapir and they have been interpreted as granite diapirs. Two rounded structures in the magnetic map west of the Götemar granite have also been interpreted as concealed granite diapirs.

The Bouguer anomaly map shows two moderate, positive gravity anomalies. The Skrikebo (Fig. 2.6) east-west elongated Bouguer anomaly consits of diorite-gabbro with very high susceptibility, whose estimated thickness is about two kilometres. The Sundsholm-Plåttorp moderate positive Bouguer anomaly also runs east-west. The rock types consists of diorite-gabbro with high susceptibilities. The estimated thickness is about one kilometre. The Släthult diorite-gabbro gives a weak Bouguer anomaly. The magnetic map indicates an outer ring consisting of diorite-gabbro and a core of porphyritic granite. The southern part of this granite-diorite-gabbro complex is affected by the anorogen Uthammar granite.

A gradient aeromagnetic map of the Simpevarp area produced using the Ebba II image processing technique is presented. This map, together with airborne electromagnetic and VLF measrurements, has been used to interpret the location and character of regional fracture zones (Fig 2.4). The Götemar and Uthammar granite diapirs are also outlined in Fig. 2.4 because of their probable tectonic influence upon the tectonic setting of the Simpevarp area.

On this regional scale an orthogonal pattern consisting of N-S and E-W fracture zones dominates the map. The width and character of the magnetic anomalies indicate that well defined N-S fracture zones are about 100 to 200 metres wide, with vertical to sub-vertical dips. The widths and the dips of the E-W fractures are more difficult to estimate because of the E-W direction of the flight lines. However, some of the fractures trending E-W have probably moderately low dips, often to the north, and are about 500 metres wide. The spacing of the E-W fracture zones is about 3 to 5 km, and that of the N-S fracture zones, about 2 to 4 km.

The lateral displacements of the N-S fracture zones are small, about 100 to 300 metres, while those of the E-W fracture zones are somewhat larger. Vertical displacements for both sets of zones have also been observed. Some of the fracture zones trending N-S appear to be the youngest or most recently reactivated fracture zones in the area.

Many of the N-S fracture zones exhibit strong anomalies, both with respect to magnetic and VLF measurements, while the opposite applies to the fracture zones trending E-W, (Fig 2.4). This indicates that the N-S fracture zones are more likely to be water-bearing than the E-W ones.

The map also shows fracture zones oriented NE and NW. These fracture zones are interpreted as representing an older orthogonal system of fracture zones. The fractures trending NE in this set are much more developed and frequent compared with the NW set. The largest displacement observed in the study is about 2 km, along a NE fracture zone crossing the Sundsholm diorite-gabbro massif.

Finally, a set of fracture zones oriented NNE and NNW was also observed. These fracture zones are interpreted as forming a conjugate shear system

The geophysical interpretation of the overall pattern of fracture zones and other structures concludes that the main deformation mechanism in the Simpevarp area has probably been tensional and due to uplift.

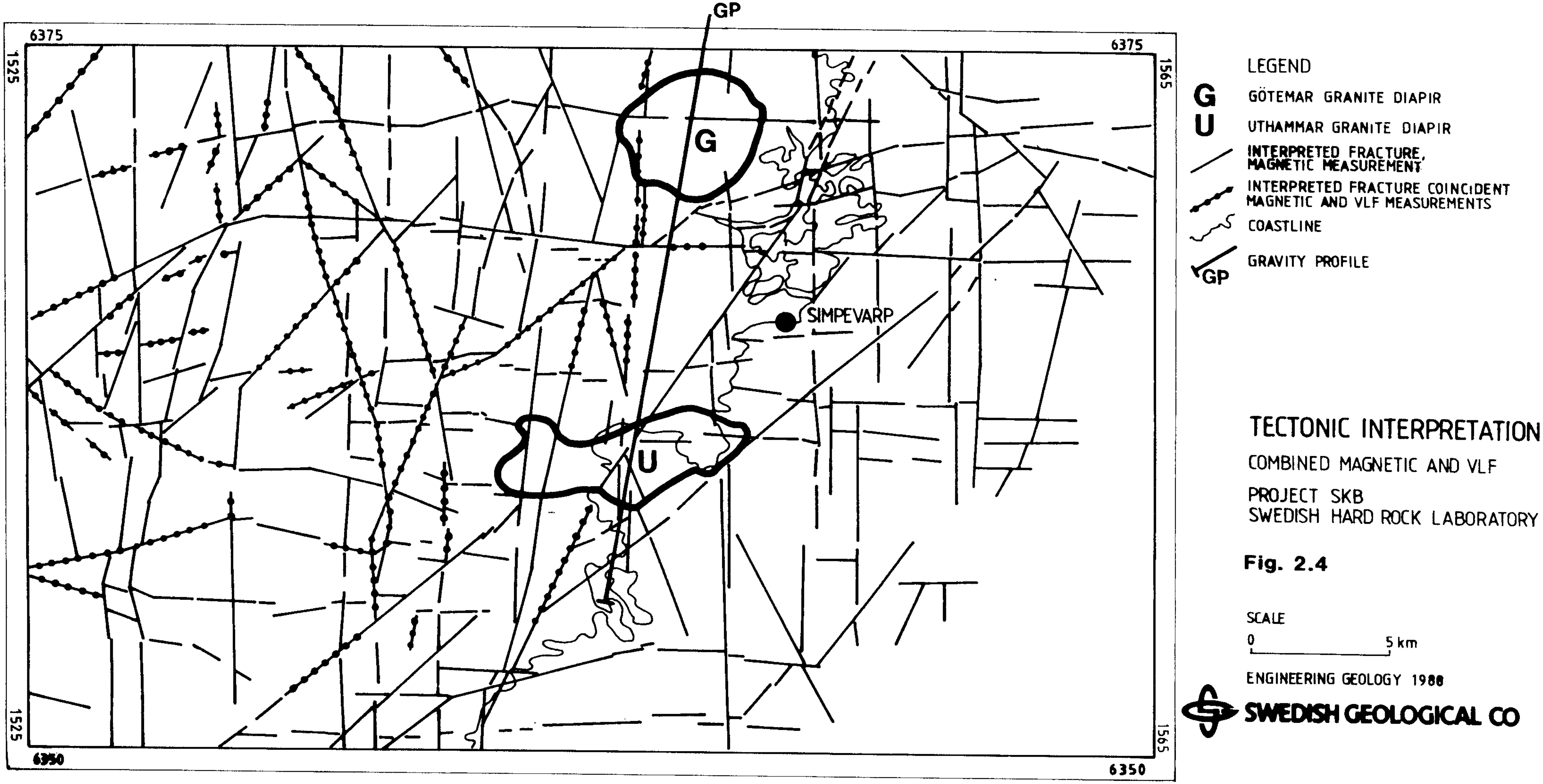


Fig. 2.4 A basic fracture analysis based on magnetic and VLF measurements. The location of the gravity profile and the Götemar and Uthammar granite diapirs are also outlined in the interpretation map (Nisca, 1987).

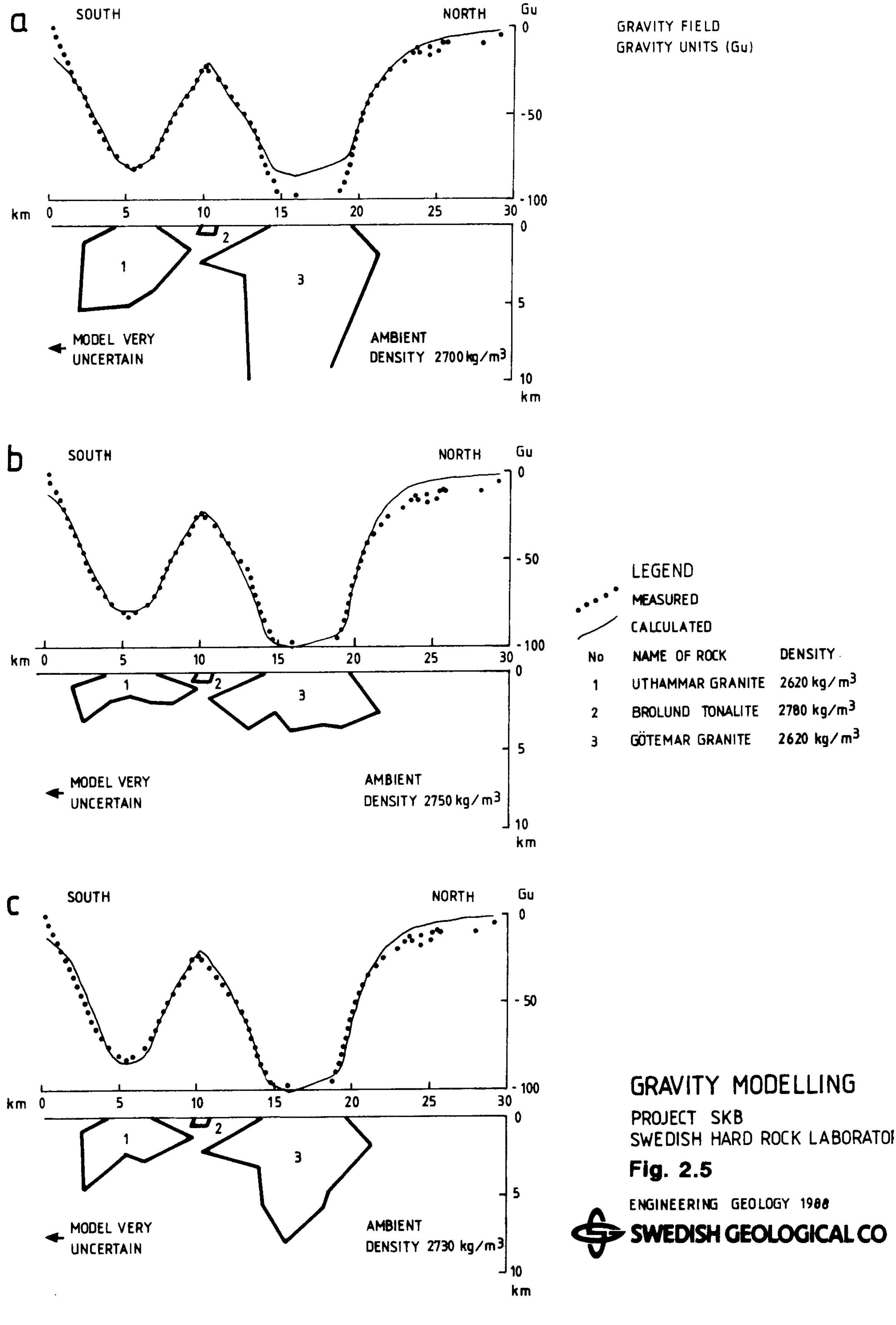
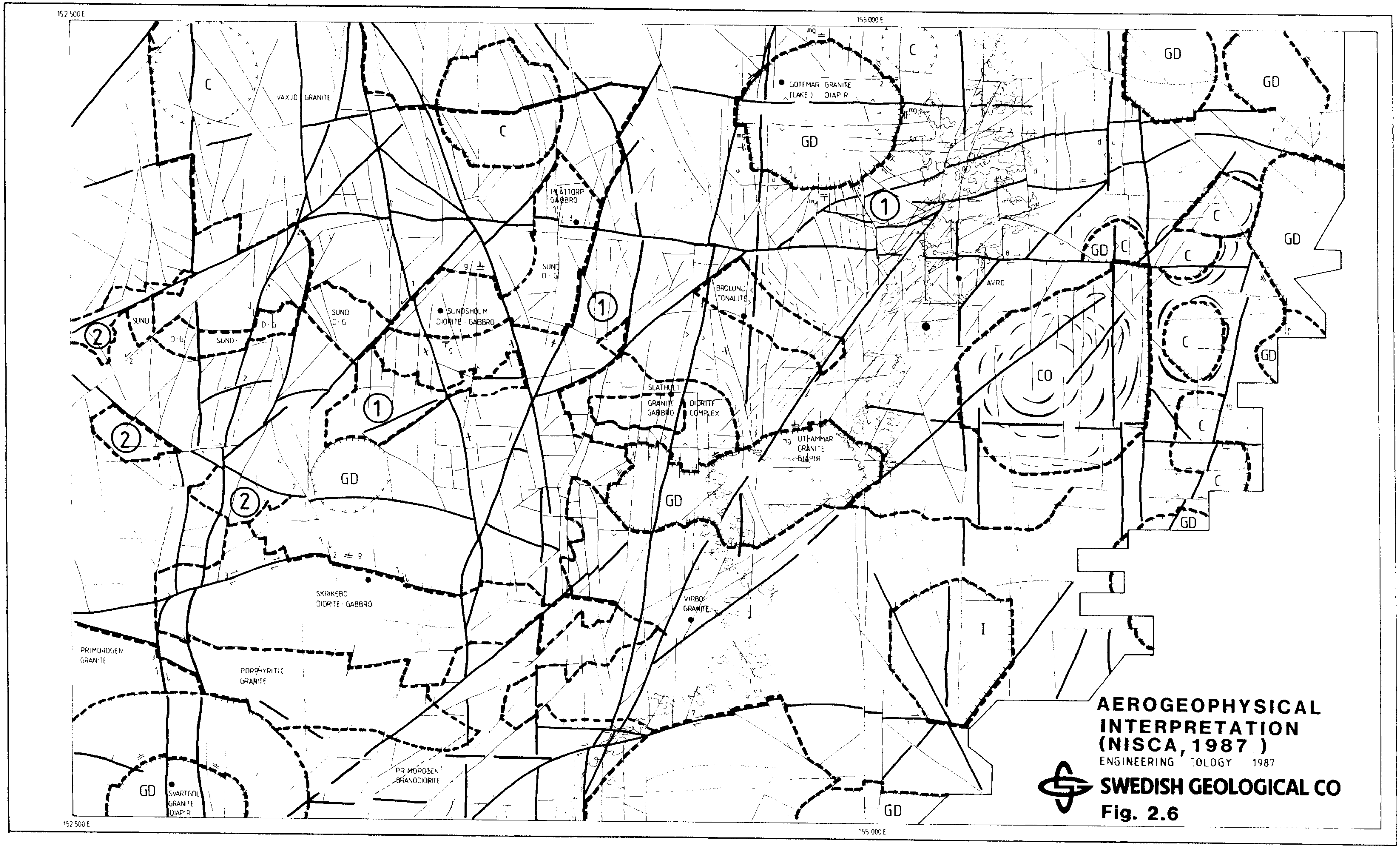


Fig. 2.5 Three computed gravity models with different ambient densities, a) 2700 kg/m3, b) 2750 kg/m3, c) 2730 kg/m3. According to the surface density model c) is the most probable one (Nisca, 1987).



AEROGEOPHYSICAL INTERPRETATION (NISCA, 1987)

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Fig. 2.6

2.1.3 Structural geology

Lineament interpretations

Relief maps, produced using the Swedish National Land Survey's hill shade techniques, have been used by Tirén-Beckholmen, 1987, to make an interpretation of lineaments in the actual area (Fig. 2.7).

The northern unit (Unit I) is dominated by pervasive NW-SE lineaments and less frequent N-S lineaments. A few pervasive undulating WSW-ENE lineaments cut across the area.

The central unit (Unit II) has a lineament pattern consisting of very gently undulating E-W lineaments together with less pervasive, but less frequent, NW-SE and N-S lineaments.

The southern unit (Unit III) has a less pronounced lineament pattern with a dominant lineament direction running ENE-WSW.

A method study of structural analysis based on digital terrain model was performed. The EBBA II image processing system has been used. Image processing has been performed on digital elevation data to evaluate the use of digital terrain models in structural analysis.

Five different digital terrain models were used: Hill-shading, Residual elevation, Edge texture, Line texture and Iso-elevation. All these maps are based on altitude data but illuminate different aspects of the landscape and thus enhance different characteristics. Relief maps produced by hill shading techniques reveal the extensive lineaments and large scale rock blocks. Residual elevation maps give a good impression of the relative quality of the bedrock concerning the degree of fracturing and, thus, give a comprehensive picture of lineaments and major rock block configurations.

Edge texture maps, Fig. 2.8, provide a check of the density of structures. Composite-coloured edge texture maps (using coloured illustrations from two directions) provide an accurate of the location of the lineaments (± 50 m for well defined structures). Furthermore, different types of lineaments, such as valleys and slopes, can be distinguished and the aspect of the slopes is indicated.

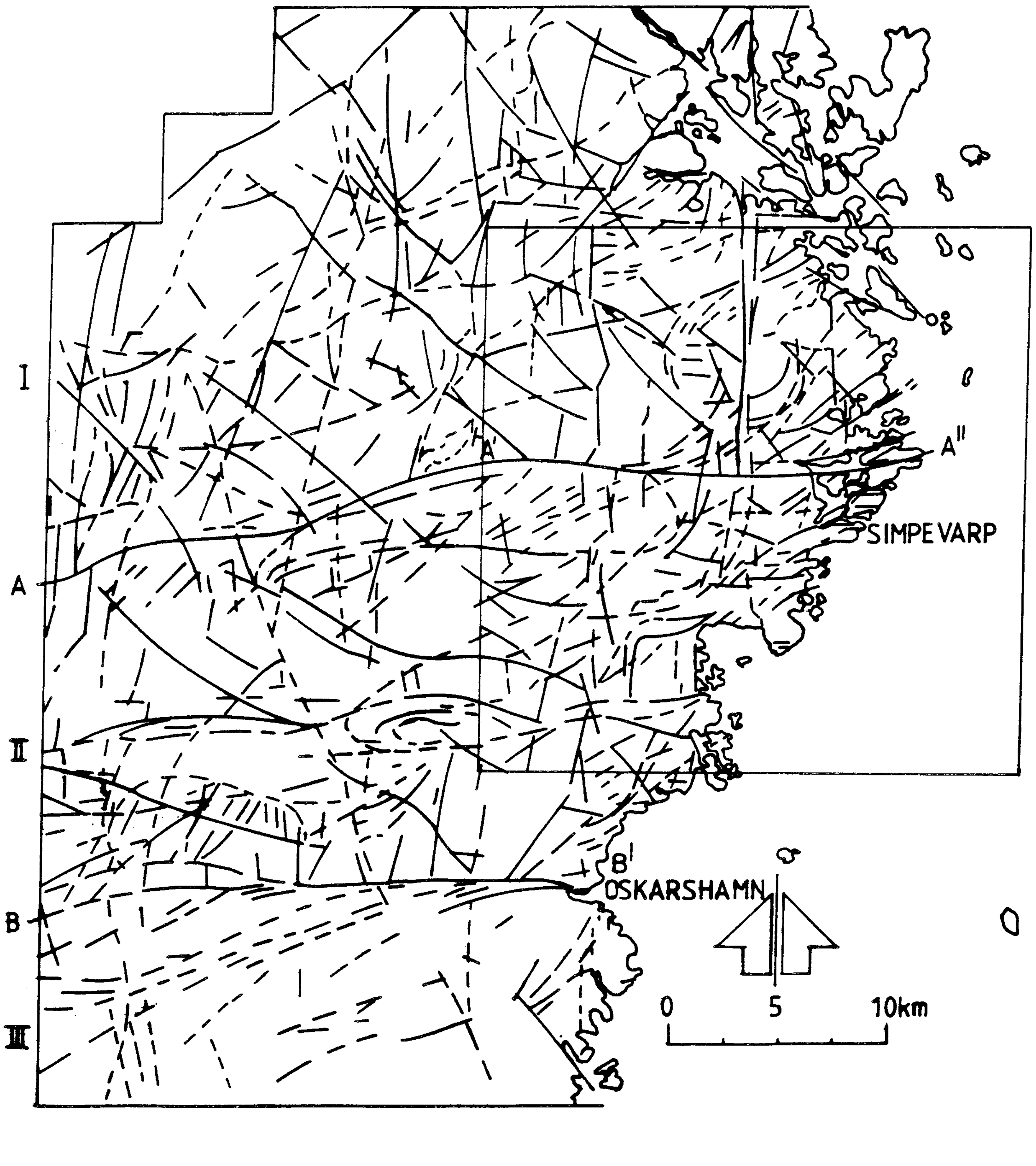

Fig. 2.7 Lineament interpretation of the relief map of the Oskarshamn area, scale 1:250 000. The Simpevarp area is outlined (Tirén et al, 1987).

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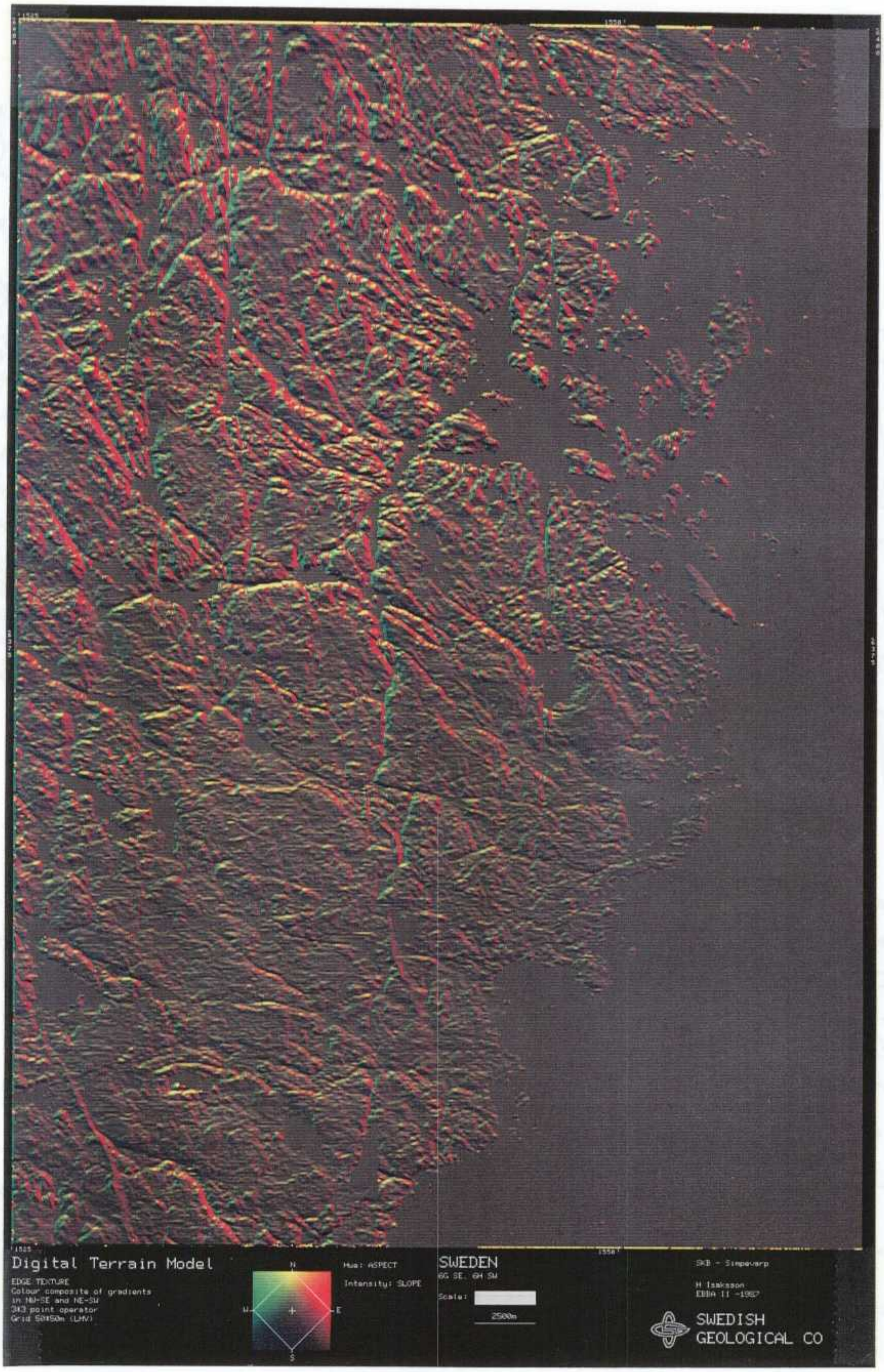

Fig. 2.8 Digital terrain model: Edge texture (Tirén et al, 1987).

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Line texture maps, though very direction dependent, can be the best indicator of neotectonic structures, as these maps, particulary, reveal sharp and narrow structures. The line texture maps indicate extremely flat surfaces as areas with a uniform grey-tone. Relatively narrow passages (up to 100-200 m wide) with a uniform grey-tone may indicate wide fracture zones covered by soil.

Iso-elevation maps combined with residual elevation maps are very useful to define rock blocks and also to study the relative vertical displacement of blocks of different orders.

The possibility of using both negative and positive images of grey-tone maps add greatly to the insight into the structural framework of an area.

Interpretation of lineaments was carried out on four of the computer-plotted maps.

Four lineament sets, representing fracture zones, are the surface expression of the structural framework of the bedrock in the area. Their orientations are NW-SE, E-W (oldest) and N-S, NE-SW (established later). All four sets occur all over the area but lineaments trending NW-SE are more expressed in the northern part and lineaments trending NE-SW in the southern part of the area.

The lineaments trending NW-SE, N-S and NE-SW occur as clusters forming approx. 1-km wide zones transecting the area. The spatial separation of these is 5.0 to 6.5 km. Comparable zones trending E-W are persistent, approx. 100-m wide lineaments. The distance between these zones shows decreases steadily; the distance between zones trending NW-SE decreases to the northeast towards the contact with the Svecokarelian rocks trending NW-SE (approx. 1.8 Ga.), the distance between N-S trending zones decreases to the east, towards the Baltic basin, the distance between NE-SW trending zones decreases to the southeast, parallel to the strike of the palaeozoic sediments in the Baltic Sea and the distance between E-W trending zones decreases to the south, towards the major lineament through Oskarshamn. Reactivation of faults has occured, often along limited parts of a fault.

Correlation of the main lineaments trending N-S and E-W determined aeromagnetically and topographical features is good. For the rest of the linear structures correlation is moderate and for curved and circular structures correlation is bad. Some lineaments determined by aeromagnetic means lack topographic expression. Sometimes only parts of an aeromagnetic lineament have topographic expression. The NE-SW trending zone of topographic lineaments, approx. 1 km wide, running from the southwestern corner of the interpretation maps to Ävrö does not appear on the aeromagnetic map. On all three digital terrain models NW-SE trending lineaments are frequent in Unit I but very few have aeromagnetic expression.

Maps presenting the rock blocks (Fig. 2.9) are mainly based on the residual elevation and iso-elevation maps. The size of higher order blocks are in the order of 100 km^2. These blocks are further divided into lower order blocks, the largest up to 25 km^2. The interaction of N-S, E-W, NE-SW and NW-SE faults gives rectangular, triangular and polyhedral blocks. Most of the higher order blocks extend outside the area. To obtain the general concept of the higher order rock block configuration an extension of the study area is needed. Relative vertical displacements of the higher order blocks has been documented.

Lower order blocks, defined as blocks with relatively uniform altitudes, overprint the configuration of higher order blocks. Some of the lower order blocks extend locally across lineaments defining the higher order blocks.

The rock block configuration in the Småland volcanites and granitoids displays a fault configuration which differs from the fault configuration in Svecokarelian gneiss terrians. Noticeable is the occurrence of triangular blocks at the junction of faults. Lateral shear is indicated along E-W, N-S and NW-SE trending faults.

Block configurations and vertical displacement of higher order and lower order rock blocks are analogous, indicating that the division of the bedrock into blocks is not related to scale. This is in full agreement with the concept of self similarity, that the deformation pattern is the same on different scales. If this is so, then the assumption that regional fracture zones will accomodate applied stresses, leaving the rock blocks in between intact, is called into questions.

The regional ground surface of the Simpevarp area is roughly coincident with the Subcambrian peneplain. Indications of younger faulting are few but all seem to involve the main N-S structures.

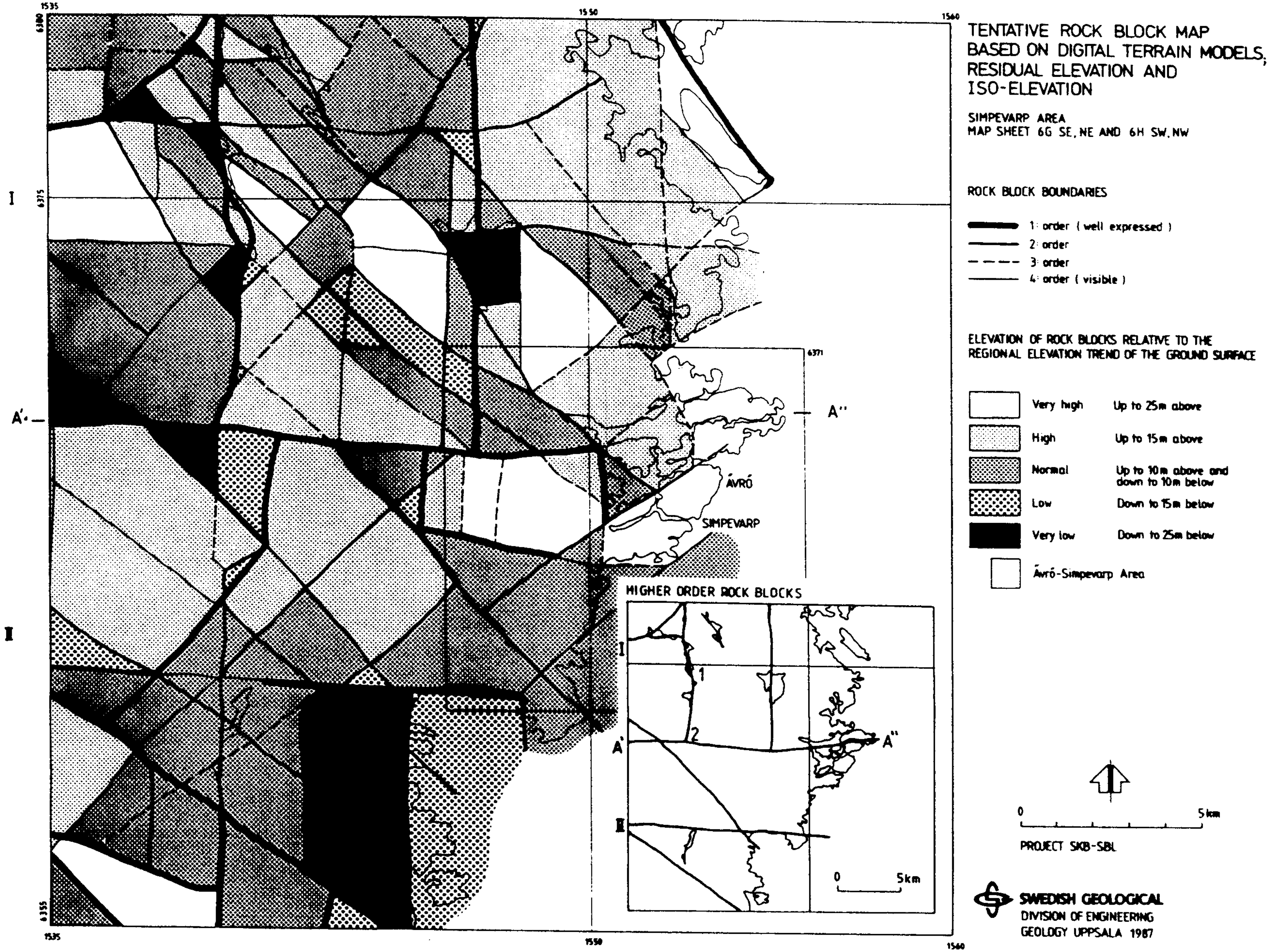


Fig. 2.9 Tentative rock block map (Tirén, 1987).

The Götemar granite is cut by one of the major N-S lineaments. The part on the western side of this regional lineament represents a deeper cutting than on the eastern side (Kresten & Chyssler, 1976). They also report that Cambrian sandstone dykes have been recorded mainly on the eastern side of the fault. The present situation, however, is that the elevation of the ground surface is higher on the eastern side of the fault.

The change in orientation of the esker running through Fårbo at the next major N-S lineament to the west, indicates that a similar morphology existed during late glacial time (approx. 10.000 y), causing the change in the direction of the subglacial melt-water stream. The highest marine shore line runs N-S for more than 200 kilometres. Boundaries of ice lakes on Sydsvenska höglandet, the mountaineous area in central southern Sweden, are defined by N-S structures persisting for 50 to 100 kilometres along strike lines.

N-S structures thus control morphology of south-eastern Sweden. Contour maps of the rate of relative uplift show that the contours swing to the N-S in southeastern Sweden. This implies postglacial activation in these zones. As the seismicity of southeastern Sweden is very low (Husebye et al, 1978, Båth, 1956 in Husebye et al, 1978, Båth, 1979, Wahlström and Ahjos, 1984, Slunga et al, 1984) the stress release in N-S zones is aseismic or intermittent. This neo-tectonic (post-Miocene, approx. 5 m.y., Bates and Jackson, 1980) deformation is interpreted as implying a reactivation of faults of Precambrain age. Possible indicators in field of this deformation are displaced shore lines and eskers, deformation of glacio-fluvial deposits and varved clays.

2.1.4 Fracture zones in the Simpevarp area

Talbot and Riad report the results of some weeks of field work in the Simpevarp area, the main aim of which was to characterize each of the main sets of tectonic zones exposed along the lineaments identified in the region.

The field results are summarized in the following points:

Self similarity

Data collected on the regional (10 km), area (1 km), and outcrop (1 m) scales in the land region around Simpevarp appear to complement each other.

Most of the deformation structures are essentially similar at each scale, and planar zones of discontinuities with much the same orientations are found on most scales. The N20°E shear zones may be unusual in this respect for they appear to be relatively local. Some of the small scale zones of ductile shear and brittle fracture have gentle dips; it is not yet clear whether these also occur on large scales.

Two structural patterns?

The subdivision of the fractures of the region into two major patterns is obvious on both the outcrop and the regional scales.

Two basic patterns of discontinuity appear to have been superimposed and, at the current level of knowledge, the stress fields responsible for the N-S and E-W lineaments and their reactivations appear to be different from those responsible for the N40°E, N60°E and N40°W lineaments. An EW-NS-horisontal cubic pattern can be interpreted in terms of principal planes of strain and/or stress trending NW and NE vertical plus horizontal.

Repeated reactivation of the same fractures, both as left and right-handed strike-slip, and as dip and oblique-slip faults, obscures the relative ages of reactivations of these two structural patterns. Furthermore, repeated swapping of the principal stress axes, one for the other, within each of these two main patterns emphasizes the complexities of the kinematics in each zone. A regionally consistent history of the offsets and stress fields when successive fillings occured has not yet been disentangled from the data.

Sub-horizontal structural zones

It is not clear whether the sub-horizontal sets of veins and fractures in the Simpevarp area relate to the NS-EW cubic pattern or the N40°E, N60°E, N40°W conjugate pattern or, as is likely, to both.

The OPEN sub-horizontal fractures in the Simpevarp area can be interpreted as surficial stress-relief to the surface exagerated by the hydraulic relief of the retreating Quaternary ice sheets. However, many of the early aplites are sub-horizontal, indicating that the sigma 1 + sigma 2 planes, were sub-horizontal in the thrust regime very early in the tectonic history. It is not yet known whether any of the sub-horizontal fractures or fracture zones reactivate Proterozoic ductile shear zones, as appears to be the case in other parts of Sweden (e.g. Lansjärv in the Svecokarelian, Finnsjön and Forsmark in the Svecofennian, and the mylonite zone in the Sveconorwegian systems).

Reactivations and their timing

The earliest and most general penetrative foliation in the region appears to dip steeply to the north. However, discrete ductile shear zones and foliations appear to be most common with strikes of N10°E, N20°E, N80°E, N40°W degrees (even where found in "EW" lineaments). This suggests that the conjugate sets making up this pattern were the first zones of localized shear but also reactivated at later stages, probably whenever the principal axis of compression (sigma 1) was in the NE quadrant.

Repeated reactivation of unexisting faults, and the generation of new fracture sets at greenschist and lower metamorphic grades, complicate the kinematic picture. Such reactivations probably result in offsets and thereby account for so few of the lineaments persisting along strike for more than about ten kilometres. The large number or significant offsets of older lineaments may also explain why so many new fracture sets appear to have formed during so many phases of reactivation. Without long planar weaknesses to reactivate, new fractures have to break new routes through old blocks to dissipate later imposed stress fields.

Major strike and reverse dip-slip displacements appear to have occurred in the region until at least zeolites were being deposited in opening fractures. Signs of significant displacements in zeolite, calcite-infilled and empty fractures are rare. No definite indications of neotectonic activity were noticed.

The times of the many deformations in the Simpevarp region are still poorly defined.

Paleohydrology

The first signs of localized flow of the groundwater in the region is in the red alteration of the feldspars within a decimetre or so of veins later infilled by epidote. Earlier quartz veins are generally rare. Many such zones smeared out with increasing semi-ductile strain to the epidotic centimetre-scale microbreccia zones which appear to take the place of true mylonites in other areas of Sweden. It seems likely that strain rates oscillated in these rather narrow zones so that brittle veins developed during stages of rapid failure were broken and then smeared by slower, more ductile strain.

As the rocks currently exposed in the region rose through the greenschist facies, the brittle fracture zones were infilled by epidote carried by groundwater travelling along diffuse zones which were characteristically <10 m thick and many kilometres long and wide. The dimensions of zones of later fracture systems, in which groundwater deposited chlorites, zeolites, iron oxides and then calcite, have not been quantified but appear to have widened with time.

We consider it ineviteable that the permeability is higher where open fractures or fracture zones intersect. The hydraulic conductivity of each zone is likely to be highest along the direction in which its en-echelon fractures intersect (i.e. a single vector). This axis has been determined for many of the individual zones we have studied and varies considerably. Consequently the increase in conductivity along the intersection of zones of open fractures need not be a simple sum; it is a complex function of the width, length, connectivity of apertures and vectors of the hydraulic conductivity of each of the intersecting zones. The axes along which fracture zones of various orders intersect could also be constrained by our approach.

Experience elsewhere in Sweden indicates that the most significant hydraulic conductors are likely to be sub-horizontal fracture zones in the top 500 m or so, although the few tests deeper than this (e.g. at Siljan) indicate that they can be deeper still. Hydraulic tests indicate such zones exist beneath Äspö and Ävrö (Nilsson, 1987, and Rhén, 1987).

Median hydraulic conductivities at constant intervals are reported to decrease with depth in borehole Av1 (Fig. 0.1 in Rhén, 1987). They do, but it may be very significant that the same diagram can be interpreted as indicating two groundwater regimes, one above, and another below about 425 m. However, two regimes are also known in the groundwater chemistry, the in-situ stresses, (and the earthquake solutions?) in various parts of Sweden, Finland and Canada. The boundaries of these regimes appear to be sub-horizontal and coincide with discrete fracture zones. This zone could be considered a second surface, or at least a decollement or delamination between a "surficial" (thrust?) regime with relatively fresh and "young" mobile groundwater, and a deeper (wrench?) regime of older immobile saline groundwater. The depth to the delamination zone varies between about 100 to 500 m from the site in Sweden; it may even crop out in the Lansjärv area and the SKB study area inland of Simpevarp. The depth of any such delamination is so far only known at one location in the Simpevarp region.

Talbot and Riad also make a comparison between Simpevarp and Lansjärv regions:

Because of the comparative lack of seismic activity, the Simpevarp area in SE Sweden has, provisionally and informally, been interpreted as "currently one of the most tectonically stable areas of Sweden". It is informative to contrast current impressions of the structures in the Simpevarp area with those in the Lansjärv area in northern Sweden which appears to be one of the neotectonically most active parts of Sweden.

The Lansjärv area is dominated by long pronounced lineaments which had long ductile histories at amphibolite metamorphic grade before later brittle reactivation at greenschist and lower metamorphic facies. By contrast, few zones of hot ductile shear or mylonites were encountered, and pseudotachylites have only been recognized in (the first deep) borehole, in the Simpevarp area.

Rather than the hundreds of kilometre-long discrete zones of repeated shear along hot ductile zones common near Lansjärv, the tectonic story near Simpevarp is more one of dispersed shorter zones of complex brittle failure mainly in the greenschist facies.

The comparative shortness of the low-order fracture zones in the Simpevarp area is probably because longer early zones have been offset along later fracture zones. Although there is plenty of evidence of repeated reactivation along the most significant zones near both Simpevarp and Lansjärv, there is also plenty of evidence of later stress fields generating new fracture sets in the blocks between the major boundaries near Simpevarp. Most, but not all, the hot shears encoutered in the drill core from Äspö reactivated to generate more brittle structures. Similarly, some of the palaeoseismic pseudotachylites and epidotic microbreccias are NOT within earlier hot ductile shears in the core. These details emphasises a generality: that the zones of both fast and slow semi-brittle reactivation did not always remain in the zones of mechanical anisotropy represented by the hot ductile shear.

Most of Sweden breaks again and again rather easily, like a piece of woood, along the strong anisotropy or grain represented by the foliations imparted when the sialic crust formed synorogenically. Most of the zones of semi-brittle and brittle reactivation followed the zones already mechanically anisotropic because of earlier ductile shear. Most of Sweden therefore probably deforms along readily identified major shear zones, at the RESIDUAL strength of the rock mass. There appear to be fewer zones of ductile gneissose and mylonitic shear in the Simpevarp region to have reactivated at later stages. The granitoids of the Värmland-Småland Transcandinavian igneous belt in the Simpevarp area appear to be generally more isotropic than the rest of Sweden. They are perhaps more resistant to brittle strains as a result.

Finally Talbot and Riad report the following conclusions of their study:

1 "Tectonic-topographic lineaments" represent the sites where diffuse planar zones of fractures intersect the bedrock surface. Most of the constitutive fractures are oblique to each planar zone in 3d.

2 "The dimensions (eg widths, lengths) and orientations of the fracture zones occuring a hierarchy of scales (1st, 2nd, nth order) and delimit rock blocks with other dimensions. NONE of the dimensions or orientations of any but some of the highest orders (individual fractures) are yet determined in 3 dimensions.

3 "Not all the fracture zones are subvertical as commonly supposed. Certainly many sets of individual fractures have gentle dips and it is unlikely that all of the lower orders are vertical.

4 "Experience elsewhere in Sweden indicates that the most significant hydraulic conductors are likely to be subhorizontal fracture zones in the top 500 m, although tests deeper than this (eg at Siljan) indicate that they can be deeper still.

5 "The most general penetrative foliation in the region appears to dip steeply to the north and may be Svecofennian (1.9 -1.8 Ga) in age.

6 "Ductile shear zones appear to be most common with strikes of N10°E, N20°E, N80°E, N40°W. Their ages are unknown but probably predate the 1.4 Ga granites.

7 "Two underlying fault patterns appear to have been superposed: an EW-NS-horizontal cubic pattern and a pattern of N40°E, N60°E, N40°W conjugate faults. The N-S fractures appear to bisect conjugate shears with strikes 30 degrees apart (Nisca 1987).

8 "Several reactivation of preexisting faults occurred at greenschist and lower metamorphic grades.

9 "Several new sets of fractures have formed since the rocks now exposed rose through the greenschist facies. The patterns of these new fractures often bear no obvious relation to previous patterns even where found within earlier fracture zones.

10 "Few zeolite or calcite infillings have been found to be slickensided implying that comparatively late (1.4 Ga) fractures dilated but did not involve large displacements.

11 "The offsets in the sub-Cambrian peneplain studied by Tirén et al (1987) may have occurred at any time in the last 1.1? Ga.

12 "Slabs of Cambrian limestones from Öland seen in museums show en-echelon sets of wide dilation veins infilled by calcite and demonstrate that significant strains (but not necessarily large displacements) have occurred in the region in the last 600 Ma.

13 "Empty fractures are considerably more widespread than earlier infilled fractures and appear to fit different stress fields.

14 "There is alredy some evidence that the two regimes appearing in the hydrology and mechanics above and below a subhorizontal fractured boundary elsewhere in Sweden also occur in the Simpevarp area.

15 "No definite indications of neotectonic activity were noticed but these would be difficult to recognize."

2.1.5 Fracture mapping

A fracture mapping programme was carried out in the Simpevarp area (Ericsson, 1987). The mapping was done on outcrops and road cuts in the area close to Simpevarp as well as in the region between Oskarshamn and Västervik. The principal aim of the fracture mapping measurements was to produce results for geohydrological and rock mechanicals model studies. Geographically integrated results, regarding strikes, dips, fracture densities, fracture lengths and the distributions of these lengths are reported. Furthermore, the strikes of some fracture in-fillings have been analysed. Fractures exceeding 0.5 m were measured on outcrops which have surface areas from about 30 to 200 square metres. In all, 116 outcrops and 9 road cuts were mapped in the area investigated.

About 9 600 of the 10 400 outcrop fractures have been mapped as steep dips of 70 to 90°. Fig. 2.10 is a summarized rosette diagram showing these determinations.

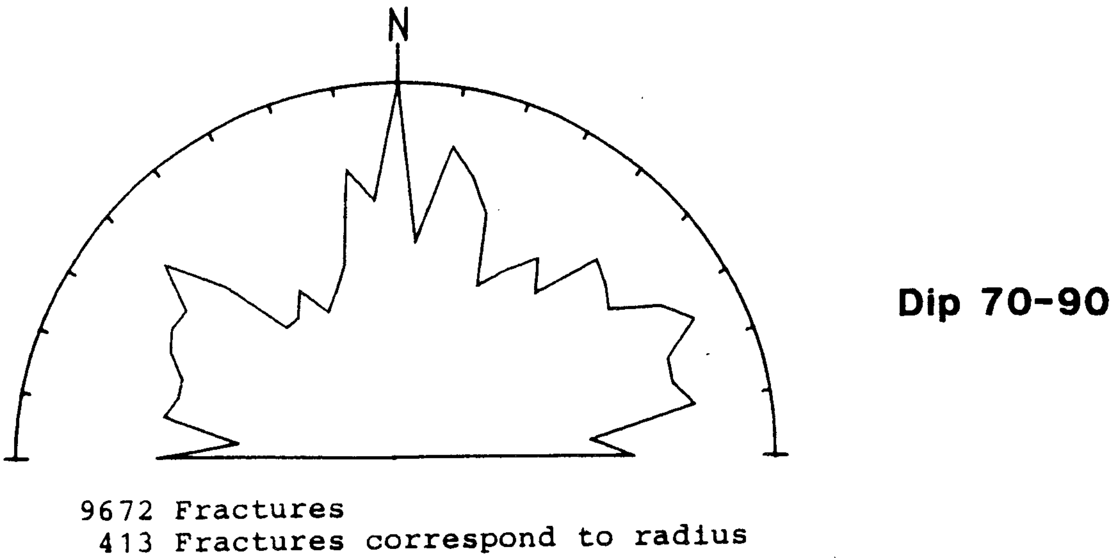


Fig. 2.10 Rosette diagram for all outcrop fractures in the region with dips of 70 to 90°. (Ericsson, 1987).

The fracture sets mainly coincide with the most conspicuous lineament directions (valleys) in the region. The general pattern shows evident strike directions around N-S and N50°W. A tendency of a predominant fracture set also strikes in an E-W direction. In the sector between N40°W and N80°E there appears a fracture set with a somewhat less predominant peak in the direction N65°E. This sector coincides with the most common foliation strikes in the region. The different rosette diagrams of the road cut mapping verify the main fracture sets that have been described for the outcrops. The main directions are found in the directions E-W, N50°W, N-S, N40°E , with one spread foliation peak varying around N70°E. Even if gentle fracture dips may have been under-estimated during the road cut mapping a "summe-rized" interpretation also shows that the pre-dominant dips are vertical or almost vertical.

The most predominant peaks of the fracture sets for the different bedrock types in the region have been evaluated. The regional fracture pattern is also reflected by the bedrock types. The two most dominant peaks strike around N-S and N50°W. The foliation influences the fracture sets, especially in the sector N45°E to E-W. E-W sets occur but are not so frequent. The fractures of the red Götemar-Uthammar granite are relative-ly less influenced by any foliation.

The fracture lengths in different rock types are presented. The geometric mean value (median) varies from about 0.6 to 1.2 m. The lengths in the greenstone are significantly shorter than those of all other bedrock types. The tonalite and porphyritic granite show the longest fractures. There is a similar length deviation among the different rocks, with a maybe somewhat larger spread in the fine-medium-grained granite and the gneissic granodiorite.

The different bedrock types have been compared with each other in order to find any significant discrepancy in respect of the fracture density.

The fracture density was found to have a log-normal distribution and the median values are almost equal. The porphyritic granite and granodiorite dominate the region. The confidence interval (95 %) for the mean (medium) value of the fracture density in this rock type is 1.4 to 1.7 fractures per square metre.

The interaction traces between an aqueous phase and a solid phase, e.g. a wall rock or former in-filling may indicate possible fluid paths.

Epidote and quartz are formed in more deeply situated processes in connection with some kind of regional metamorphism close to the plastic or semi-plastic crust. Calcite and red staining tend to be more superficial processes within a brittle environment. Calcite may be precipitated under hydrothermal as well as low-temperature conditions. Thus, the distribution of calcite-filled fractures may be used as an indicator of previous and present water paths in the rock. Strong alteration of a rock often implies a colouring around the fractures (See Tirén, 1986). For example, a red hematite staining of the wall rock may be used as an indicator of hydrothermal activity. Referring to the above, the calcite-filled fractures and fractures with red staining may constitute relatively young discontinuities with the ability to transport water. Fig. 2.11 shows that the calcite and red-stained fractures have predominant N-S strikes. The altered fractures in wall rock also occur relatively frequently in the E-W direction. This result indicates that fractures in the N-S and E-W directions could be most water conductive.

Different geophysical anomalies (Nisca, 1987) show the existence of the relatively young granite diapir at Götemar. The association between the outcrop densities and the radial distance from the centre of the dome has been tested. The nearest outcrops are situated within the dome. From the border of the dome to a radial distance of about 16 kilometres there is a tendency for the fracture density to decline.

At a larger distance other structures probably influence the fracture behaviour to an obvious extent.

The most conspicuous structures in the region are some N-S and E-W valleys. These lineaments have been analysed in a terrain study (Tirén et al, 1987) and were interpreted as being block boundaries, i.e. fracture zones in the macroscopic regional scale. A special correlation study was carried out on the outcrops which surround one N-S lineament and one NE lineament. Furthermore one E-W lineament has been evaluated. Only outcrops within a distance of 2.5 kilometres have been involved in the association test. The test stresses the correlation between the lineament direction and the dominant fracture sets in relation to the distance from the lineaments.

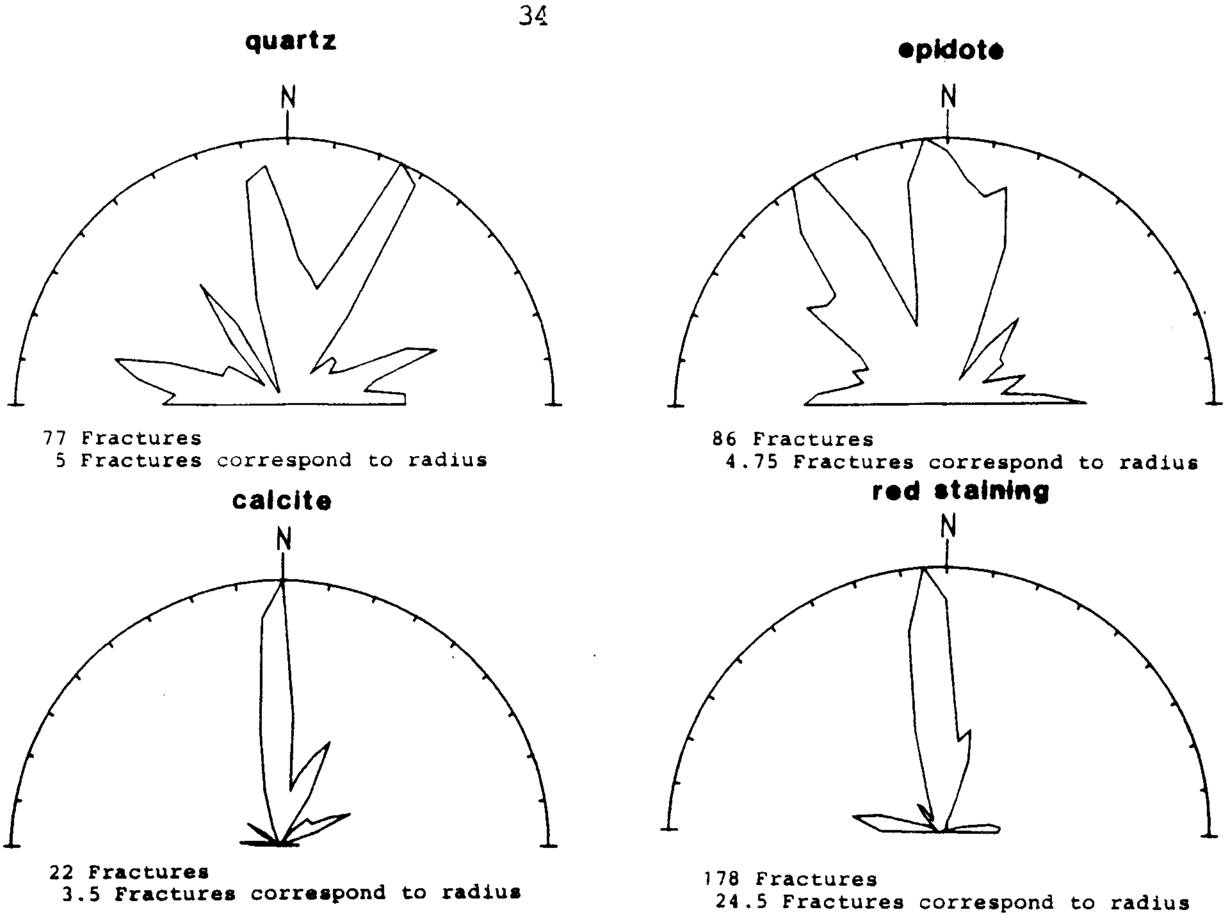


Fig. 2.11 Rosette diagram, filtered and summarized for the region, with infillings of quartz, epidote and calcite in addition to fractures surrounded by red hematite staining. Dips 70 to 90° (Ericsson, 1987).

It is evident that the main regional structures influence the fracture sets in their environment. A decreasing trend has been observed for the N-S fracture set versus the distance from the N-S regional fracture zone. The results from the E-W lineament are similar to those from the N-S zone, i.e. a decreasing trend for the E-W fracture set with distance. The summarized rosette diagram for Ävrö presents the most evident fracture sets in the E-W and NS-N20°E directions. Tendencies are found of an increasing fracture frequency around N50°W and N40°E. No foliation peaks are obvious.

Referring to Fig. 2.12, the Äspö summarized picture, relatively more fractures are found around N50°W-N70°W. The N-S strikes are more spread and there is also a "foliation peak" around N60°E. The EW set is not so predominant but still evident.

The granite or granodiorite concerned has its population mean of the lengths in the interval 0.98-1.02 m (95 % level of confidence) and of its logstandard deviation is 0.35. The samples of Ävrö and Äspö show somewhat larger deviation in respect of the lengths. Furthermore, the Ävrö median length is longer and the Äspö median length shorter than that of the population.

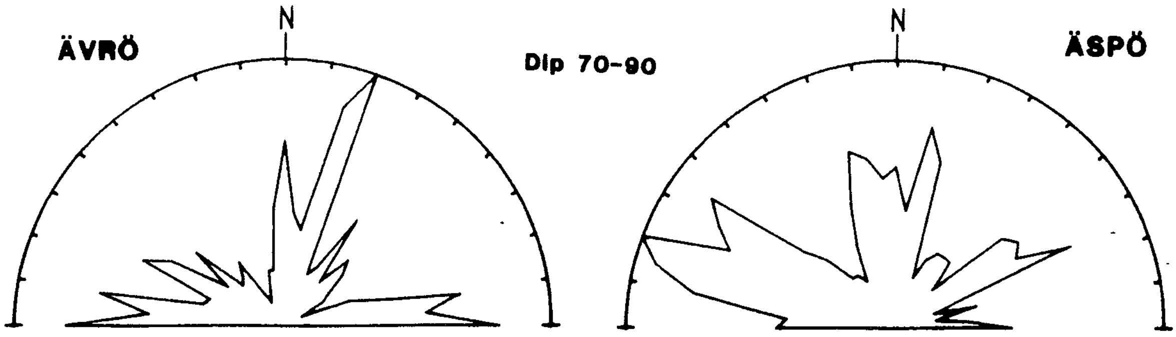


Fig 2.12 Ävrö vertical fracture strikes. Äspö vertical fracture strikes. (Ericsson,1987).

The formation and reactivation of four sets of faults (NW-SE, E-W, N-S and NE-SW) comprise the main outline of the brittle history of the investigated area. Faults of all four sets have been reactivated. Often, however, the reactivation of faults has occured only along restricted parts of the faults. The oldest fault set appears to be the NW-SE set, possibly together with the E-W, set according to Tirén. Lateral shearing is indicated along both of these sets.The NE-SW and N-S trending fractures have been established as being later. Right lateral shear is locally indicated along a N-S trending fault. The occurrence of NE-SW and N-S trending Cambro-Ordovician clastic dykes indicates that these fractures were under tension at that time. Block faulting of the Precambrian peneplain indicates faulting younger than 600 m.y.

Five regional fracture zones, three trending N-S, one E-W and one NE cross the Simpevarp area. Besides the regional zones there are also semi-regional fracture zones trending E-W, N-S, NE and NW. The spacing of the E-W zones is 3 to 5 km and that of the N-S trending zones about 2 to 4 km.

The N-S fracture zones have most probably vertical-sub-vertical dips and the E-W trending zones have, according to Nisca, vertical - moderate dips.

2.2 GEOLOGICAL - TECTONIC MODELS OF THE SIMPEVARP AREA

For the planned modelling work it is of importance to set up mass descriptions on different scales.

Based on present geological knowledge it seems possible to make rock mass descriptions on the following three scales:

Regional scale	(approx. 5 000 m x 5 000 m)
Site scale	(approx. 500 m x 500 m)
Detailed scale	(approx. 50 m x 50 m)

2.2.1 Regional scale

Interpretation of geological field investigations and geophysics show that the Simpevarp area is mainly of granitic composition. Different types of the Småland granite dominate in the study area. Some E-W elongated massifs of basic rocks, greenstone, are indicated by positive magnetic and gravity anomalies. The estimated depth of these massifs is according to Nisca, 1987, about 1 to 2 km (e.g. Släthult and Sundsholm).

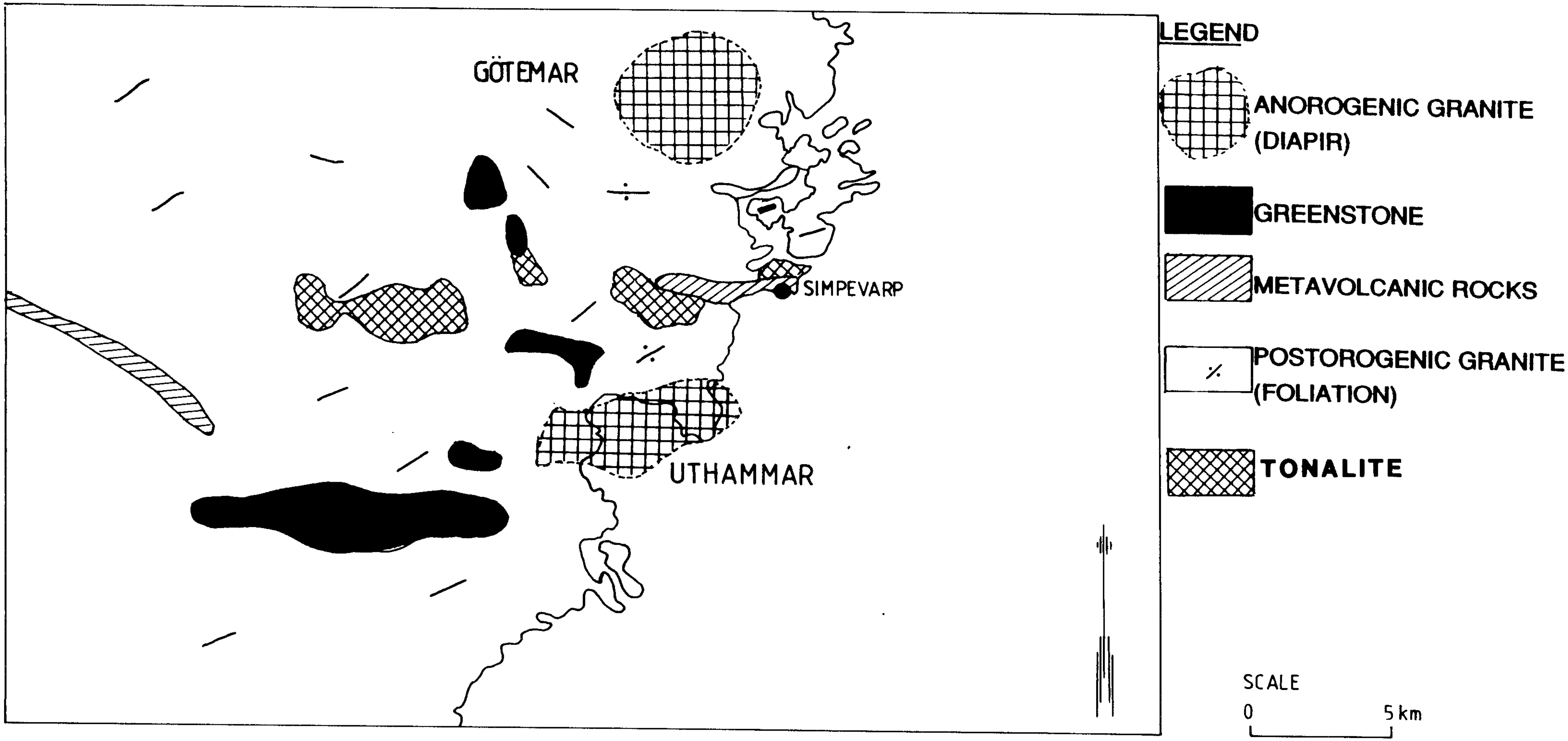
Besides the more coarse-grained types, such as gabbro and diorite, fine-grained irregular bodies and xenoliths of greenstone are found as remnants within the granite mass. Greenstone occupies only a minor part of the Simpevarp area. Fig. 2.13.

Some circular-semicircular structures in the investigated area are interpreted as granite diapirs. They are all represented by a more or less round nonmagnetic pattern and positive Bouguer anomalies. The Götemar and Uthammar granites are two of these structures which are indicated out as true diapirs (Nisca).

Magnetic-gravity modelling with different density contrasts has given outward-pointing moderately-low dips. The estimated depths of these two granites are about five kilometres. The joints in and around the granite diapirs are of several types but especially important are the flat ones, which can be seen in some quarries. Very low-dipping pegmatites and, to a lesser degree, aplite granite are characteristic of the area around the Götemar granite. This granite may be very extensive below the Småland granites and may perhaps have caused not only joints but also gently dipping shear-zones.

According to Röshoff et al, 1977, no main tectonic zone of regional character is affecting the Simpevarp area but a regional fault bordering the area to the east in Kalmarsund probably is.

Fig. 2.13 GENERALIZED GEOLOGICAL - TECTONIC **MAP** MODEL IN A REGIONAL SCALE OF THE SIMPEVARP AREA - **BEDROCK**



Information from all geological and geophysical investigations supports a tectonic picture of the Simpevarp area dominated by one almost orthogonal system of 1st order fracture zones (N-S and E-W (Fig. 2.14). These zones are often about 300 to 500 m wide and extend in the order of 20 to 50 km. The N-S fracture zones have most probably vertical-sub-vertical dips and seem to be of a tensional, more open, character according to coincident magnetic and VLF indications. The zones trending E-W are mostly vertical moderately-lowdipping to the north or to the south. They seem to be more complicated with an early dip-slip ductile phase, indicated by intense mylonites, followed by a semi-ductile strike-slip phase and a late stage of reverse faulting with local development of thrust sets with a mainly low to moderate dip to the SSE.

The fracture zones trending N-S are probably more permeable than those trending E-W.

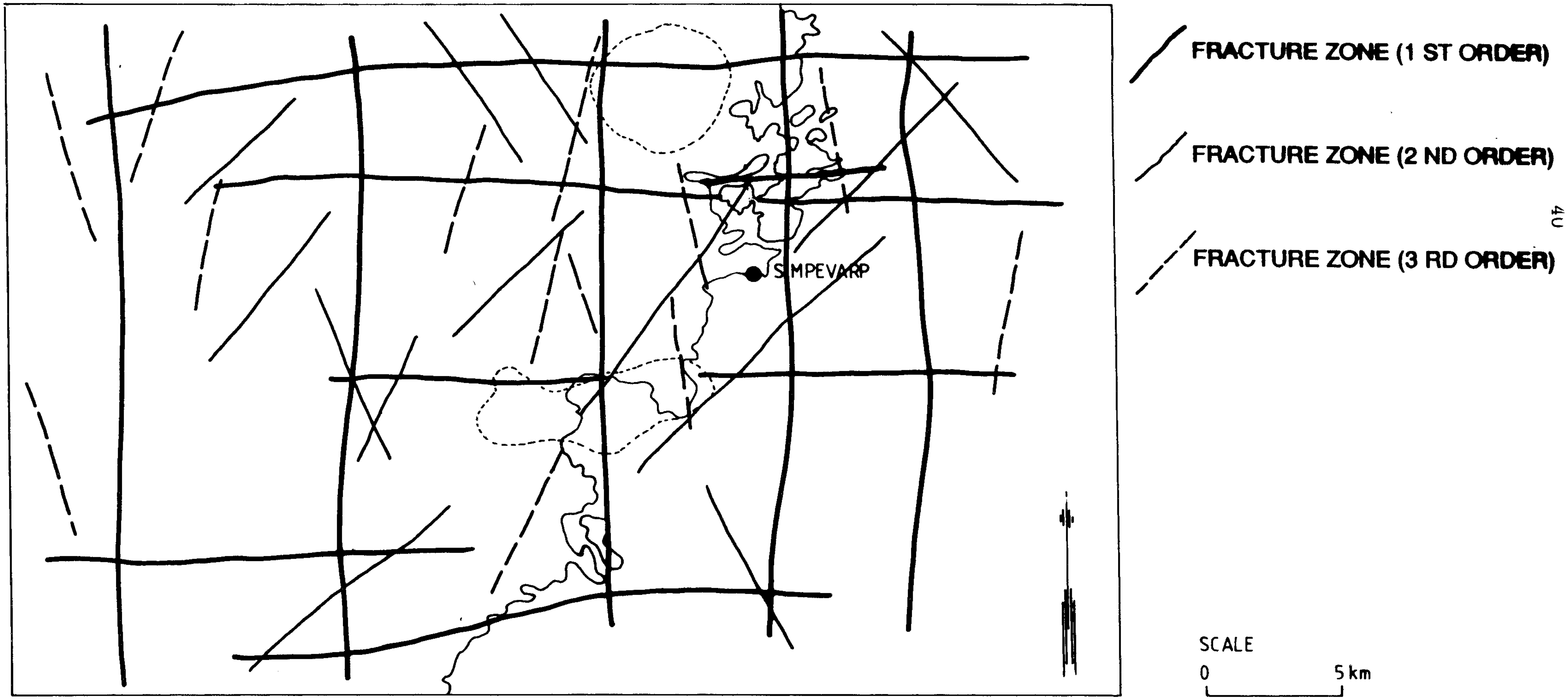
Besides the system of the 1st order fracture zones, there are also 2nd order zones trending NW and NE of forming another almost orthogonal system. The 2nd order zones are mostly in the order of 100 to 200 m wide and extend 1 to 20 km.

The most prominent of the NE trending fracture zones, running immediately west of Simpevarp and crossing the island of Äspö, is indicated by mylonites in some outcrops in the granite. For many of the zones trending NW there seems to be a better coincidence between VLF and magnetic indications than for the NE trending zones. According to a general interpretation most of the zones trending NE and NW are older than the N-S and E-W fracture zones.

Fracture zones trending NNW and NNE (3rd order zones) are geophysically interpreted as being a conjugate shear set to the tensional fracture zones trending N-S.

Most of the regional fracture zones in the Simpevarp area have been preliminarily interpreted as being vertical or sub-vertical. Both geological and geophysical indications, however, point to the possibility of more flat or low-dipping structures, especially connected to the anorogen granites (e.g.flat pegmatite dykes in the Götemar granite area). Dykes of fine-grained granites and aplitic dykes are probably more sub-vertical or moderately dipping.

Fig. 2.14 GENERALIZED GEOLOGICAL - TECTONIC MAP MODEL IN AREGIONAL SCALE OF THE SIMPEVARP AREA - FRACTURE ZONES



There are probably also low-dipping shear zones, especially connected to the E-W lineaments. Earlier geomorphological investigations report thrust zones especially trending NW and with low dips to the WSW (Nordenskjöld, 1944).

On the island of Ävrö a fracture zone at least 120 m wide was encountered in three boreholes at varying depths between 100 to 500 m. This fracture zone is interpreted as having a N-S strike and dipping about 40° towards the west (Gentzschein et al, 1987).

The first order fracture zones, and to some extent also the second order zones, have divided the Simpevarp area into rectangular or triangular rock blocks of different sizes (Fig. 2.9 and 2.14). Large blocks in the order of 100 km^2 are further divided into blocks of a lower order - 25 km^2 or less. The block configurations of higher and lower order rock blocks are often analogous.

Conclusions on the regional scale, especially regarding the water-bearing ability of different rocks and fracture zones

a. Metavolcanic rocks show no prominent foliation. Compared with the intrusive rocks, the metavolcanics show more intense and closely spaced fracturing. The fracture length is often shorter than that of the granitic rocks. Common fracture fillings are epidote and quartz. Highly fractured dykes or remnants of metavolcanic rocks in a surrounding granitic rock mass, are probably conductive.

b. Greenstone in larger massifs normally has fracture lengths significantly shorter than those of all other rock types in the Simpevarp area. The fracture fillings are often calcite and chlorite. Greenstone can normally be regarded as having low permeability. In areas with greenstone xenoliths and dykes, however, the contacts with the surrounding bedrock can be permeable.

c. Anorogenic rocks, such as the Götemar granite, often have a very characteristic cubic fracture pattern, with a few long persistent fractures. The fracture density, however, is often low. Especially notable are the flat fractures which can be seen in the quarries. Highly permeable open, single fractures and flat dykes of fractured pegmatite and aplite seem to be very important conductive elements in the anorogenic granite. The vertical fractures, especially those with N20°W and N55°E orientations, seem to be more tight than the flat fractures. Most common are fracture fillings of fluorite and Cambrian sandstone (Duran et al, 1983).

d. The Småland granites (including the "tonalite" variant) are always more or less foliated and rather heterogenous. The fracture length is normally rather long and the fracture density is about 1.70/m2.

The fractures are often filled with quartz, epidote and calcite. Fine-grained granite in dykes, often 0.5 to 5 metres wide, frequently occur following the direction of the foliation in the direction about E-W to NE-SW and dipping sub-vertical. Typical of these dikes is that many of them are highly fractured and highly permeable. Flat pegmatite dykes, probably also permeable, cannot be excluded in the Småland granite mass, especially at greater depth and connected to the anorogenic granites. Xenoliths of greenstone are, in some parts of the Simpevarp area, very common in the Småland granite. Their contact zones with the granite are very often chemically and mineralogically altered and are in the case of fracturing more or less conductive.

e. The N-S and the NE trending fracture zones, are interpreted as being the most permeable subvertical zones. The NW trending zones are probably less permeable than the NE striking ones. The zones running E-W seem normally to be less important as conductive elements but locally variations may occur due to reactivations of these zones. Sub-horizontal fracture zones like the Ävrö zone are likely to be the most important hydraulic conductors.

2.2.2 Site scale

Based on the results of the regional investigations in the Simpevarp area two smaller areas - the Laxemar area (fig 2.15a) and the island of Äspö (fig 2.15b) - were selected for more detailed investigations. The rock mass description on the site scale is concentrated to these two areas and will now be the target areas for further investigations - especially core drilling.

For the Laxemar area (Fig. 2.15a) three different rock mass descriptions, Lx 1-3, are presented in

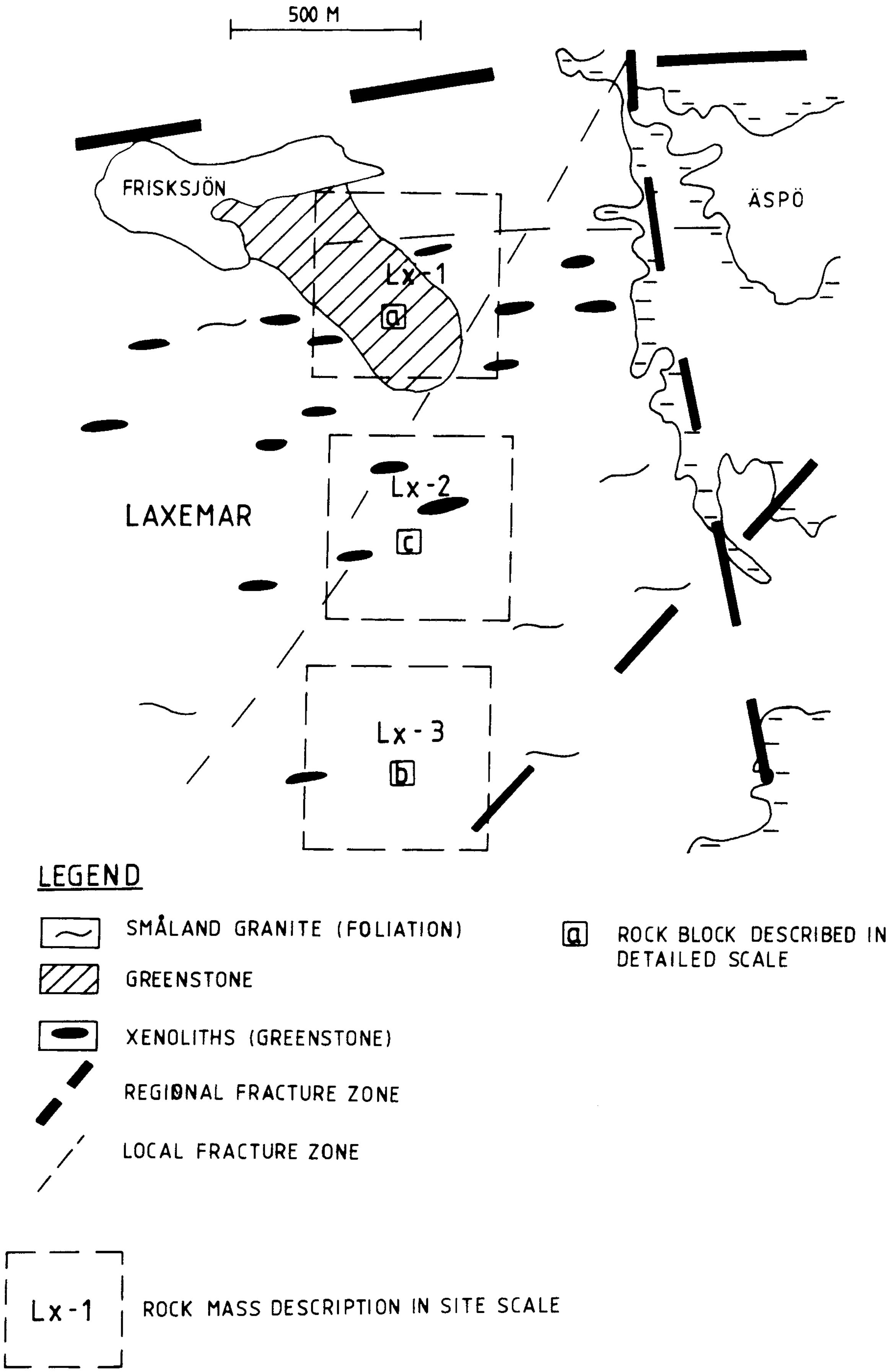


Fig. 2.15a The Laxemar area. Geological-tectonic model.

271b.1.42.1484-01

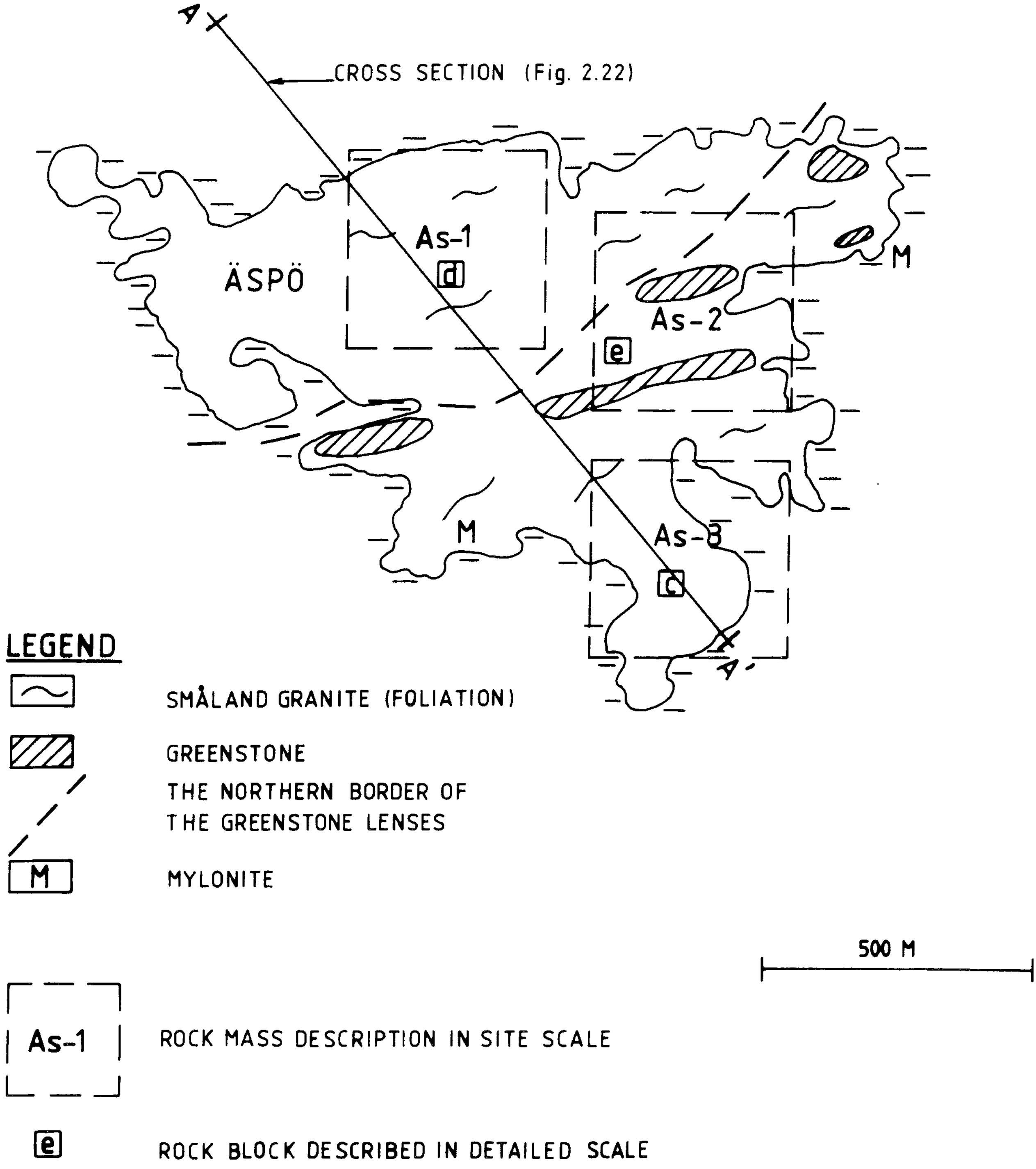


Fig 2.15b The island of Äspö. Geological-tectonic model.

271b.1.42.1484-01

Figs 2.16 to 2.18. Three different rock mass descriptions, As-1-3, are also presented in Figs. 2.19 to 2.21 for the island of Äspö (Fig 2.15b).

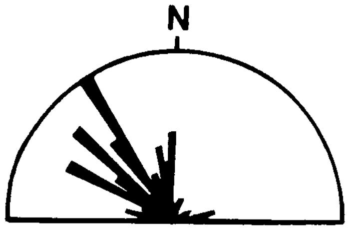
In a cross section through the island of Äspö (Fig 2.22) a prediction of the geological-tectonic conditions is presented on the basis of present knowledge, before the first core drilling campaign. The location of the section is shown in Fig 2.15b.

2.2.3 Detailed scale (approx. 50x50 m)

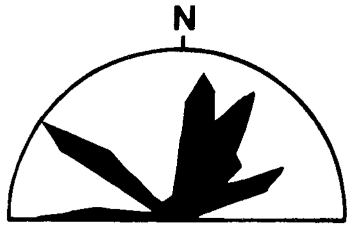
Rock mass descriptions to such a detailed scale as about 50x50 m, can, of course, only be of a very preliminary character until the descriptions can be based on results from core drilling and more detailed geological mapping. Rock mass descriptions - based on the present knowledge of the geological conditions in the Simpevarp area - may however, be of interest as a test of the prediction ability in this first stage of the pre-investigation programme for the Hard Rock Laboratory.

Five rock volumes, blocks a to e, are described for the Laxemar area and the island of Äspö. Some examples of a more general nature are presented in Figs. 2.23 to 26.

THE LAXEMAR AREA. LX-1.



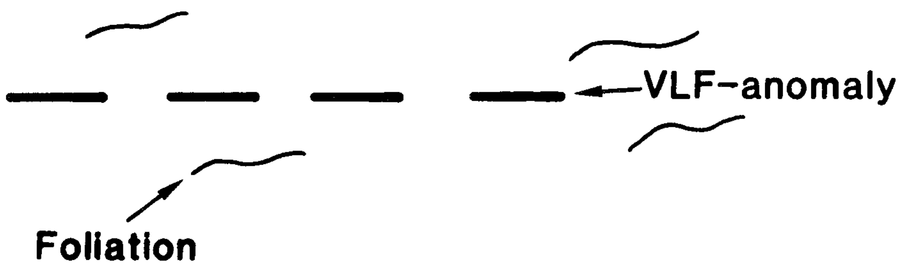
LINEAMENT ORIENTATION



FRACTURE ORIENTATION

ca 500 M

GREENSTONE OF GABBROIC COMPOSITION INTRUDED BY A GREAT AMOUNT OF GRANITIC MATERIAL



ca 500 M

DENSITY OF LINEAMENTS: 0.019 m/m^2. Should be compared to 0.014 for the whole Laxemar area.

FRACTURE DENSITY: 2.0 per m^2

FRACTURE LENGTH: 0.62-0.69 m. Mean length = 0.65 m

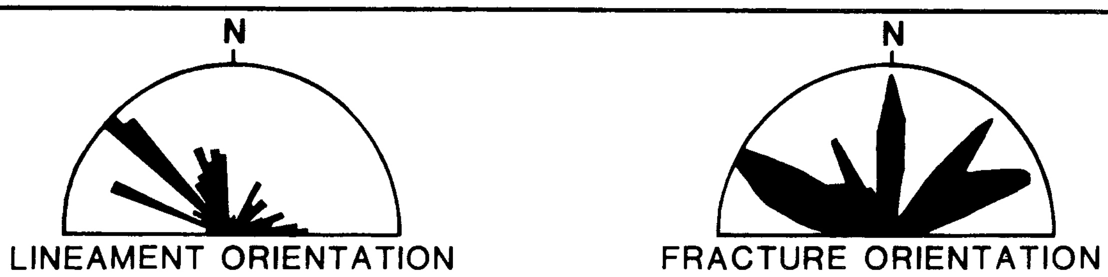
GEOPHYSICAL INDICATIONS: Minor E-W trending VLF-anomaly

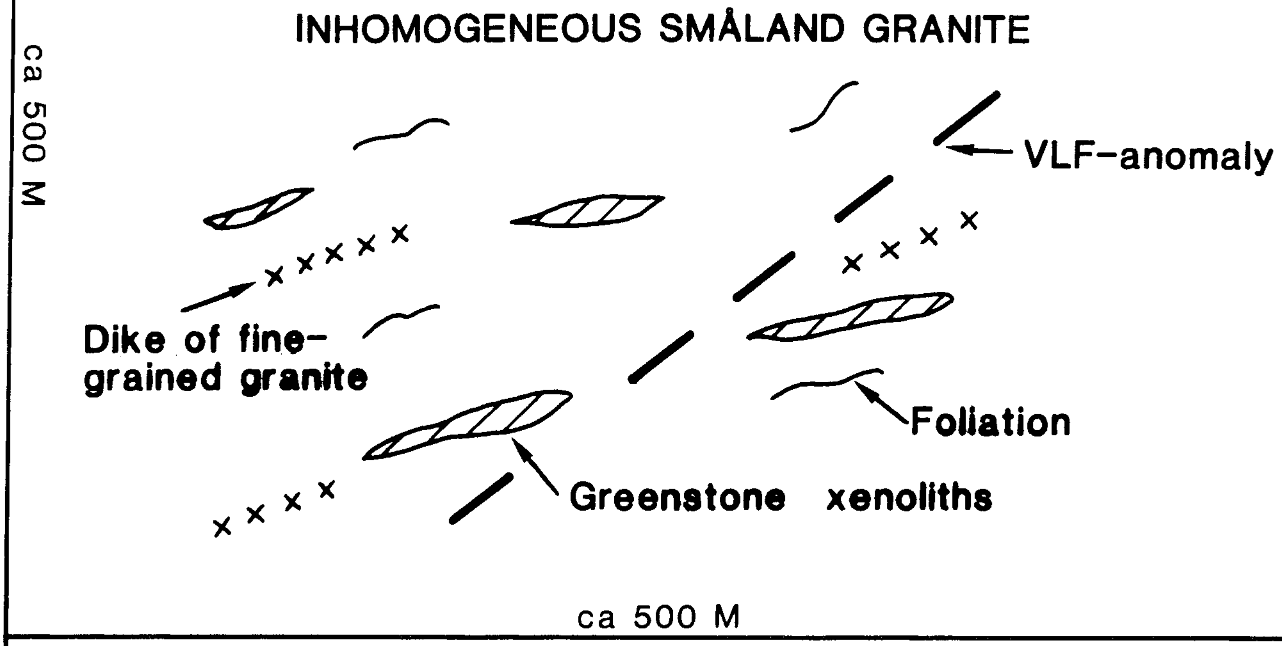
PERMEABLE ASPECTS:

The gabbroic rock mass is probably low-permeable - tight! The contacts between granitic material in form of narrow dikes, 0.5-2 m wide, and irregular veins may be permeable to some extent. The E-W trending VLF-anomaly possibly indicates a permeable granitic dike.

Fig. 2.16 The Laxemar area. Rock mass description.

THE LAXEMAR AREA. LX-2.





DENSITY OF LINEAMENTS: 0.007 and 0.012 m/m^2

FRACTURE DENSITY: 1.30-2.30 per m^2

FRACTURE LENGTH: 0.85-1.02 m. Mean length = 0.95 m

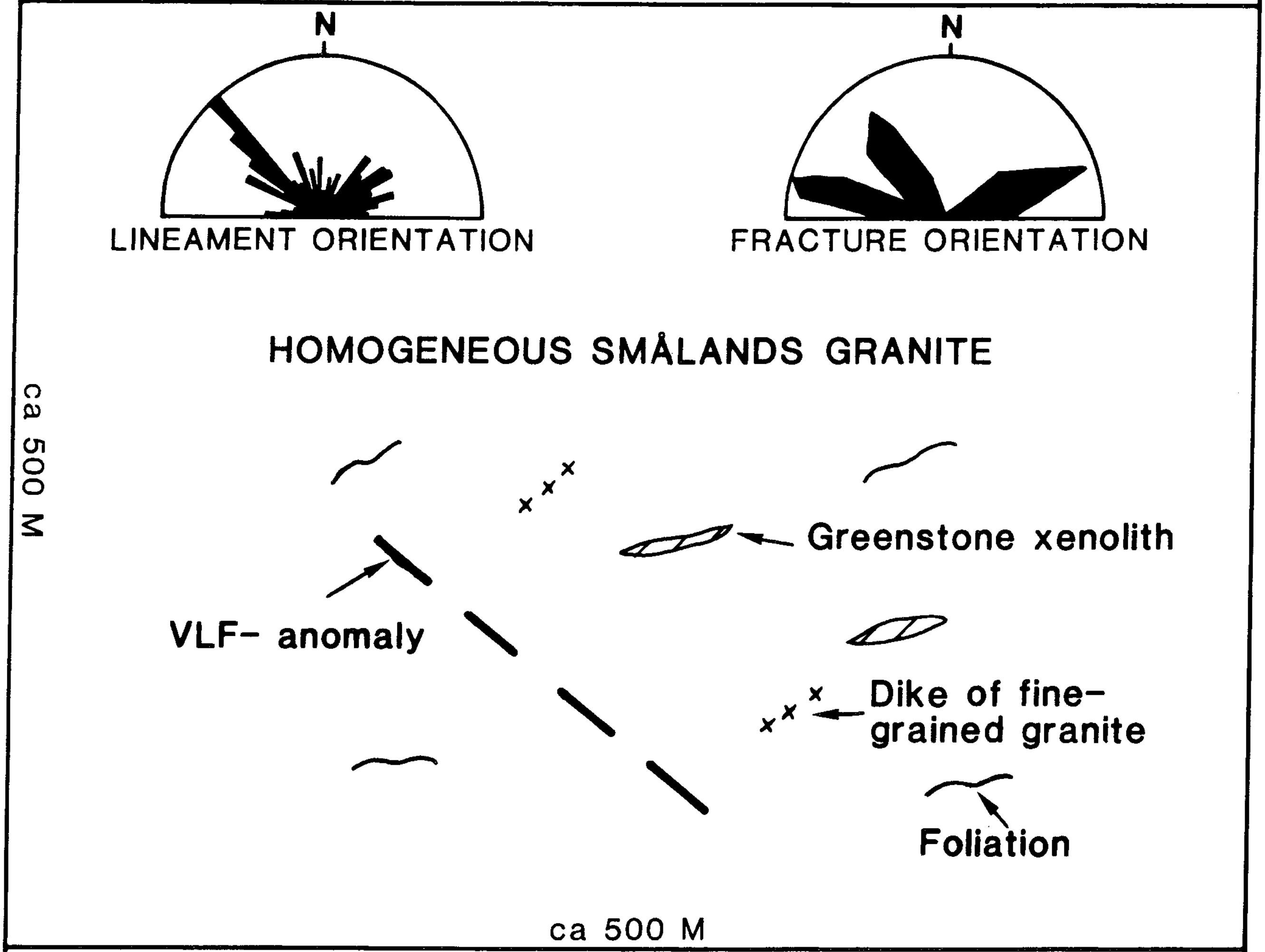
GEOPHYSICAL INDICATIONS: NE trending VLF-anomaly

PERMEABLE ASPECTS:

Vertical - subvertical fractures are probably the most permeable besides the single low-dipping ones. Fractured dikes of fine-grained granite and flat-lying pegmatites may be high-permeable. Contact zones between greenstone xenoliths and the surrounding granite may also be regarded as suspected conductive elements. NE-trending fracture zone - probably low-permeable. NW-trending, topographycally indicated fracture zone, seems to be more permeable according to data from percussion boreholes.

Fig. 2.17 **The Laxemar area. Rock mass description.**

THE LAXEMAR AREA. LX-3.



DENSITY OF LINEAMENTS: 0.011 m/m^2

FRACTURE DENSITY: 1.72 per m^2

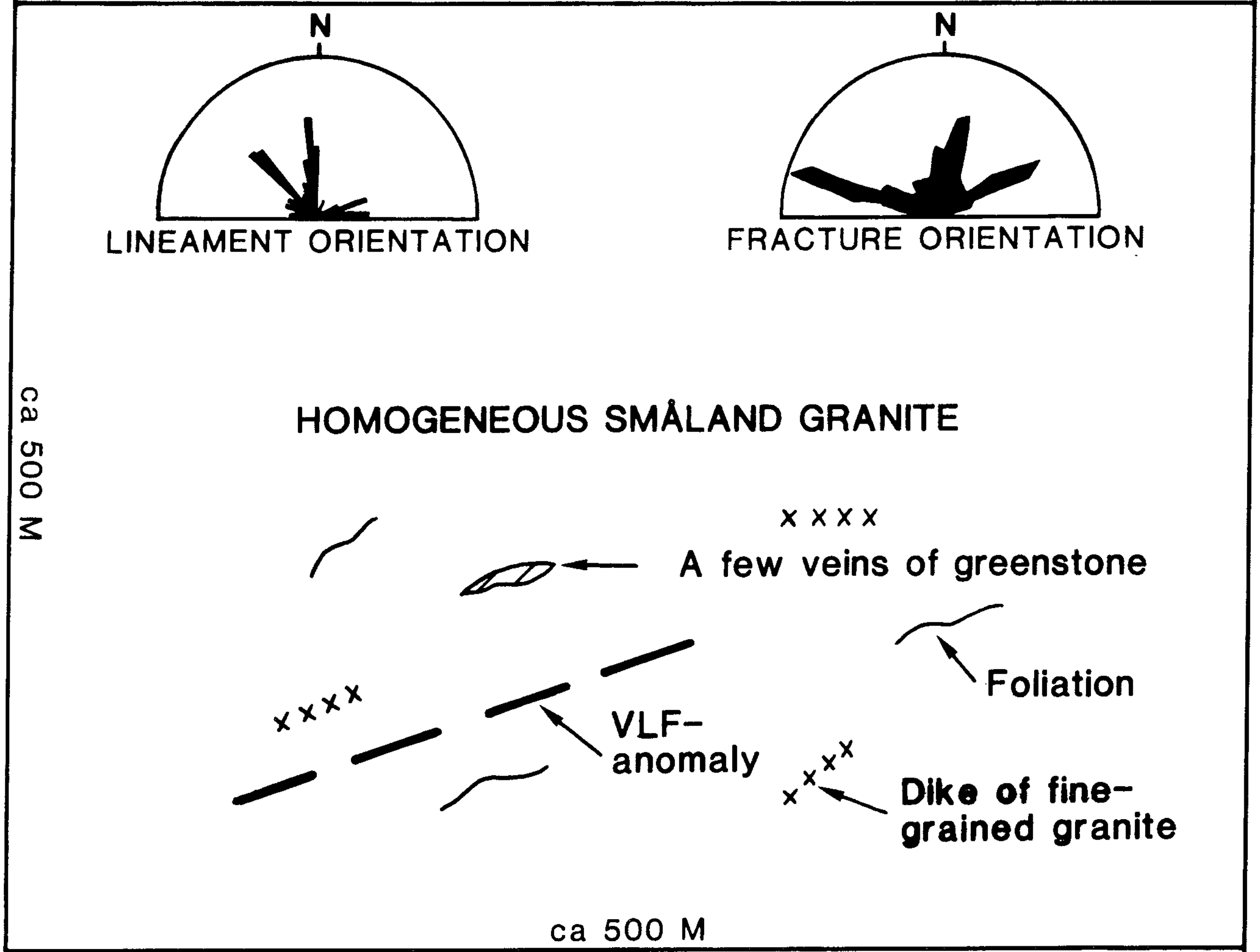
FRACTURE LENGTH: Mean length = 1.00 m

GEOPHYSICAL INDICATIONS: Minor NW trending VLF-anomaly

PERMEABLE ASPECTS:
Fractured low-dipping pegmatite (especially at increasing depth) and single low-dipping open fractures may be high-permeable. Subvertical dikes of fine-grained granite and aplite are also expected to be permeable.

Fig. 2.18 The Laxemar area. Rock mass description.

THE ISLAND OF ÄSPÖ. As-1. NW ÄSPÖ.



DENSITY OF LINEAMENTS: 0.018 m/m^2

FRACTURE DENSITY: 1.75 per m^2

FRACTURE LENGTH: Mean length = 1.40 m

GEOPHYSICAL INDICATIONS:

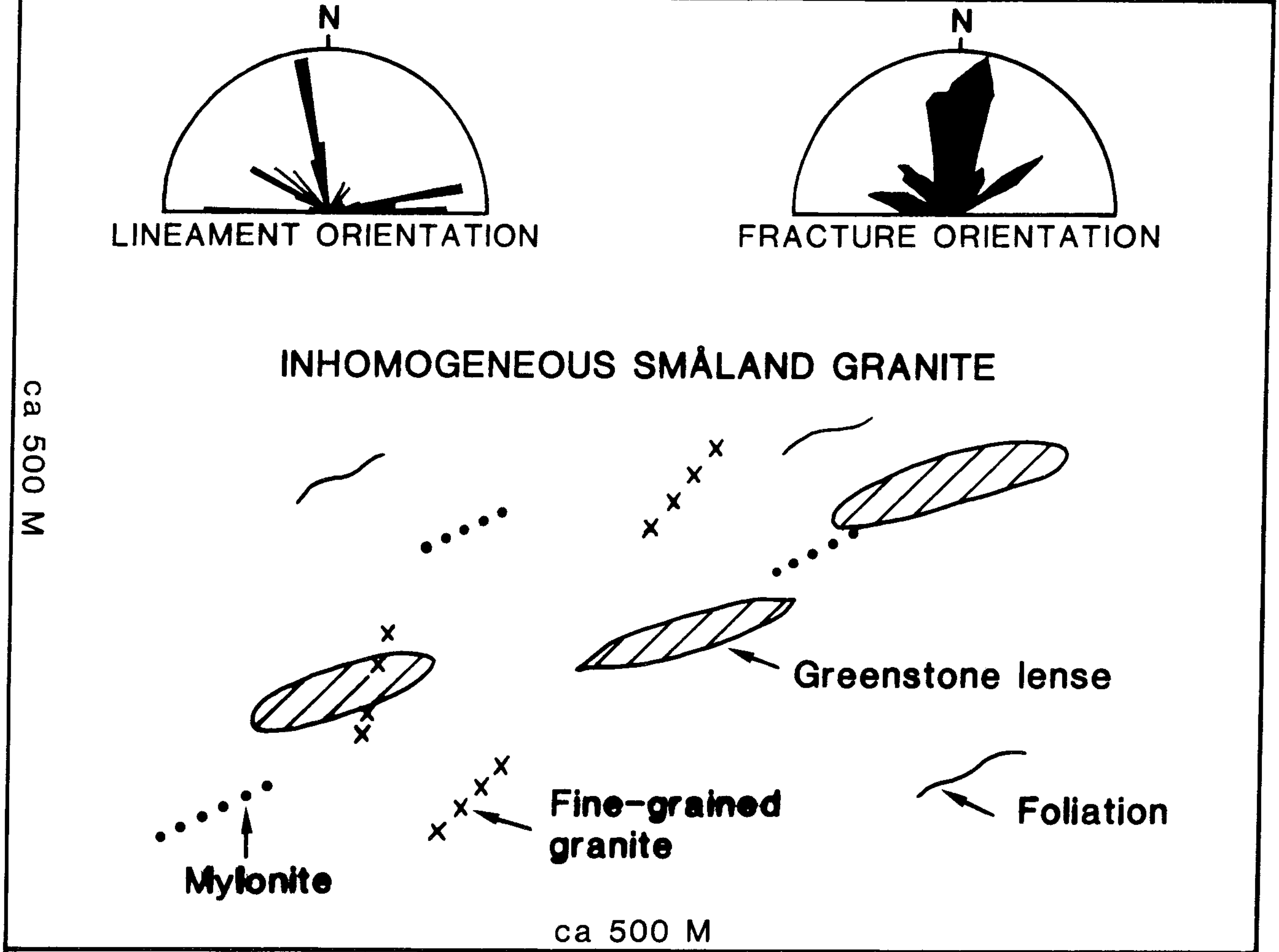
Some magnetic indications are interpreted as inclusions of basic rocks, trending N60°E. A VLF-anomaly indicates a narrow fracture zone trending N70°E.

PERMEABLE ASPECTS:

The more or less fractured dikes of fine-grained granite may probably be high-permeable. Flat-lying permeable pegmatite dikes are expected at increasing depth. Two or three almost vertical, narrow fracture zones, trending ENE, may also be permeable.

Fig. 2.19 The island of Äspö. Rock mass description.

THE ISLAND OF ÄSPÖ. As-2. The border zone



DENSITY OF LINEAMENTS: 0.016 m/m^2. Mean density for the island of Äspö.

FRACTURE DENSITY: 1.90 per m^2

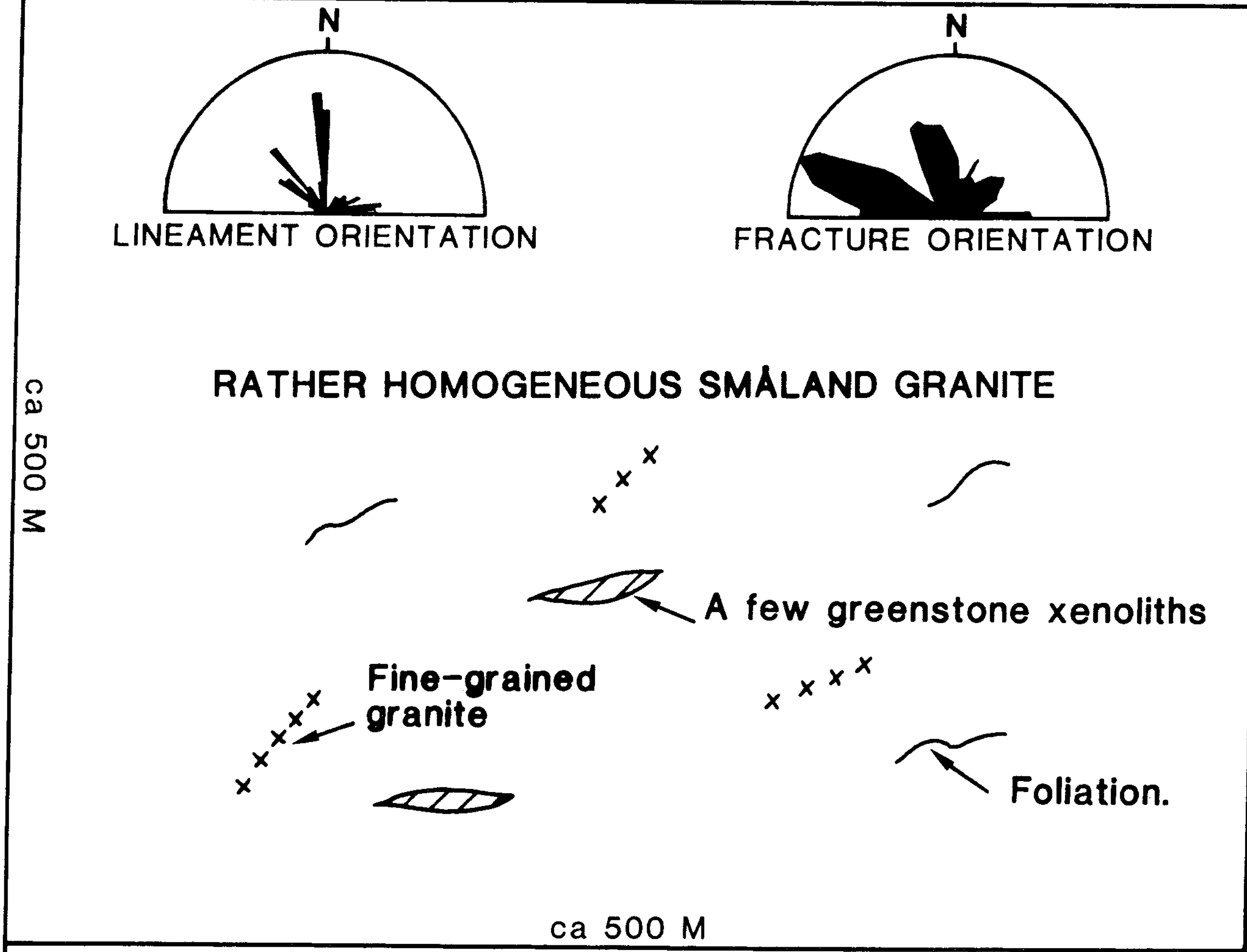
FRACTURE LENGTH: 0.65 m

GEOPHYSICAL INDICATIONS: The mylonite zone - trending N50^{o}E in the greenstone belt - has been identified by airborne and ground surface measurements. Seismic refraction profiles crossing the mylonite zone, identified three almost parallel, narrow, low-velocity zones trending about NE.

PERMEABLE ASPECTS:
The area as a whole is probably low-permeable. More or less fractured dikes of fine-grained granite, however, and contact zones between green-stone lenses (xenoliths) and the surrounding granite may act as more permeable elements in the rock mass.

Fig. 2.20 The island of Äspö. Rock mass description.

THE ISLAND OF ÄSPÖ. As-3. SE Äspö.



DENSITY OF LINEAMENTS: 0.015 m/m^2

FRACTURE DENSITY: 1.60 per m^2

FRACTURE LENGTH: 1.00 m

GEOPHYSICAL INDICATIONS:

PERMEABLE ASPECTS:

Vertical-sub-vertical fractures in the N20^{o}W-10^{o}E direction are probably the most permeable. Fractured dykes of fine-grained granite, flat lying pegmatites and to some extent also the contact zone between single basic xenoliths and the surrounding granite are probably more or less high-permeable.

Fig. 2.21 **The island of Äspö. Rock mass description.**

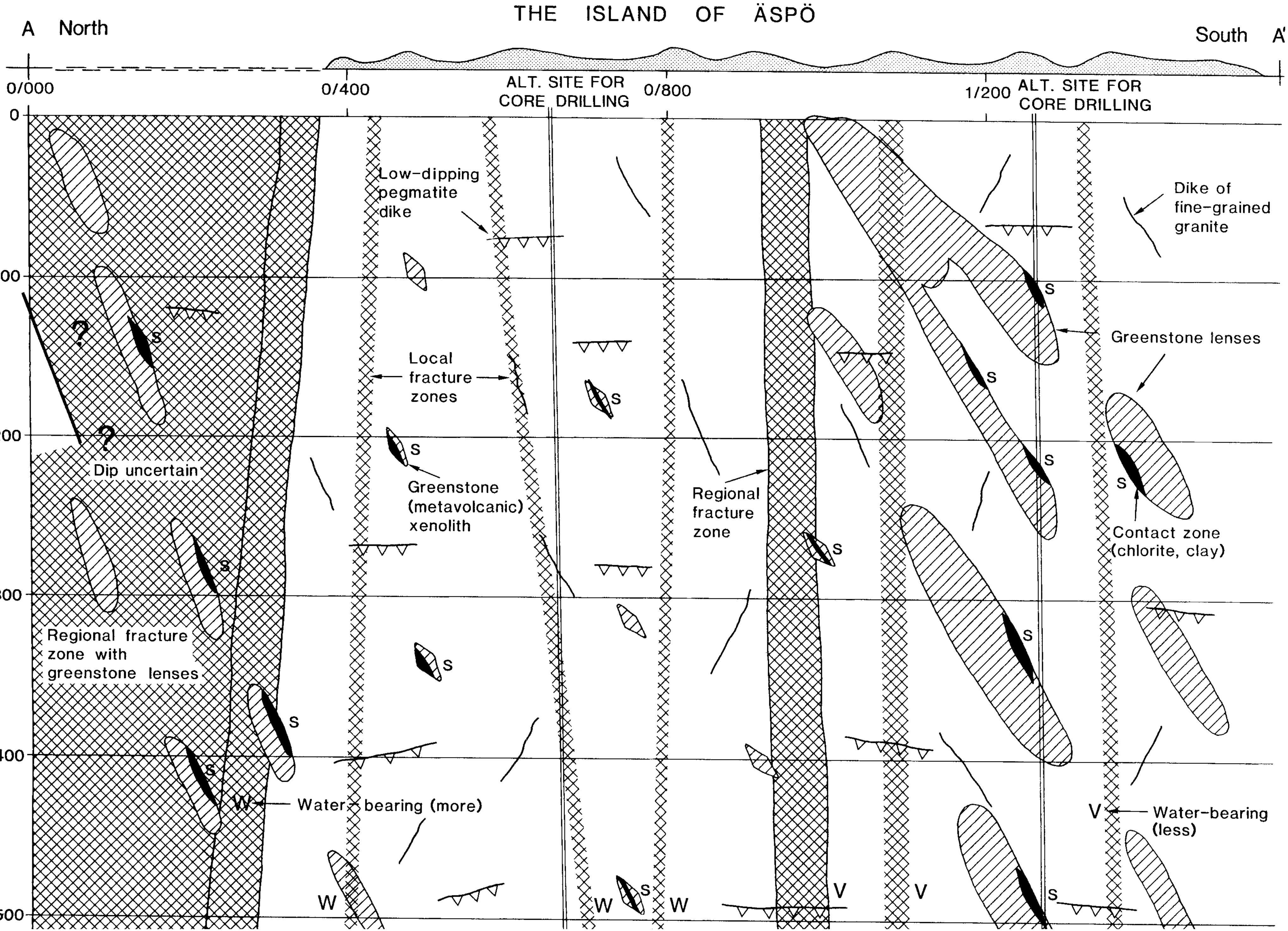


Fig. 2.22 Cross section through the island of Äspö.

Block a (Fig. 2.23)

Rock in a greenstone massif such as the area south of Lake Frisksjön (Fig. 2.15a).

The area is divided into minor rhombic and triangular block by short lineaments trending mainly NS ± 10° and N70-80°E, and there is a coherent body of rather coarse-grained greenstone (diorite-gabbro), intruded by a great amount of granitic material in irregular veins.

Single narrow dykes (0.5 to 2 m wide) of fine-grained granite intersect the greenstone.

The fracture density is rather high (2/m2) and the fracture lengths are significantly shorter than those of the granitic rocks type (0.70 m). Predominant directions of sets of fractures are N75°W, N-S, N45°E and N75-80°E. Predominant fracture infill materials are chlorite, epidote and calcite. The rock volume is probably split up into rectangular and triangular blocks of volume about 0.5 m^3.

Permeability: The rock as a whole may normally be tight! The contacts between granitic veins and surrounding greenstone can locally be permeable. Granite dykes - if fractured - are probably also permeable to a certain extent.

Block b (Fig. 2.24)

Rock volume in the Småland granite, such as in the southern part of the Laxemar area (Fig 2.15a).

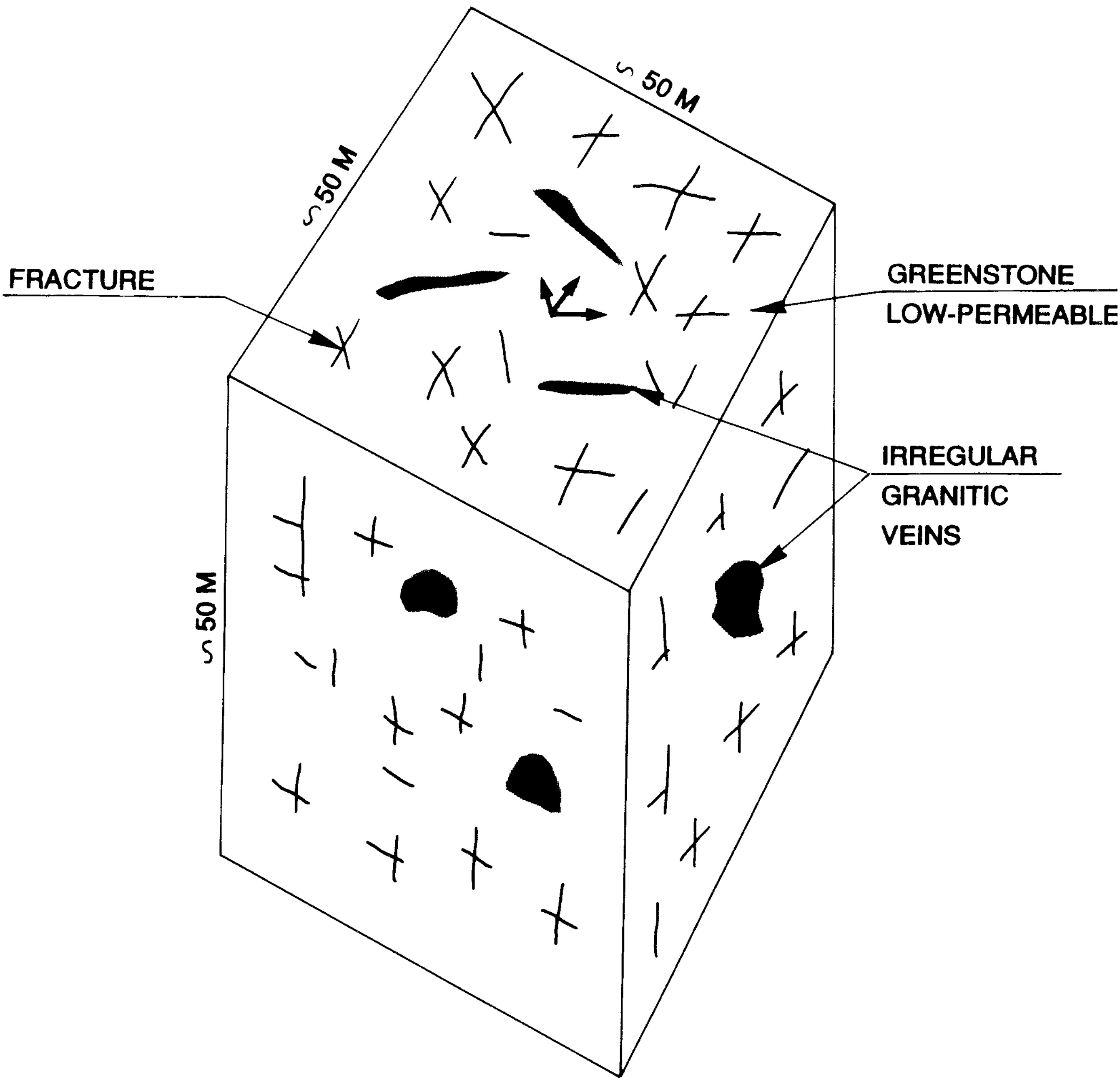
The area is divided into rectangular blocks trending NNE or NNW.

Bedrock: Medium to coarse-grained, grey to reddish-grey, porphyritic granite is predominant. Narrow - often sub-vertical - dykes of fine-grained granite are often oriented parallel to the foliation, which is normally weak. Lenses of zenoliths of greenstone may constitute 1-5% of the rock mass.

The fracture density is estimated to be about 1 to 1.5/m^2 and the fracture lengths are probably 1.00 to 1.30 m. Predominant sets of fractures are N75°W, N45°W and N70°E.

Quartz, epidote and chlorite are the most common fracture infillings. The block volume in this rock mass is expected to be 1 to 1.5 m^3.

GEOLOGICAL MODEL IN DETAILED SCALE



HIGH FRACTURE DENSITY

SHORT FRACTURES

CHLORITE FRACTURE IN FILLING
(CALCITE)

Fig. 2.23 Block a. Rock in a greenstone massif.

GEOLOGICAL MODEL IN DETAILED SCALE

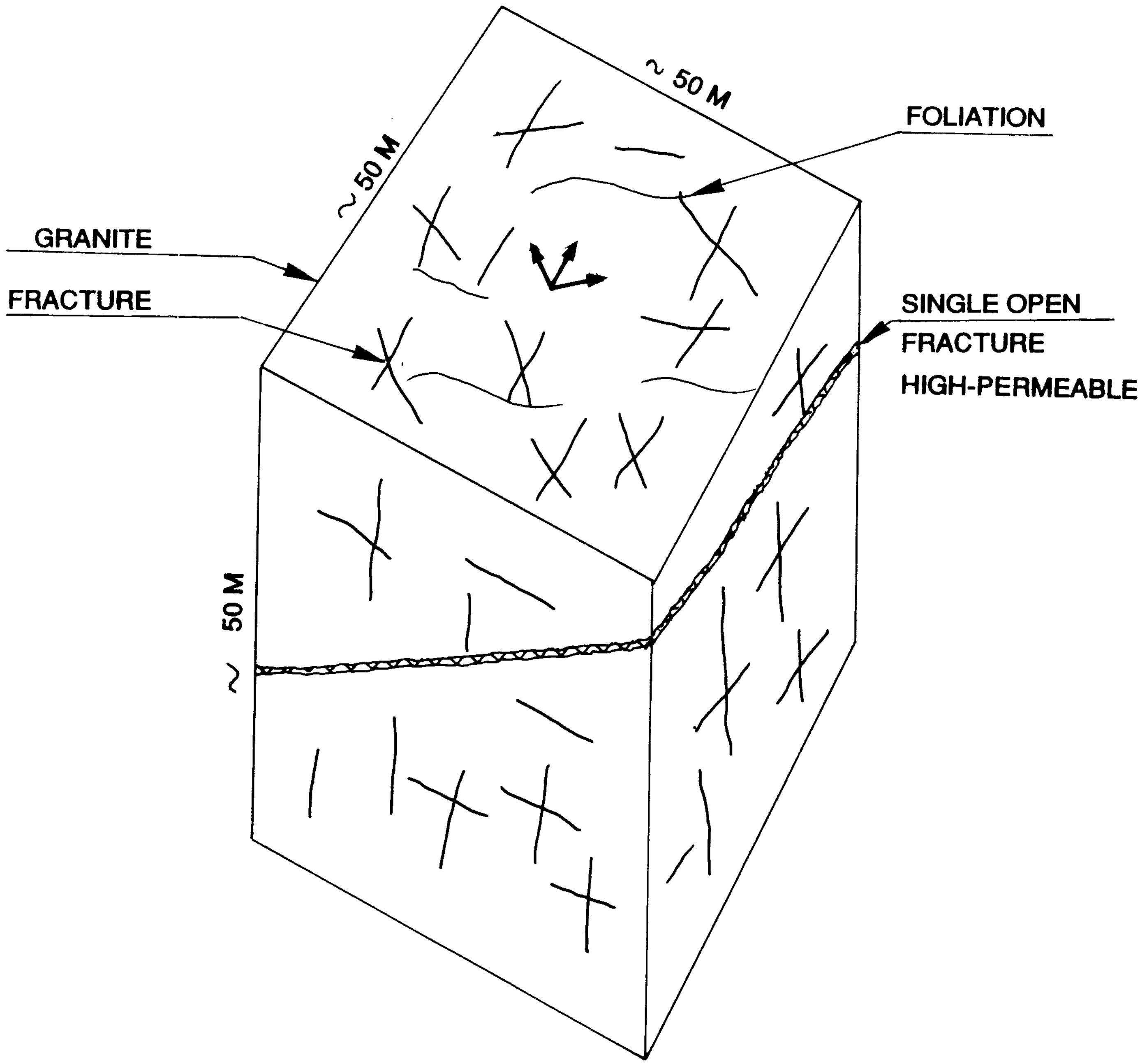


Fig. 2.24 Block b. Rock in the Småland granite.

Permeability: The rock mass as a whole is probably tight or of low permeability. More permeable elements in the porphyritic granite mass are single fractures, fine-grained dykes of granite and contacts between greenstone lenses and surrounding rock.

Block c (Fig. 2.25)

Rock in the Småland granite with greenstone lenses such as in the central part of the Laxemar area (Fig. 2.15a) and the SE part of Äspö (Fig. 2.15b).

The area is divided into minor N-NE trending rectangular blocks.

Bedrock: Medium-grained, reddish grey, porphyritic granite is predominant. This rock is sometimes intruded by fine-grained greyish-red granite in smaller veins and dykes. The dykes - often sub-vertical - are often narrow and oriented parallel to the foliation in the EW-NE direction. Xenoliths or lenses of greenstone may constitute 1-10% of the rock mass.

The fracture density is estimated to be about 1.70/m^2 and the fracture lengths are probably about 1.00 m. Predominant sets of fractures are N55°W, N-S and N70°E.

Quartz, epidote and calcite are the most common fracture infillings. The block volume in this rock mass is ecxpected to be about 0.5 to 1 m^3.

Permeability: The fractures trending NW and ENE are expected to be the most permeable. This rock mass as a whole is probably of low permeability. Contact zones between greenstone xenoliths and the surrounding granite may be more permeable. Dykes of fine-grained granite - if they are fractured - are very often very permeable.

Block d (Fig.2.26

Rock to the north of the mylonite zone on the island of Äspö (Fig. 2.15b).

The area is divided into minor rhombic or rectangular blocks mostly elongated in the ENE-WSW direction.

Bedrock: Medium-grained, greyish-red porphyritic granite is predominant. Dykes of fine-grained granite may occur trending NE or ENE, parallel to the foliation. Xenoliths or lenses of fine-grained greenstone and single flat pegmatites may also occur at increasing depth. The fracture density is probably $1.5/m^2$ and the fracture length 1.00 m. Fractures striking WNW and NW are very dominant and are cut by younger N-S and NE-trending fractures. Many fractures are empty and quite a few epidote-filled. There are also red-stained and quartz-filled fractures. The volume of blocks is expected to be 0.5 to 1.0 m^3.

Permeability: N-S fractures are probably the most permeable. Fractured dykes of fine-grained granite and flat pegmatites at increasing depth may be very permeable. Contacts between green-stone lenses and granite are probably more permeable than the rock mass as a whole, which is expected to be of low permeability.

Block e

Rock in a fracture zone such as the mylonite zone that divides Äspö into two parts (Fig. 2.15b).

The internal structure of the mylonite zone, which has the character of a shear zone trending NE-ENE, is dominated by lensoidal and triangular blocks.

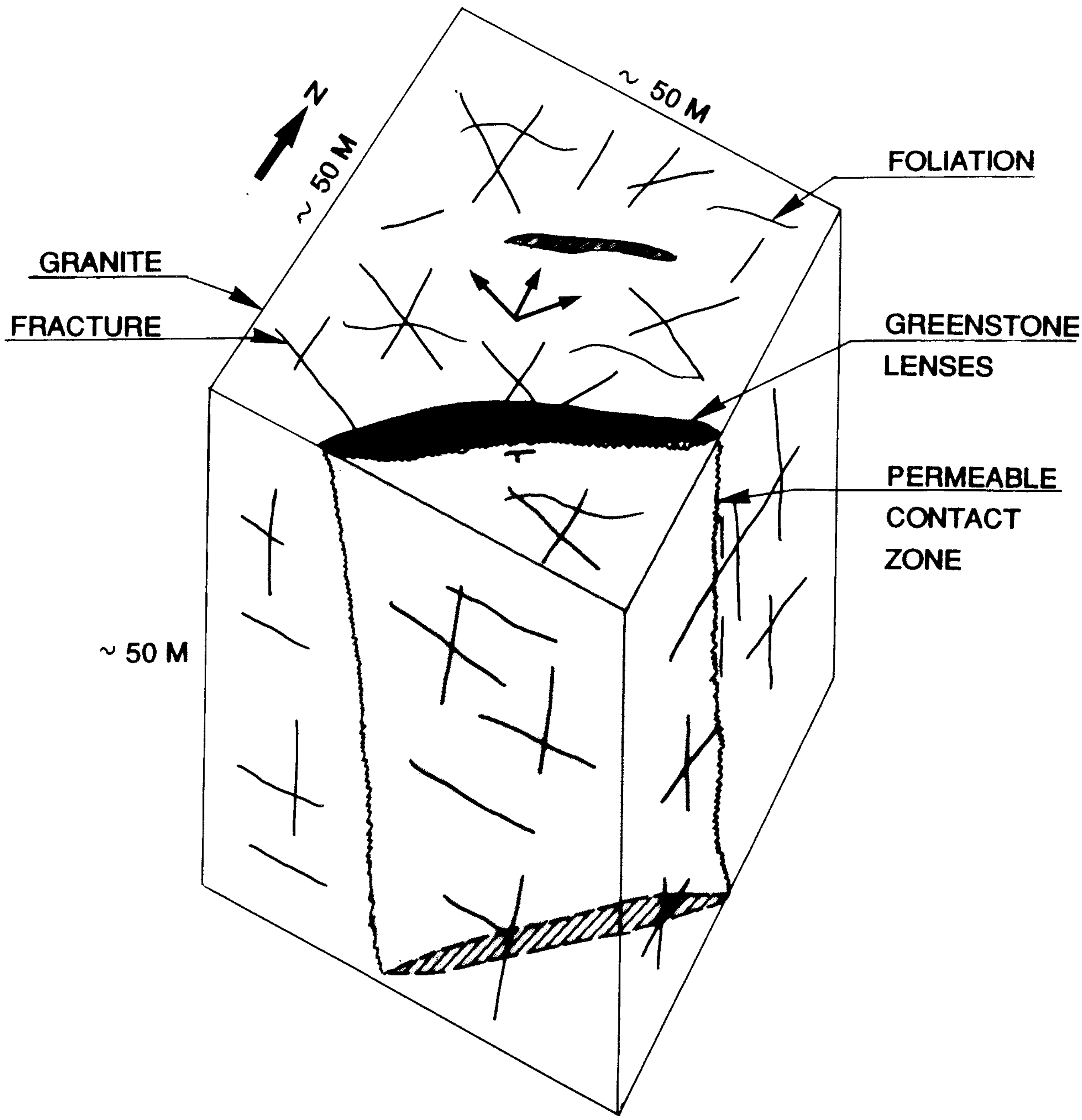
Bedrock: The rock mass in this zone is typically inhomogeneous, with strongly foliated medium-grained porphyritic granite and greenstone in the form of lenses and xenoliths, as the predominant rocks. Narrow dykes of fine-grained granite trending ENE, often highly fractured, intersect the rock mass.

The fracture density is estimated to be very high and the fracture lengths are probably about 0.50 m. Predominant sets of fractures are WNW, NW, NS and NE.

Calcite, epidote, chlorite and clay minerals are the most common fracture infillings.

The rock mass in this zone is expected to be split up into small triangular or rectangular blocks, mostly less than 0.5 m^3.

GEOLOGICAL MODEL IN DETAILED SCALE



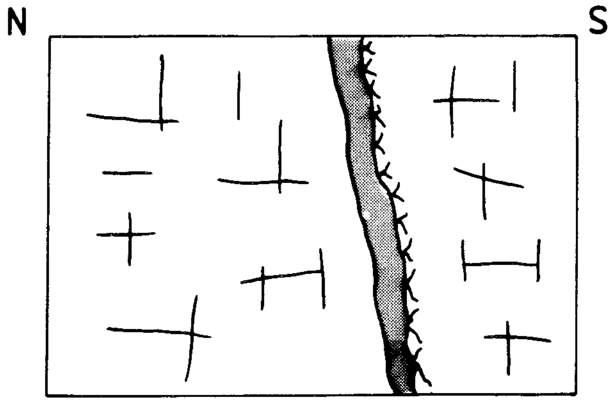


Fig. 2.25 Block c. Rock in the Småland granite with greenstone lenses.

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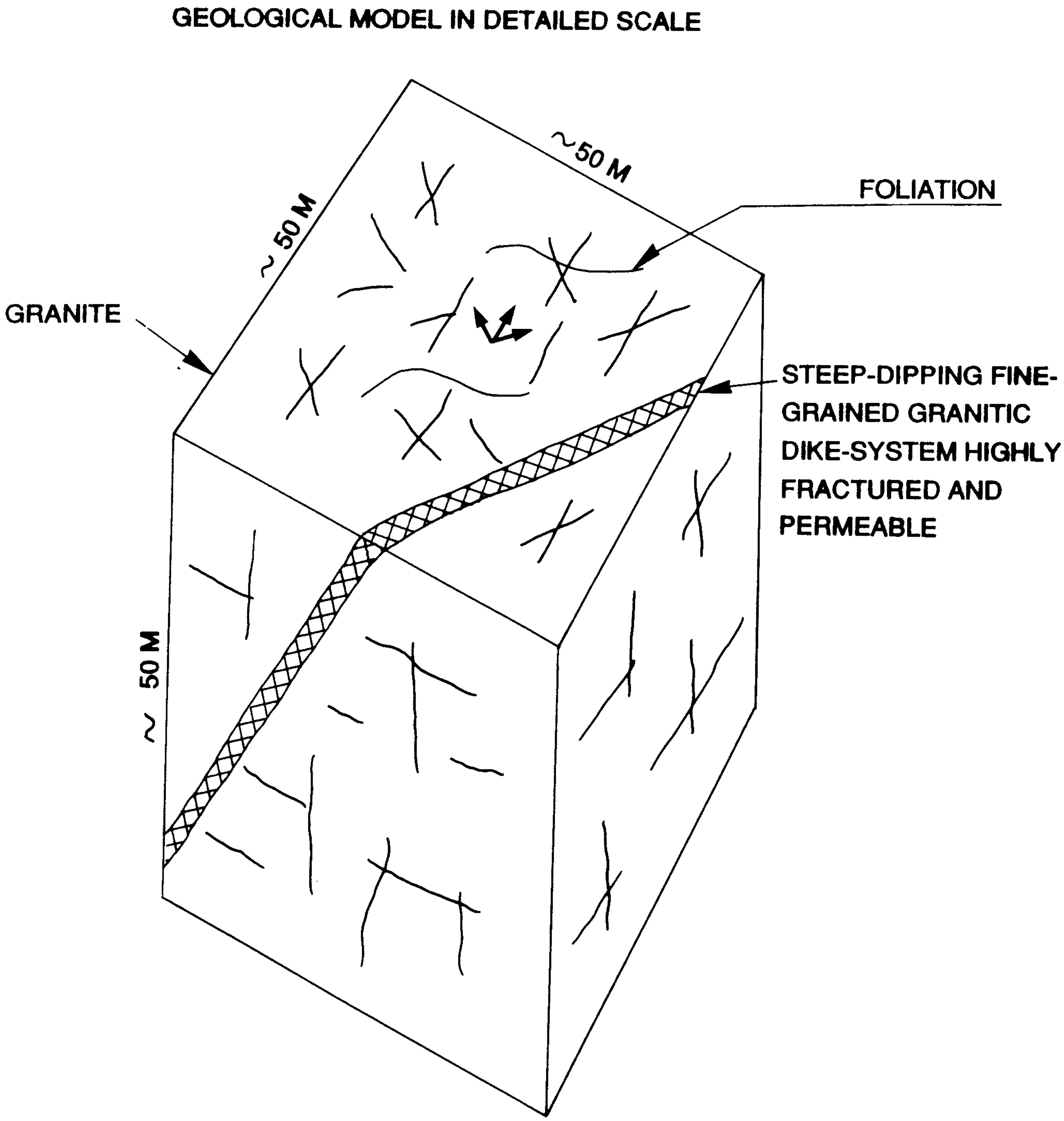

Fig. 2.26 Block d. Rock in the Småland granite with dykes of fine-grained granite.

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Permeability: The permeability of this rock mass is of course highly influenced by the complex bedrock situation. Highly fractured or partly crushed contact zones between greenstone and granite are probably tight or of low permeability. Fractured dykes of fine-grained granite may be more permeable.

2.3 BOREHOLE SITING

During the investigations in 1987 drilling was performed at different stages in the areas of Ävrö, Äspö and Laxemar. For reasons not connected with the Rock Laboratory Ävrö was excluded from the target areas and the investigations proceeded in Äspö and Laxemar.

Furthermore, the siting of boreholes in investigation programme 2 was carried out on the basis of data collected during 1987. A short motivation for the siting of all boreholes in programme 1 and programme 2 phase 1 at Äspö and Laxemar is given below.

2.3.1 Percussion boreholes at Äspö, first batch

The aim of these boreholes was to obtain preliminary information on the bedrock composition and the hydraulic properties of the shallow portion of the bedrock.

Preliminary interpretations on existing rocks, geophysical measurements, fracture mapping and lineaments were available at this stage. These investigations were later reported by Kornfält and Wikman (1987), Stenberg (1987), Ericsson (1987) and Tirén et al (1988 a and 1988 b). Greatest importance was at this stage attached to the structural analysis as shown in Fig. 2.21. The motivations for the percussion boreholes HAS 01-07 are as follows:

HAS 01: The junction of several lineaments at the central part of Äspö. The borehole is situated in a major geophysical anomaly that crosses the mylonite zone.

HAS 02: A prominent NW-SE block boundary crossed by a lower order E-W lineament.

HAS 03: A prominent NE-SW block boundary coinciding with the mylonite zone.

HAS 04: Junction of several block boundaries corresponding to geophysical zones.

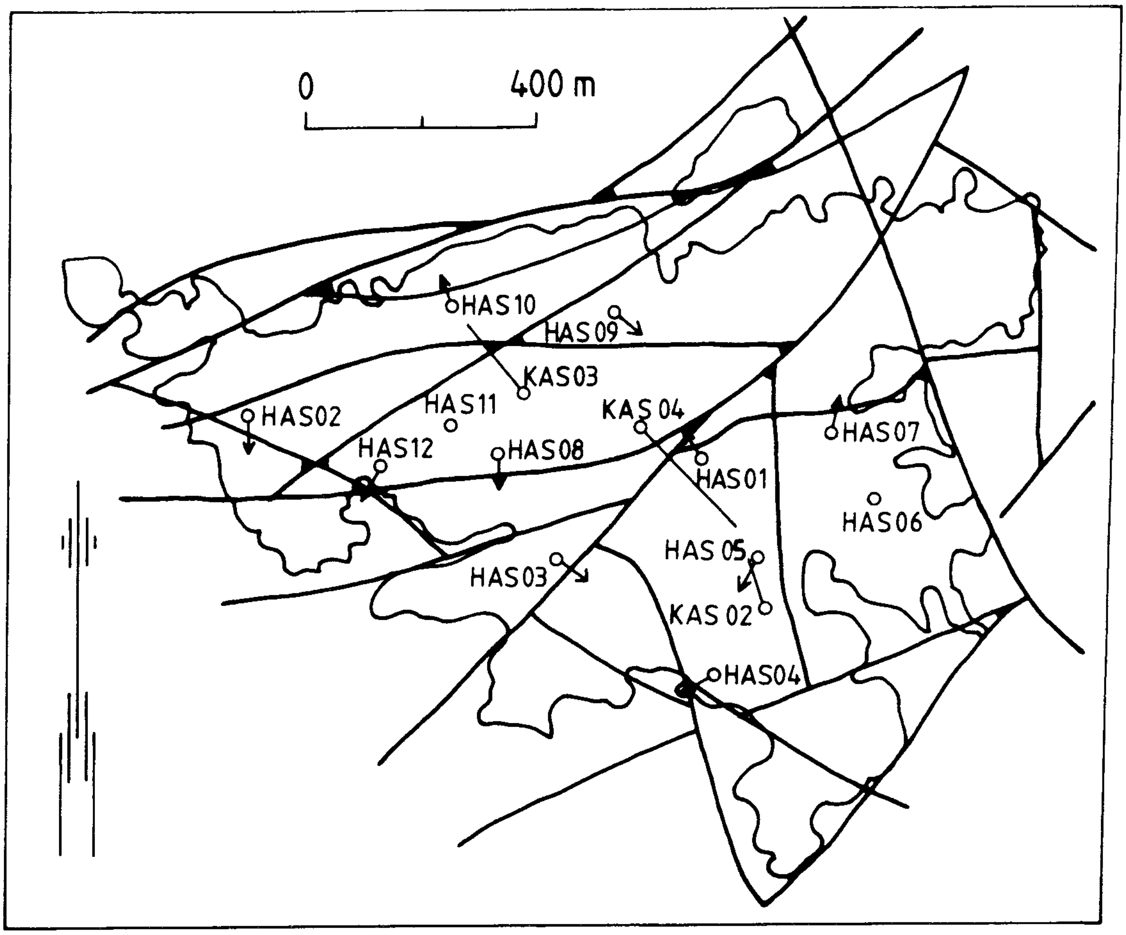

Fig. 2.27 Boreholes on Äspö. Fourth order block boundaries from Tirén et al (1988 a).

HAS 05: Reference hole in a block away from boundaries and geophysical indications.

HAS 06: Reference hole in a block away from boundaries and geophysical indications.

HAS 07: An E-W block boundary close to or within the geophysical indication of the mylonite zone.

2.3.2 Core boreholes KAS 02 and KAS 03

These boreholes were sited in a preliminary geological and geohydrological model of Äspö, the final version of which is given in Chapters 2.2 and 3.2.

At an early stage of the investigation it was found that Äspö consisted of two comparatively undisturbed blocks separated by a major tectonic zone. The core boreholes were sited in the central parts of these blocks.

KAS 02: A sub-vertical borehole to approximately 1 000 m in the central part of the SE block. It was originally called KAS 01 but this first hole was abandoned due to drilling difficulties.

Kas 03: A sub-vertical borehole to approximately 1 000 m in the central part of the NW block.

2.3.3 Percussion boreholes at Äspö, second batch

These boreholes were sited in order to obtain the boundaries of a sub-block around KAS 02. At this stage of the investigation a refraction seismic survey of Äspö (Sundin, 1988), was also available.

HAS 08: Block boundary of high order. Magnetic indication.

HAS 09: Seismic low-velocity zone. Block boundary of low order.

HAS 10: Block boundary of high order.

HAS 11: Reference hole of a block away from boundaries and geophysical indications.

HAS 12: Seismic low-velocity zone. Block boundary. Magnetic indication.

2.3.4 Core borehole KAS 4

An inclined borehole across the mylonite zone. The zone is indicated by the surface-geology map, the magnetic measurements and the seismic profiles.

2.3.5 Percussion boreholes in the Laxemar area

The aim of the boreholes was to obtain preliminary information on the bedrock composition and the hydraulic properties of the shallow portion of the bedrock.

At this stage of the investigation a preliminary, detailed geological map, fracture mappings, lineament analyses and some VLF-profile measurements were available.

HLX 01: A junction of several block boundaries. VLF-indication.

HLX 02: Prominent block boundary.

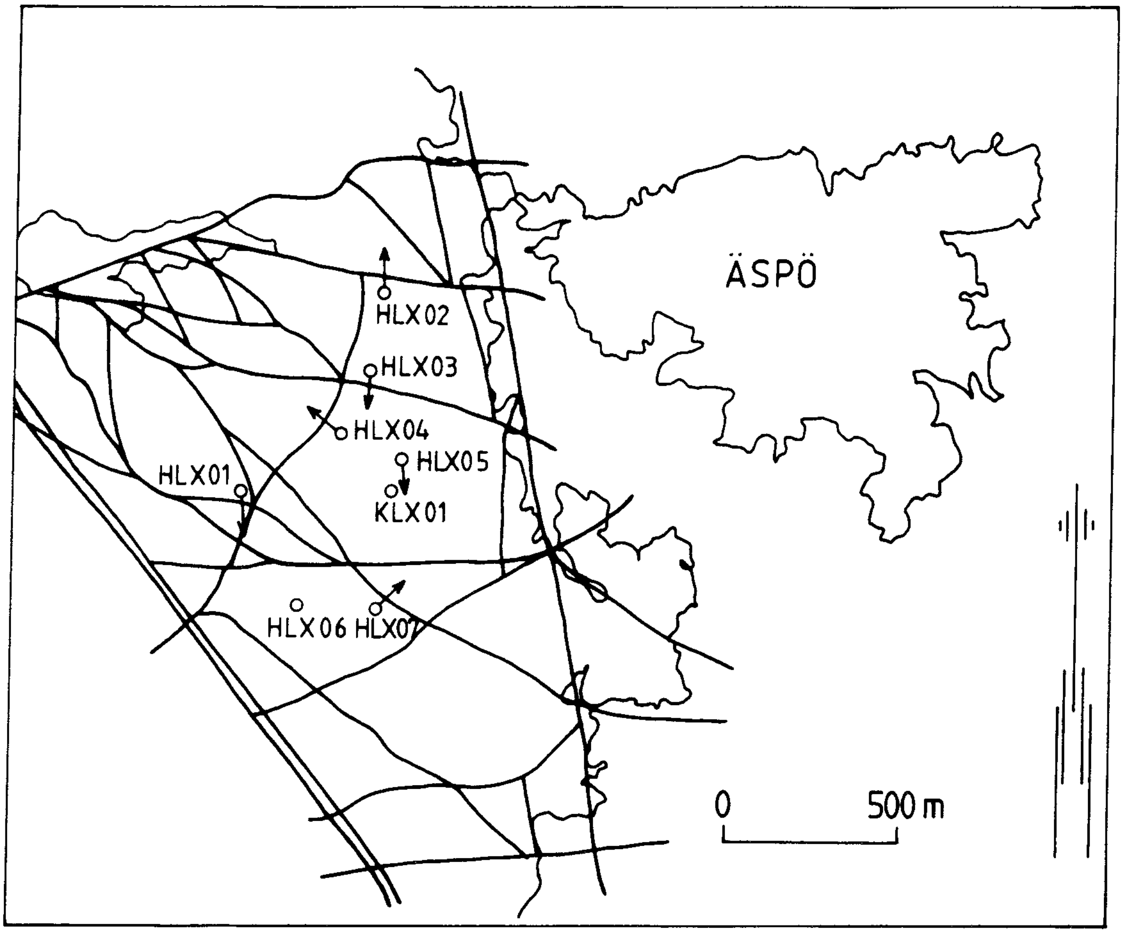

Fig 2.28 Boreholes at Laxemar. Fourth order block boundaries from Tirén et al (1986).

HLX 03: Block boundary. VLF indication.

HLX 04: Block boundary. VLF indication.

HLX 05: Reference hole in a block away from boundaries and geophysical indications.

HLX 06: Reference hole in a block away from boundaries and geophysical indications.

HLX 07: Block boundary. VLF indication.

2.3.6 Core borehole KLX 01

The borehole is sited in the central part of a major block. The borehole is sub-vertical and 700 m deep.

3 GEOHYDROLOGY

The geohydrological information from the Simpevarp area and its surroundings was partly gained from existing data and earlier work. In addition to this, geohydrological studies were performed during 1987. The following contains a short summary of the studies performed and their results, followed by conceptual models of the regional geohydrology, the geohydrology of the Äspö and Laxemar areas, and block scale models of certain rock types.

3.1 GEOHYDROLOGICAL STUDIES

3.1.1 Hydrological conditions in the Simpevarp area

The hydrological conditions in the Simpevarp area is reported by Svensson (1987).

The area is situated on the eastern coast of southern Sweden. Despite the coastal position the climate is due to the prevailing westerly winds, which are comparatively dry with a total precipitation of 650 to 700 mm/a.

The average temperature in Oskarshamn is 6.4°C, with February as the coldest month, -2.9°C, and July as the warmest, 16.2°C.

Of the annual precipitation, about 125 mm/a falls as snow and the durability of the snow cover is on average 91 days.

The total evapotranspiration is calculated to be somewhat less than 500 mm/year, leaving a runoff of somewhat more than 150 mm/year.

In the region around Simpevarp there are two major catchment areas, Virboån (Q_m = 3.6m^3/s) and Marströmmen (Q_m =2.9 m^3/s) and some small streams like Gerseboån and Laxemarån. See figure 1.1. The lake area comprises 7-12 % of the catchment areas for all streams except Laxemarån which has only 1.2 % of lakes.

The groundwater levels in the area are at maximum in the spring, at the snow melt-period. At a distance from the coast winter minimum levels may occur, but the annual absolute minimum is the summer one. The annual recharge has been estimated to be 128 to 218 mm/a in pervious ground.

3.1.2 Regional Well Data Analysis

Data from a great number of water wells in the region around Simpevarp are stored in the Well and Bore hole records of the Swedish Geological Survey. Several geological studies mentioned earlier such as geological mapping, geophysics and structural geology permit correlation with the geohydrological data from the different boreholes. A study of this kind is performed by Liedholm (1987).

The area studied is the same as the one covered by the regional map of the bedrock geology. Within this area 162 wells in bedrock are registered in the Well Records.

In the study the specific capacity, Q/s_w, was used as a significant measure of the transmissivity of the upper part of the bedrock. In different statistical analyses the specific capacity is then correlated to rock type, fracture frequency, geophysical structures and other relevant factors.

In the area studied the coarse-grained granites of Götemar-Uthammar type have the greatest specific capacity. The tonalite and medium-grained grey gneissic granite have a somewhat lower specific capacity than the average. Least pervious are the greenstones of the area.

The data follow lognormal distributions and it is found that the spread of the data is greater for lower median specific capacity. The data for the greenstones are, however, an exception in which a small specific capacity coincides with a moderate spread.

An analysis of the specific capacity of different sub-areas has shown that the most pervious rock is to be found in an area directly west of Simpevarp. This can also be correlated to an area of the bedrock with low magnetisation levels and the occurrence of radial fracture systems, possibly indicating a granite diapir not penetrating to the surface.

Except for the above no significant correlations to terrain features have been found. A correlation to the fracture mapping has indicated that structures striking NE-SW and to some extent NW-SE are associated with a high specific capacity.

3.1.3 Geohydrological data from the Simpevarp Area

Geohydrological data from the Simpevarp peninsula and the island of Ävrö were analysed by Rhén (1987).

During pre-investigations and construction of the power plants and CLAB at the Simpevarp peninsula, geohydrological information was produced. On the island of Ävrö immediately east of the Simpevarp peninsula preliminary investigations were performed within SKB's fracture zone project (Gentzschein et al, 1987).

All data from the area show that the fracture system is dominated by two dominating sets striking N60-70°E and N30-40°W. The foliation and dykes of aplite strike in the sector NE-E.

The hydraulic conductivity of the rock was analyzed from a large number of tests performed in investigation boreholes for the power plants, the tunnel for cooling water for OIII, the CLAB and in the investigation boreholes at Ävrö. See Fig. 1.1. Conductivity distributions for the Simpevarp peninsula are shown in Fig. 3.1. On Ävrö there is an evident tendency of a decreasing conductivity with depth, interrupted, however, by a fracture zone in the eastern part of the island. In the upper 300 m the conductivity is in the range of K = 10^{-8} - 10^{-7} m/s. In the Simpevarp peninsula the conductivity is in the range of K = 10^{-9} - 3 · 10^{-8} m/s. This lower value may be caused by the occurrence of volcanites.

The groundwater level was found to be 8-10 m below ground level. Measurements made near the existing facilities show that these only have a small influence on the level variations.

3.1.4 Hydraulic tests at Ävrö, Äspö and Laxemar

In the percussion boreholes at Ävrö, Äspö and Laxemar build-up and interference tests were performed. Data from these tests were evaluated by Nilsson (1987, 1988). From the preliminary data obtained a direct comparison with the data from the Well Records of the Geological Survey can be made (see Fig. 3.2).

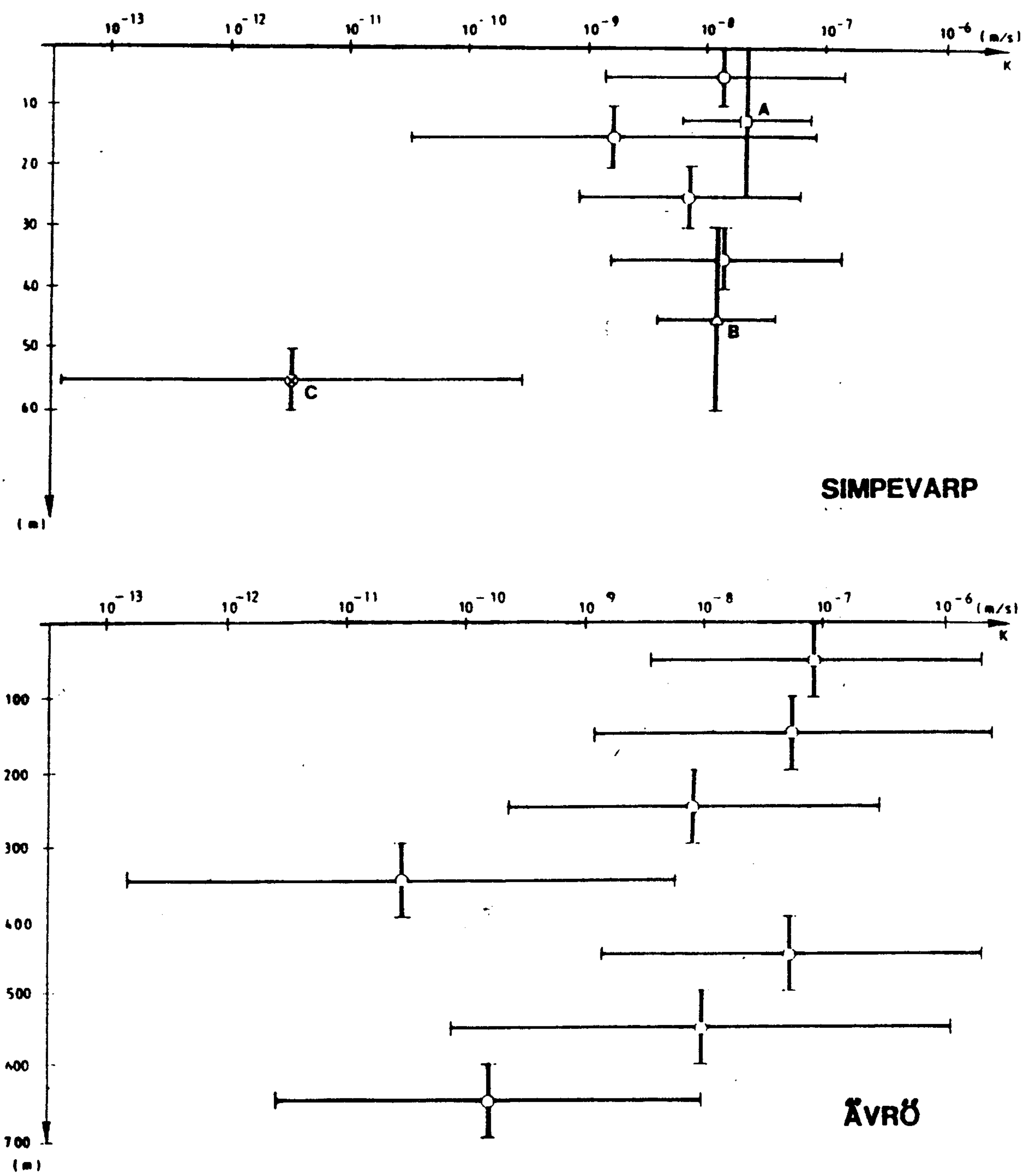

Fig. 3.1 Hydraulic conductivity (K) for the Simpevarp peninsula and Ävrö. The median value and ± one standard deviation are shown for different depth intervals.
K is calculated from:
A: Specific capacity
B, C: Single-packer injection tests
The rest: Mainly double-packer injection tests (Rhén, 1987)

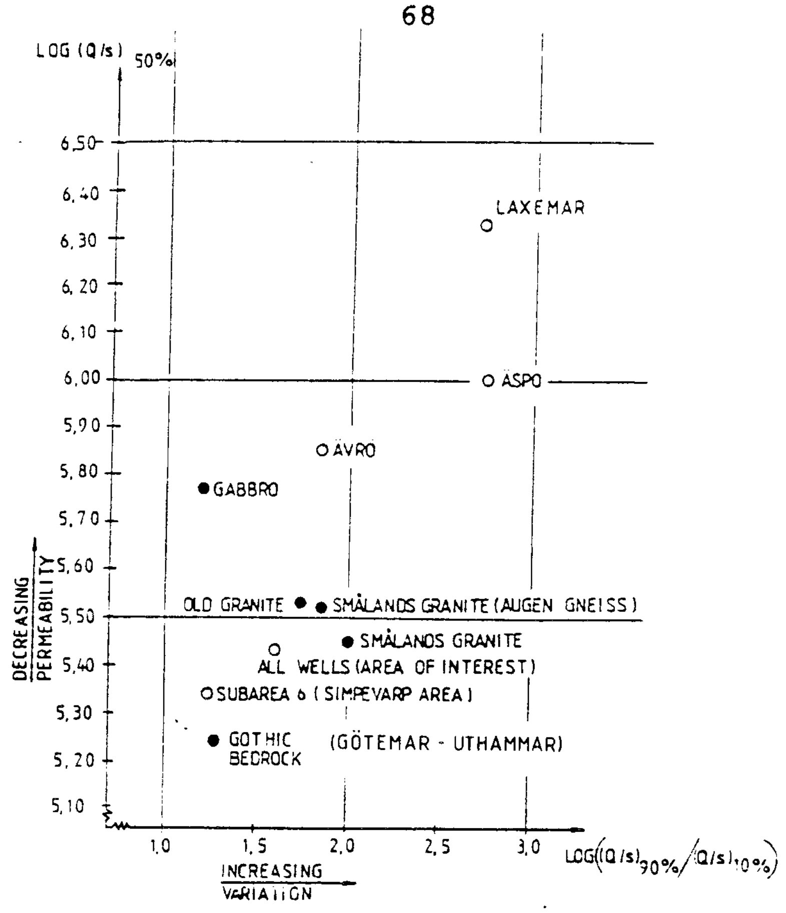

Fig 3.2 **Bedrock-related median and variation of specific capacity, Q/s (Nilsson, 1988).**

Thus, data show that the medians of the specific capacities for the areas studied are lower than what is normal for the different rock types. The figure also shows that the variation in the data for the three areas increases with decreasing specific capacity as was stated in Section 3.1.2.

Interference pumping tests were performed in the boreholes with higher yields. Analyses of these data have shown transmissivities as high as $T = 2.2 \cdot 10^{-4}$ m^2/s on Ävrö, $T = 3.3 \cdot 10^{-4}$ m^2/s at Äspö and $T = 9.0 \cdot 10^{-5}$ m^2/s at Laxemar. These are values that exceed the corresponding median specific capacities shown in Fig. 3.2 by one or two orders of magnitude.

Hydraulic interference with other boreholes occurred in all four tests at Ävrö, in one test at Äspö and in one test at Laxemar. However strict interference within the same conductor was only shown in the fracture zone in the eastern part of Ävrö (HAv3) and in one test in the Laxemar area (HLx1). Although no complete set of observation boreholes exists some conclusions on the direction of the conductive structures can be drawn, since interference occurred mainly in the NW-SE and NE-SW directions. This is probably caused by the major fracture sets found to run roughly in these directions in the whole area, but also on Äspö by the foliation and the direction of greenstone bodies in the rock.

Fig. 3.3 shows a cross plot of ground and groundwater levels of Ävrö and Äspö. As shown the groundwater level is very influenced by the topography. However, some boreholes differ such as HAv3 and HAs2, with levels very close to sea level. In both this cases the boreholes have a high transmissivity and contain saline water. Pumping tests indicate a fracture zone in contact with the sea.

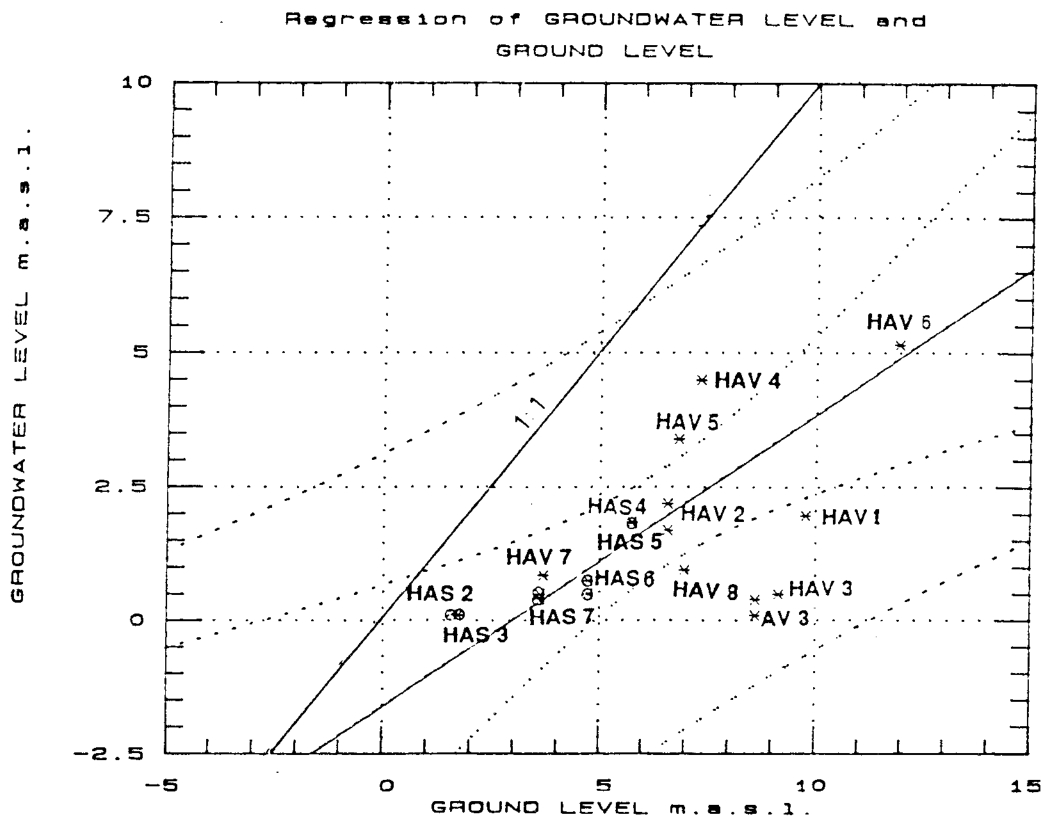

Fig. 3.3 Cross plot of groundwater level and ground level from Ävrö and Äspö.

3.1.5 Generic modelling of the SKB Hard Rock Laboratory

Generic modelling of two possible layouts for the Swedish Hardrock Laboratory was performed using the analytical element method (Axelsson 1987).

The two layouts chosen were a double shaft down to a depth of 500 m and a spiral ramp down to 331 m. The study was performed under the simplified assumptions of a homogeneous bedrock and a constant head at ground level.

All calculations were made using the hydraulic conductivity as base unit, making it easy to convert calculated flows to real values when the parametres become known. The calculated potentials are, however, directly applicable.

The drawdown during the construction period was simulated by a series of steady state models for different stages.

The calculations show that the radius of influence around the shafts will be approximately 1 900 m in the final stage and will probably be of the same magnitude for the ramp design, (see Fig. 3.4).

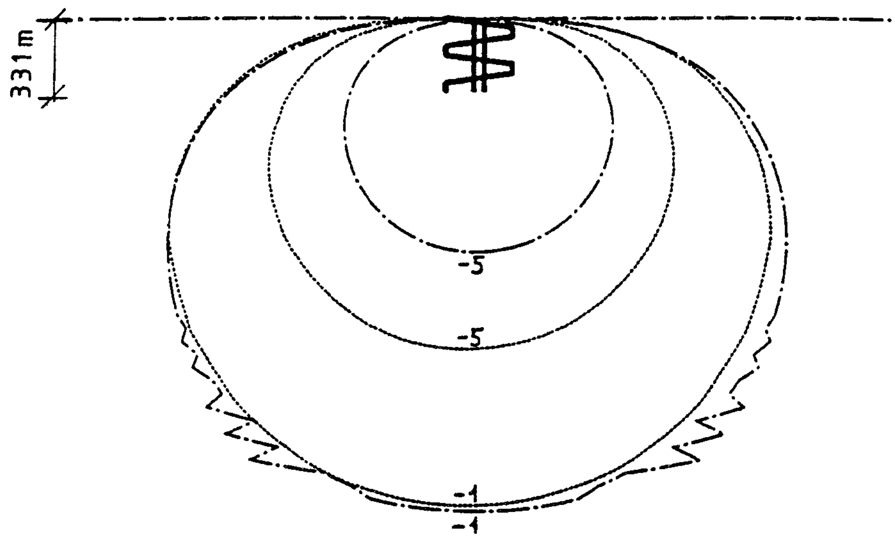

Fig. 3.4 Comparison of the radii of influence for the shaft (-·-·-·-) and the spiral (·······) layout. Figures indicate drawdown in metres.

For a homogeneous bedrock the inflow will increase rather drastically with depth. However, a more realistic assumption of a conductivity that decreases with depth as shown by Rhén (1987) reduces the total inflow to about 1/4 of the amount calculated using homogeneous conductivity.

3.2 CONCEPTUAL MODELS OF THE GEOHYDROLOGY OF THE SIMPEVARP AREA

In this study conceptual models of the geohydrology of the Simpevarp peninsula are put forward on three different scales i.e.:

Regional scale	(approx. 5 000 m x 5 000 m)
Site scale	(approx. 500 m x 500 m)
Detailed scale	(approx. 50 m x 50 m)

In this approach basically the same units are used and described as in the geological models. It is also understood that the conceptual models rather put forward the general, and as we see them, the important features rather than the details and the exceptions.

It should also be observed that values of hydraulic parametres etc. are estimates based on investigations and data from a large area. This means that they must be seen in a framework in which succesive investigations leads to refinements in accuracy and spatial variation.

The conceptual models are thus based partly on stated facts, partly on deduced analogies and on some professional judgement. They can thus be seen as the investigators' principal points of view at this stage of the investigation.

3.2.1 A conceptual regional model

The area covered by the geohydrological model may be roughly defined as the area between the Götemar and Uthammar granites as shown in Fig. 2.4. The western part of the area consists of the Swedish mainland and the eastern part of the archipelago in the Baltic with islands and peninsulas, of which the Simpevarp peninsula is one.

a) Surface hydrology and groundwater recharge

The western part of the area is dominated by small watersheds, of which Laxemarån covers the largest area, giving a mean flow of 0.24 m^3/s. A precipitation, P, of 675 mm/s and a calculated evapotranspiration, E, of 490 mm/a gives a surplus of P-E = 185 mm to be distributed as groundwater recharge and runoff.

The small runoff basins, however, imply that the terrain may be subdivided into a mosaic of in and outflow areas thereby giving a small average annual recharge as long as the groundwater is not utilized or drained to an underground utility.

The main recharge, however, takes place in conjunction with the melting of snow thereby giving a maximum level in the spring and a minimum in the late summer.

b) Hydraulic conductivity of different rock units

The area consists basically of four different types of rock: Småland Granite, Tonalite, Greenstone, and Götemar-Uthammar Granite (Kornfält & Wikman, 1987). Well data from these were analysed in the Regional Well Data Analysis (Liedholm, 1987).

A median specific capacity was calculated for every rock type, that can be considered as a characteristic value for the conductivity of each rock type.

The specific capacity, Q/s, is normally proportional to the transmissivity, T. For wells with a moderate drawdown the coefficient of proportionality is in the range of 1 to 2, but for a well in a fractured bedrock that can be almost emptied by air-lift pumping it can be considerably higher. A regression analysis for the pumped wells at Ävrö, Äspö and Laxemar (Nilsson, 1988) gave the result:

$$T_{50} = 6.02(Q/s)_{50} \qquad (3.1)$$

Data from the area shows that there is a decrease in hydraulic conductivity with depth (Rhén, 1987). A simple regression analysis of data from Ävrö (HAv1, Gentzschein et al, 1987) with an exponential decrease gives the model

$$K_{50} = K_o \cdot \exp(-Z/L) = 2.23 \cdot 10^{-8} \exp(-Z/205) \qquad (3.2)$$

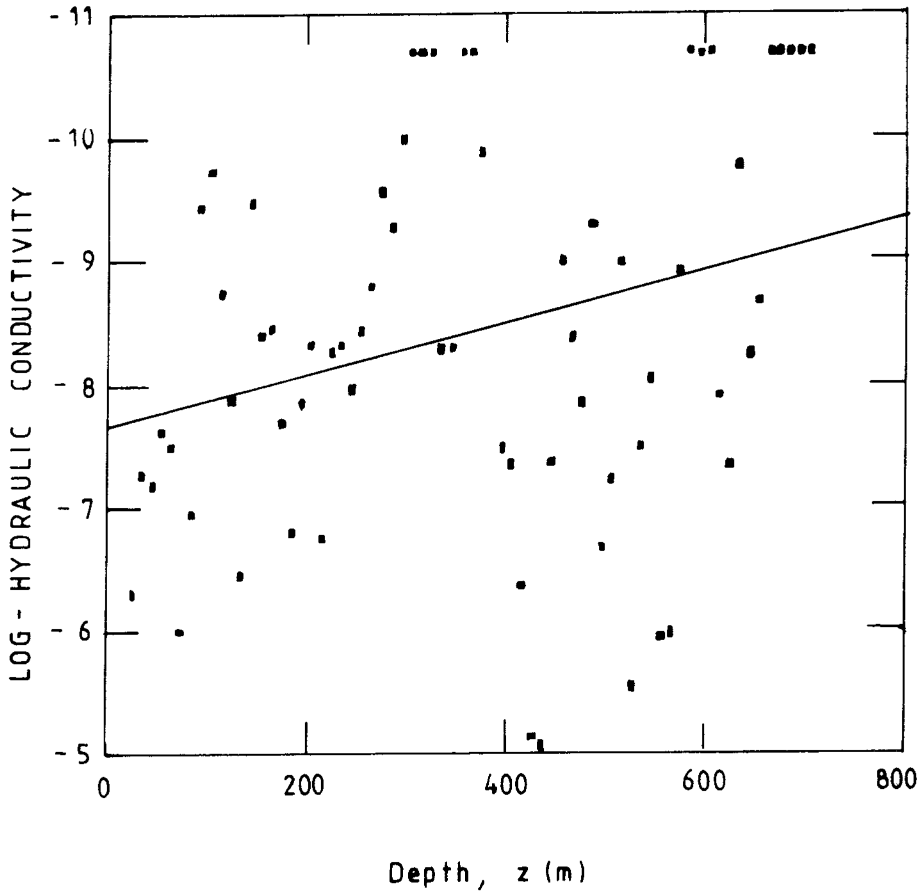

Fig. 3.5 Conductivity measurements in Av1.

Furthermore, it can be shown that for a slim well the transmissivity obtained is close to the integral of the conductivity over the well depth, d, or:

$$T = K_o \cdot L(1 - \exp(-d/L)) \quad (3.3)$$

This makes it possible to calculate the most probable hydraulic conductivities at the surface for the different rock types if the well depths are known. In this calculation, as a first assumption, the decrease in the conductivity is taken as being the same as for the data from HAv1. This means that the median hydraulic conductivity at the surface for the above rock types can be estimated to be as shown in Table 3.1.

Table 3.1 Hydraulic conductivity of different rock types

Rock type	Småland granite	Tonalite	Greenstone	Götemar-Uthammar granite
Median specific capacity $(Q/s)_{50}$ (m^2/s)	$2.6 \cdot 10^{-6}$	$1.6 \cdot 10^{-6}$	$1.3 \cdot 10^{-6}$	$9.8 \cdot 10^{-6}$
Transmissivity T_{50} (m^2/s)	$1.6 \cdot 10^{-5}$	$9.5 \cdot 10^{-6}$	$8.1 \cdot 10^{-6}$	$5.9 \cdot 10^{-5}$
K_o (m^2/s) $(d_m = 60$ m)	$3.0 \cdot 10^{-7}$	$1.8 \cdot 10^{-7}$	$1.6 \cdot 10^{-7}$	$1.1 \cdot 10^{-6}$

Thus, it can be seen that there is a significant difference between the probable hydraulic conductivity at shallow depth for the different rock types.

It should also be noted that the variability of data is very great, (ses Fig. 3.2).

c) Conductive structures

From the terrain analysis and geophysical investigations several structures have been found and interpreted as fracture zones.

A first order pattern of N-S and E-W zones is shown in Fig. 2.9 together with a second order pattern of NW-SE and NE-SW zones.

In the Regional Well Data Analysis (Liedholm, 1987) attemps were made to correlate the specific capacity of the wells to major tectonic structures. In this study many kinds of correlation were tried but very few found to be significant. A slight tendency towards higher capacities along NW-SE and NE-SW structures were found rather than in the N-S and E-W system.

This complies with data from the pumping tests (Nilsson, 1987, Nilsson, 1988), in which interference has been observed in the former directions rather than in the latter. Data show, however, that the NW-SE and NE-SW zones are not always conductive but that the very local structural conditions determine the conductivity.

In Ävrö a moderately-dipping fracture zone was localized. Thus, zones of this type may occur in the area.

On the regional scale, however, no fracture zones seem to be large enough to dominate the geohydrological conditions.

d) Piezometric levels

Data from the investigations (Rhén, 1987, Nilsson, 1988) showed that the groundwater level is closely related to the ground level, (See Fig. 3.6).

ÄVRÖ, ÄSPÖ AND LAXEMAR

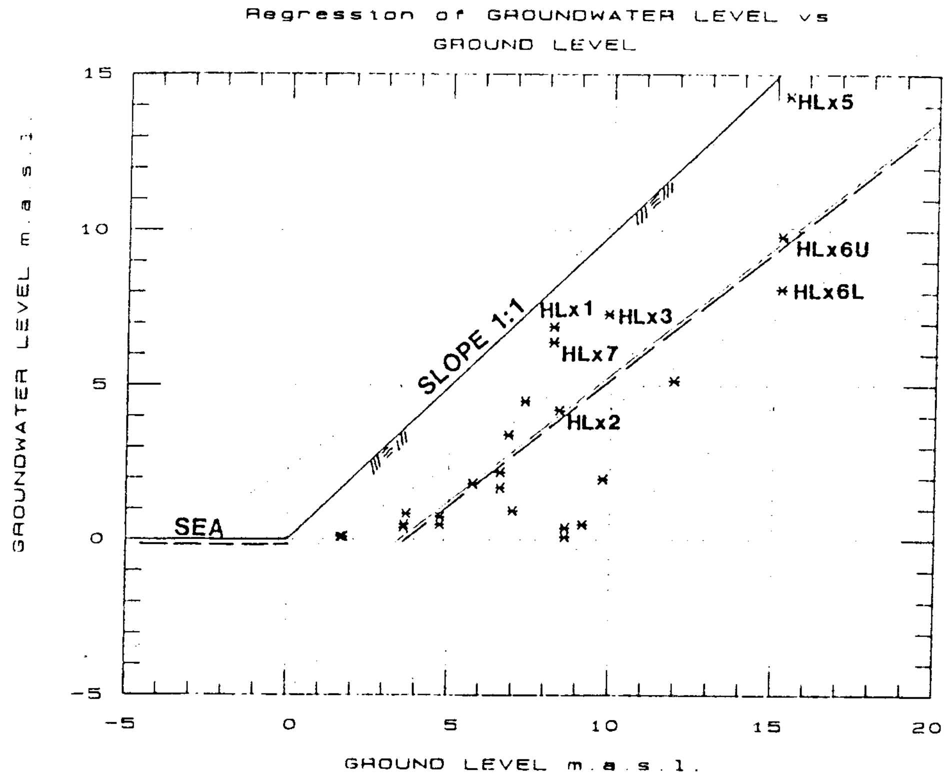

Fig. 3.6 Cross plot of groundwater levels and ground levels from Ävrö, Äspö and Laxemar.

Exceptions are some boreholes situated in conductive structures on Ävrö and Äspö. In these the level is very close to the sea level, and pumping tests indicated that the structures are in contact with the sea. The water in these structures is, however, more saline than the water in the Baltic indicating stagnant water at depth. The depth and shape of the interface are, however, still not known.

e) Model geometry

The most significant differences found so far have been between the different rock types of the area. No tectonic zone has so far been found to be significant to the geohydrology on the regional scale.

Model geometry on the regional scale is therefore defined by the different masses of rock. On a plane the geological map defines the boundaries between the units. In profile for instance the gravity profile can be taken as an outline of the geometry of the different units, (see Fig. 3.7).

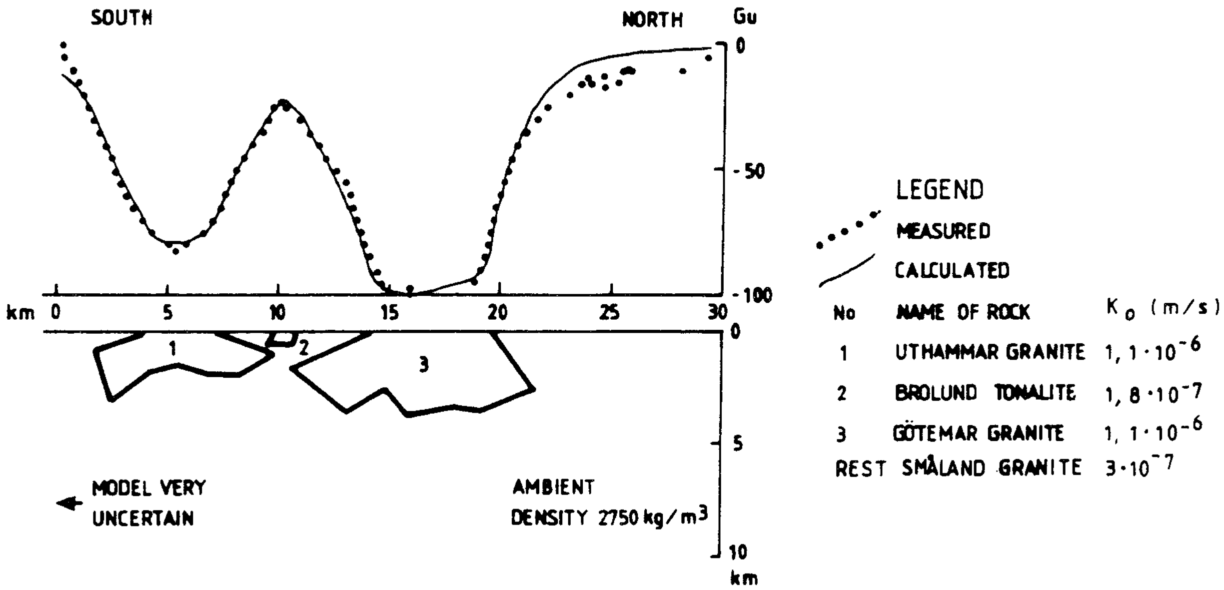

Fig. 3.7 Gravity model from Uthammar to Götemar, identified as hydraulic units (after Nisca, 1987).

The hydraulic units correspond to the different rock types with given hydraulic median conductivities, K_o, at the surface. The decrease in the conductivity with depth is assumed to be one order of magnitude per 473 m for all units.

The groundwater table, h_w, is related to be ground level, h_g, as:

$$h_w = h_g/1.2 \qquad (3.4)$$

Salt groundwater at depth

In some boreholes salt groundwater has been found (Laaksoharju, 1988). The salinity at depth is approximately one percent, thus higher than the salinity of the Baltic Sea. This, together with the chemical composition, indicates that there is stagnant relict sea water at depth. The position of the interface is not known in detail and data indicate that its position depends very much on the conductive structures in the bedrock. The position of the interface must be subject to further investigations.

3.2.2 Conceptual models on the site scale

Specific conceptual models are given on the basis of the results from the regional investigations and the investigations performed in the Laxemar area and on the Äspö site. In these models a general geohydrological description of the areas are given together with different sub-area descriptions as they are defined in Chapter 2.

The Laxemar Area

The Laxemar area can be sub-divided into three different rock types: A more or less homogeneous greenstone (gabbro) in the north, an intermediate zone of alternating Småland granite and gabbro, and, in the south, a more or less homogeneous Småland granite. Since the rock type has shown to be the most significant factor determining the hydraulic properties of the bedrock of the area this sub-division is also used for the geohydrological characterization, see figure 2.15.

Lx-1 The gabbro area south of Frisksjön

The gabbro was found to be very tight in the percussion boreholes in the area. In Fig. 3.2 the median specific capacity is very much governed by this. The median surface conductivity estimated from these data was therefore found to be K_O = $5.8 \cdot 10^{-8}$ m/s, which is a very low value.

In the area several lineaments confirmed by VLF measurements are assumed to be significant fracture zones. However, the boreholes show that they are as tight as the rest of the rock. The reason for this is presumably the fracture fillings.

Lx-2 The transition area from gabbro to Småland granite

South of the gabbro area the bedrock is inhomogeneous, with a Småland granite with large greenstone xenoliths as well as sub-vertical dykes of fine-grained granite. Both the xenoliths and the dykes are generally parallel to the foliation striking E-W to NE-SW.

The area is similar to the SE part of Äspö, described later, from where some more data are available. This means that the xenoliths act as hydraulic barriers giving an over all low median surface conductivity, K_o estimated to be $1.2 \cdot 10^{-7}$ m/s, and a macro conductivity parallel to the foliation.

No boreholes with high specific capacity were found in the major fracture zone crossing the area from NE to SW.

Lx-3 The Småland granite area

In the southern part of the Laxemar area the Småland granite is more homogeneous. The major lineament direction is NW-SE.

The boreholes in this area have a high specific capacity especially if they are sited in these NW-SE lineaments. Pumping tests also revealed an interference along these lineaments. They therefore correspond to distinct sub-vertical fracture zones with a transmissivity in the range of $5 \cdot 10^{-6}$ m^2/s. The median surface conductivity of the area, K_o, is estimated to be the same as for the Småland granite of $3.0 \cdot 10^{-7}$ m/s.

Flat pegmatites and sub-vertical dykes of fine-grained granite may act as conductive zones in the rock.

The island of Äspö, Fig. 2.15b

As shown in Fig. 2.15b the island of Äspö can be sub-divided into three geological units: The NW part of the island dominated by Småland granite, As-1, the SE part of the island with Småland granite and with greenstone xenoliths, As-3, and the border zone in between, consisting of the mylonite zones and the greenstone lenses, As-2. These units also correspond to geohydrological units as described below.

The specific site conceptual model of Äspö must however, also be consistent with the setting given by the regional model. The most striking feature is the pervious Götemar-Uthammar granite that may influence the hydraulic conductivity at depth, by veins of brittle, fractured granite that may have intruded from below. The conceptual model is therefore mainly valid from the surface down to some hundred of metres.

As-1 NW Äspö

In this area only one percussion borehole, HAs2, was drilled in 1987. This borehole has very high transmissivity, T, of 1.3 · 10^{-4} m^2/s, and is probably in contact with the sea.

The area consists, however, of homogeneous Småland granite, and data from the regional analysis are therefore assumed to be valid. This means a median hydraulic conductivity at the surface, K_o, of 3 · 10^{-7} m/s, and a decrease of one order of magnitude per 473 m.

As shown in borehole HAs2 conductive zones are likely to exist. The zones are probably distinct and narrow. Whether there exists a preferred direction of the zones is not clear, but lineaments running in the ENE-WSW and NW-SE directions and with a steep dip are relatively frequent. Gently dipping zones with high conductivity may also occur.

For geological reasons an increased conductivity is to be expected in flat pegmatite veins and in steep dykes of more or less fractured fine-grained granites. These are normally oriented parallel to the foliation in the ENE-WSW direction.

In gently dipping zones in contact with the sea the salinity is high, about 0.9 %, indicating stagnant water below. The position of the boundary between fresh and saline water is not known as in the rest of the area.

As-2, The border zone

Äspö is sub-divided into two parts by a series of valleys and troughs with a main trend running NE-SW. Adjacent to the valleys are bodies of greenstone and some mylonites are found close to the lineament.

The valleys represent a series of steeply dipping fracture zones. Whether the dip is towards the SE or NW is at present not clear. Two boreholes were drilled into the main zone, of which one is tight, HAs1, and one penetrates a very conductive fracture at shallow depth, HAs3. Data from the pumping test however, indicates that conductivity decreases rapidly with depth.

The impression of the border zone is therefore that it may be fractured but fracture fillings makes the fractures moderately permeable.

As-3, SE Äspö

Southeast of the border zone there are bodies of greenstone and greenstone xenoliths in the Småland granite. The strike of these seems to comply with the general direction of the foliation.

The greenstone affects the hydraulic conditions in two ways. Firstly, the greenstone bodies give the rock a banded structure on the macro scale, with alternating greenstone and granite. Since the granite is more pervious it acts as a system of conduits thus giving a macro-conductivity that is greater parallel to the foliation. Whether this is also the case within the granite is not clear.

Secondly, it gives the whole area a low median hydraulic conductivity, (see Fig. 3.2). The median specific capacity of the Äspö boreholes gives a hydraulic conductivity, K_O, of $1.2 \cdot 10^{-7}$ m/s at the surface, calculated with the same rate of decrease with depth as earlier.

Flat pegmatite veins and steeply dipping fine-grained granite dykes may occur as conductive zones, as in As-1.

3.2.3 Conceptual models on the detailed scale

Chapter 2 contains rock mass descriptions of blocks of different rocks in different areas. From a geohydrological point of view these blocks can be seen as basic elements, irrespective of the areas in which they are situated. Fig. 2.23 to 2.26 show block diagrams of these rocks. Apart from these two types of fracture zone element are also given.

Block a - Greenstone, (Fig. 2.23)

Greenstone (gabbroid or amphibolitic) as in the northern part of the Laxemar area or the Äspö greenstone bodies.

The rock has a high fracture frequency but the fractures are short. Fracture fillings give mostly tight fractures. There is some conductivity in granitic veins and dykes.

The estimated gross conductivity, K, is $5 \cdot 10^{-8} \cdot \exp(-Z/205)$ m/s.

From inside a tunnel this rock appears dry with some moisture in the leucocratic veins.

Block b - Småland granite, (Fig 2.24)

Småland granite as in the southern part of the Laxemar area and the northwestern part of Äspö.

The fracture frequency is moderate but the fractures are long and relatively open. Increased conductivity occurs in granite veins and dykes.

The estimated gross conductivity,K, is $3.0 \cdot 10^{-7} \cdot \exp(-Z/205)$ m/s.

From inside a tunnel this rock appears moderately wet. Inflows and drops of moisture occurs as point flows along horizontal fractures and fracture intersections. More than 50 % of the inflow is in the bottom area.

Block c - Småland granite with greenstone lenses, (Fig. 2.25)

Småland granite with greenstone xenoliths, as in the central area of Laxemar and the southeastern part of Äspö.

The fracture frequency is moderate in general but increases in the granite in the contact zone with the greenstone lenses. The lenses follow the foliation and act as barriers between the more pervious granite areas. This gives a gross anisotropy to the rock. Because of the influence of the greenstone the fractures are filled and sealed, giving a moderate to low overall permeability.

The estimated gross conductivity, K_o, is $1.2 \cdot 10^{-7} \cdot \exp(-Z/250)$ m/s.

From inside a tunnel this rock appears as dry to moderately wet. Drops of moisture occur in the fractured granitic contacts with the greenstone and some inflows in fractured granitic veins and dykes.

Block d - Conductive single fracture, (Fig. 2.26)

Conductive single open fractures, as in borehole HAs2.

This type of fracture zone consists of one or a few interconnected open fractures. It contains very little rock debris and is very conductive. The zones may vary from gently dipping to vertical.

The transmissivity of the zone, T, is 10^{-5} - 10^{-4} m^2/s.

The zone occurs as one or a few fractures that give water as point inflows. Sub-vertical zones of this type may be obscured by the fact that most of the inflow takes place in the tunnel floor.

Block e - Fracture zones

Major fracture zones like the zone that divides Äspö in two parts.

This type of fracture zone consists of large portions of crushed rock varying in thickness from some metres to some tens of metres. Some zones of this type are mapped as mylonites in the geological maps. During the fracturing mineral changes took place that have filled most of the fracture space. This means that the zone is normally moderately permeable but more permeable parts may occur. The dip of this type of zone may be from sub-horizontal to vertical.

The transmissivity of the zone, T, is 0 - 10^{-4} m^2/s.

This zone occurs in the tunnel as a heavy fractured section causing stability problems unless reinforced. Mineral alterations may have resulted in clay in the zone. Moderate flows of water and drops of moisture are the rule but locally heavy flows may occur in some places causing erosion problems.

4 CHEMISTRY

The chemistry of the groundwater reflects the chemical conditions of the rock mass as well as the hydrological conditions. The types of reaction that determine the chemical composition are dictated by the type of rock minerals that have interacted with the groundwater. The concentration of the species dissolved in the water, on the other hand, is determined by the time the water has been in contact with the rock minerals, i.e. by the hydrological conditions. It should therefore be possible to define the geological, geohydrological or chemical conditons on the basis of knowledge of two of the three conditions.

The boundary conditions for the type of exercise sketched above are extremely difficult to define. For the chemical conditions, however, the chemistry of the infiltrating water will set the boundary conditions and in the case of the Simpevarp area this is fairly simple since there are only two different types of infiltrating groundwater. One is precipitation and the other one is instrusion of sea water. As the chemistry of these two types of water is very different there is a good possibility of finding groundwater flow paths on the basis of the chemical composition of the groundwater.

4.1 CHEMICAL STUDIES

4.1.1 Well Water Analysis

Existing data from chemical analyses of well water in Kalmar County have been compiled and evaluated statistically by Liedholm (1987). The material consists of results from 86 well water analyses. Both saline and non-saline waters were included in the study. The maximum and minimum values of the main element concentrations are given in Table 4.1.

The results of the statistical evaluation point to the fact that it is difficult to find statistically defined correlations between the bedrock type, groundwater composition or any other non-chemical parameter. The most firm correlations found by Liedholm are:

* The chloride concentration is high in wells with a high capacity, indicating that highly conducting parts are normally connected with bedrock sections that contain sea water.

* The chloride concentration in the water is higher in wells which lie close to the coast.

* The pH-carbonate system is determined by the thickness of the soil cover through which the water percolates.

4.1.2 Shallow groundwater chemistry at Laxemar, Äspö and Ävrö

An analysis of the chemistry of the shallow groundwaters at Laxemar, Äspö and Ävrö were performed by Laaksoharju (1988).

In order to find the major water conducting zones in the upper part of the bedrock, shallow percussion holes were drilled at the three sites (see Chapter 2). Water samples were collected from 13 of these boreholes and analysed. The maximum and minimum values of the main constituents are given in Table 4.1, the full data is shown in Table 4.2.

The results of the analyses were evaluated and modelled by Laaksoharju, 1988. The equilibrium modelling indicates that the groundwater, even in the shallow part of the bedrock, has a long residence time. This is further supported by the results of tritium analyses, showing that only a few samples contain large portions of water precipitated later than the 1950s.

Both saline and non-saline water was encountered. The saline water source can be either present or relict Baltic Sea water. Chloride concentrations above the present one of the Baltic Sea strongly suggest the relict sea water source.

With respect to the composition the waters were classified as sea water, mixed water and fresh water (See Fig. 4.1), and illustrated schematically for Äspö (Fig. 4.2).

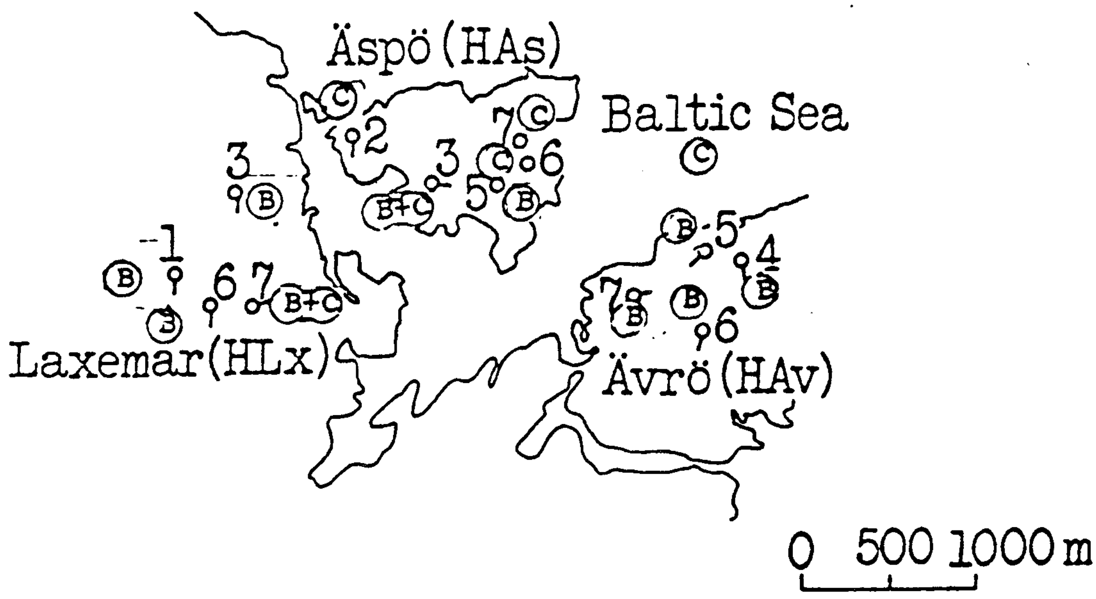

Fig. 4.1 The water types in boreholes at Laxemar, Äspö and Ävrö (drawn after Nilsson, 1984).

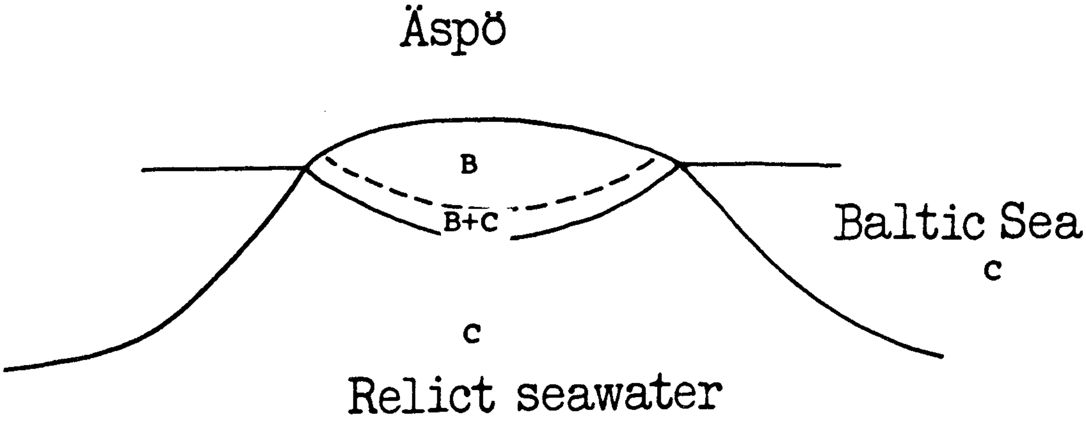

Fig. 4.2 A schematic profile through Äspö showing the water types.

4.1.3 Surface waters from Laxemar, Äspö and Ävrö

Surface waters from lakes, streams, ditches, etc. were analysed for their composition of main constituents. The material consists of twenty samples on which the natural radioactivity and radium contents have also been analyzed. The results, in the form of maximum and minimum values of the main constituents, are given in Table 4.1.

These data were used by Laaksoharju, 1988, who compared the "evolution line" of the surface waters with that of the shallow groundwaters. The result of the exercise shows that the surface waters are a pure mixture of fresh water and sea water, in contrast to the shallow groundwaters which have passed through an ion exchange process.

Table 4.1 Maximum and minimum values of the concentrations of major elements in the water samples from wells, shallow boreholes and the surface.

Element mg/l	wells (25-75) % quartiles	boreholes all data	surface all data
pH	6.8 - 8.6	6.5 - 8.4	4.9 - 6.7
Cond. ms/m	11 - 190	40 -1550	5 - 120
Bicarbonate	1 - 334	102 - 373	0 - 83
Sulphate	1 - 430	9 - 283	4 - 66
Chloride	2 - 840	6 -5500	1 - 236
Potassium	1 - 21	2 - 28	0.4 - 16
Calcium	17 - 135	10 - 818	4 - 74
Magnesium	3 - 17	1 - 244	0.5 - 10
Sodium	5 - 335	33 -2300	3 - 220

4.2 CONCEPTUAL MODELS OF THE GROUNDWATER CHEMISTRY OF THE SIMPEVARP AREA

In this study conceptual models of the the ground-water chemistry of the Simpevarp peninsula are put forward on three different scales i.e.:

Regional scale (approx. 5 000 m x 5 000 m)
Site scale (approx. 500 m x 500 m)
Detailed scale (approx. 50 m x 50 m)

In this approach basically the same units have been used and described as in the geological and the geohydrological models.

4.2.1 Regional model

Table 4.1 indicates that all three categories of water are fairly similar as regards the maximum and minimum values. Therefore the well water material, despite being obtained from a very large area, can be considered representative of the regional area of interest. Because of this the area is also normal with respect to the chemical composition of the groundwater.

The fact that the chemical conditions are considered to be "normal" suggests that the hydrological and geological conditions are also "normal" and that the regional area is typical.

The rather limited amount of data does not give a detailed picture of the groundwater chemistry situation in the region. However, the work by both Liedholm and Laaksoharju indicates that saline water with a hydraulic head determined by the sea level can be expected in the highly conducting zones. At the shore line the saline water is obviously reaching the ground surface. At any other location the salt/fresh water interface is solely determined by the local hydrogeological sitution. There is perhaps neither a well established interface nor a distinct depth for the interface. In between the highly conducting zones, fresh water with a higher hydraulic head occurs in more restricted fracture systems.

4.2.2 Site models

The results of analyses of the main constituents in the groundwater sampled from shallow (100 m) percussion boreholes are presented in Table 4.2. All concentrations are given in mg/l, the conductivity in ms/m.

The results in Table 4.2 clearly illustrate that the water analyzed is in many cases very saline. This is not surprising since the sampling locations are all close to the Baltic Sea.

The conductivity (=salinity) is generally higher at Äspö than it is at Laxemar and Ävrö, (see Fig. 4.3).

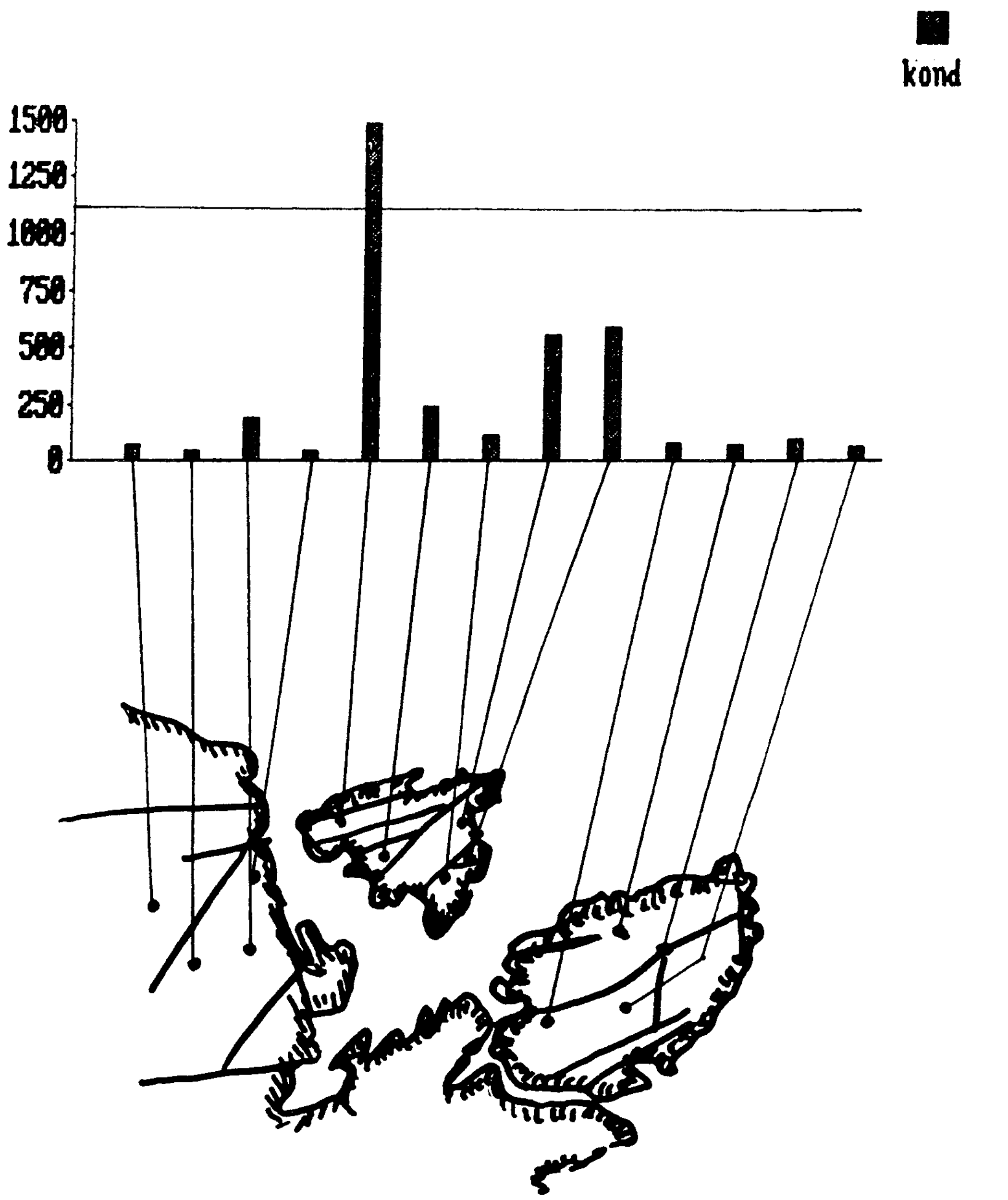

Fig. 4.3 The electrical conductivity of the water (= salinity) sampled in percussion boreholes at Laxemar, Äspö and Ävrö. The horizontal line indicates the conductivity of the Baltic Sea water.

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The highest conductivity is also found in a borehole on Äspö. The salinity of this water is even higher than that of the surrounding sea, which, together with the chemical composition, indicates that this is relict sea water. In turn, this suggests that the water is rather stagnant.

Based on the data available at present the conceptual models for the Äspö and Laxemar sites can be summerized:

Äspö. Distinct vertical flow paths on the middle of the island carry fresh water. The closer to the shore line these paths, the greater the probability of the water being sea water or a mixture of sea water and fresh water. The stagant character of the Äspö groundwater is further defined by the presence of relict sea water at depth.

Laxemar. Fresh water which, as in the case of Äspö, has been subject to ion exchange reactions indicates a discrete fracture system without dominating connections to saline water reservoirs. Only one borehole gave an enhanced chloride concentration. It is not possible to tell whether or not the chloride is a recent intrusion of sea water.

4.2.3 Detailed scale models

The salinity of the water varies considerably between the different boreholes. The boreholes with a high capacity are the ones giving the most saline water. This implies that the highly conducting parts of the rock mass are connected to saline water sources, whereas the discrete fractures carry fresh water.

The different types of block (50 m x 50 m x 50 m) which have been geologically defined in the area, (see 2.2.3), and their hydraulic properties in 3.2.3. These can also be ascribed a chemical character with respect to the groundwater in them. It should be noted, however that the chemical character of the groundwater in the different blocks may vary considerably depending on where in the sites they are encountered. Therefore the chemical character of the blocks should be seen not in absolute terms but only relative to the other blocks.

Block a - Greenstone

The greenstones, with their low hydraulic conductivity, contain stagnant water the character of which is defined by the greenstone minerals, high pH and saturated by some ferrous minerals.

Block b - Småland granite

Compared to the greenstones the water in the Småland granites will have a lower pH and a lower redox buffer capacity.

Block c - Småland granite with greenstone lenses

This water is dominated by the saline or non-saline character. Furthermore, the iron (ferrous) content is high (mg/l level).

Block d - Conductive single fracture

With a vertical direction these can transport fresh sodium-calcium-bicarbonate water deep (>100 m) into the rock. In such cases high tritium concentrations and slightly oxidizing conditions can be encountered at shallow depths (< 100 m). The opposite situation is also possible where the single fracture carries very old relict sea water.

Block e - Fracture zones

These will carry relict sea water, with a salinity far above that in the surrounding sea. This water will not have a constant composition due to the fact that it always contains portions of either present sea water or fresh water or both. At great depth the salinity is expected to be more than twice that of the surrounding sea.

Table 4.2

Borehole	Depth	pH	SO4	Fe	HCO3	Ca	Mg	Cl	Na	K
HLx1	50	8.1	63	.13	233	12	2	41	140	3
HLx3	25	8.0	21	.03	204	17	4	6	67	4
HLx6	45	7.8	23	.27	249	12	2	12	92	2
HLx7	20	7.5	260	.05	200	42	9	440	430	6
HAs2	44	7.2	155	-	219	741	244	5200	2250	28
HAs3	46	7.1	104	-	235	87	39	608	336	12
HAs5	45	8.0	118	-	370	25	6	119	237	4
HAs6	40	7.8	283	-	155	297	56	1760	900	12
HAs7	71	7.7	116	-	106	361	55	1740	656	5
HAv4	35	8.1	71	.70	290	13	3	106	202	4
HAv5	49	8.3	97	.30	271	12	2	15	144	3
HAv6	73	8.3	71	-	223	11	1	36	127	2
HAv7	69	8.0	69	.60	257	21	2	72	133	2
Baltic Sea		7.0	630	<.05	86	99	<1	3600	2700	120

The chemical composition of groundwaters sampled from percussion boreholes at Laxemar (HLx) Äspö (HAs) and Ävrö (HAv). The composition of the Baltic Sea water is also included.

5 EVALUATION OF THE METHODS OF INVESTIGATION

During the first phase of the site investigation for the Hard Rock Laboratory numerous geological and geophysical techniques were applied to characterize the geological and geohydrological conditions in the Simpevarp area. Now it may be of interest to try to make an evaluation of the usefulness of the different methods applied based on our present experience. However, this must be based on the judgement of the investigators, since only further investigations will give the pertinent data for a validation of the findings of this report.

The gravity and aeromagnetic methods were found very useful, especially for studies of a regional nature, i.e. for investigating the boundaries of the Götemar-Uthammar diapirs in three dimensions. The densities and magnetic contents of these granitic rocks usually vary from those of the surrounding rocks and they were therefore good targets for both these methods.

The aeromagnetic method was also used for mapping such fracture zones in which oxidation of magnetite to other non-magnetic minerals may cause magnetic minima.

Aeromagnetic and VLF measurements seem to be quite superior to the AEM measurements in respect of interpretation of fracture zones. Coincident magnetic and VLF fracture zones may be of special interest in the search for the most permeable fracture zones. The VLF measurements, however, are strongly disturbed by the commonly occuring powerlines and by the salt water in the coastal area outside Simpevarp. The high outcrop density in the actual area made the radiometric measurements valuable in the bedrock interpretation work.

The petrophysical interpretation, based on physical measurements in the laboratory of some hundreds of representative samples, is necessary for making a geological-geophysical model of the area investigated.

Ground geophysical methods were used for more detailed investigations in some areas (Ävrö, Äspö, Laxemar, Bussvik). The VLF method may, under favourable circumstances, indicate water-bearing fracture zones and the ground magnetic measurements can provide bedrock information, like the locations of mafic xenoliths or dykes, if the contrasting magnetic susceptibility is big enough in relation to the surrounding granitic rocks. Seismic refraction profiling across the island of Äspö and surrounding water confirmed some of the regional fracture zones and gave a good picture of the fracture density in different parts of the island.

Seismic reflection may be useful to detect fracture zones with low dips at depths of about 300 m or more.

Lineament interpretation of relief maps and structural analysis based on different digital models on a regional scale seems to be a very good base for further site investigation work.

Structural analysis of terrain fractures on a more detailed scale, based on topographical contour maps, is also valuable but the subdivision of an area into more than third order blocks seems to be questionable.

The detailed maps with modern petrographic descriptions, complemented with fracture mapping and a characterization study of the main fracture zones, performed in the Simpevarp area, have been very valuable in the geological and geohydrological modelling work.

Aerogeophysical surveys, especially magnetic and VLF ones, complemented with a gravity network, lineament, interpretation of relief maps and some bedrock information have been the most useful methods for preparing the rock mass description on a regional scale. Ground geophysics, especially seismic refraction and VLF, and petrographic mapping, complemented with fracture studies, have been the most important methods for the interpretation of the rock mass on the site scale. The rock mass description on a more detailed scale was in first instance based on detailed bedrock mapping and fracture studies on outcrops.

When evaluating the geohydrological work the importance of a thorough analysis of existing data must be emphasized. At an early stage of an investigation, as in this case, the main features of the surface hydrology, the bedrock properties and the groundwater regime can be rapidly obtained from sets of existing data.

The use of shallow percussion boreholes for pumping tests is a valuable technique for determining the basic properties of the upper part of the bedrock, such as hydraulic conductivity, anisotropy and hydraulic connections in fracture zones. A proper placement of the boreholes also permits extrapolation of the hydraulic properties down to depths of some hundred metres.

The generic modelling of the hydraulic conditions around the laboratory was carried out in three dimensions with the analytical element technique. The results, though simplified since no inhomogeneities are considered and simple boundary conditions are used, have been very useful in assessing the influence area of the rock laboratory and to provide the principal features of the drawdown around it.

Chemical studies have so far been extremely limited. The three different activities, statistical evaluation of existing well water chemistry, analyses of surface water and analyses of water from shallow percussion boreholes, have proved to be very useful for the understanding (= conceptual modelling) of the chemistry. The evolution of the groundwater is obtained from a comparison between surface water and groundwater. The well water data have indicated that the area investigated has the same composition as the rest of Kalmar County.

6 DISCUSSION OF THE RESULTS WITH RESPECT TO THE SITING OF THE HARD ROCK LABORATORY

The geological, geohydrological and chemical predictive models (see Chapters 2, 3 and 4) are presented in such detail that it is possible to define the main features in the rock mass in the sites investigated. It is therefore possible to define the conditions that are likely to be found in the laboratory. As the investigation has been slightly focused on Äspö this discussion will be made only for the Äspö site.

The different conditions which it is desirable to determine in in an underground laboratory are of course of geological, hydrological and chemical character. However, there are also a few fundamental aspects which should be addressed separately. The most important of these is to have a large enough rock block to place the laboratory in. The northern part of Äspö provides this opportunity. Additionally, the geology also provides a complex chemical situation. This is perhaps not an optimal situation for a repository site, but for a laboratory site it is desirable to find both favourable and unfavourable conditions.

Based on our present knowledge of the general geological conditions of the area investigated it seems to be quite possible to find a suitable site for the Hard Rock Laboratory in the near vicinity of Simpevarp.

Persistent fracture zones of a more regional character divide the rock mass - of mostly granitic composition - in orthogonal or triangular blocks of the kilometre size. Such a rock block in the Småland granite area - as homogeneous as possible - may preliminarily be the best site for further detailed investigations.

A carefully selected site for the laboratory in a rock block of Småland granite will provide the opportunity of reaching rock mass units of different kinds in the near vicinity of the laboratory by tunnelling.

It may be of very great interest to be able to compare the geohydrological properties of fracture zones of different orders and rock mass units, e.g. in anorogenic granites of the Götemar type (few but persistent fractures - often with low dips) with more or less massif greenstone (high fracture density but normally shorter and filled fractures).

A site in the inner Simpevarp area will also favour the possibility to make investigations by tunnelling in the bedrock under the Baltic Sea.

The geohydrological conditions favourable to the rock laboratory can be condensed to two main issues:

1) That there is a rock block large enough in which to site the laboratory and with a homogeneous rock with good quality.

2) That there are within reasonable distance, accessible with drifts, certain important geohydrological features such as fracture zones, different rock qualities, areas below sea water, etc.

The first issue is with great probability fulfilled in the island of Äspö. In this area a homogeneous Småland granite is available. The rock is found to have a low effective hydraulic conductivity. Some few distinct and permeable fractures exist.

The second issue is also fulfilled, since the general geological inhomogeneity of the Simpevarp area makes it possible to reach relevant rock types, different types of fracture zone and areas covered by the sea within a distance of 1.5 km.

One word of caution must be given, however. The possible existance of the permeable Götemar-Uthammar granite at greater depth may imply an atypical geohydrological situation. It may give both drawbacks and advantages for the Hard Rock Laboratory, and its possible influence on the situation must be analysed when further investigations are made.

We have used the present data in two ways, to describe the area investigated and to predict the conditions at depth at Äspö. The prediction is made assuming that no unexpected features are encountered at depth. In this way we can test our capability to predict the characteristics of the deep laying rock based on data from very shallow depths.

However, there is always a possibility to encounter unexpected conditions. The question is therefore not if but rather which type of unpredicted features we will encounter. This is the experience which will determine the basis for the future detailed site investigations.

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KBS Technical Reports 1 – 120
Summaries
Stockholm, May 1979

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

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

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

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

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

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

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

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

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

Technical Reports
List of SKB Technical Reports 1988

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1 Chalmers University of Technology
2 University of Linköping
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US Geological Survey, Lakewood, CA, USA
Linköping University, Linköping
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Stefan Sehlstedt
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Department of General and Marine Microbiology,
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1 Royal Institute of Technology, Stockholm
2 Israel Institute of Technology, Haifa
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2 Kemakta Consultants Co, Stockholm
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