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Final disposal of spent nuclear fuel in Finnish bedrock — Hästholmen site report

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Nimeke – Title FINAL DISPOSAL OF SPENT NUCLEAR FUEL IN FINNISH BEDROCK – HÄSTHOLMEN SITE REPORT	
Tiivistelmä – Abstract Posiva Oy is studying the Finnish bedrock for the geological disposal of spent nuclear fuel. The study is based on the site selection research programme started originally in 1983. The programme is in accordance with the decision in principle by the Council of State in 1983 and aims at the selection of one site in 2000. Four sites, Hästholmen in Loviisa, Kivetty in Äänekoski, Olkiluoto in Eurajoki and Romuvaara in Kuhmo, have been studied in detail. This report summarises the results of the site investigations carried out at Hästholmen. The Hästholmen area is located within the anorogenic Wiborg rapakivi granite batholith, about 1630 million years in age, representing one of the youngest rock formations in Finland. Wiborgite, pyterlite, porphyritic rapakivi granite and even-grained rapakivi granite are the rock types present. 25 bedrock structures have been modelled at the site. Most of them are steeply-dipping fracture zones trending NW-SE and NE-SW, but several sub-horizontal zones, mainly dipping to the N-NE and the SW, are also present. The rock mass between the fracture zones represents what is termed "intact rock", which is typically hard, unweathered and sparsely fractured. The bedrock structures are generally hydraulically more conductive than the intact rock and their mean transmissivity is $8 \cdot 10^{-6}$ m²/s or $1.3 \cdot 10^{-6}$ m²/s, depending on how structures are defined. The corresponding mean of the hydraulic conductivity values measured for the intact rock using a 2 m packer interval, is $1 \cdot 10^{-12}$ m/s, if a lognormal distribution for all measured values is assumed. A clear decrease in hydraulic conductivity with depth has been found in the intact rock. In addition, the hydraulically conductive fractures seem to be more frequent and their transmissivities higher in the uppermost 100-200 m of the bedrock than at greater depths. The groundwater chemistry reflects the post-glacial history of the island of Hästholmen, which rose from the Baltic Sea some 4000 years ago. The groundwater varies from modern fresh water at shallow depth to saline water at greater depths, the saline water normally representing a mixture of relic Litorina Sea water and meteoric and glacial meltwater. The maximum Total Dissolved Solids (TDS) in the groundwater is 32 g/l and the chloride content 19 g/l. Reducing conditions are expected to exist at depth, which are favourable for low radionuclide solubility and slow canister corrosion. Suitable bedrock volumes have been identified at the site for locating a repository in the depth range of 400-700 m. No significant geotechnical, hydrogeological and hydrogeochemical constraints have been found to its construction, although it is recommended that certain fracture zones, mainly those that are sub-horizontal, should be avoided when locating the deposition tunnels and disposal holes. The salinity of the groundwater will probably place limits on the use of certain materials for construction purposes.	
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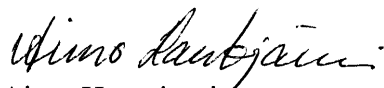
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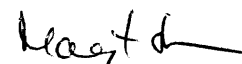
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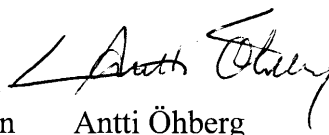
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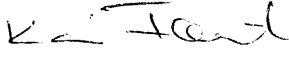
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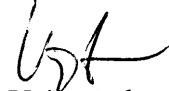
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Nimeke – Title KÄYTETYN POLTTOAINEEN LOPPUSIJOITUS SUOMEN KALLIOPERÄÄN – HÄSTHOLMENIN PAIKKARAPORTTI	
Tiivistelmä – Abstract Posiva Oy tekee Olkiluodon ja Loviisan ydinvoimalaitosten käytetyn polttoaineen loppusijoitusta varten kallioperätutkimuksia, jotka tähtäävät lopullisen sijoituspaikan valintaan vuonna 2000. Yksityiskohtaisia tutkimuksia on suoritettu neljällä paikkakunnalla; Kuhmon Romuvaarassa, Äänekosken Kivetyssä, Eurajoen Olkiluodossa ja Loviisan Hästholmenilla. Tässä raportissa esitetään yhteenveto Loviisan Hästholmenilla tehdyistä tutkimuksista ja niiden tuloksista. Hästholmenin alueen kallioperä on osa Kaakkois-Suomen eli ns. Viipurin rapakivimassiivia, joka on iältään noin 1630 miljoonaa vuotta. Tutkimusalueen pääkivilaji on rapakivigraniitti, joka esiintyy useana muunnoksena. Näistä yleisimmät ovat viborgiitti, pyterliitti, porfyryinen rapakivigraniitti sekä tasarakeinen rapakivigraniitti. Tutkimusalueen kallioperästä on mallinnettu yhteensä 25 pääosin jyrkkäkaateista rako- tai rikkonaisuusvyöhykettä, mutta lisäksi on paikannettu useita loivasti pohjois-koilliseen tai lounaaseen viettäviä vyöhykkeitä. Rikkonaisuusvyöhykkeiden välinen kallio on enimmäkseen kiinteätä, rapautumatonta ja harvakseltaan rakoillutta. Se saattaa kuitenkin sisältää myös yksittäisiä rikkonaisia vyöhykkeitä, joita ei ole luokiteltu kalliomallin rakenteiksi. Mallinnetut rikkonaisuusrakenteet ovat merkittävästi vettäjohtavampia kuin niiden välinen ehjä kallioperä. Rakenteiden transmissiviteetti on keskimäärin $8 \cdot 10^{-6}$ m²/s tai $1.3 \cdot 10^{-6}$ m²/s, rakenteiden määritystavasta riippuen, keskimääräinen vedenjohtavuus 2 m mittausväleille ehjässä kalliossa on $1 \cdot 10^{-12}$ m/s, edellyttäen että kaikki erot noudattaisivat lognormaalia jakaumaa. Ehjän kallion vedenjohtavuus pienenee syvyyden kasvaessa, niinkään vettäjohtavia avoimia rakoja esiintyy runsaammin kallion pintaosassa noin 100-200 metrin syvyydelle. Hästholmenin saaren jääkauden jälkeinen kehitys heijastuu kallioperän pohjaveden kemiassa. Saari kohosi Itämerestä noin 4000 vuotta sitten. Kallion pintaosissa vesi on makeaa muuttuen syvemmällä suolaiseksi, joka on sekoitus Itämeren Litorina-kautista merivettä sekä makeaa meteorista ja jääkautista sulamisvettä. Suurin mitattu liuenneiden suolojen, TDS, määrä on 32 g/l ja kloridipitoisuus 19 g/l. Loppusijoitussyvyydellä pohjavesiolosuhteet ovat pelkistäviä, mikä hidastaa radionuklidien liukenemista sekä jättekapselin korroosiota. Tutkimusalueen kallioperästä, noin syvyydsväliltä 400-700 m on paikannettu kalliolohkoja, jotka soveltuvat hyvin loppusijoitustilojen rakentamiseen. Kallioperästä ei ole tavattu sellaisia ominaisuuksia, jotka estäisivät loppusijoitustilojen rakentamisen tavanomaisin kalliorakennusmenetelmin, joskin tilojen sijoittelussa on suositeltavaa välttää tiettyjä, pääasiassa loiva-asentoisia rikkonaisuusrakenteita. Suolainen pohjavesi saattaa asettaa rajoituksia loppusijoitustilojen rakenteissa käytettävälle materiaaleille.	
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PREFACE

Posiva established a site evaluation project PARVI in 1997 for summarising, the investigations conducted at the four investigation sites for the deep disposal of spent fuel. The project was set up with the view completing the site selection research programme commissioned and for assessing the safety of the proposed final disposal system. The current report summarising the site conditions at Hästholmen has been prepared by a group of authors from several organisations and the work has been supervised by the PARVI project led by Aimo Hautojärvi. The authors of this report wish to thank them and all their other colleagues at Posiva and at the other investigation institutes, universities and consulting companies who participated in the preparation of this report by correcting and commenting on the various drafts. The comments by Petteri Pitkänen and Ari Luukkonen of VTT Communities and Infrastructure, and Paula Ruotsalainen and Eero Heikkinen of Fintact Oy have been especially important in this regard.

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1 INTRODUCTION

In Finland, two companies utilise nuclear energy to generate electric power – Teollisuuden Voima Oy (TVO) at the Olkiluoto Nuclear Power Plant (NPP) (2 x 840 MWe BWR) and Imatran Voima Oy (at present Fortum Power and Heat Oy) at the Loviisa NPP (2 x 488 MWe PWR). TVO and IVO have already at an early stage prepared themselves to take care of all activities associated with the management of the nuclear waste they produce and also collect funds necessary for the future activities. Both companies have committed themselves to a policy which enhances the responsibility for the environment. One part of this policy is the development of solutions for safe nuclear waste management. Practical results of this are the interim storage facilities for spent fuel and the underground repositories for final disposal of low- and intermediate-level operating waste at Olkiluoto and at Hästholmen. Based on the current law, the Nuclear Energy Act, all nuclear waste generated as a result of electricity production shall be disposed of in Finland.

The power plants at Olkiluoto and Hästholmen were built during 1970s. The return of the spent fuel from the Loviisa power plant back to Soviet Union (later Russian Federation) was included in the original agreement. The planning of the spent fuel management of Olkiluoto power plant was started during the construction of the power plant. The work included studies on the availability of reprocessing services, as well as, planning of the interim storage capacity at the power plant area. The preparatory work for nuclear waste management resulted in 1978 in a report (Imatran Voima Oy & Teollisuuden Voima Oy 1978), drafted jointly by TVO and IVO, in which the power companies assessed that nuclear waste management can safely be implemented as a whole in Finland. For the coordination of the future work TVO and IVO established the Nuclear Waste Commission of Finnish Power Companies (YJT).

For the final disposal of spent nuclear fuel TVO and IVO founded in 1995 a jointly owned company, Posiva Oy. Posiva is in charge for the final disposal of spent nuclear fuel. The total amount of spent fuel to be disposed in the repository is currently estimated to be about 2 600 tU.

The studies for the final disposal of spent fuel were started already in the early 1980s. The general guidelines and schedules for implementing the work, especially for the site selection of the deep repository, were set forth in the Council of State's decision in principle in 1983. According to the decision the research and development shall make progress so that by the end of 2000 there has been selected and characterised a site which can be used for the construction of the deep repository. The content of this decision has been included later in the decisions of the Ministry of Trade and Industry, in charge for the supervision concerning the implementation of the nuclear waste management.

The site selection research programme has progressed in a good compliance with the Council of States's decision. After screening of the whole country in 1983 - 1985 a great number of areas were identified for further investigations. In parallel, technical plans for encapsulation and final disposal of spent fuel were developed and safety studies were carried out. Five areas, Kivetty in Äänekoski, Olkiluoto in Eurajoki, Romuvaara in Kuhmo, Syyry in Sievi and Veitsivaara in Hyrynsalmi (Fig. 2.1-1), were selected for preliminary site

characterisation to be performed over the period from 1987 to 1992. The results of these investigations were reported and presented to the authorities in 1992 (Teollisuuden Voima Oy 1992a). The TVO-92 safety analysis showed that the proposed safety requirements could be met at all the five sites investigated (Vieno et al. 1992). Kivetty, Olkiluoto and Romuvaara were selected for further characterisation (Fig. 1-1).

The first stage of the detailed site characterisation programme was carried out over the period 1993 - 1996, and the results were presented in an interim report in 1996 (Posiva Oy 1996a). At the same time site-specific technical plans (Posiva Oy 1996b), as well as the safety assessment, TILA-96 (Vieno & Nordman 1996), were presented to the authorities. In addition to these three sites selected in 1992, Hästholmen in Loviisa (Fig. 1-1) was included in the site selection research programme in the beginning of 1997.

The research programme for 1997 - 2000 is focussed around the need to complete the site selection by the end of 2000. The current work is divided into two parts, of which the PARVI project includes the site evaluation of the four candidates and site-specific safety assessment of final disposal. The other project is the work organised to carry out the Environmental Impact Assessment (EIA) process according to the law and aiming at the compilation of the EIS report (Environmental Impact Statement).

The objective of the PARVI project is to summarise the characterisation conducted at the sites, with a view to selecting the final disposal site and assessing the safety of the suggested final disposal system. Studies under the project have supplemented the detailed site characterisation programme carried out earlier at Kivetty, Olkiluoto and Romuvaara. At Hästholmen in Loviisa, investigations have been performed with a view to enabling the suitability of this site for final disposal to be assessed in a similar manner to the other sites. The project involves geological, geochemical, geophysical and hydrogeological investigations. In addition, the quality and quantity of rock potentially suitable for final disposal at each investigation site is being assessed.

Posiva aims at the selection of a disposal site by the end of 2000. After the selection the purpose is to develop an underground characterisation facility at the site and carry out confirmatory characterisation for ten year's time. The construction of the encapsulation facility and the deep underground repository is planned to start around 2010, so that final disposal could commence in 2020. After emplacement of spent fuel canisters, it is planned for the repository to be sealed around 2050. The final time schedule for the closure of the repository is very dependent on the operating times for the present or possible future nuclear power plants.

According to the Nuclear Energy Act before any significant nuclear facility can be built in Finland, a Council of State's decision in principle is required. The decision, however, does not grant a license for a construction or operation of the facility in question, the construction permit and operation license have to be applied separately afterwards. The purpose of the decision is to judge whether "the facility is in line with the overall good of society". As part of this decision the Radiation and Nuclear Safety Authority (STUK) have to make a preliminary statement on the safety of the facility and the candidate municipality (or municipalities if several candidate sites exist) must state their acceptance of siting the

facility. A positive decision can only be made by the Council of State if both STUK's and the municipalities' statements are positive, and this decision has still to be ratified by the Parliament. Posiva aims to submit the application for the Council of State's decision in principle in 1999. This decision has been found essential in connection with the site selection.

This report on the Hästholmen site in Loviisa summarises the geological, geochemical and hydrogeological characteristics of the site based on the large amount of data and material gathered since early 1980s. The report also presents the updated bedrock models, indicates which parts of the rock mass are believed to show most promise for locating a repository and discusses the general principles associated with its design and construction. The report concludes by discussing the particular features of the site and its overall suitability.

The report is designed to be used as background information for the environmental impact assessment, the technical design of the repository and the site evaluation and safety assessment TILA-99 (Vieno & Nordman 1999). The groundwater flow and transport modelling for the Hästholmen site is reported separately (Löfman 1999, Poteri & Laitinen 1999).



Figure 1-1. Investigation sites for final disposal of spent nuclear fuel in Finland. Sites for detailed investigations are bold faced.

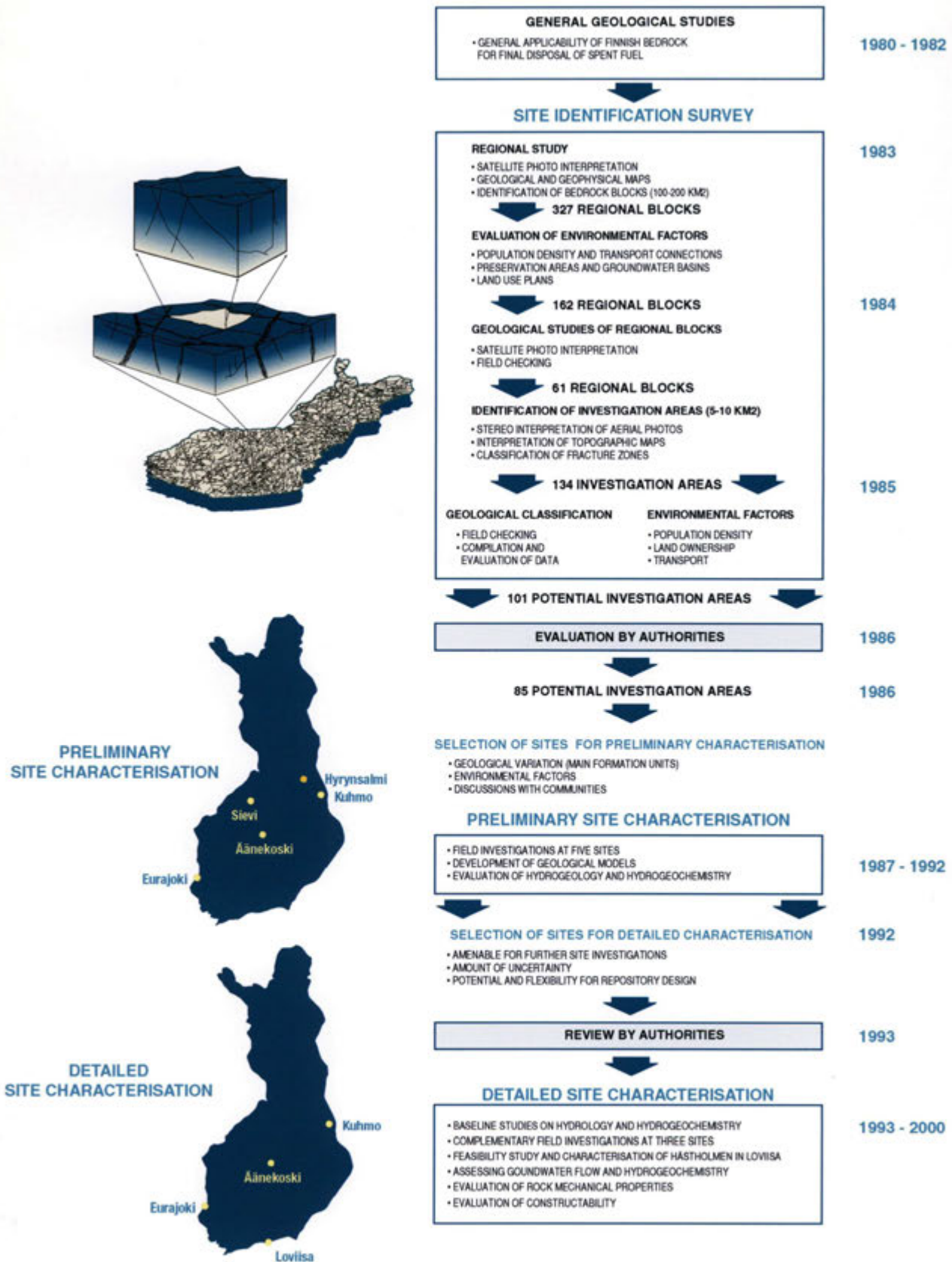


Figure 2.1-1. The progress of site selection process (modified from Teollisuuden Voima Oy 1992a).

Äänekoski, Syyry in Sievi and Olkiluoto in Eurajoki (Teollisuuden Voima Oy 1987). The five sites were characterised by means of an extensive investigation programme with closely-related modelling, and were reported to the Ministry of Trade and Industry in 1992 (Teollisuuden Voima Oy 1992a).

On the basis of the preliminary investigations, in 1992, TVO proposed to continue site characterisation at three sites: Romuvaara in Kuhmo, Kivetty in Äänekoski and Olkiluoto in Eurajoki. The reason for selecting these three sites was that there were fewer uncertainties in the bedrock models developed and the explorability of these sites was considered to be superior to the two other sites investigated (Teollisuuden Voima Oy 1992a).

A complementary study on the basic rock types of Finland and their potential to final disposal was carried out during 1991 - 1994 (Teollisuuden Voima Oy 1993, Posiva 1996f). An inventory of mafic plutonic rocks and basic volcanic rock types was made and the properties of the formations were evaluated. The study could not assess any properties of these rock types more favourable than the properties of the felsic granitic rocks under characterisation. Moreover, the rather sparse basic rock formations have very often associated ore mineralisations which can increase the possibility of adverse human intrusion in a form of ore exploration purposes.

Hästholmen, the island of the Loviisa Power Plant, was included by Posiva in the list of potentially suitable sites for disposal of spent nuclear fuel in the beginning of 1997 (Fig. 2.1-1). The decision was based on the feasibility study which was started by IVO in 1995 and completed by Posiva at the end of 1996 (Posiva Oy 1996c). According to the results of this study Hästholmen exhibited potential for the location of a repository for spent fuel and also has advantages similar to those of Olkiluoto, an existing nuclear technical infrastructure and less spent fuel to be transported, for example. The bedrock block structure was already determined in previous studies, e.g. Kuivamäki & Tuominen (1985) and Anttila (1988). Figure 2.1-2 indicates the existence of the "Hästholmen block". Figure 2.1-3 shows an aerial view of the Hästholmen investigation area.

Detailed site characterisation is now under way at Romuvaara, Kivetty, Olkiluoto and Hästholmen, the main emphasis being at Hästholmen. The research programme, initiated in 1983, is approaching its completion and one of the candidates will be selected to host a deep repository by the end of 2000. The selection, however, is a rather complex process which comprise also the consideration of other criteria than geological. One important process affecting the selection process is the application of the Council of State's decision in principle during which the communities in question have to give their answers to the Council of State, as well as, the regulator STUK has to give the preliminary safety evaluation, too. Finally, the Finnish Parliament has to ratify the decision.

The selection of the site is to be followed by further confirmatory characterisation lasting approximately another ten years, so that the construction of the repository is planned to commence in 2010 with final disposal planned for 2020. The investigations would also continue in some form even during the construction and operation phases of the repository.

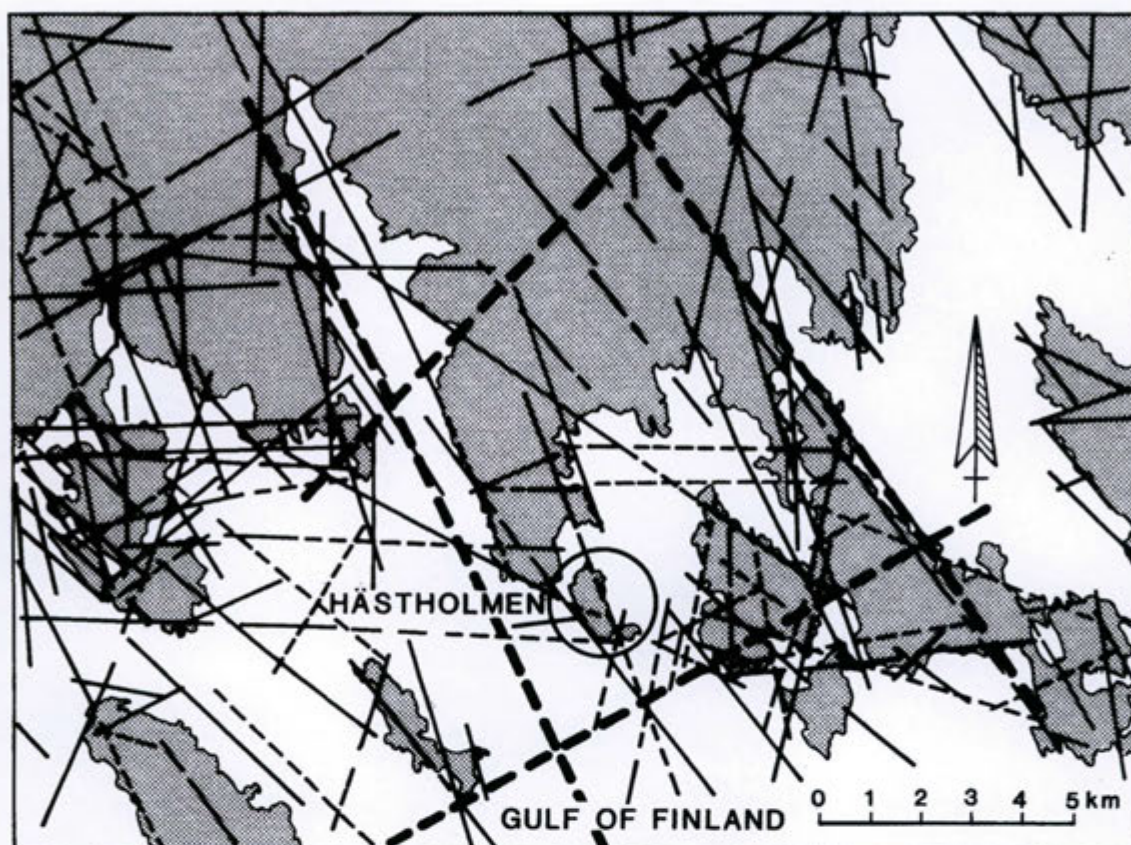


Figure 2.1-2. Bedrock structures determined for the Hästholmen area (Anttila 1988, based on interpretations by Kuivamäki & Tuominen 1985).



Figure 2.1-3. An aerial view of the Hästholmen investigation area from the north. KR1 to KR6 are the deep boreholes drilled in the area, the distance between KR1 and KR2 is about 300 m (see also Fig. 2.2-2 and Fig. 2.3-2).

2.2 Studies Prior to the Detailed Site Characterisation

It was decided in 1996, as a result of the amendment of the Nuclear Energy Act, that the spent nuclear fuel of IVO was to be disposed of in Finland instead of returning it to Russia. After TVO and IVO had founded a joint company, Posiva Oy, the work that IVO had started in 1995 was combined with the ongoing investigation programme for the final disposal of spent fuel and was extended to include a feasibility study for the island of Hästholmen. This study was regarded as important, since the island of Hästholmen is, as the host to a nuclear power plant, in a similar position to that of the island of Olkiluoto.

2.2.1 Investigations Related to the VLJ Repository

Preparations for the final disposal of low- and intermediate-level (VLJ) operating waste from the Loviisa NPP at depth on the power plant site were started with preliminary site investigations in 1979 (Fig. 2.2-1). In addition, some results from the geological investigations associated with the design and construction of the power plant from the 1960s were already available. The objective of the investigations for the VLJ repository was to determine the bedrock conditions beneath the island in order to locate the repository and to supply input data for the PSAR (Preliminary Safety Analysis Report). Most of the investigations were completed by the end of the 1980s and all the investigations carried out at Hästholmen before 1988 are presented in Anttila (1988).

Additional site investigations were carried out during the construction of the transport tunnel (1993 - 1994) for the VLJ repository and also during the construction of the repository itself. The construction of the first stage of the repository started in November 1994 and the rock excavation, reinforcement and grouting work was completed in January 1996. The operation of the repository was commenced in 1997. The aims of the investigations were, in addition to documenting the geological data, to assure the suitability of the rock mass at depth for construction purposes, and to collect the necessary data for the groundwater flow modelling and the final safety analysis. Investigations have included geological mapping, drilling of boreholes, rock mechanical measurements, vibration measurements, measurements of groundwater ingress and the monitoring of pressure, flow rate and hydraulic head of groundwater, as well as chemical analyses of groundwater samples. The investigations performed during the construction phase have been briefly summarised by Anttila (1997).

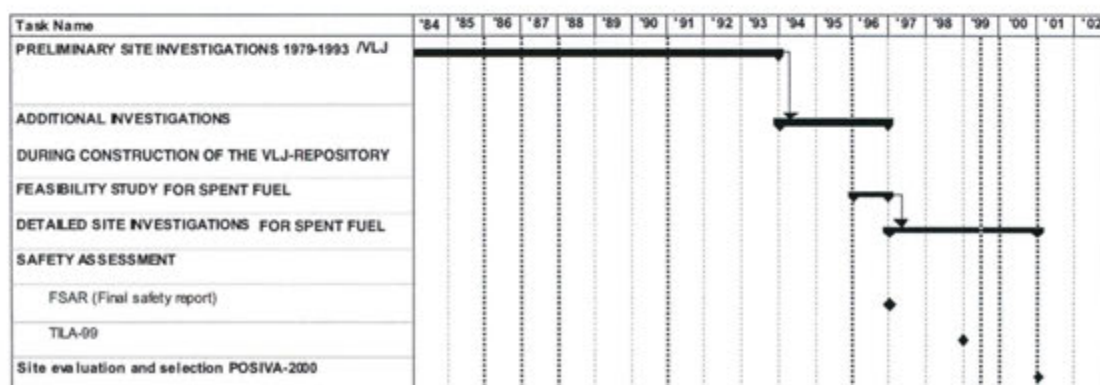


Figure 2.2-1. Different characterisation phases at Hästholmen.

Geological investigations

Sixteen cored boreholes were drilled in the area, the deepest being 240 m. In addition, some percussion boreholes, between 5 and 69 m in depth, were drilled for hydraulic measurements and groundwater observations. The locations of the boreholes are shown in Figure 2.2-2. A summary of the geological studies in boreholes Y1...Y11 were reported in Suominen (1983). The geology of the site based on the completed investigations was presented by Anttila (1986, 1988).

The tin mineralisation potential of the island of Hästholmen was originally carried out in 1983 by Lehtiö (1983), and a more recent evaluation of the mineralisation potential of the Hästholmen area was conducted during detailed site investigations by Kuivamäki et al. (1997b).

Valuable data have been collected during and after completion of the excavation of the VLJ repository. All exposed rock surfaces in the repository were mapped. Seven cored boreholes (YT1...YT7) were drilled underground during the construction phase with the objective of investigating the geological conditions in the regions of the rock mass where caverns were planned (Anttila 1997).

The suitability of the Wiborg rapakivi massif (the large massif in which Hästholmen lies) for final disposal of spent fuel was studied in 1995 by Kuivamäki et al. (1995). No unexpected features, which could possibly jeopardize its use as a host rock for disposal purposes, were found during this study. It was admitted during this study, however, that very little was known about the conditions at depth.

Geophysical investigations

The surface and borehole geophysical measurements and those in boreholes constituted an essential part of the field investigations. Ground surveys were conducted both on the island of Hästholmen and offshore (Fig. 2.2-2). Offshore, the aim was to clarify the general features of the sea bed and the location of high angle fracture zones. The methods employed were echo and seismic refraction sounding.

The main objective of geophysical surveys on the island was to locate gently dipping fracture zones. The methods used comprised vertical resistivity sounding, by which the interface between fresh and saline groundwater was located, in addition to the fracture zones. Georadar (impulse radar) was used to study the bedrock at shallow depths.

Single-hole geophysical borehole measurements were used to determine the following properties: the dip of the fractures (dipmeter); the acoustic velocity of the rock (acoustic log); the density (gamma-gamma log); the porosity (neutron-neutron log); the specific resistivity; the occurrence of radioactive minerals (natural gamma log); the diameter of the borehole (caliper) and its orientation; and the specific resistivity and temperature of the groundwater. The borehole radar method was used during the construction phase of the VLJ repository, due to the presence of saline groundwater the data achieved was very limited. The geophysical methods employed in the structural study of the bedrock are reported in Rouhiainen (1986).

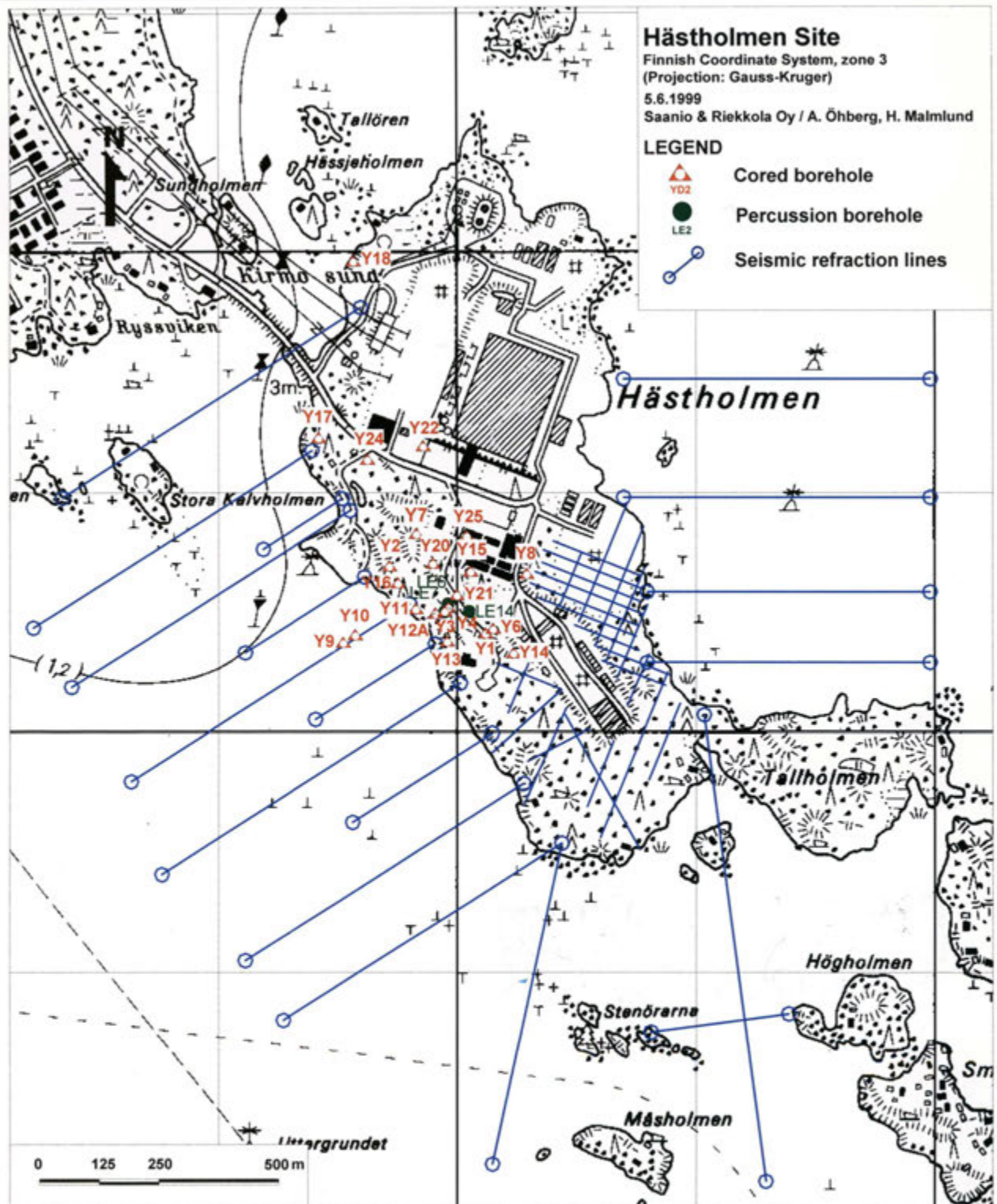


Figure 2.2-2. Most significant investigation boreholes and seismic refraction lines related to investigations before 1996.

The fracture porosity and the directional properties of water-filled apertures associated with the fractures in the bedrock were studied by Rouhiainen (1989). Methods with high spatial resolutions along the borehole were chosen for his study and the methods employed were the dipmeter, the sonic log and the bed resolution density log (gamma-gamma). The results from Hästholmen revealed that fracture apertures were unevenly distributed, with the fracture porosity tensor being strongly oriented in a horizontal direction.

The structure of the rock mass, especially the continuity of fracture zones, has been studied by cross-hole charged potential and seismic methods (Rouhiainen 1986).

During 1984 - 1996 altogether 134 micro- and ultra-microearthquakes ($M_L = 0.1 - 1.2$) were observed by the small seismic network established in the Loviisa area and the source parameters of the earthquakes were determined (see also section 3.5). Multi-event locations have been performed to define the geometry of the seismically-active block boundaries. The results fit well with the interpretations of the seismotectonics and the lineaments in the area (Saari 1990, 1998).

Rock mechanical investigations

The in situ stress was measured at depths of <115 m in borehole Y6 in 1981 and in borehole Y20 in 1987 and 1992 (Ljunggren & Klasson 1992). A stress analysis for the VLJ repository was carried out by Halonen (1987) and, after excavation of the repository, rock stress measurements were made underground in borehole YT2 in 1994.

In 1996 rock mechanical instruments including extensometers, load gauges, thermic gauges and one displacement transducer were installed in the repository for long-term monitoring of the stability of the rock caverns. The monitoring results from 1997 are reported in Auvinen (1998).

Hydrogeological investigations

The objective of the hydraulic borehole measurements was to supply the parameters that would be necessary for input to the groundwater flow modelling and for the associated safety analysis. Water loss tests were carried out systematically using a double-packer system with a 3.2 m packer separation. In some boreholes the so-called Lugeon test, which uses only a single packer, was used. Pressure head tests were performed in order to acquire data on flow potentials and to measure the hydraulic gradient. Pulse tests were used to study the hydraulic connections between certain boreholes. The interpretation of the hydraulic pulse tests is presented in Ylinen (1985).

The groundwater table and fluctuations in hydraulic heads have been monitored since 1980. A summary of hydrogeological long-term monitoring results for 1980 - 1993 is presented in Ahokas (1986, 1993) and Anttila (1986). More recent hydrogeological results from the first phase of repository construction are presented in Ahokas & Hänninen (1996) and Anttila (1997). The effects of the excavation of the access tunnel of the VLJ repository on the groundwater flow regime at Hästholmen was studied by Herva & Ahokas (1994). The hydrogeological monitoring results from the first year of repository operation are reported in Anttila et al. (1998).

Groundwater flow measurements were carried out in borehole Y20 in 1993 and repeated in 1995 (Rouhiainen 1993a, 1995). No transverse flow in the borehole was detected in regions where saline groundwater was present.

Geochemical investigations

The interface between the fresh and saline groundwater has been studied with specific resistivity measurements. Groundwater samples have been taken from several boreholes and also samples of sea water have been taken offshore. IVO's sampling equipment was used in the period from 1980 - 1983 and TVO's sampling equipment, which was constructed specifically for the preliminary site investigations for spent fuel disposal, in 1985 and 1992. The geochemical investigations in the period from 1980 - 1992 are presented in Hyypä (1984), Kankainen (1986), Nordstrom (1986) and Snellman & Helenius (1992).

Since the repository was constructed hydrogeochemical conditions have been monitored at five locations in the repository (Anttila 1997).

2.2.2 Feasibility Study in 1996

Investigations carried out

The feasibility study was launched at the beginning of 1996 and the geological evaluation was based mainly on the previous investigations on the island. Additional geological mapping (Fig. 2.2-3), to determine the structural and lithological conditions, was carried out by Kuivamäki et al. (1997a) within a radius of 20 km of the island. The study was divided into two parts, a regional area with a radius of 20 km was mapped using satellite images and existing geological and geophysical maps. A near-field area within a radius of 5 km from Hästholmen, was mapped in more detail. Marine geological studies are presented in Rantataro (1996). A geochemical evaluation of the Loviisa area was carried out by Hatanpää (1997).

An outline of the investigations at Hästholmen is presented in Appendix 1, which contains list of the investigations carried out, their timing, the methods used, their aims and references to the work reports (field work and interpretation) where more detailed information and the results concerning each individual investigation can be found. A summary of the investigations carried out as part of this study is reported in Posiva Oy (1996c).

The results of the feasibility study

The dominant rock type in the Hästholmen area, rapakivi granite, does not differ noticeably from the rock types at the other investigation sites. The structure of the bedrock is rather simple and the fracture zones which appear to be important in determining the groundwater flow are easier to predict than in less homogeneous rock types. The information from the hydrogeochemical studies indicated that the salinity of the groundwater increases with depth.

The results of the feasibility study indicated (Posiva Oy 1996c) that it is possible to delineate a sufficiently large volume of bedrock for housing the repository at approximately 500 m depth beneath the island. The site for the surface encapsulation plant can be located in the vicinity of the power plant. Further questions regarding possible further site characterisation work are related to the presence and frequency of the horizontal fracture zones, the hydrogeochemical conditions at depth and the nature of the groundwater flow. To investigate these matters further boreholes would be required to depths of approximately one kilometre.



Figure 2.2-3. All outcrops in the vicinity of Hästholmen were mapped during the feasibility study phase.

2.3 Detailed Site Characterisation 1997 - 2000

2.3.1 Characterisation Programmes

Following the preliminary investigations, the guidelines for the next investigation period, which included the detailed site investigations at the selected three sites (Romuvaara, Kivetty and Olkiluoto) were presented in 1992 (Teollisuuden Voima Oy 1992b). The eight-year research period extending from 1993 to 2000 was considered to be too long in practical operational terms to allow for the development of a single programme, and it was considered more appropriate to divide it into successive sub-programmes. The investigations at the fourth site, Hästholmen, were included in the latter phase, 1997 - 2000, with the aim of bringing the state of knowledge for this site to the same level as that of the three other sites. The time available for carrying out the necessary work at Hästholmen is short but, on the basis of the feasibility study and because investigations had already been carried out on the site for the VLJ repository, the starting point at Hästholmen was quite different from that at the other sites. In addition, the experience in carrying out such work, which has been built up over recent years, and the concentration of work at a single site have made the task considerably easier.

The most important tasks for the 1997 - 2000 (complementary studies) period, which included the work at Hästholmen, were presented in the 1996 status report (Posiva Oy 1996a). These tasks were:

- Preparation of a summary evaluation of the geological, hydrogeological and hydrogeochemical properties of the sites by carrying out the required field and laboratory investigations and the associated interpretations and modelling programmes,
- an evaluation of the state of knowledge regarding the overall understanding of the sites and an evaluation of the remaining uncertainties,
- the definition of potentially suitable volumes of the rock mass for housing a repository and an evaluation of the overall suitability of the sites for final disposal in terms of technical and safety aspects and
- the preparation of a performance assessment for the potential disposal sites.

The proposed investigations associated with the complementary studies over the period 1997 - 2000 are presented in more detail in the proposed investigation programme for the years 1997 - 2010 (Posiva Oy 1996d). The PARVI project, or more accurately a subproject of PARVI, which was established for planning and carrying out the practical work at Hästholmen, compiled an investigation programme for its own internal use.

In addition to the detailed descriptions of the investigation programmes, summaries of the investigations for the following year were also presented in the radioactive waste management programmes of the nuclear power plants of Olkiluoto and Loviisa (Posiva 1996e, 1997).

2.3.2 Detailed Site Characterisation - Approaches and Extent

The objective of the investigations at Hästholmen has been to extend the structural model generated earlier during the studies for the VLJ repository to the greater depths required for HLW disposal. Over the period 1997 - 2000 the investigations concentrate on the following key questions (Posiva Oy 1996a, d):

- What are the hydrogeochemical properties of the groundwater at depth and does the salinity change with depth?
- Do the sub-horizontal fracture zones that occur at shallow depths continue to greater depths and what is the hydraulic conductivity of those zones?
- What is the extent of the observed horizontal fracture zones and does the current land uplift cause groundwater to flow from the inland beneath Hästholmen island?
- What is the rate of groundwater turnover in the intact rock between the fracture zones?

The equipment and methods used at Hästholmen have been essentially the same as those used in the detailed site investigations at the other sites. Some of the equipment were improved after the preliminary investigations at the other three sites and, in addition, some new methods have been applied (Hinkkanen et al. 1996). The investigation methods used at Hästholmen over the period 1997 - 1998 can be found in Appendices 1-9.

The investigations at Hästholmen have, since March 1997, involved the drilling of eight deep boreholes (600 - 1000 m), with associated geophysical borehole logging, groundwater sampling and hydrogeological testing, the analysis of groundwater samples, surface and airborne geophysics and regional studies of possible mineralisation events. Boreholes KR7 and KR8 are located north of the study site. The drilling of the ninth borehole KR9 and all borehole investigations in it will be carried out during the latter part of year 1999. The drilling technique is described in Figure 2.3-1 and the location of the deep boreholes is presented in Figure 2.3-2.

A new sampler for obtaining pressurised groundwater samples was developed over the period from 1993 - 1996 (Ruotsalainen et al. 1996, Hinkkanen et al. 1996). Sampling with this PAVE groundwater sampling system allows high quality samples to be taken from individual fractures or fracture zones. The pressurised water samples has been used in microbial studies and in the analyses of dissolved gases. Twenty samples had been taken with the PAVE groundwater sampling system from the six first deep boreholes KR1-KR6 (Fig. 2.3-2) by the end of 1998. The drilling of borehole KR1 through the transport tunnel of the VLJ repository enabled groundwater sampling to take place during drilling. Water sampling has also been carried out from groundwater pipes and shallow boreholes and from precipitation.

The development of investigation equipment has been most active in the hydrogeological area. For example the software and hardware of the HTU (Hydraulic Testing Unit, Fig. 2.3-3) were replaced over the period 1993 - 1994, which improved the resolution of the tool and enabled the routine interpretation of hydraulic conductivity measurements in the field (Hämäläinen 1998a, b, 1999). Also new flowmeters for difference flow and transverse flow measurements (Hinkkanen et al. 1996) have been used systematically for measurements

within the deep boreholes at Hästholmen (Pöllänen & Rouhiainen 1998a, b, c, 1999). The principle of transverse flow measurement is presented in Figure 2.3-4. Fluid logging (repeated measurements of fluid resistivity and temperature), which was carried out systematically during the preliminary investigations at the other sites, was replaced with difference flow measurements at Hästholmen. The method gives the locations of hydraulically-conductive fractures, without the requirement to replace the borehole water with de-ionized water, as is the case in fluid logging. The good correlation between the results from the HTU and the difference flow measurements has given confidence in the use of the two methods.

The aim of the geophysical studies has been to supplement the bedrock data obtained during the earlier investigations and to obtain more precise data on the rock mass. The studies have mainly been focussed on the boreholes and on their immediate surroundings. The detailed investigations regarding the lithology, the determination of fractured and broken sections

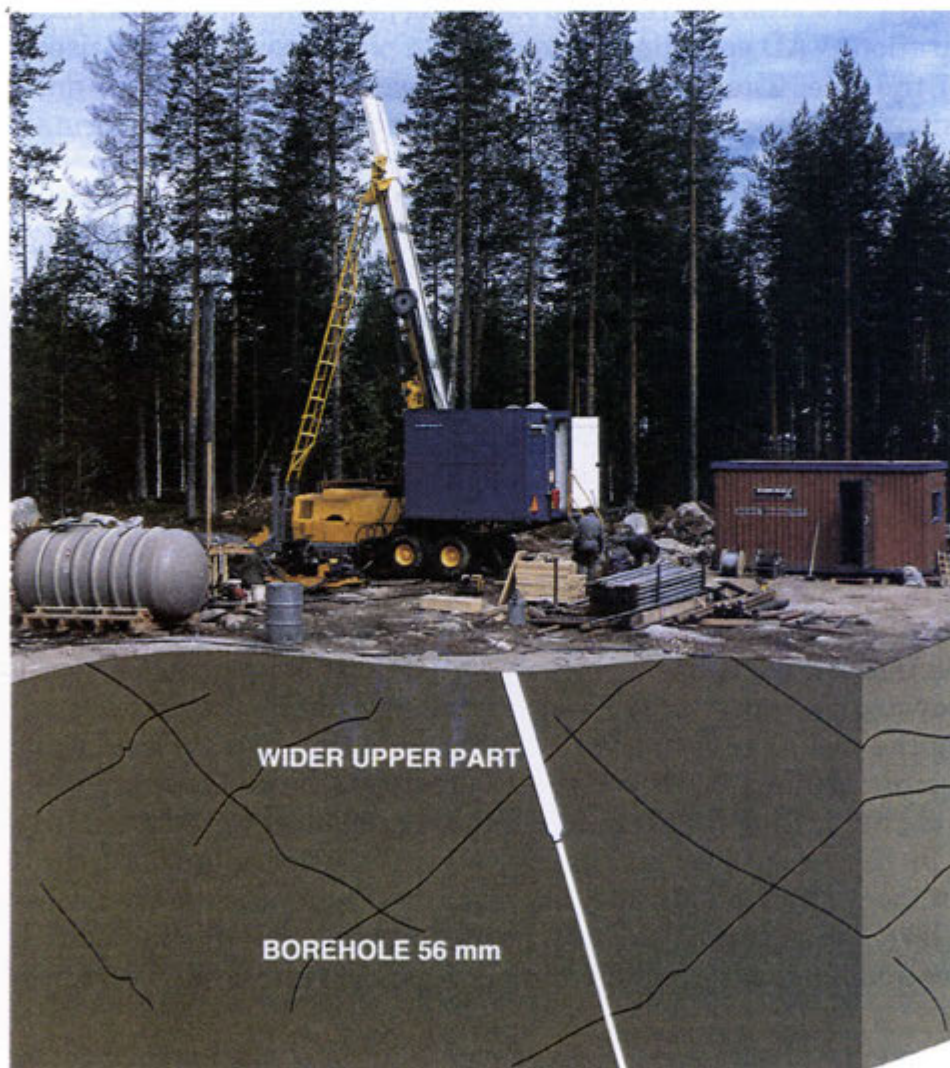


Figure 2.3-1. Core drilling technique used in the site investigations. The upper part was drilled with the down-the-hole technique to a depth of approx. 40 m and lined with steel casing. The lower part of the borehole was then sunk with a T-56 mm core bits.

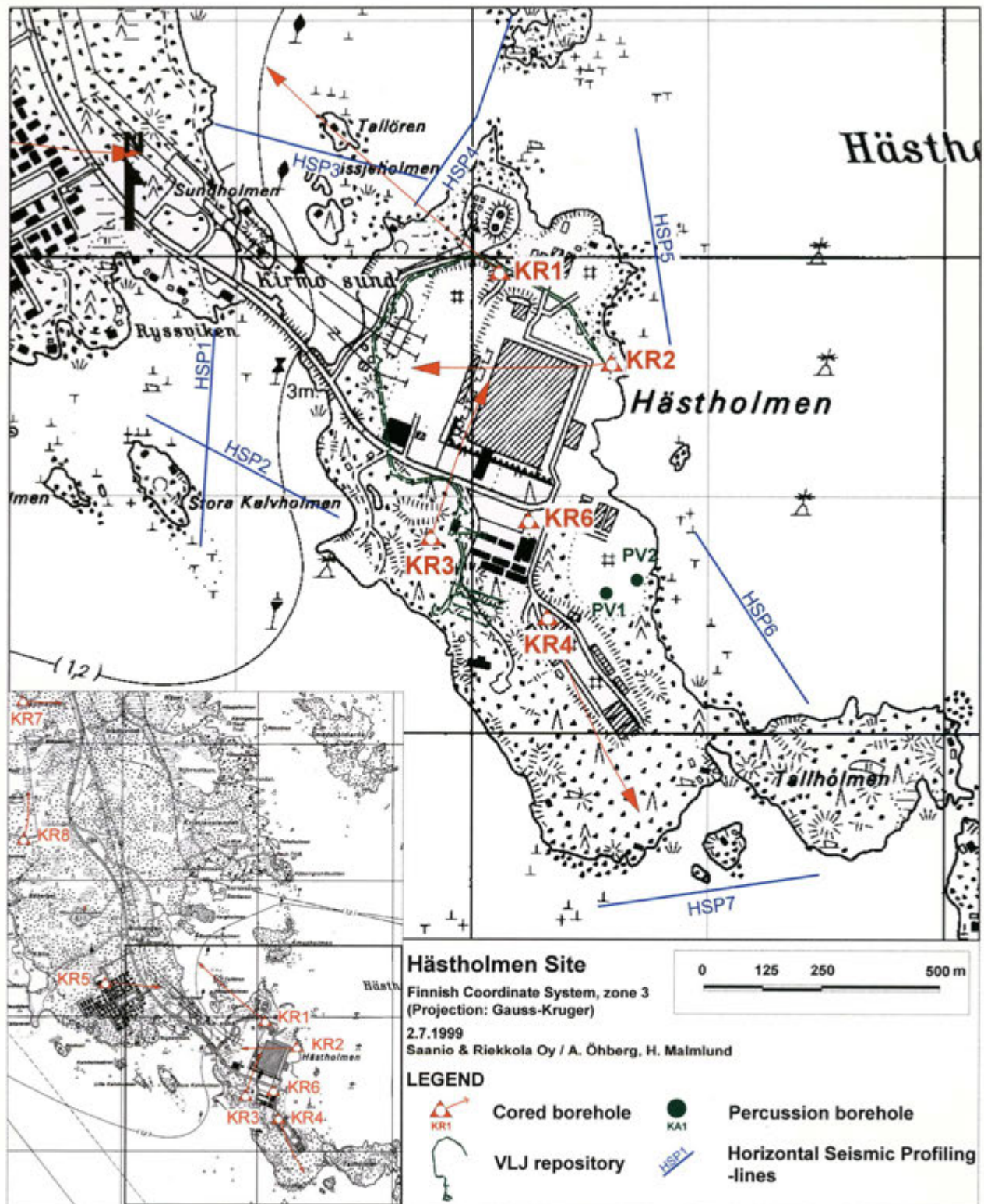


Figure 2.3-2. Most significant investigation boreholes and seabed HSP reflection seismic lines related to detailed site investigations.

and the mapping of potentially hydraulically conductive features have been carried out using similar standard logging methods as those used at the other sites. Fracturing has been studied using new kinds of borehole wall scanning techniques: borehole-TV (Strähle 1998, 1999) and dipmeter (Siddans et al. 1997, 1998). The tools have provided data on the orientation of fractures, on the contacts between the different rock types, on the foliation and on the location of veins. The results obtained with the scanning techniques have in some cases made it possible to determine the locations of single, potentially conductive fractures. Borehole radar measurements have not been performed in the boreholes at Hästholmen due to poor experience in their case at Olkiluoto, where similar saline groundwater conditions limited the radar range with the directional 60 MHz antenna to only 10 - 25 m (Posiva Oy 1996a). VSP-surveys have systematically been carried out using a 3-component geophone system and a new processing and interpretation technique (Cosma et al. 1994a, b, c), which allows for a better characterisation of the structures, including their orientation and continuity, even if they are gently dipping.



Figure 2.3-3. Hydraulic testing unit (HTU) mounted on a trailer. The data acquisition and processing equipment are in a separate compartment in the front part of the trailer. The hydraulic cable winch and instruments for measurement, control and operating can be seen in this picture. The cable is lowered into the borehole through a hatch in the floor.

The electromagnetic frequency soundings (Jokinen & Lehtimäki 1997) have produced additional data on the distribution of saline groundwater and the variations in the salinity and occurrence of fracture zones at Hästholmen. There are, however, difficulties in the application of such electromagnetic methods due to the presence of the sea and the effects caused by the infrastructure of the nuclear power plant (Paananen et al. 1998). Ground-penetrating radar has been used to map the thickness of the overburden at Hästholmen (Sutinen 1997). This technique also produced information on the degree of fracturing. As Hästholmen is an island, it is difficult to obtain information on the rock mass offshore. Fracture zones situated beneath the sea have been studied using the Horizontal Seismic Profiling (HSP) method (Fig. 2.3-2) (Keskinen et al. 1998).

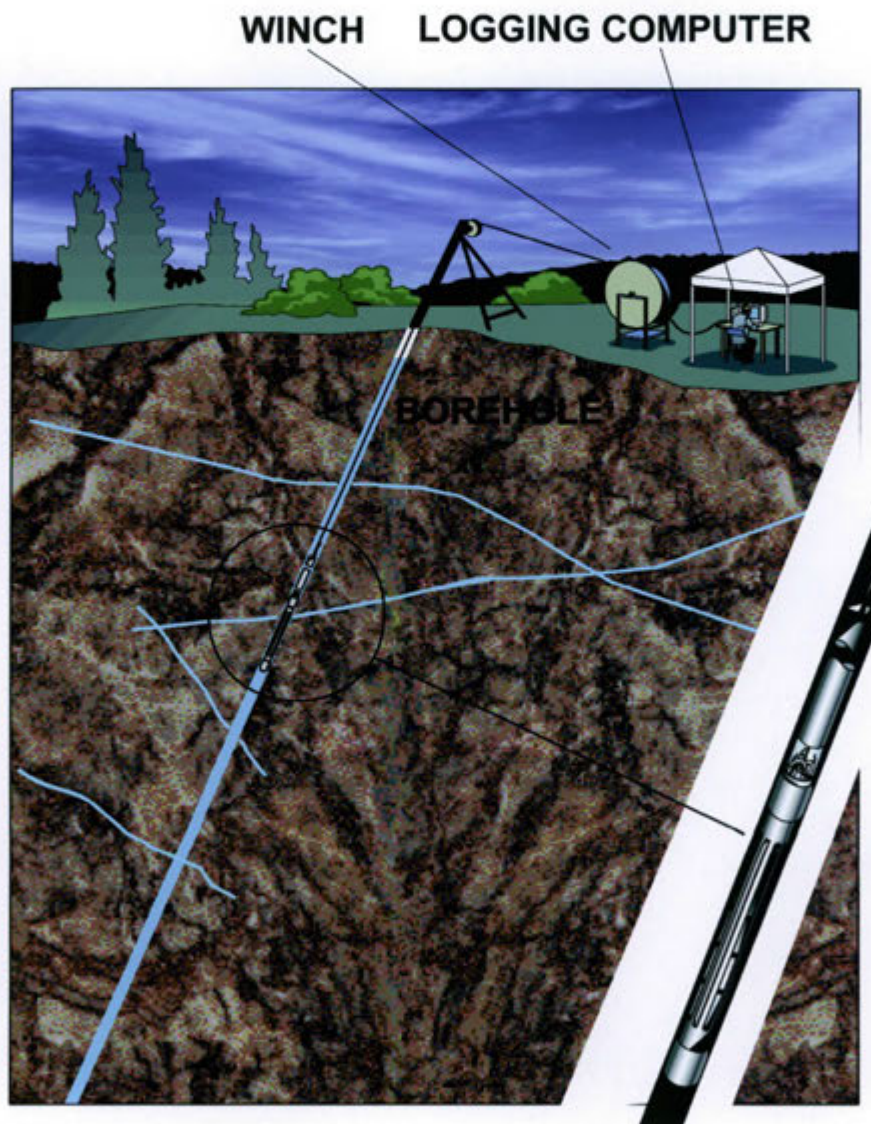


Figure 2.3-4. Principle of transverse flow measurement (left). The section to be measured is 2 m long with inflatable packers at both ends. Four longitudinal sealings separate the section into four sectors. The flow magnitude (ml/h) and the approximate direction of flow is measured with heat pulse flow sensor (right). Radial distribution of hydraulic conductivity can also be measured in connection with flow measurement.

An aerogeophysical survey has also been carried out in the Hästholmen area (Multala & Hautaniemi 1997). Its primary purpose was to examine the occurrence of different rapakivi granite phases using magnetic measurements, but electromagnetic and radiometric measurements were also included. The interpretation of the aerogeophysical measurements is presented in Paananen & Paulamäki (1998).

Rock stress measurements have been carried out using the 3D overcoring technique in borehole KR6. The initial plan was to carry out measurements at three depths of 300, 450 and 600 m, but due to rock mechanical problems, in the form of core discing, the programme had to be rearranged. The only measurements that were obtained, and these were only partially successful, were between depths of 297 and 360 m. Below that core discing prevented successful testing, although several attempts were made (Ljunggren 1998). Difficulties were also encountered with the measurements recently being made using the hydraulic fracturing method. The results from these tests will be reported in 1999.

Geological investigations have included a study of greisen veins at Hästholmen and in the surrounding area and an appraisal of the mineralisation potential of the veins (Kuivamäki et al. 1997b).

The Romuvaara, Kivetty and Olkiluoto investigation sites have been equipped with integrated GPS monitoring systems to investigate any current deformation of the bedrock (Hinkkanen et al. 1996). It was not considered necessary to monitor the stability of the bedrock at Hästholmen, however, because there is a measuring station of the permanent GPS network operated by the Finnish Geodetic Institute in Virolahti, about 70 km east of the site (Ollikainen et al. 1997). A study by Saari (1996) concerning the seismicity in the Loviisa area also uses data obtained from the investigations carried out for the nuclear waste disposal.

2.4 Rock Modelling

2.4.1 Interpretation Process

The interpretation and model development process has had a very central position in the site investigations, starting from the processing of data and the interpretation of models for each geological and geophysical survey and continuing to the multi-disciplinary integration and assessment of all the results. Geophysical surveys which have a high resolution combined with significant investigation ranges have been important in the investigation of large volumes of the rock mass. An assessment of the particular methods of interpretation of such surveys is beyond the scope of this report, however examples of practical work in this area can be found in Pitkänen et al. (1991), Paulamäki & Paananen (1991, 1996) and Front & Okko (1996). The major categories of interpretation work have been those associated with surface surveys, borehole measurements, from surface to borehole measurements and interpretation and vice versa, cross-hole surveys and the interpretation of surveys which could not be tied into borehole data. Hydrogeological interpretations and the techniques applied are summarised by Ylinen & Väättäinen (1993) and Ahokas et al. (1997). A description of the process associated with the transfer of the interpreted data to the geological conceptual model is presented in Saksa (1995).

An important issue is the conceptual basis which is applied in the interpretation process. Of particular interest in this regard with reference to the Hästholmen site is how fracture zones have been defined and what assumptions have been made regarding their properties, their planar geometry and their mutual relationships. Different classes of fracture zone have been used which have been based on the intensity of the fracturing and weathering and on the hydraulic properties, and also on expert judgement. A description of the development of these classes of fracture zone is presented in the summary reports listed above. In addition, the properties of these zones and the definition of their boundaries have been analysed by principal component analysis and using the so-called Fracture Zone Index (Olsson et al. 1992, Korkealaakso et al. 1994). The genesis of fracture zones and their geometries was investigated by carrying out a literature review (Front & Okko 1994) to find out whether the modelling approach being applied should be modified. The main conclusion of this review was that the number of drilled boreholes in an investigation programme should be large enough to enable a reliable structural interpretation of the fracture zones to be carried out. Deviations from planarity in fracture zones in similar rocks to those at Hästholmen have been detected in underground research laboratories (URLs). However, rock mass models developed in URL programmes have been developed successfully using this planar fracture zone approach, and a similar assumption of planarity has been assumed to be appropriate here.

A single-phase site investigation programme has been carried out at Hästholmen for spent fuel disposal purposes from 1996 - 1997. There has been no testing, yet, of the assumptions and hypotheses regarding the rock mass parameters and the models developed.

2.4.2 Computer Modelling

Lithological and structural models of the rock mass have been developed for the Hästholmen site. All the structures described consist of varying types of fracture zones. These two models are used to develop a bedrock model which is compiled using computer-aided geological ROCK-CAD modelling system (Saksa 1995) which contains all the necessary modules to allow for the efficient construction of complicated 3D geological models. It is able to handle boreholes and their associated data, a variety of coordinate systems and grids and can display geological fill symbols and colour patterns. It features a rock object database and possesses its own parametric high-level definition language. Surface topography can be included in the modelled objects. ROCK-CAD takes care of the 3D assembly and the graphics presentation. Different submodels, representing specific volumes of the rock mass, can be constructed and viewed. The system has been used in modelling the spatial distribution of rock types, structures (i.e. fracture zones) and the geometry of hydraulically important features. Output can be presented as maps, cross-sections or perspective views in vector or raster format.

The software has improved the assessment of the sites studied and has provided a better method of documenting the interpretation and modelling work. It has replaced hand-drawing and has enabled the digital transfer of data for numerical analysis, such as in the development of groundwater flow models or in repository design. The data flow in the software and use of the system is illustrated in Figure 2.4-1.

The development of the models for the Loviisa H stholmen site has taken place mainly within a single-phase programme. When possible, interdisciplinary and iterative processes have taken place. The preliminary VLJ site characterisation programme from 1980 to 1993 resulted in the development of the first model of the rock mass for the H stholmen area (version 1.0) (IVO International Oy 1996, Lindh et al. 1997). Site investigations for spent

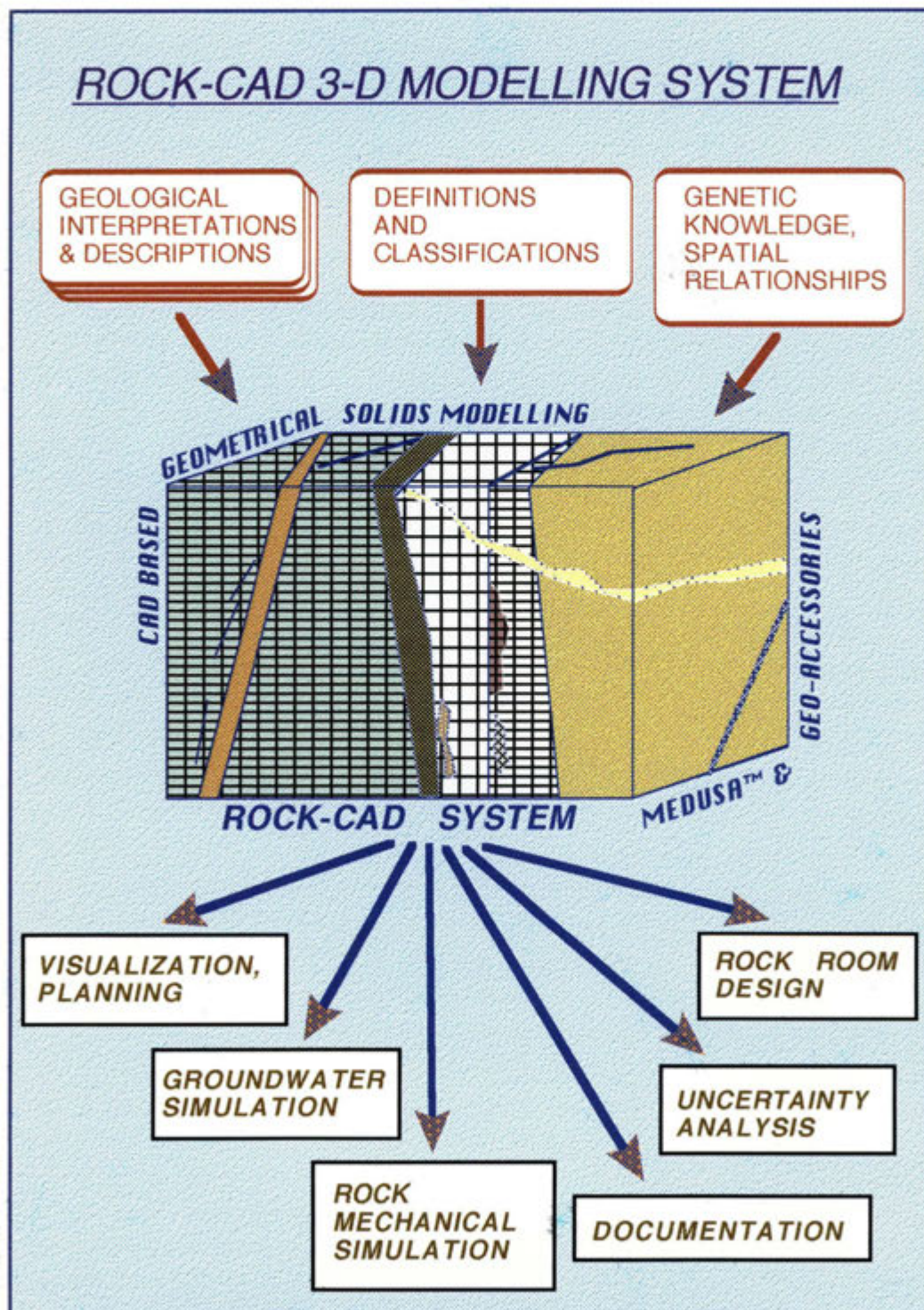


Figure 2.4-1. ROCK-CAD system use and data flow (Saksa 1995).

fuel disposal started in 1997, have involved the investigation of a larger volume of the rock mass and have increased the understanding of the site. The number of lithological and structural units identified in the model of the rock mass has increased considerably. Investigations at the site as well as the assessment of the site from 1997 to 1998 have resulted in the production of a revised model, version 2.0 (Lindh et al. 1998). This model includes all the data from boreholes KR1 - KR3 and part of the data from borehole KR4.

Modelling work has focussed mainly on the interpretation of the geometry of the hydraulically-conductive fracture zones and the parameters describing their properties. The geometry and properties of the fracture zones were also assessed in cases when there was no direct observation of hydraulic conductivity values that were greater than what might be expected in the intact rock. This was considered necessary because the hydraulic conductivity of structures can vary greatly from one observation point to another (i.e. values of hydraulic conductivity within what might be considered, from other evidence, to be associated with a fracture zone could be in places no greater than those expected for the intact rock).

A starting point for the 3D structural interpretation has been the assumption of a linear continuity in structural properties and the planar form of fracture zones. The extrapolation or interpolation of structures between boreholes, or between these and the ground surface, has been based almost entirely on the assumption of planar continuity, unless other additional geological information was available. The assumptions made and the specific aim of combining the observations in the manner described led to a straightforward manner of visual presentation for these zones. The assumptions made also resulted in a simplification of the geological structures used in the models (compared with their actual, but largely unknown properties) and may have resulted in an increase in their continuity, i.e. making them more continuous than would be the case in reality.

2.5 Definition of Structural Terms of the Bedrock

The terminology used in the present report has been developed over the period of the site characterisation programmes in Finland and has been previously applied in several of the reports. The terms mainly concern the description of the geological and structural features of the bedrock, and those most frequently used in the reports are defined below.

A classification of the lineaments (which, from the outset of the site selection programme have been assumed to be fracture zones) was developed by the Geological Survey of Finland for the site selection studies (cf. Section 2.1) in order to describe the regional structures of the bedrock (Salmi et al. 1985). The classification is based on the interpretation of lineaments from maps, aerial photos and satellite images, with the assumption that these lineaments represent more densely fractured or crush zones of the bedrock, which can typically be seen as elongated depressions. This assumption can be shown to be generally valid for the geological environment of Finland and is, in any case, a conservative assumption with regard to the disposal of radioactive waste. In a regional context, the terms *lineament* and *fracture zone* or *crush zone* can be regarded as being synonymous. The classification of these lineaments or fracture zones is presented in Table 2.5-1.

The Finnish engineering geological classification has been applied in this report, in particular for the description of the fracturing of the rock mass, and for the structural modelling of the bedrock. The classification (Korhonen et al. 1974, Gardemeister et al. 1976), which is published only in Finnish, was developed with reference to the specific bedrock conditions found in Finland, and was designed to be applied to construction activities. The criteria used in this classification system are:

- the properties of the rock mass (consisting of its state of weathering, the orientation of any internal structure, its grain size and its major minerals) and
- the fracture properties (geometry of fracturing, fracture frequency and type of fractures) which together determine the rock quality.

A simplified description of rock quality based on this classification system is given in Table 2.5-2.

The structural solidity of the rock mass is divided into three classes: *intact*, *loose* and *broken rock mass*. In this report only the classes intact and broken are applied, because rock in the loose rock mass class has not been found. The rock is regarded as broken if the number of fractures is more than 10 fractures/m (fractures of core samples per metre) (as measured from samples of drill core), it is dominated by filled and/or open fractures, or it is mesoscopically weathered.

The key terms used in the structural modelling (cf. Sections 2.4 and 5) are defined as follows:

A *structure* in a rock is any geological feature defined geometrically (Kearey et al. 1993). A *tectonic structure* is produced by deformation and is synonymous with the use of the term *deformation structure*. In this report the use of the term structure implies a tectonic structure, unless otherwise stated. Every *structure* (or R-structure) in the bedrock model has a unique object name (i.e. R(number)) and is accompanied by information which describes the attributes of the structure, e.g. its fracture density, its transmissivity, etc. The term R-structure is specially used in Section 6 for separating the modelled structures (fracture zones) from other hydraulically conductive features included in the rock mass.

A *fracture zone* is a general term describing varying types of fracture structures as shown in Table 2.5-1 or a structure in the bedrock model with block-structured or fracture-structured properties (RiII or RiIII), as explained in Table 2.5-2.

A *major fracture zone* contains crush-structured (RiIV) portions (Table 2.5-2). A *crush zone* contains clay-structured (RiV) portions. The classification of such zones can also be based on the quantitative interpretation of their properties or, where only indirect evidence is available, on expert judgement (Table 2.5-1).

In this report the term *intact rock* is synonymous with the term *averagely fractured rock mass* which has been used commonly in other radioactive waste disposal programmes (e.g. that in Sweden). The intact rock contains all types of fractures and fracture zones, both known and unknown, but only those which are *not* defined as structures in the bedrock model for the site.

The term *zone* (e.g. fracture zone) refers to a geometry in which the dimensions along the strike and along the dip direction of the zone are considerably larger (≥ 10) than its perpendicular thickness. The geological terms used in Sections 3 and 4 are defined, e.g. in Bates and Jackson (1980).

Table 2.5-1. Classification of the lineaments or fracture zones according to Salmi et al. (1985).

Class	Width of the fracture zone	Length of the fracture zone	Supposed depth extent of the fracture zone
I	> 1 km	from tens to hundreds of kilometres	> 10 km
II	100 - 1 000 m	from 5 to tens of kilometres	from several kilometres to 10 km
III	10 - 100 m	2 - 5 km	> 1 km
IV	<< 10 m	100 m - 2 km	<< 1 000 m

Table 2.5-2. Rock quality description according to the Finnish engineering geological classification (Korhonen et al. 1974, Gardemeister et al. 1976).

Structural solidity of rock mass	Structural types of rock mass	Structural types and frequency of fractures (described in terms of the most dense fracturing) ¹	Hardness and toughness of main rock types
Intact rock mass	Mass-structured	Sparsely fractured Slightly fractured Abundantly fractured	Soft Brittle Tough Hard
	Schistose structured	Sparsely fractured Slightly fractured Abundantly fractured	
	Mixed-structured	Sparsely fractured Slightly fractured Abundantly fractured	
	Loose-structured	Sparsely fractured Slightly fractured Abundantly fractured	
Loose rock mass	Weathered-structured (Rp0 - Rp3) ²	Should be described as thoroughly as possible bearing in mind the degree of weathering	
	Cleft-structured (RiI)	Planar fractures divide the rock mass into two or more separate sections	
	Block-structured (RiII)	Abundantly fractured	No fracture filling
Broken rock mass	Fracture-structured (RiIII)	Densely fractured	Little filling in fractures
	Crush-structured (RiIV)	Abundantly or densely fractured	Fractures filled with clay minerals
	Clay-structured (RiV)	–	Abundantly clay material in rock mass

¹ Sparsely fractured: <1 fractures/m
Slightly fractured: 1-3 fractures/m
Abundantly fractured: 3-10 fractures/m
Densely fractured: >10 fractures/m

² Rp0: Unweathered
Rp1: Slightly weathered
Rp2: Strongly weathered
Rp3: Completely weathered

3 LOCATION AND REGIONAL SETTING

3.1 Location and Topography

The Hästholmen site comprises the island of Hästholmen and its immediate area on the mainland, located about 10 km southeast of the centre of the town of Loviisa and 80 km east of Helsinki (Fig. 1-1). Two units of the Loviisa nuclear power plant are situated within the study site, as well as the VLJ repository for low- and intermediate-level reactor waste.

The area has a subdued, prominently NNW-SSE oriented topography, being in most places less than 10 m above the sea level, with the greatest elevation of approx. 16 m in the middle of the study area (Fig. 2.2-2). The highest parts of the island rose above the sea level about 4 000 years ago, the current annual uplift rate being 2 - 3 mm a year (Ekman 1996). The sea bottom immediately offshore has a general elevation of between -5 m and -10 m. In the sea area east of Hästholmen there is a clay- and till-filled basin, where the rock surface descends to a depth of ca. -70 m (Anttila 1988, Rantataro 1996). Another basin, trending NW-SE, and with a maximum depth of greater than -30 m, has been found southwest of the island. In general, however, the rock surface around Hästholmen is less than 20 m below sea level (Anttila 1988).

The soil cover consists mainly of silty, sandy till, which typically contains abundant surface boulders. The till cover is usually 2 - 3 m thick, but in places may be about 8 m, the thickest and most continuous layers being in the eastern and southern parts of the island (Anttila 1988). The area is rather well exposed, the outcrops comprising about 6% of the total area and being most abundant in the western part of the island. The Quaternary deposits on the sea bottom consist mainly of till, gravel and sand, overlain by silt and clay in the sub-sea depressions (Anttila 1988).

3.2 Regional Geology

The crystalline bedrock of Finland (Fig. 3.2-1) is a part of the extensive Precambrian Fennoscandian Shield. The oldest part of the Finnish bedrock is the Archaean basement complex (3 100 - 2 500 million years in age) of northeastern Finland which consists mainly of tonalitic and granodioritic gneisses (Gaál & Gorbatshev 1987). Within the basement complex are narrow Archaean greenstone belts, which are composed of metavolcanics and metasediments. The majority of the Finnish bedrock is comprised of Palaeoproterozoic metamorphic and igneous rocks. Its long history of volcanism, sedimentation and igneous activity culminated in the Svecofennian orogeny 1 900 - 1 800 million years ago (Koistinen 1996). Later the crust was intruded by anorogenic rapakivi granites, 1 650 - 1 540 million years in age, which originated from partial melting of the lower crust. The youngest basement rocks are the Jotnian sandstones (1 400 - 1 300 million years) which are cut by Post-jotnian olivine diabase dykes, 1 270 - 1 250 million years in age, and the 1 100 and 1 000 million years old dykes of Salla and Laanila in northern Finland. The bedrock had been eroded almost to its present level before the beginning of the Cambrian (about 600 million years ago). Due to subsequent erosion and continuous continental conditions, it is almost totally lacking in sedimentary rocks younger than the Precambrian.

Bedrock of Finland

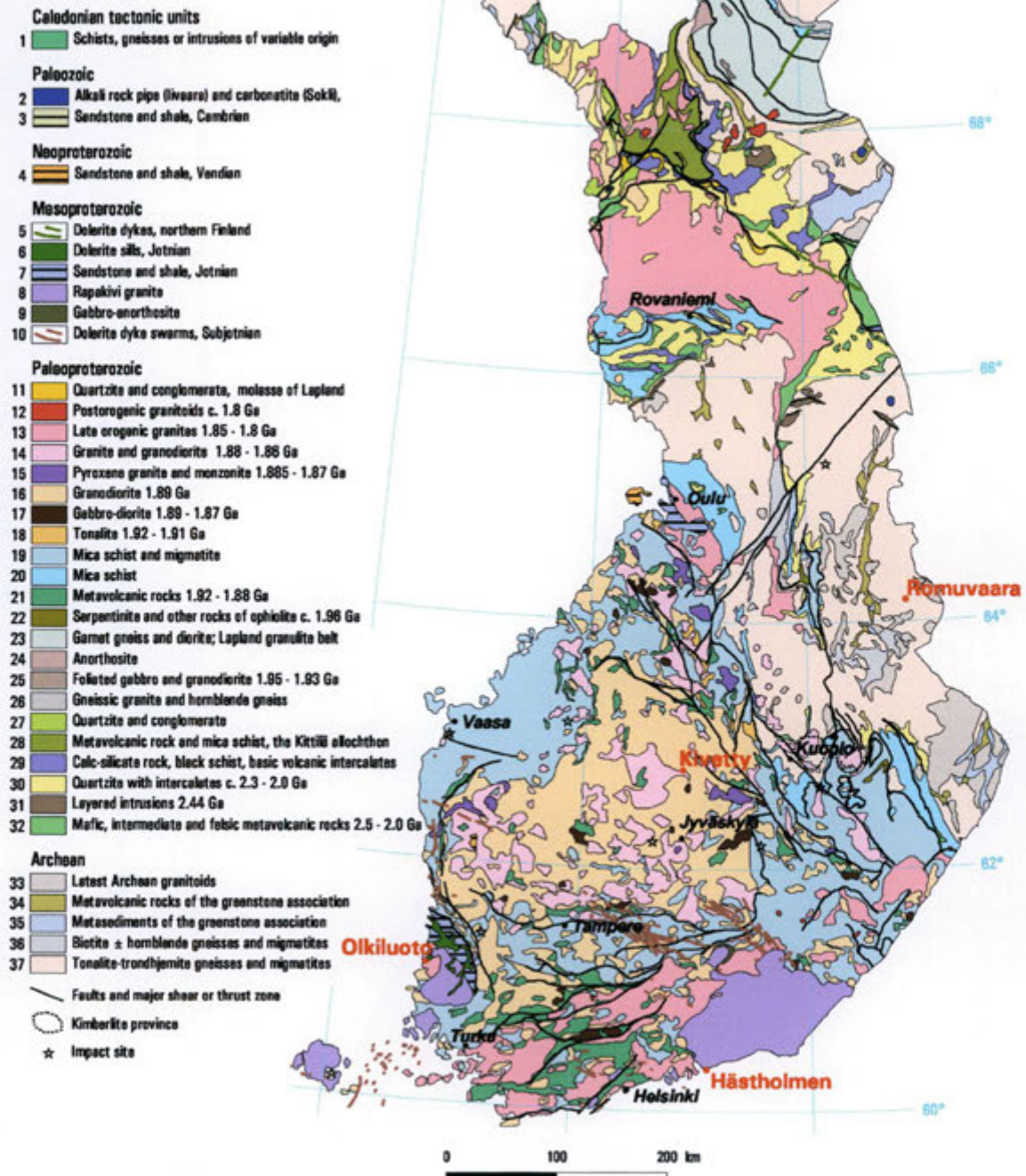


Figure 3.2-1. The bedrock of Finland (Geological Survey of Finland 1999).

The Hästholmen study site is situated within the southwestern part of the anorogenic Wiborg rapakivi batholith (Fig. 3.2-2). The age of the batholith is 1 650 - 1 620 million years, the emplacement of the rapakivi having occurred after the main phase of the Svecofennian orogeny (1 900 - 1 800 million years). The exposed parts of the batholith cover an area of about 18 800 km² on both sides of the Finnish-Russian border and it continues for about 20 km to the south of Hästholmen under the Gulf of Finland, where it is in contact with the Svecofennian rocks (see Koistinen 1994). The Precambrian basement dips very gently (at less than 0.5°) southwards towards Estonia and the St. Petersburg region of Russia, where it is overlain by hundreds of metres of Vendian and Phanerozoic sedimentary rocks (Puura et al. 1996).

The country rocks southwest from the rapakivi batholith are composed of Palaeoproterozoic Svecofennian metamorphic and plutonic rocks (Fig. 3.2-2). The metamorphic rocks are of sedimentary and volcanic origin, including quartz-feldspar gneisses, mica gneisses, amphibolites, hornblende gneisses and uralite and plagioclase porphyrites (Laitakari & Simonen 1963, Laitala 1984). The plutonic rocks include peridotites, gabbros, diorites, granodiorites and abundant granites. The Onas granite pluton, 1 630 million years in age, occurs in the southwestern part of the Svecofennian area (Fig. 3.2-2). It consists of medium- to coarse-grained red granites and has sharp contacts against the country rocks with associated intrusive breccias.

Wiborgite, characterised by ovoidal potassium feldspar megacrysts mantled by plagioclase, comprises over 80% of the Finnish part of the Wiborg rapakivi batholith (Simonen & Vormä 1969). Other rapakivi granite types include pyterlite (rapakivi with ovoidal potassium feldspar megacrysts are usually lacking in the plagioclase mantle), porphyritic rapakivi granite with angular potassium feldspar megacrysts, dark-coloured, even-grained, hornblende- and fayalite-bearing rapakivi granite, even-grained rapakivi granite and porphyry aplites (Vormä 1971). The dyke rocks are granite porphyry, porphyry aplite, aplite and quartz porphyry. The rapakivi magmatism is bimodal in nature, the above rock types representing the silicic suite, whilst the gabbro, anorthosite and diabase, which are associated spatially and temporally with the granites, comprise the mafic suite (Rämö et al. 1994).

The Finnish word *rapakivi* (crumbling stone) refers to its special kind of weathering, the ultimate result of which is the granular disintegration of the rapakivi granite into a saprolite of *grus* type, locally known in Finnish as *moro*. Within the Wiborg batholith two types of weathering can be distinguished, the commonest of which results in the disintegration of the matrix around the potassium feldspar ovoids into a gravelly sand, the ovoids themselves remaining less weathered (Kejonen 1985). The other type of weathering causes what is known as microsheeting, which intersects all minerals randomly and develops subconformably to the rock surfaces and or primary jointing planes. Bulk weathering of the rock mass in general occurs only occasionally and the weathering products are more common and thicker in the central part of the batholith, where they are 1 - 3 m thick, than on the margins, where they are <1 m (Kejonen 1985). The weathering has penetrated to as much as 10 m from the surface and, in places, occurs as horizontal sections between portions of intact rock.

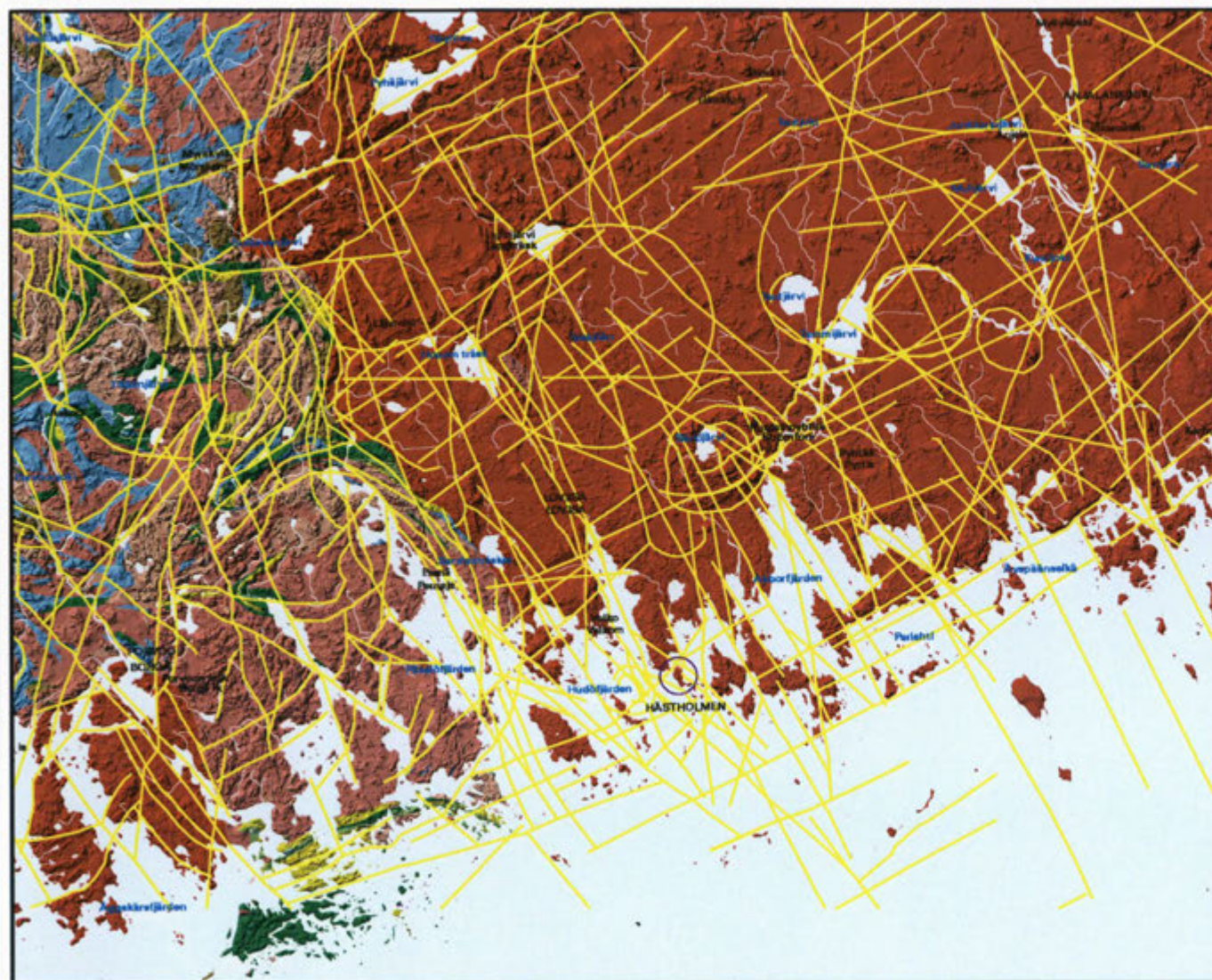
Geophysical data suggest that the batholith consists of a relatively thin sheet-like body, about 10 km in thickness (Luosto et al. 1990). The magnetic and gravity anomalies within the batholith provides evidence that it consists of separate intrusions and intrusion phases (Elo & Korja 1993). According to the seismic soundings, a 6 km thick body, interpreted as gabbro-anorthosite, lies beneath the batholith at a depth of 10 km. The batholith has sharp, outward dipping contacts against the country rocks. Vormaa (1972) describes a contact metamorphic aureole around the batholith, which is defined by the inversion of orthoclase to microcline. The aureole is less than 5 km wide in the northeastern part of the batholith and has a similar width or is slightly narrower in the southwest. Roof pendants are common, composing of migmatite-forming granite in the western part and diabase in the northeastern part of the batholith (Vormaa 1975, Simonen 1987).

Uneconomic greisen- and vein-type Sn-polymetallic mineralizations have been found in connection with the late-stage topaz-bearing microcline-albite granites, which resemble the Phanerozoic tin-bearing granites (Haapala 1977, Edén 1991).

The lineaments shown in Figure 3.2-2 are based on the interpretation of 1:400 000 satellite images, 1:100 000 hill-shaded topographic relief maps, combined with bedrock maps and maps of Quaternary deposits, high-altitude aeromagnetic maps and seafloor maps, showing the depth to the bedrock surface obtained from the offshore sonar surveys (Kuivamäki et al. 1997a). The lineaments are interpreted as regional fracture zones and are reflected in the surface topography in the form of elongated depressions and lakes. The Hästholmen area is dominated by NW-SE and NE-SW trending fracture zones, which divide the bedrock into blocks of variable shape and size. The most prominent swarms of NW-SE trending fracture zones occur in Ruotsinpyhtää, in the Bay of Loviisa and especially at the western contact between the rapakivi batholith and the Svecofennian country rocks in the Pernaja area. The most notable NE-SW trending fracture zones are present offshore, south of Hästholmen. East of Lake Hopjärvi there is a large circular structure in the magnetic map which, according to the interpretation of Elo & Korja (1993), represents a strongly magnetised body, the upper surface of which lies at a depth of 12 - 15 km and which extends to the base of the crust. Several smaller circular structures are revealed by topography and bedrock maps in the vicinity of this large structure, e.g. around Lake Särkijärvi.

The most common soil types in the area shown in Figure 3.2-2 are till and clay (Valovirta 1972, Tynni et al. 1976, Punakivi et al. 1977). Till deposits are predominantly sandy, and are usually thin, and within the rapakivi area, are associated with abundant surface boulders. The accumulation forms of till have usually no clear orientation, however, small end moraines occur both within the rapakivi batholith and in the Svecofennian area. Glacial striae demonstrate that the older movement of the continental ice sheet was from the northwest (315 - 330°) and the younger one almost from the north (350 - 360°). Abundant clay deposits, in some places over 20 m thick, are present in river beds, hollows and valley bottoms, the most extensive deposits occurring in the northern part of the rapakivi area. Deposits of sand and gravel include thin and small shore deposits and a few discontinuous eskers trending roughly NW-SE. Peat bogs cover 10 - 15% of the land area in the region.

Figure 3.2-2. Regional geology of the Hästholmen study site.



Regional geology of the Hästholmen area



GEOLOGICAL SURVEY OF FINLAND
Regional office for South Finland
Espoo 1998

Palaeoproterozoic rocks

- Mafic metavolcanics
- Intermediate metavolcanics
- Mica schist and gneiss
- Quartz feldspar gneiss/schist
- Gabbro
- Granodiorite or tonalite
- Granite
- Pegmatite

Mesoproterozoic rocks

- Rapakivi granite
- Watercourse
- Topographic lineaments

Map of Pre-Quaternary Rocks © Geological Survey of Finland
Digital elevation model and base map © National Survey of Finland,
permit No 13/mat/98
Hillshading is from NW, angle is 45 degrees.



3.3 Regional Hydrology

The Hästholmen site is located on the island of Hästholmen and on the mainland north-west of the island (Fig. 2.3-2). Both areas form a hydrological unit of its own. The site differs in this respect from Romuvaara and Kivetty, which are parts of larger drainage system. The surface waters from Hästholmen thus flow directly into the sea. The official annual precipitation figure for this region in 1961 - 1990 was about 600 mm (Finnish Meteorological Institute 1991), although actual precipitation, after correction for observational errors, is likely to be some 10 - 20% greater (National Board of Waters 1980). About 60 - 70% of this precipitation evaporates and the remainder provides runoff into streams and the sea (Solantie 1987).

3.4 Climate

3.4.1 Climate Past and Present

Glaciations have occurred periodically for at least the last 900 000 years (Eronen 1991). There is also overwhelming evidence that the timing and extent of glaciations are triggered by small periodic changes in the Earth's orbit around the sun (the so-called Milankovitch orbital parameters), resulting in changes in the solar radiation reaching the Earth.

The most reliable evidence for the impact of previous glacial advances is obtained from the most recent ones, which are known as the Saalian and the Weichselian. The Saalian began about 200 000 BP (Before Present), and is sub-divided into an older period known as the Drenthe and a younger period, the Warthe. During the Drenthe period an extensive ice sheet covered the whole of Scandinavia, northern Europe and the majority of Ireland and Great Britain (Eronen 1991), and may be the largest to have developed in Europe in the last few hundred thousand years. The centre of the Saalian ice sheet was most probably located over the northern part of the Gulf of Bothnia or in northern Sweden, where its thickness was over 3 km. Deglaciation at the end of Saalian was rapid and semi-continuous (Eronen & Lehtinen 1996).

Rapid climatic warming began in the Eemian interglacial (warm period) about 130 000 BP. During the Eemian maximum temperatures were generally considerably higher than the present ones and the sea level has been estimated to have been 5 - 6 m higher (Zagwijn 1983). During this period the Eemian Sea was saline and was connected to the Arctic Ocean through the Karelian Sea and the White Sea and also to the Atlantic Ocean through the strait of Denmark. Isostatic uplift, however, caused the Karelian connection to be closed in the early Eemian (Forsström et al. 1988). Diatoms found in the Eemian Sea sediments indicate that the salinity was higher than during the period of the Litorina Sea, which occurred after the Weichselian glaciation. The climate at this time was probably humid and warm with a mean annual temperature at the beginning of Eemian 4 to 5°C higher than at present. The seawater, however, was probably not warmer than at present because of the connection of the Eemian Sea to the Arctic Ocean. The rates of isostatic uplift at the end of the Eemian are thought to have been similar to those of the end of the Weichselian (Eronen & Lehtinen 1996).

According to Eronen & Lehtinen (1996), the climate became rapidly colder in the late Eemian resulting in glaciation at the beginning of the early Weichselian, about 117 000 BP. The extent of ice sheets during early-Weichselian times is unknown. Information about this period, when the Hästholmen area may have been free of ice at least periodically, would be of interest, since long periods of cold climate with no ice cover could have resulted in the formation of deep permafrost.

Climatic deterioration began at 75 000 BP and the climate was at its coldest during 20 000 - 18 000 BP when the ice sheet was largest, extending to eastern and central Europe (Fig. 3.4-1). The centre of the ice sheet was in northern Sweden, where it was also thickest, over 3 km (Fjeldskaar 1994, Ehlers 1994, 1996). At the southern and eastern margins of the ice sheet a broad zone of tundra vegetation and permafrost extended over large parts of Europe (Eronen & Olander 1990). It seems that the Weichselian ended rather abruptly at 13 000 BP when the climate underwent rapid warming and temperatures became close to the present ones. Climatic deterioration however occurred again around 11 000 BP with mean annual temperatures being lowered by 5 - 7°C in a few decades (Mangerud 1987, Mayewski 1994) and with a concomitant advance in the ice sheets. At about 10 000 BP

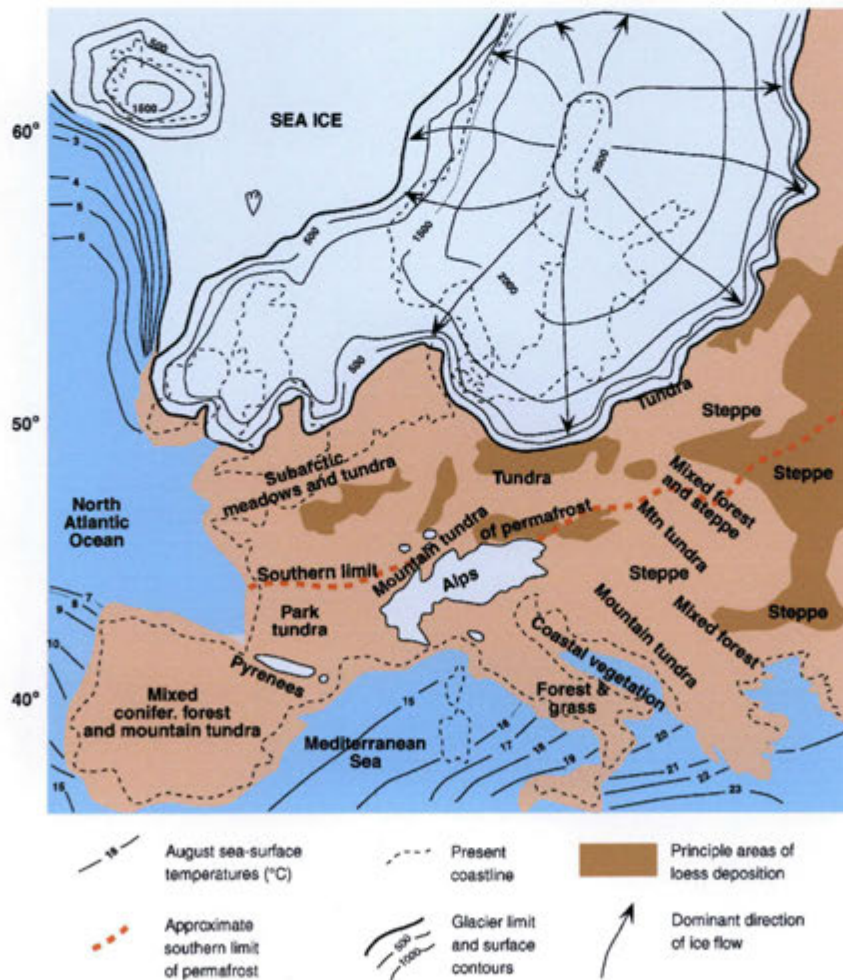


Figure 3.4-1. A reconstruction of the palaeogeography of northern and western Europe during the last glacial maximum, about 18 000 BP according to Skinner & Porter (1987).

temperatures again increased rapidly and evidence from glaciers in Greenland, in the form of oxygen isotope analyses, shows that the mean annual temperature rose about 7°C in 10 years (Dansgaard et al. 1993, Mayewski 1994) with the result that Finland was free from ice at about 9 000 BP (Taipale & Saarnisto 1991).

The Hästholmen area became free of ice at about 11 700 BP (Forsström 1999), but was submerged beneath the freshwater lake, the Baltic Ice lake, formed from glacial meltwater. Further retreat of the ice opened a connection to the North Sea draining the freshwater lake and resulting in the formation of the Yoldia Sea at about 10 000 BP, and the submergence of the Hästholmen area by up to 100 m (Crawford & Wilmot 1998). At about 9 300 BP the saline Yoldia Sea became diluted with glacial meltwater, and a freshwater lake, known as the Ancylus Lake, formed within the Baltic Sea basin. At about 8 000 BP, continued eustatic uplift caused sea water to enter the Ancylus Lake via the Danish Straights, and water in the Baltic Sea basin changed slowly to brackish. At about 7 500 - 7 000 BP this saline water had spread to the whole Baltic Sea basin and the Litorina Sea - stage began (Eronen & Lehtinen 1996). The Hästholmen area remained submerged by water depths of 30 - 50 m (Crawford & Wilmot 1998). Following the Litorina transgression there have been no significant changes in the development of the Baltic Sea. Over the last 6 500 years uplift has resulted in a continuing retreat of the coastline around the Baltic Sea, resulting in emergence of new areas of land, and the associated narrowing of the Danish Straights has caused a decrease in its salinity. The island of Hästholmen emerged from the Litorina Sea about 3 800 BP. According to the shore line displacement curve the uplift rate has been greater during and immediately after deglaciation than at present, and it has been steady for the last 3 000 years, at about 2 mm in a year (Miettinen et al. 1999). Pässe (1996) calculated a further uplift of about 45 m over the next 10 000 years for central Sweden, and this continued uplift means that the Hästholmen area will lie at some distance from the coast by the time of the next glaciation (Crawford & Wilmot 1998). The emergence of the Hästholmen area occurred after the temperature maximum had taken place and the development of the present vegetation was complete.

Temperatures at 9 000 BP were probably close to those of today and summers are likely to have been warmer. The climate was at its warmest at 6 000 - 5 000 BP. Over the last 5 000 years the climate has slowly become generally colder, and from about 2 500 BP generally more humid. Temperature oscillations have also occurred, for example the period between 1 500 and 1 850 is known as the Little Ice Age, because of the lower average temperatures and very uncertain weather, whereas temperatures have risen throughout most of this century (Eronen 1990a, 1991, 1996, Eronen & Zetterberg 1996).

3.4.2 Future Climates

It is believed that the world's climate will be dominated by glaciations in the near few hundred thousand years in the same way as it has been for the past million years. This forecast is based on the last 20 years of research, which have concluded that future predictable changes in the Earth's orbit enable general predictions to be made of future climate changes. These predictions are based on climate models, such as ACLIN (Astronomical Climate Index) (Kukla et al. 1981), the Imbrie & Imbrie (1980) model of future climate and the LLN 2D model (Berger & Loutre 1997).

Astronomical data suggests that we are presently approaching the end of an interglacial period, with the climate slowly changing towards periglacial and possibly glacial conditions. Anthropogenic (human) effects, such as greenhouse warming may, however, delay the development of glacial conditions (Ahlbom et al. 1990). Forsström (1999) have suggested the following two ice age scenarios (A and B) based on the output from the ACLIN, the Imbrie & Imbrie and the LLN models and the conditions during a glaciation cycle. The LLN models and scenario B of Forsström (1999) take into account the anthropogenic effects, and assume the complete melting of the Greenland ice cap.

Scenario A

The climate at Scandinavia will gradually become colder, permitting the growth of glaciers at 5 000 AP (After Present) in the mountainous area of Norway and Sweden. Gradually the ice sheet will enlarge, so that at c. 20 000 AP ice will cover the most of Sweden and Finland and there will be permafrost in the ice-free areas. During a milder period between 25 000 and 50 000 AP the ice sheet will slowly become smaller, however, northern Finland will remain covered by ice. Permafrost will occur generally and periglacial conditions similar to Greenland will dominate the ice-free areas. The previous period's cold climate will make the ice sheet respond rapidly during the cold glacial phase between 50 000 and 70 000 AP. Ice advance is expected to culminate at 63 000 AP with an ice sheet extending over the whole of Finland. The thickness of the ice sheet in the central part is expected to be 2 km. During the subsequent interstadial phase (a warmer period, which is not as warm as an interglacial), which will culminate in about 75 000 AP, the ice sheet will retreat, however, the Stockholm-Helsinki region is expected to remain covered by ice. During the maximum phase of the glaciation, 80 000 - 100 000 AP, the ice sheet is expected to extend to northern Poland and Germany, and have a maximum thickness of 2.5 km. The associated crustal downwarping will be 600 m in its central part and the global sea-level 100 m below the present. The next warm phase, from 110 000 - 125 000 AP, is expected to have a climate similar to the present one, with the ice sheet melting almost completely. The global sea level will rise to the present level and the highest shoreline in areas around Stockholm and Helsinki will be 100 m above the present.

Scenario B

During the next 25 000 AP the climate at Scandinavia will become cooler, mountain glaciers will enlarge, permafrost will occur in mountainous areas and sea level will drop some meters globally. At this time, the Håstholmen area will still be sufficiently close to the coast for permafrost to be largely absent. However, as the climate cools further and sea level falls in response to global ice sheet expansion, continuous permafrost will develop at the Håstholmen area (Crawford & Wilmot 1998). Between 25 000 - 50 000 AP the climate will become a little warmer than at present, mountain glaciers will melt, the areas of permafrost will reduce in size and sea level will rise some metres to above the present coastline. Around 65 000 AP a rapidly growing ice sheet will cover the whole of Finland and reach as far as Estonia. During the maximum phase of the glaciation, 80 000 - 110 000 AP, the ice sheet will advance and cover almost the whole of the Baltic basin. The next warmer period, 110 000 - 125 000 AP, will result in a retreat of the ice sheet, but the areas around Stockholm and Helsinki will remain covered by ice and the global sea level will be 25 m below the present. According to Crawford and Wilmot (1998) there will be the possibility of a return to climatic conditions similar to those of the present day after 120 000 AP.

The differences between these two scenarios are especially great for the period of the next 50 000 years. However, whichever scenario is assumed, the Hästholmen area is expected to be covered by ice some time during the next 100 000 AP.

According to Forsström (1999) permafrost occurs both during the advance and retreat of ice sheets. The extent and thickness of permafrost during a glaciation phase could, however, vary considerably due to global as well as local conditions. It is therefore not possible presently to suggest a probable maximum permafrost depth, as it could vary from shallow depths to more than 500 m. Crawford & Wilmot (1998), however, suggest that permafrost will develop to the depth of 250 m in the Hästholmen area during the climatic cooling at 15 000 to 20 000 AP. Regardless of the depth of the permafrost, during the freezing process dissolved ions will tend to be concentrated below the permafrost due to a process known as cryogenic metamorphism. If this process continues for a long time, the salinity of the groundwater beneath the permafrost might rise and a downward percolating saline front could develop and extend to great depths due to density inversion, along a large scale penetrating fracture zone (Ahlbom et al. 1990).

In the region close to the ice front, non-saline and oxidising glacial meltwater with high alkalinity may infiltrate to the bedrock due to the development of large groundwater heads (Ahlbom et al. 1990).

According to Bäckblom & Stanfors (1989) evidence of postglacial fault movements have been found in several parts of northern Sweden and Finland, where the postglacial movements have occurred by the reactivation of existing fracture zones. The postglacial reactivation of faults seems to occur at the early phase of rebound, or shortly after the ice front has left an area, which had been covered by a thick ice sheet for an extensive period (Forsström 1999). No evidence has been presented to suggest that these reactivated faults extend to repository depths (Ahlbom et al. 1990), and no evidence for the post-glacial reactivation of existing faults has been found in the Hästholmen area (Miettinen et al. 1999).

The average erosion during a glaciation cycle in the low relief areas of Finland and Sweden is estimated to be 5 - 10 m (Ahlbom et al. 1990) with plucking as probably the most important erosional process related to ice sheets (Forsström 1999). Glacial erosion during the next and subsequent glaciations will tend to lower the overall relief in the Hästholmen area, with greater erosion taking place over higher ground than in the depressions (Crawford & Wilmot 1998).

Climatic conditions immediately in advance of glaciation, when tundra and steppe are present and permafrost may form, result in a decrease in the groundwater recharge. The subsequent ice sheet may, therefore, advance over frozen ground. Immediately behind the frontal section of the ice sheet, which may be frozen to the surface of the ground, the ice will be warm based, i.e. glacial meltwater will be generated at the base of the ice sheet and groundwater recharge could result. The extent of any such recharge will be dependent on the transmissivity of the ground, which will be in turn related to the extent of any previous permafrost. Infiltration rates may be similar to those of the present day. The subsequent advance of the ice sheet, combined with an increased thickness of ice, will result in the ice at the site becoming cold based. Glacial meltwater will no longer be generated at the base

of the ice sheet, the ice will be frozen onto the underlying rock and ice flow will take place predominantly within the ice sheet and not along its base.

Deglaciation releases large volumes of water, local run-off is likely to be great and water will flow towards the ice margin on the surface of the ice and inside the ice in crevasses. Most water is likely, however, to be discharged in tunnels at the ice-rock interface. Large groundwater heads (up to 400 m), and the hydraulic conditions at the ice front may temporarily result in extensive infiltration of groundwater into the bedrock. At the same time great amounts of meltwater would be present at the surface and strongly dilute and disperse any groundwater discharged from below. Finally, during the glaciation cycle with both lowering and rising of the relative sea level, groundwater of both marine and non-marine origin might infiltrate into the bedrock in the Hästholmen area (Forsström 1999).

3.5 Seismicity

This section summarises the main conclusions of the study of the seismicity and seismotectonics of the Loviisa area (Saari 1998), which is based on two separate catalogues of seismicity. The study of regional seismicity utilises the latest updating of the earthquake catalogue for Northern Europe by Ahjos & Uski (1992), whereas the local characteristics of seismicity and seismotectonics are investigated by means of the local microearthquake observations of the Loviisa area.

The seismic characteristics of Finland suggest that an area within a distance of 500 km from the Loviisa site is considered large enough to include all regionally significant seismic events. This data set has been homogenised by excluding events below magnitude $M_L=1.5$ (M_L = Richter's local magnitude scale), and has also been divided into two subsets, macroseismically- (1610 - 1964) and instrumentally-located (1965 - 1995) earthquakes, representing location accuracies of the order of 20 - 100 km and 5 - 10 km, respectively.

Earthquakes in the Loviisa area are small and sparse, even by the standards of the Fennoscandian Shield. The data set includes only 299 earthquakes ($M = 1.5 - 4.7$) and about 25 % of these (75 events) were located by seismic instruments (M = Magnitude scale in general). The nearest areas of higher activity are just outside the borders of the study area: the west coast of the Bothnian Sea in the west and the northern Bothnia-Kuusamo region in the north. Areas of lower activity are in eastern and western Finland, as well as in Russia and in the eastern Baltic.

Although the study area is characterised generally by a low seismic activity, two NW-SE oriented belts of relatively high seismic activity run through it (Fig. 3.5-1). The northern zone of higher activity (B-L) runs from the southern part of the Bay of Bothnian (north of the Bothnian Sea) towards Ladoga. The other active belt (Å-P-P) runs from the Åland archipelago to Estonia, where it extends from Paldis to Pskov in southeastern Estonia. All significant ($M \geq 3.5$) earthquakes in southern Finland are related to the Å-P-P and B-L zones (Saari 1998). Loviisa lies between these two zones and is separated by about 100 km from the boundaries of both.

Possible seismic and aseismic movements of the bedrock are likely to occur along existing fractures or fracture zones. The Gulf of Finland and the adjacent shore areas and, contain three dominant fault directions: E-W, SW-NE and NW-SE, except for the area west of Loviisa, the major zones of weakness are mainly over 100 km from the site. The seismic belt Å-P-P seems to consist of chains of long, NW-SE oriented zones of weakness with several shorter intersecting fault zones and faults (Fig. 3.5-1).

Some epicenters of relatively large earthquakes which occurred in the Å-P-P zone (1934, 1935 and 1976) can be related to the fracture zones which run about 60 and 70 km NW from the island of Håstholmen (Fig. 3.5-1). However, it seems that any seismic energy that is transmitted NE from the Å-P-P zone is reduced strongly as a function of distance from this zone. Any seismotectonic connection that might exist between the B-L zone and the immediate neighbourhood of Håstholmen seems to be weak or practically missing.

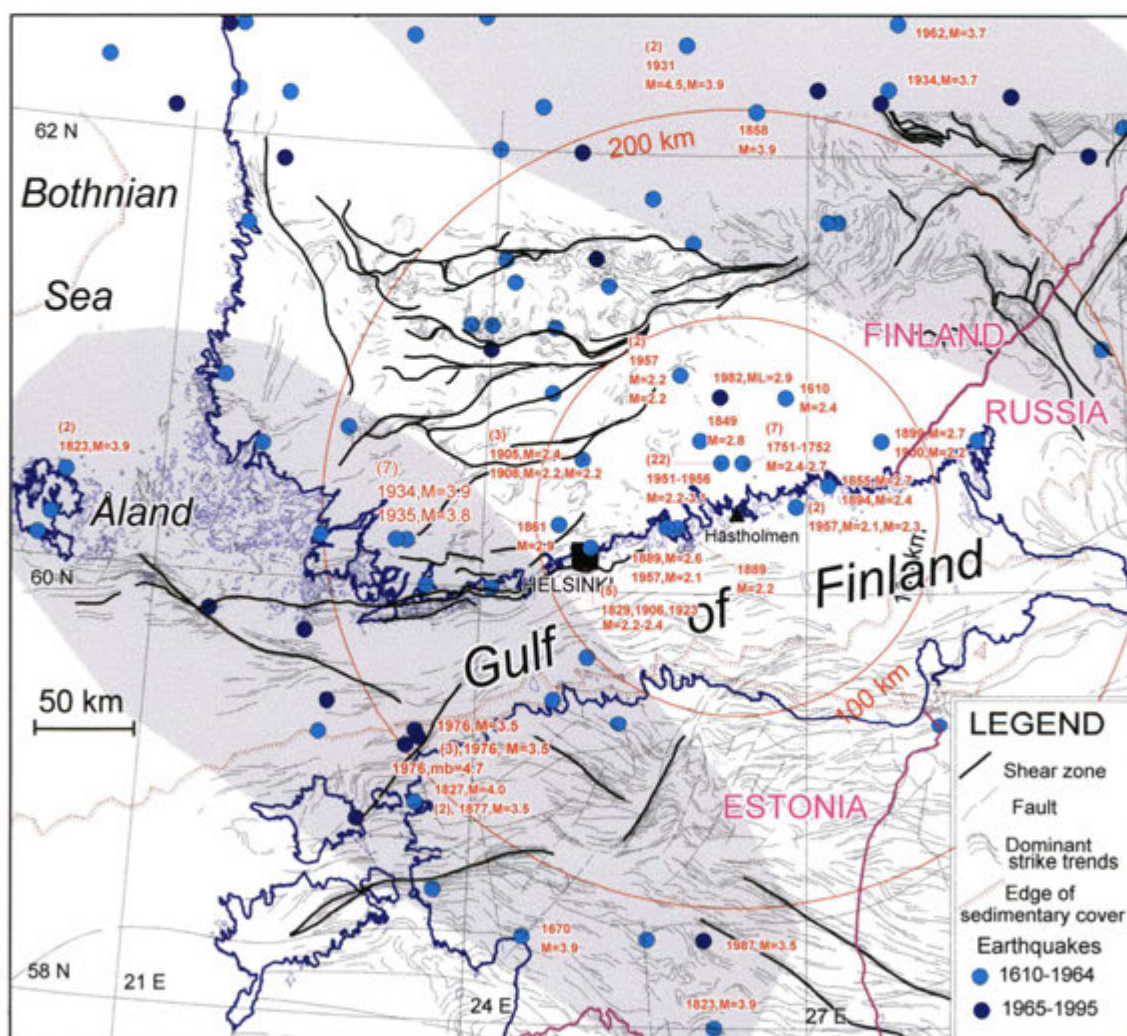


Figure 3.5-1. Earthquake observations (Ahjos & Uski 1992) and the main tectonic structures of Gulf of Finland and surrounding area (Koistinen 1994). The shaded areas outlines the Å-P-P and B-L seismic zones. Håstholmen is shown by a triangle. Years of occurrence and magnitudes for the closest (distance < 100 km) and largest ($M \geq 3.5$) earthquakes are given. The number of overlapping epicenters is denoted in parenthesis.

The area within a distance of 100 km from Hästholmen includes 51 events with a magnitude of $M = 2.2 - 3.1$, and all except one, were macroseismically observed. These events were felt not more than 10 - 20 km from their epicentres and the majority (29) occurred during two earthquake sequences (1751 - 1752 and 1951 - 1956) about 25 km north from Hästholmen.

Altogether 94 earthquakes ($M = 1.6 - 4.7$) have occurred within a distance of 200 km from Hästholmen, during a period of almost 400 years (1610 - 1995). The epicenters are mainly in the mainland and in the western end of the Gulf of Finland. Central and eastern regions of the Gulf seem to be less active. The interpretation for the Gulf area is reliable when instrumentally-located or relatively large events are concerned. The seismic network for southern Finland has operated in the Helsinki area for over 30 years, in addition, microearthquake measurements were carried out in the Loviisa area from 1984 to 1996. Before the era of instrumentally-located events, only the largest offshore events (say larger than $M = 3.5 - 4.0$) would have been felt widely in the surrounding coastal areas.

In the vicinity of Hästholmen (Fig. 3.5-2), the prevailing rock type is relatively undeformed rapakivi granite and the fracture zones are relatively small (lengths are less than tens of kilometres and widths less than one kilometre, see Table 2.5-1).

Altogether 134 microearthquakes ($M_L = -1.8 - 1.3$) were observed in the Loviisa area from 1984 to 1996, and were examined within the framework of the local fracture zone interpretation (Fig. 3.5-2). The observations covered an area within a radius of 40 km from Hästholmen and the peak slip values of the events varied from 0.8 mm to 0.6 mm. The depths of the microearthquakes (< 5 km) were lower than those values (5 - 20 km) usually found in Finland.

According to the fault plane solutions of the microearthquakes observations, the fault mechanisms tend to be of the strike slip type. The horizontal slip rates are generally 1 - 3 times higher than the vertical ones, the estimated strike directions of the earthquakes fit well with the local fracture interpretation (Fig. 3.5-2) and the events have occurred in almost vertical fault zones. The solutions indicate that the maximum compressive stress in the Loviisa area is mainly horizontal and generally in agreement with the NE-SE-oriented regional stress field.

The earthquake sequences and clusterings of epicenters are a characteristic feature of the Hästholmen area (Fig. 3.5-2). More than 90% of the microearthquakes have occurred at six locations, namely in Ahvenkoskenlahti, in Kaunissaari and in Vådsholmsfjärden (over 20 events) as well as in Klobbfjärden, in Keipsalo and in Lapinjärvi (7 - 9 events).

The fault zones in Klobbfjärden, 3 - 4 km NE, and in Vådsholmsfjärden, 4 - 5 km south, from the island of Hästholmen seem to be the closest active block boundaries in the vicinity of Hästholmen (Fig. 3.5-2). North and west of the site the interpretation of seismic events is less certain. According to the multi event analysis of the Ahvenkoskenlahti area and the fault plane solution for the Orregrund event, active zones of weakness may also run about 5 km north and 3 km SW of Hästholmen.

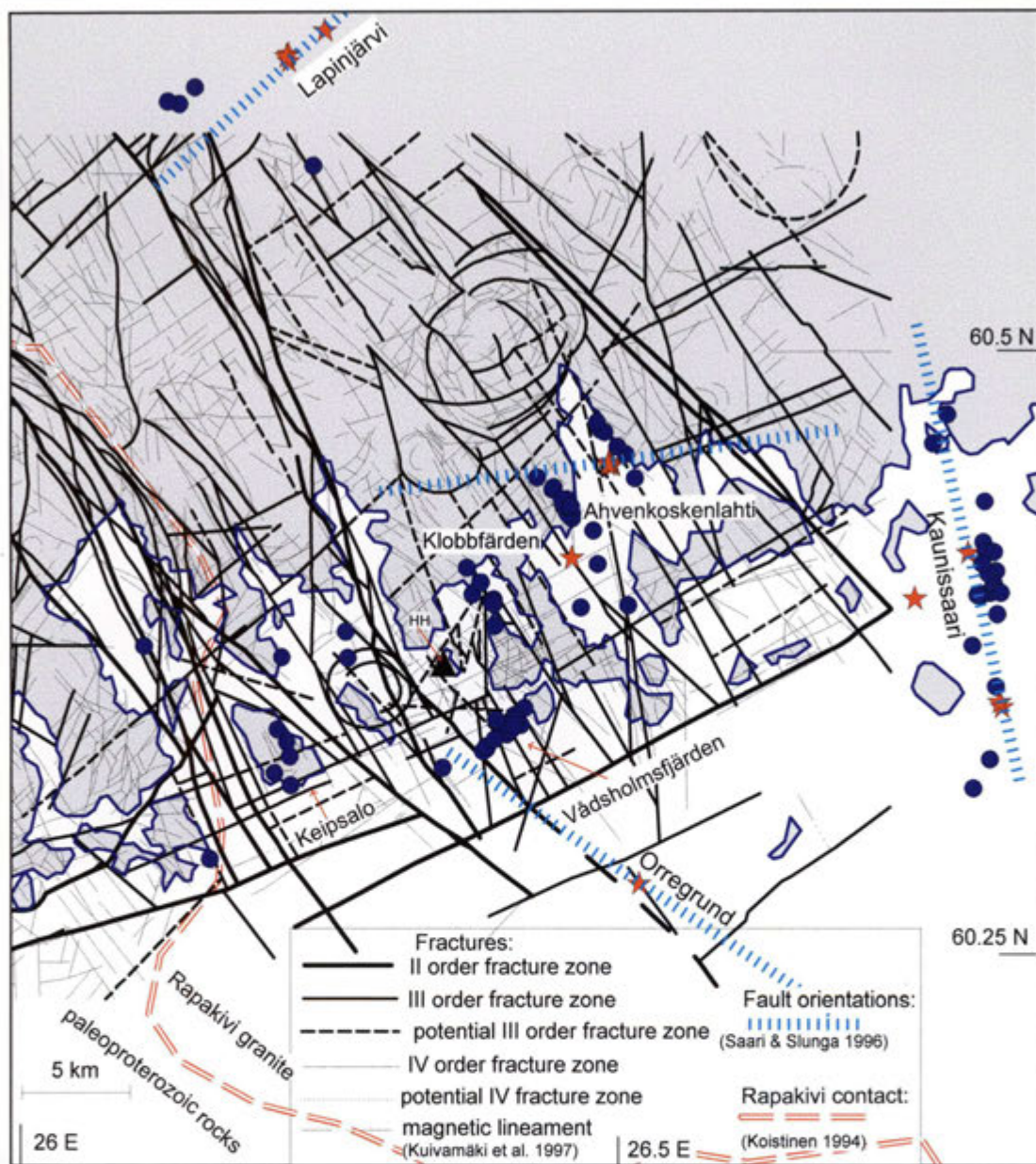


Figure 3.5-2. Fracture zone interpretation, strike directions and the microearthquake observations in the vicinity of Hästholmen. Epicenters: star = located by the local seismic network, filled circle = located by one three component seismic station. HH = Hästholmen (triangle).

4 GEOLOGY

4.1 Rock Types

The determination of rock types at Hästholmen is based on visual, microscopic and lithogeochemical investigations of rocks in outcrops, in the VLJ repository and in core samples (Suominen 1983, Anttila 1988, Anttila & Viljanen 1995, Lindberg 1994, 1996, Kuivamäki et al. 1997a, Gehör et al. 1997a, b). The bedrock at the study site is well exposed, especially on the small islands around the island of Hästholmen and along the shore line, thus enabling accurate observations to be made. Eight deep boreholes (600 - 1 000 m) and 16 shallow ones (max. depth 240 m) have been drilled at the site, to produce a good coverage of the central investigation area. The existing repository with its access tunnel and shafts has a cross-sectional length of about 1 km and a depth of 120 m. On the basis of information from all the above sources, it is considered that a reasonable understanding exists of the distribution of rock types in the area covered by the boreholes. The bedrock of the site and its immediate area consists solely of different varieties of rapakivi granite, the most common forms being pyterlite, wiborgite, porphyritic rapakivi granite and even-grained or weakly porphyritic rapakivi granite.

Wiborgites and pyterlites are rapakivi granites with ovoidal potassium feldspar megacrysts. In the wiborgites (Fig. 4.1-1) most of the ovoids (> 50%) are mantled with plagioclase rims, whereas in the pyterlites (Fig. 4.1-2) the ovoids are usually lacking in the plagioclase mantle. However, there are pyterlites in Hästholmen with large number of ovoids mantled by plagioclase, making it difficult to distinguish between the two varieties. Because of a gradual transition between wiborgite and pyterlite, they have been combined in Figs. 4.1-3 and 4.1-4. The most common type of rapakivi granite in outcrops and core samples at Hästholmen is, however, pyterlite (Suominen 1983, Kuivamäki et al. 1997a, Gehör et al. 1997a, b).

The wiborgites and pyterlites are usually ordinary granites in their modal mineral composition, containing on an average ca. 30% quartz, 34 - 44% potassium feldspar, 14 - 25% plagioclase, 3 - 4% biotite and 3 - 7% hornblende (Gehör et al. 1997a, b). Accessory minerals include chlorite, epidote, apatite, carbonate, fluorite, sericite, sphene, zircon and opaque minerals. The diameter of ovoidal potassium feldspar megacrysts with plagioclase mantles ranges from 1 cm to 6.5 cm and that of ovoids without a mantle from 4 cm up to 12 cm (Kuivamäki et al. 1997a, Gehör et al. 1997a, b). The plagioclase mantle has a width of 1 - 5 mm and consists of 1 - 3 mm long, randomly oriented plagioclase grains or laths. The groundmass between the ovoids is medium-grained (0.2 - 4 mm), and consists of quartz, plagioclase, potassium feldspar, biotite and hornblende. Sometimes plagioclase and quartz also occur as phenocrysts, measuring 5 - 15 mm in diameter.

Dark-coloured pyterlite, characterised by a greater amount of groundmass and grey plagioclase compared with the ordinary, reddish pyterlite, is found southeast from Hästholmen (Kuivamäki et al. 1997a). Plagioclase occur as euhedral phenocrysts, which are frequently twinned, which further separates it from the reddish pyterlite. No dark-coloured pyterlite exists in the boreholes, but it is the most magnetised rapakivi variety in the area,

and the interpretation of airborne magnetic survey suggests that it may occur under Hästholmen at the depth of about 1 km (Paananen & Paulamäki 1998).

Porphyritic rapakivi granite (Fig. 4.1-5), characterised by angular potassium feldspar phenocrysts without plagioclase mantles (5 - 25 mm in diameter), is present in boreholes KR2 (at 756 - 767 m and 780 - 850 m), KR3 (at 546 - 558 m and 680 - 735 m) and KR4 (at 756 - 867 m). It is not exposed within the study site, and is only present in some outcrops south of Hästholmen. Its presence in boreholes KR2 and KR3 has been interpreted as due to there being two inclusions of the porphyritic rapakivi granite within the even-grained rapakivi granite (Fig. 4.1-4). Porphyritic rapakivi granites contain on average 31% quartz, 16% plagioclase, 46% potassium feldspar, 2.7% biotite and 1% hornblende (Gehör et al. 1997b). In addition to potassium feldspar, quartz and plagioclase may also occur as phenocrysts. The groundmass between the phenocrysts is medium-grained (0.2 - 2 mm), consisting of potassium feldspar, plagioclase and quartz.

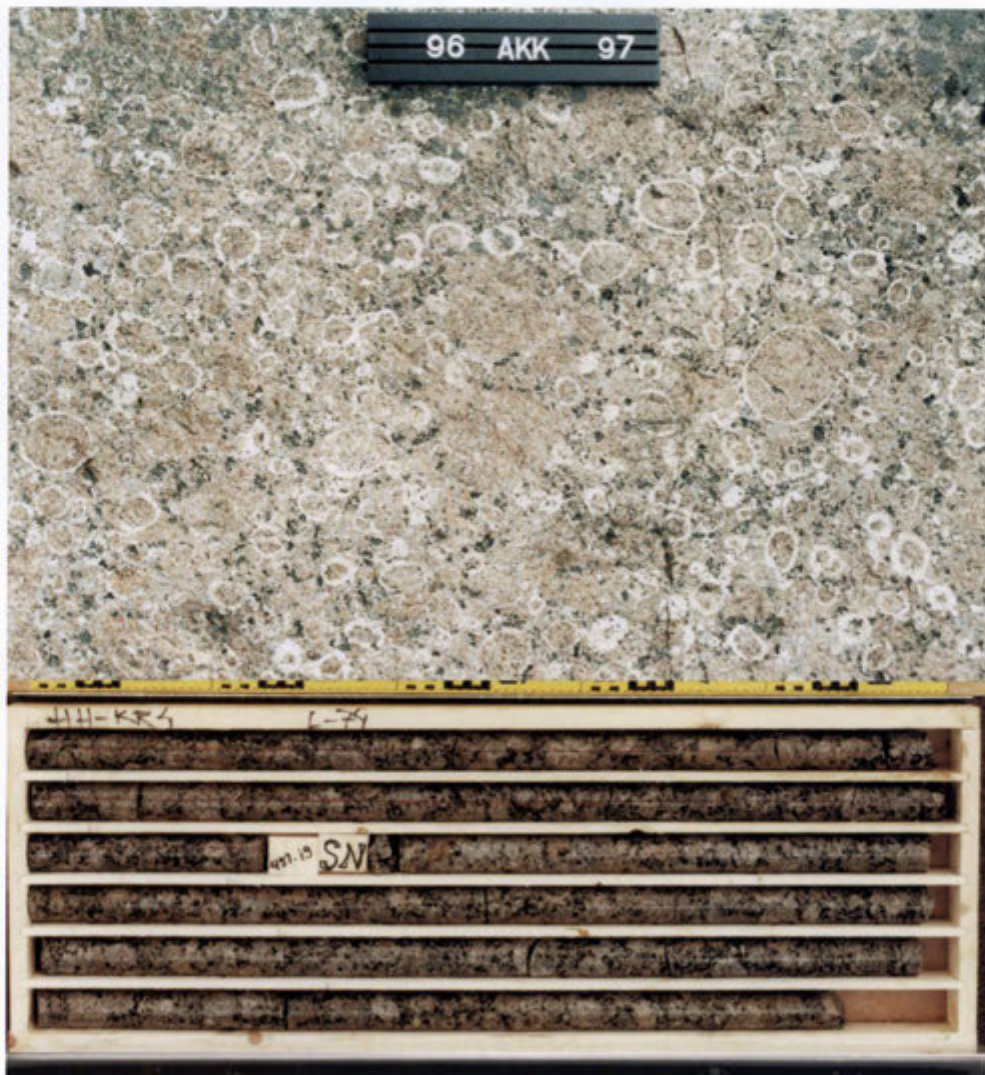


Figure 4.1-1. Wiborgite on the outcrops and as core drilled rock samples.

Even-grained or weakly porphyritic rapakivi granites (Fig. 4.1-6) are present both in outcrops and in boreholes KR2, KR3, KR4 and KR6 over the depth range of ca. 300 - 1000 m. Reddish or brownish even-grained rapakivi granites are fine- or medium-grained, being typical granites in their mineral composition and containing 30% quartz, 18% plagioclase, 46% potassium feldspar, 2% biotite and 1.5% hornblende (Gehör et al. 1997b). Leucocratic, weakly porphyritic rapakivi granites are also even-grained and medium-grained, but they also contain occasional potassium feldspar and quartz phenocrysts, 3 - 10 mm in diameter, and also small number of homogenous or concentric ovoids. On average they contain 33% quartz, 25% plagioclase, 36% potassium feldspar, 3.7% biotite and sometimes very small amounts of hornblende. In Figures 4.1-3 and 4.1-4 the even-grained and weakly porphyritic rapakivi granites have been combined because of the similarities in their texture, mineralogy and chemical composition (see below).



Figure 4.1-2. Pyterlite on the outcrops and as core drilled rock samples.



Figure 4.1-3. Surface geological map of the Hästhölm study site. The vertical cross-section of the bedrock along the line through borehole KR3 is shown in Figure 4.1-4.

The extent and the form of the even-grained/weakly porphyritic rapakivi granite in Figure 4.1-3 is based on the interpretation of aerogeophysical data, combined with the outcrop and borehole observations. Even-grained/weakly porphyritic rapakivi granites can be separated from the wiborgites/pyterlites because of the weaker average magnetisation of the former (Paananen & Paulamäki 1998). The circular structure revealed by the sea bottom topography within the even-grained rapakivi west of Hästholmen (see Fig. 5.2-1) has been interpreted as indicating an intrusion structure (Kuivamäki et al. 1997a). Within the area covered by boreholes KR1 - KR4 and KR6 the even-grained and weakly porphyritic rapakivi granites have been interpreted as forming a lithological unit within the pyterlite/wiborgite, with a thickness of ca. 500 m and a dip of approx. 20° to the NNE (Fig. 4.1-4) (Paananen & Paulamäki 1998). The majority of the unit consists of medium-grained, even-grained or weakly porphyritic rapakivi granite, whilst the upper part is fine-grained and densely fractured, being associated with one of the main subhorizontal fracture zones in the study site (Paananen & Paulamäki 1998). Another subhorizontal slab of even-grained rapakivi granite a few metres in thickness occurs closer to the surface between 25 m and 50 m depth (Fig. 4.1-4) (Suominen 1983, Paananen & Paulamäki 1998).

The southern contact of the even-grained rapakivi granite, which occurs on the mainland northwest from Hästholmen (Fig. 4.1-3), can be seen in borehole KR1 at approx. 30 m depth. Based on the interpretation of the airborne magnetic data, the contact dips 30 - 40° NNW to a depth of approx. 200 m and then becomes steeper at greater depths (Fig. 4.1-4). The northern contact has been interpreted as dipping 75° to the SSE (Paananen & Paulamäki 1998).

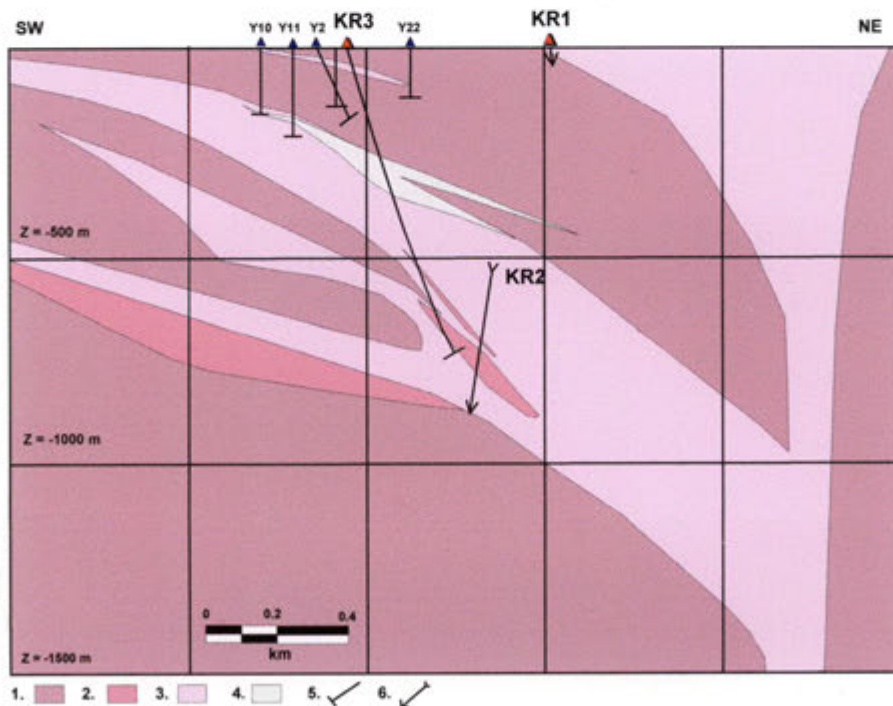


Figure 4.1-4. A schematic NE-SW trending vertical cross-section through borehole KR3 along the line shown in Figure 4.1-3 (after Paananen & Paulamäki 1998). 1. Wiborgite/pyterlite, 2. Porphyritic rapakivi granite, 3. Even-grained rapakivi granite, 4. Fine-grained rapakivi granite, 5. Borehole, 6. Borehole projected onto the plane.

In boreholes KR1 - KR3 the fine-grained, even-grained rapakivi granite is also present as narrow veins, ranging from a few centimetres up to one metre in thickness. According to TV-logging (Stråhle 1998) these veins are either subhorizontal (in boreholes KR1 and KR2) or dipping steeply (70°) to the south (in borehole KR3).

Narrow aplite veins cutting the rapakivi granites are medium-grained, reddish and composed of quartz, potassium feldspar and plagioclase (Gehör et al. 1997a), with the amount of mafic minerals less than 5%. Pegmatite is present as veins a few centimetres wide which, according to TV-logging (Stråhle 1998), dip steeply ($70 - 80^\circ$) to the SSE or SSW. A few greisen veins, consisting primarily of quartz, mica and topaz, and recording the circulation of late-stage magmatic fluids in the fracture system, have been found in the vicinity of Hästholmen, but not from the actual study site (Kuivamäki et al. 1997b).



Figure 4.1-5. *Porphyritic rapakivi granite on the outcrops outside the study site and as core drilled rock samples.*

Miarolitic cavities, filled with quartz or into which small idiomorphic crystals of potassium feldspar, albitic plagioclase and quartz protrude, are present both in outcrops and in some of the shallow boreholes, especially in the medium- to coarse-grained, even-grained rapakivi granite, being more frequent near the upper contacts of the granite (Suominen 1983, Lindqvist & Suominen 1987, Kuivamäki et al. 1997a). They are usually 5 - 20 cm in diameter, but more than 100 cm long cavities have been observed. Miarolitic cavities are originally gas- or liquid-filled vesicles. Their occurrence provides evidence for the internal structure of the rapakivi granite, as the gas bubbles in the magma are confined to regions close to interfaces, e.g. boundaries between different rapakivi granite types (Suominen 1983).

In some outcrops the rapakivi granites show compositional variations, which can be interpreted as a magmatic flow structure or a magmatic bedding, with the main strike of such structure or bedding being NE-SW (Kuivamäki et al. 1997a). The subhorizontal patterns

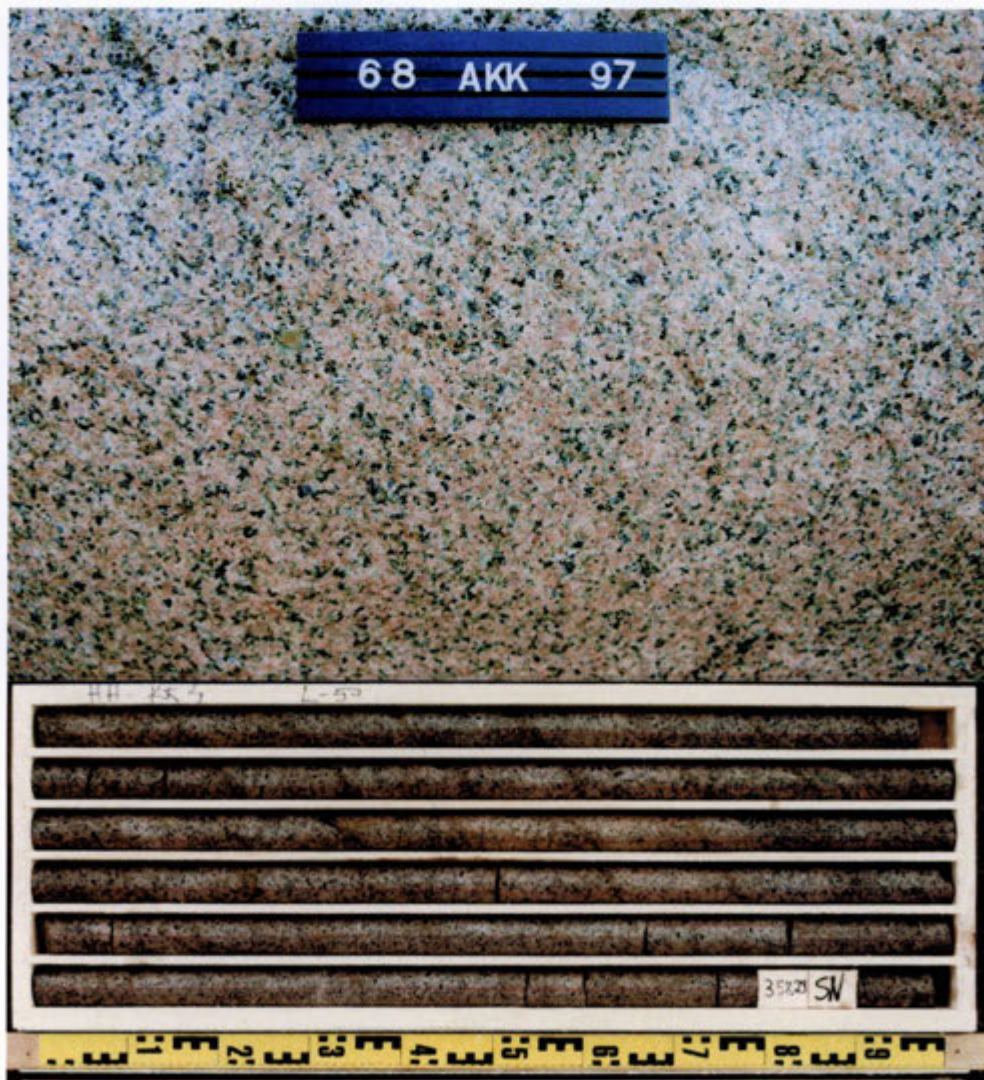


Figure 4.1-6. Even-grained rapakivi granite on the outcrops and as core drilled rock samples.

observed in the dipmeter survey, have been interpreted as being due to some sort of layering or banding (Siddans et al. 1997, 1998). Based on observations from shallow (< 200 m) boreholes, Suominen (1983) has suggested a lamellar internal structure for the rapakivi granite, in which lenses and layers of various rapakivi granite types dip gently eastwards. The interpretation for the even-grained rapakivi granite presented in Figure 4.1-4 is in accordance with this presumption.

Thin, 10 - 20 mm wide, subhorizontal mylonites have been observed by TV-logging at three depth levels: shallow (100 m), intermediate (300 - 500 m) and deep (800 - 900 m) (Stråhle 1998) and coincide with the most significant subhorizontal fracture zones observed, R1, R18 and R19 respectively (see Section 5).

All the rapakivi granites described above are chemically similar, being metaluminous or slightly peraluminous (Gehör et al. 1997b). They are close to typical granites of rapakivi composition, which are characterised by high Fe/Mg- and K/Na -ratios and high Rb, F and Zr contents (cf. Nurmi & Haapala 1986). The analyzed samples have been interpreted to be members of a rather limited differentiation series, in which the wiborgites and pyterlites represent the most basic differentiates, containing ca. 69% SiO₂ and the even-grained or weakly porphyritic rapakivi granites the most acid differentiates, containing ca. 75% SiO₂ (Gehör et al. 1997b). The porphyritic rapakivi granites often lie between these end members. The Al₂O₃ content in the most basic members is about 15%, decreasing to about 11% in the most acid differentiates. The TiO₂ contents decrease respectively from ca. 0.5% to 0.1%, Mn contents from 500 ppm to 100 ppm, CaO contents from 2.5% to 0.5%, Fe₂O₃ contents from 5% to 2% and MgO contents from 0.5% to almost 0%. In parallel with the changes the K₂O content increases from 5.5% to 6%. Table 4.1-1 shows chemical compositions of the different rapakivi varieties at Hästholmen.

The trace element compositions of the analyzed rapakivi varieties are rather similar, however, samples of the even-grained and porphyritic rapakivi granites contain markedly less Ba, Mn, P and Sr and more Rb, Cs and Nb than the wiborgites and pyterlites (Table 4.1-1). The fluorine contents are highest in the leucocratic, weakly porphyritic rapakivi granites. Also their Th, U and Y contents are often higher than those of the wiborgites and pyterlites. The Cl content is higher in the most basic rapakivi types than in the acid rapakivi granite varieties. The trace element compositions (especially the much lower Y content) of some granite and porphyritic granite samples indicate that they are either of Svecofennian origin (xenoliths) or granitoid varieties heavily contaminated by Svecofennian rocks (Gehör et al. 1997b). Only a few greisen veins from the vicinity of Hästholmen show elevated Sn, Zn, Pb and Cu contents (Kuivamäki et al. 1997b). Consequently, the potential for economic mineralisation in the Hästholmen area is rather limited.

The kind of granular weathering of the rock surface described in Section 3.2 is not present at the Hästholmen site, except in some boulders. However, a different form of weathering does occur within the fracture zones at greater depths, the weathering products containing unaltered, mechanically broken major minerals of the rock as well as chemical alteration products (Anttila 1988). The fracturing of the rock has enhanced the interactions that have occurred between the primary minerals of the rapakivi granite and the aqueous solutions circulating in the fractures.

Table 4.1-1. Analyses of different rapakivi types of the Hästholmen study site (from Gehör et al. 1997b). WIB = wiborgite, PYT = pyterlite, PORGR = porphyritic rapakivi granite, EGR = fine-grained, even-grained rapakivi granite, LPOR = leucocratic, weakly porphyritic rapakivi granite. Negative value means contents below the detection limit.

Sample	1	2	3	4	5	6	7	8
Borehole	KR1	KR2	KR2	KR3	KR2	KR3	KR2	KR3
Depth (m)	121.40	306.30	785.20	554.60	380.10	364.20	633.10	445.85
Rock type	WIB	PYT	PORGR	PORGR	EGR	EGR	LPOR	LPOR
SiO ₂ %	68.5	69.5	72.4	70.1	75.8	73.9	74.6	74.7
TiO ₂ %	0.461	0.333	0.257	0.184	0.407	0.282	0.229	0.157
Al ₂ O ₃ %	13.7	13.9	12.9	15.0	11.5	12.1	12.1	12.3
Fe ₂ O ₃ %	4.31	3.58	2.98	2.94	2.91	2.99	2.63	2.10
MnO%	0.05	0.04	0.03	-0.01	0.01	0.02	0.02	-0.01
MgO%	0.27	0.18	0.13	0.05	0.14	0.06	-0.01	-0.01
CaO%	2.18	1.83	1.39	0.29	0.45	1.27	1.07	0.96
Na ₂ O%	3.02	3.26	2.73	3.87	2.30	2.84	2.81	2.73
K ₂ O%	5.53	5.52	5.93	6.54	6.10	5.19	5.78	6.4
P ₂ O ₅ %	0.1	0.06	0.04	0.01	0.03	-0.03	0.01	0.01
Th ppm	18	36	30	69	30	43	57	75
Rb ppm	219	227	262	346	251	352	416	542
Y ppm	70	51	60	95	54	84	129	116
Ba ppm	1110	1300	905	284	347	249	146	122
Zr ppm	354	236	323	370	587	326	359	233
Nb ppm	22	17	20	24	21	24	33	30
Sr ppm	156	165	120	34	56	56	36	26
Cs ppm	5	5	6	1	6	10	8	8
U ppm	5.7	8.6	6.4	8.5	8.2	10.6	15.3	9
Mn ppm	393	346	274	140	165	265	207	148
F ppm	2060	2070	2400	407	1260	5620	5970	7000
Cl ppm	702	745	601	161	193	601	601	389
S%	0.05	0.01	0.03	0.01	0.02	-0.01	-0.01	0.01
Total	99.3	98.7	99.4	99.7	100.2	99.3	99.6	100.0

4.2 Fracturing

4.2.1 Surface Fracture Studies

Geological surface mapping of the site and its immediate surroundings, within a distance of 3 - 5 km from the island of Hästholmen (and referred to below as the Hästholmen area) has involved making measurements on fractures from 237 outcrops (Kuivamäki et al. 1997a). During the fracture mapping, all the fractures, equal to or longer than one metre, were investigated. For each fracture, the dip direction and dip, rock type, length, form (straight or curved), type (tight, open or filled), width and infilling, where present, were recorded. A total of 4426 fractures were investigated. Fracture orientations were displayed using the Schmidt equal-area, lower hemisphere stereographic projection. In addition, orientation data were also presented using rose diagrams.

The distribution of all fracture orientations measured in outcrops is shown in Figures 4.2-1 and 4.2-2. The main sets of fracture directions are presented in Table 4.2-1 in order of decreasing frequency. Surface fractures form a distinct orthogonal system, with three perpendicular fracture directions: steeply dipping ($> 75^\circ$ dip) fractures striking NE-SW and NW-SE plus horizontal or subhorizontal ($< 30^\circ$ dip) fractures. Because of the flat surface of the outcrops, gently dipping and horizontal fractures are under-represented in the data. The majority of the open (aperture over 1 cm) and long, (length over 10 m) fractures have a NE-SW orientation (fracture set I), whilst the tight fractures are evenly distributed in both of the steeply dipping fracture sets.

The fracture frequencies at the Hästholmen area were measured across each outcrop in N-S and E-W traverses (a total of 15 km). When possible, the fracture frequency for the horizontal fracturing was also measured. The resulting very low average fracture frequencies are shown in Table 4.2-2. Within the actual study site on the island of Hästholmen the maximum fracture frequency is 2.0 fractures/m and the average fracture frequency 0.6 fractures/m, the frequencies being lowest in the western part of the island (Suominen 1980). No essential differences exist in fracture frequencies between the different rapakivi granite types, although fracturing in the even-grained rapakivi granite tends to be slightly more frequent than in the pyterlites and wiborgites (Kuivamäki et al. 1997a). No fracture zones (> 10 fractures/m) have been observed during the mapping, the outcrops therefore represent the intact, i.e., least fractured rock. However, seismic refraction and ground radar surveys (Sutinen 1997, Paananen & Paulamäki 1998) demonstrate that such zones may occur in the till-covered areas in the southeastern part of the island.

Table 4.2-1. Distribution of fracture orientations measured in outcrops at the Hästholmen area (Kuivamäki et al. 1997a). More dominant dip direction in bold.

Main sets of fracture directions (maximum)	Dip direction (maximum)	Dip
I 58°	145° 328°	$>75^\circ$ $>75^\circ$
II 328°	58° 238°	$>75^\circ$ $>75^\circ$
III variable	variable	Horizontal or $<30^\circ$

Table 4.2-2. The fracture frequencies of the outcrops at the Hästholmen area (Kuivamäki et al. 1997a).

Traverse	Number of outcrops	Fracture frequency (fractures/m)		
		Mean	Minimum	Maximum
E-W	211	0.58	0.05	1.62
N-S	212	0.62	0.0	1.39
Vertical	18	0.60	0.08	1.60

The majority of the fractures are either open (54.5%) or tight (38.7%) (Kuivamäki et al. 1997a). The mean length of the measured fractures is 8 m, the fractures of the pyterlite being slightly longer than those of the wiborgite, porphyritic rapakivi granite and even-grained rapakivi granite. Open and filled fractures are longer (mean length 10.2 m) than tight fractures (mean length 4.5 m). Because the outcrops are extensive and well exposed, it has also been possible to measure reliably the longest fractures. The proportion of fractures over 20 m in length is 5.9%, the longest fracture being over 100 m long. The distribution of the fracture lengths is shown in Figure 4.2-3.

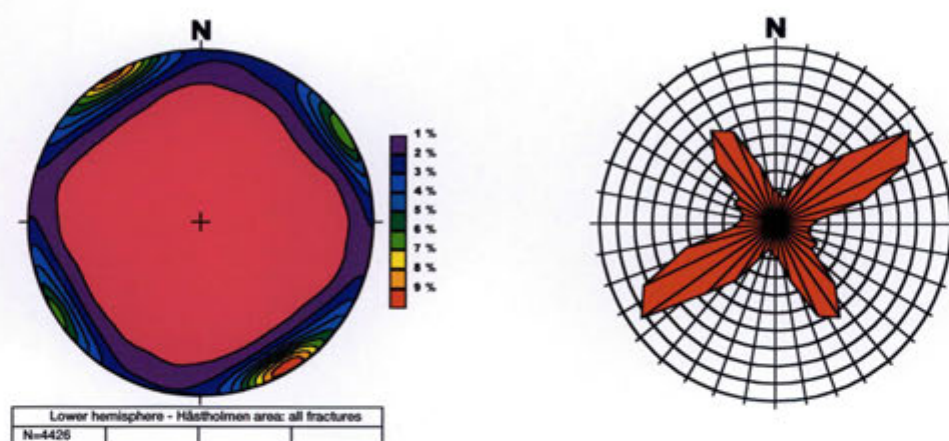


Figure 4.2-1. Distribution of all fracture orientations ($N = 4426$) measured in outcrops at the Hästholmen area (Kuivamäki et al. 1997a). Schmidt equal area, lower hemisphere projection and rose diagram. Each ring in the rose diagram represents 7% of the distribution.

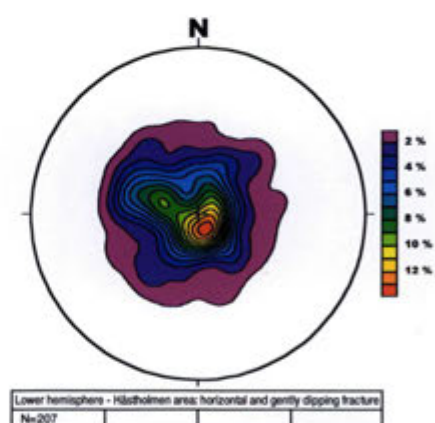


Figure 4.2-2. Distribution of horizontal and gently dipping fractures ($\text{dip } \pm 45^\circ$, $N = 207$) measured in outcrops at the Hästholmen area (Kuivamäki et al. 1997a). Schmidt equal area, lower hemisphere projection.

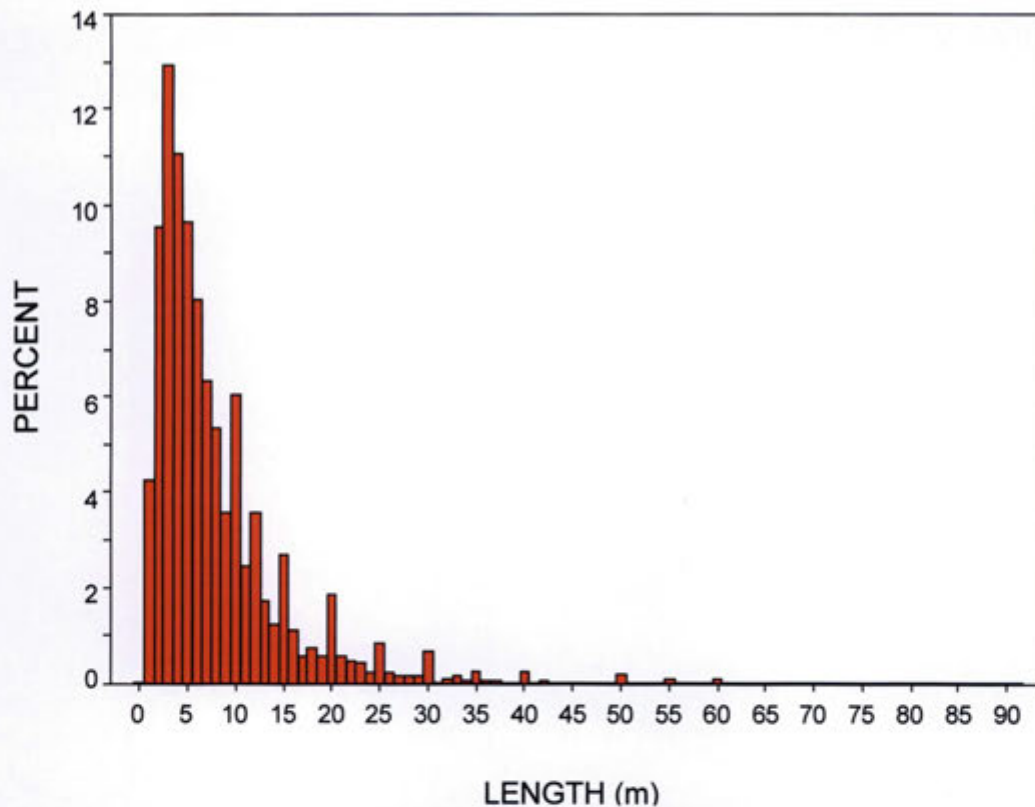


Figure 4.2-3. Distribution of fracture lengths at the Hästholmen area (Kuivamäki et al. 1997a).

4.2.2 Fracture Studies in the VLJ Repository

All the fractures over 2 m in length were investigated in the access tunnel and in the VLJ repository, which has a maximum depth of 120 m (Viljanen 1994, 1996). Steeply dipping fractures oriented ENE-WSW and NW-SE (Fig. 4.2-4) dominate over the (sub)horizontal fractures, almost 80% of the fractures having a dip of over 45°. However, the fracture zones, in which the fracture frequency exceeds 10 fractures/m, are characterised by dense (sub)horizontal fracturing with clayey material, composed of kaolinite and fragments of the main rapakivi granite minerals (Viljanen 1994, Lindberg 1994, 1996). The steeply dipping fractures typically have chlorite-coated surfaces and are commonly filled with carbonates, and more rarely with fluorite and kaolinite. The fracture frequency in the intact rock outside the densely fractured, (sub)horizontal zones is 0.8 - 1 fractures/m (Viljanen 1994, 1996). The mean length of the fractures (fracture traces) in the access tunnel is 10.6 m and in the repository 9.14 m. The fracture orientations, lengths and frequencies correlate well with those observed in the outcrops. The number of open fractures is smaller in the repository and in the access tunnel than in the outcrops and it decreases with increasing depth (Kuivamäki et al. 1997a).

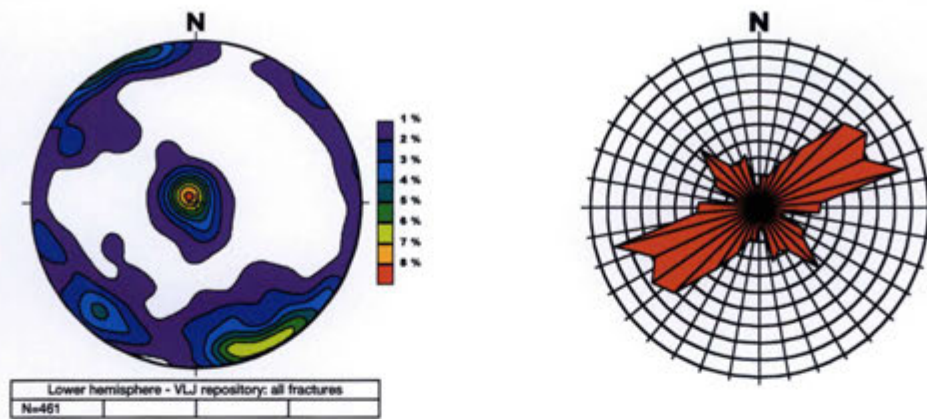


Figure 4.2-4. Distribution of fracture orientations measured in the VLJ repository (Kuivamäki et al. 1997a). Schmidt equal area, lower hemisphere projection and rose diagram. Each ring in the rose diagram represents 5% of the distribution.

4.2.3 Fracturing in the Core Samples

The fracturing in core samples was determined by measuring the proportion of broken rock and the number of fractures outside the broken sections as functions of the depth and rock type. According to the Finnish engineering geological bedrock classification (Gardemeister et al. 1976), a core sample is regarded as broken if the number of fractures is more than 10 fractures/m, if it is dominated by filled and/or open fractures, or if it is mesoscopically weathered. On account of these features, such samples are often damaged during drilling, resulting in core loss and difficulties in observing the number and types of fractures.

The broken sections in the core samples (boreholes KR1 to KR4 and KR6) represent about 5.7% of the total length of the core material (4 186 m). In most of them (98%) the rock is densely fractured (> 10 fractures/m) and represents 2.3 - 9.0% of the total length of individual borehole cores (Okko et al. 1998). The rest of the broken sections represents crush- or clay-structured and densely-fractured (> 10 fractures/m with clay-filled fractures or abundant clay material in rock mass) rock.

Broken sections occur in every drill core, and they are most often 1 - 5 m in length. There is a close association at Hästholmen between the presence of these broken sections and the even-grained rapakivi granites, or the contact of these granites with pyterlite and wiborgite. In these sections, borehole-TV studies found only isolated open fractures or cavities which, however, possess remarkable large apertures and have high hydraulic conductivities (Okko et al. 1998).

Typically core samples are usually slightly fractured (1 - 3 fractures/m), and some cores are sparsely fractured (< 1 fracture/m), even close to the surface. Even-grained rapakivi granites are in places abundantly fractured (3 - 10 fractures/m), especially near to their contacts with pyterlite and wiborgite or when they occur as narrow dykes. Table 4.2-3 shows the mean fracture frequencies by fracture types in the intact rock of borehole KR3.

The contact zone between even-grained rapakivi granites and pyterlite-wiborgite seems to control the subhorizontal set of the major fracture zones at Hästholmen. In general, the mean fracture frequency does not change much as a function of depth or between the different boreholes, but is clearly related to the proximity of the above-mentioned contact zone and particularly to the fine-grained variety of the even-grained rapakivi granites (Okko et al. 1998). In borehole KR3, more than 50% of the fine-grained variety of the even-grained rapakivi granite unit between 273 - 360 m is densely fractured (> 10 fractures/m) and the mean fracture frequency is about 4.7 fractures/m, even in the intact part of the fine-grained rapakivi granite.

Most of the fractures recorded from the core samples are filled or tight. Calcite, dolomite, Fe hydroxides and clay minerals (illite, montmorillonite and kaolinite) form the most typical fracture mineral phases throughout the drill cores. Calcite and/or dolomite are frequently found in core from every borehole, and surfaces coated with chlorite and chloritic slickensides are also present at all depths (Gehör et al. 1997b, 1998). Open fractures in core are abundant only to depths of 100 - 150 m, but single open fractures can be found at all depths - an attribute typical of granitic formations - and as sporadic clusters close to sections of broken rock.

Table 4.2-3. Mean fracture frequencies (fractures/m) for open (Op), filled (Fi) and tight (Ti) fractures in intact bedrock sections as a function of depth and rock type. Borehole KR3. Rock types: PYT - WIB = pyterlite-wiborgite, EGR = even-grained rapakivi granite; (F) = fine-grained and (M) medium-grained variety, PORGR = porphyritic rapakivi granite.

Rock type	Depth [m]	Fracture frequency [fractures/m]			
		Op	Fi	Ti	Tot
PYT-WIB	202.30 - 220.85	-	0.27	0.54	0.82
EGR (M)	- 222.40	-	0.65	0.65	1.29
PYT-WIB	- 273.60	-	0.18	0.35	0.53
EGR (F)	- 359.30	0.33	3.16	1.17	4.66
EGR (M)	- 444.00	0.12	1.69	0.93	2.75
PORGR	- 456.00	-	1.00	0.42	1.42
EGR (M)	- 470.90	-	0.27	0.87	1.14
EGR (F)	- 473.80	-	5.86	1.03	6.90
EGR (M)	- 545.60	0.01	0.42	0.71	1.15
EGR (F)	- 558.80	-	2.20	2.42	4.62
EGR (M)	- 659.00	-	0.26	0.70	0.97
PYT-WIB	- 670.50	-	-	1.74	1.74
PORGR	- 679.90	-	0.32	0.64	0.96
EGR (M)	- 734.20	-	0.66	0.98	1.64
PORGR	- 803.35	0.03	0.13	2.59	2.75
Average		0.05	0.82	1.06	1.93

One specific feature of the core samples of rapakivi granite from this site is the presence of core discing, which has been noted in sections of core several metres or tens of metres in length. The first observations of core discing fractures were seen at a depth of about 200 m at Hästholmen. Core discing is seen as repeated subparallel fractures in core with a spacing of about 1 - 1.5 cm. The phenomenon itself is associated with an in situ state of stress which is high in relation to the tensile strength of the rock, and it is neither observed in borehole studies by TV-logging nor by geophysical acoustic logging method which is highly sensitive to fractures.

Oriented fracture data were gathered from the drill cores and by borehole-TV logging (Fig. 4.2-5) from borehole walls. The majority of the fractures in the drill cores are horizontal or very gently dipping (Okko et al. 1998). In boreholes KR1, KR2, KR3 and KR6 there are, below the near-surface fracturing, some sections with mainly steeply dipping fractures. These sections are 260 - 600 m (fracture orientation 295°/90°) in borehole KR1, 295 - 350 m (75°/90°), 390 - 435 m (125°/90°) and 630 - 765 m (195°/50°) in borehole KR2, 385 - 790 m (345°/90°) in borehole KR3 and 590 - 690 m (280°/75° and 50°/80°) in borehole KR6. There appear to be no differences in fracture orientations with regard to rock type or depth.

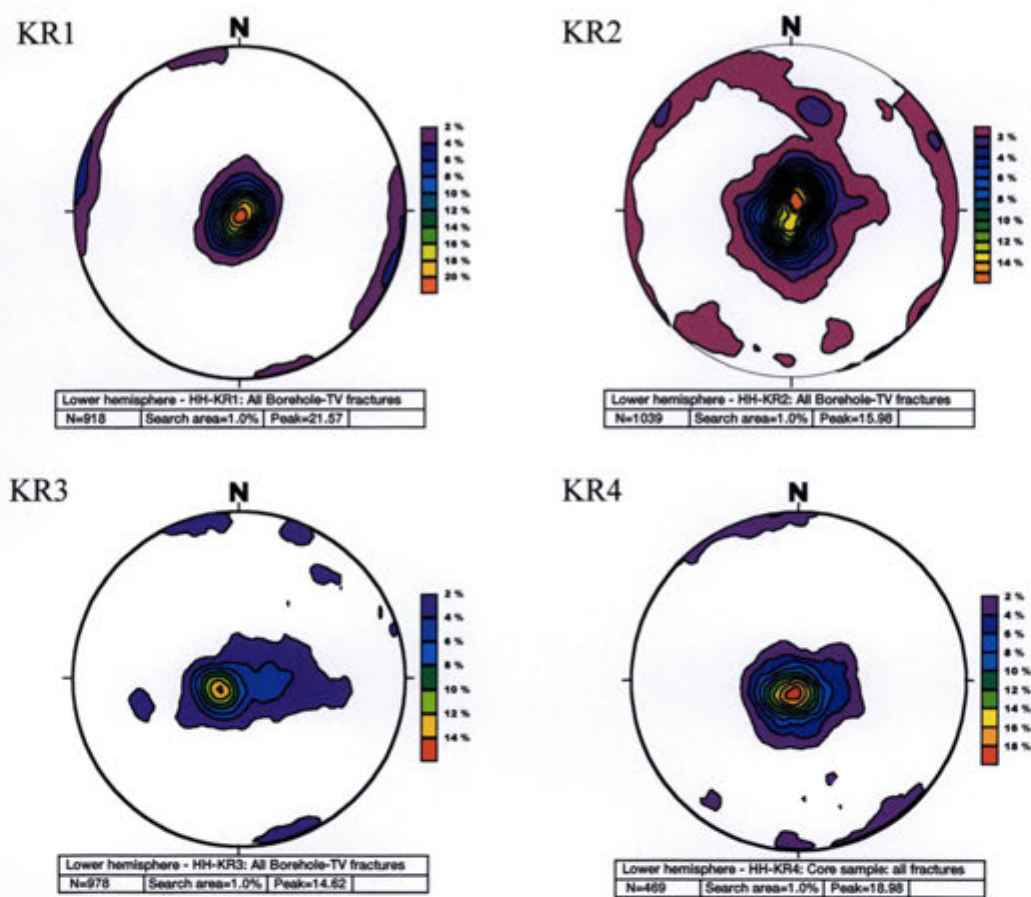


Figure 4.2-5. Distribution of the fracture orientations in Hästholmen boreholes. a) KR1, TV-logging, b) KR2, TV-logging, c) KR3, TV-logging, and d) KR4, core sample. Schmidt equal-area lower hemisphere stereographic projection.

4.3 Rock Mechanical and Thermal Properties

Knowledge of rock mechanical and thermal properties are of importance when planning a deep repository. The rock strength, in situ state of stress and the stress-strain behaviour of the rock affect the choice of repository depth, as well as the shape and orientation of the deposition tunnels and disposal holes. The thermal properties of the rock must be taken into consideration, too, because temperatures are expected to increase in the immediate vicinity of the repository due to the radiogenic heat produced by the spent fuel.

4.3.1 Strength Properties

The strength properties of the different rock types at Hästholmen have been studied by carrying out preliminary loading tests in the field with more detailed tests taking place in the laboratory. Table 4.3-1 presents the mean values for the uniaxial compressive strength (σ_{UCS}), tensile strength (σ_t), Young's modulus (E) and Poisson's ratio (ν) as compiled from different reports (Anttila 1988, Kuula 1994, Eloranta & Hakala 1999). The majority of the

Table 4.3-1. Strength and deformation properties of the rock types at Hästholmen. Values presented are arithmetical means, standard deviation is given in brackets, n = number of samples. Based on Äikäs et al. 1999.

Rock type	Uniaxial compressive strength σ_{ucs} (MPa)	Tensile strength σ_t (MPa)	Young's modulus E (GPa)	Poisson's ratio ν
Pyterlite, wiborgite	169.4 (28.0) $n = 64$	9.4 (2.3) $n = 36$	64.8 (6.0) $n = 70$	0.21 (0.05) $n = 70$
Even-grained rapakivi granite	216.6 (59.7) $n = 14$	14.7 (2.8) $n = 21$	71.1 (2.2) $n = 12$	0.25 (0.02) $n = 12$

tests took place on pyterlite/wiborgite and even-grained rapakivi granite which are the dominant rock types at Hästholmen. The values presented in Table 4.3-1 are those measured on dry rock samples. Strength values for water-saturated samples of pyterlite/wiborgite are about the same as for the dry samples. Samples tested under confining pressure exhibit considerably higher strength values.

4.3.2 In Situ State of Stress

In situ stresses have been measured in four deep boreholes (KR4, KR5, KR6 and KR7) and during the VLJ repository investigations at the depth interval 10 - 140 m, both by hydraulic fracturing and overcoring methods (Anttila & Johansson 1994, Ljunggren 1998). Due to geotechnical problems in the form of core discing, only few measurements at 300 m depth using the overcoring method were successful, although several attempts were made. However, core discing observations are being used to evaluate the in situ stresses. Difficulties were also encountered with the use of the hydraulic fracturing method and only horizontal fractures were recorded at greater depths thereby preventing the evaluation of the in situ stress. Because of the difficulties in hydraulic fracturing method a HTPF-method (hydraulic testing in pre-existing fractures) is also being tested in two deep boreholes (KR5 and KR6). The results below 300 m and the trend line drawn from the preliminary results show that the stresses are clearly increasing with depth, having a value of about 30 - 35 MPa at a depth of 500 m (Fig. 4.3-1). The maximum principal stress is sub-horizontal with the average dip of 16°. The orientation of the maximum horizontal stress is approximately east-west (Fig. 4.3-2).

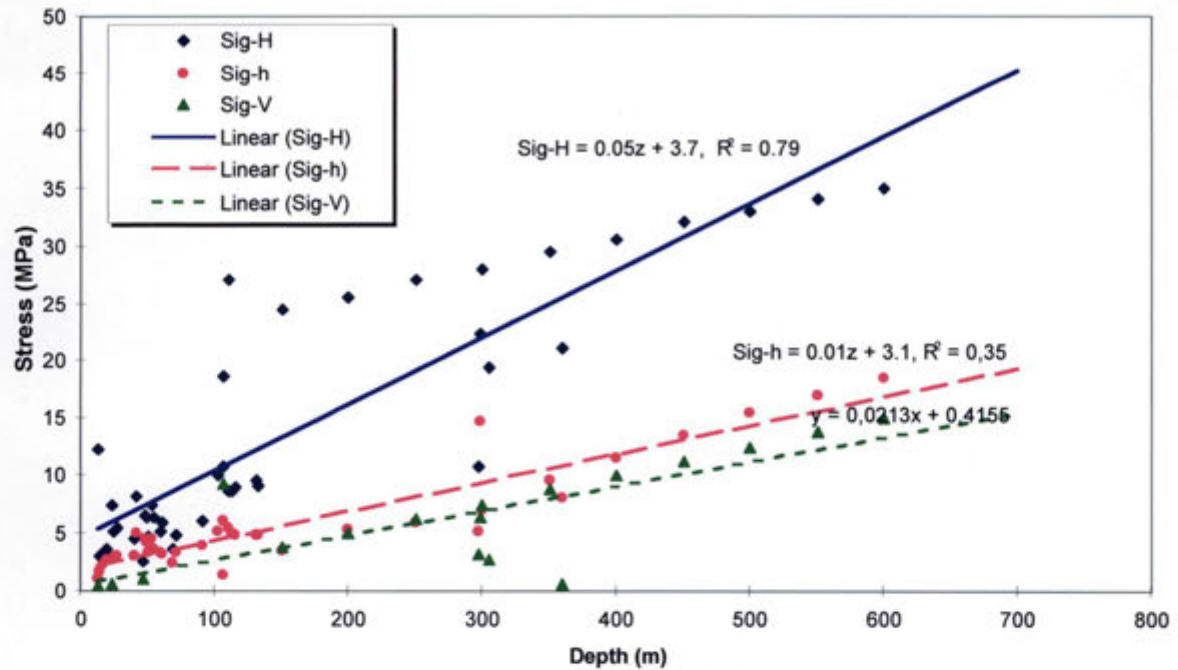


Figure 4.3-1. The magnitudes of maximum and minimum horizontal (Sig-H, Sig-h) and vertical (Sig-v) in situ stresses with depth at Hästholmen.

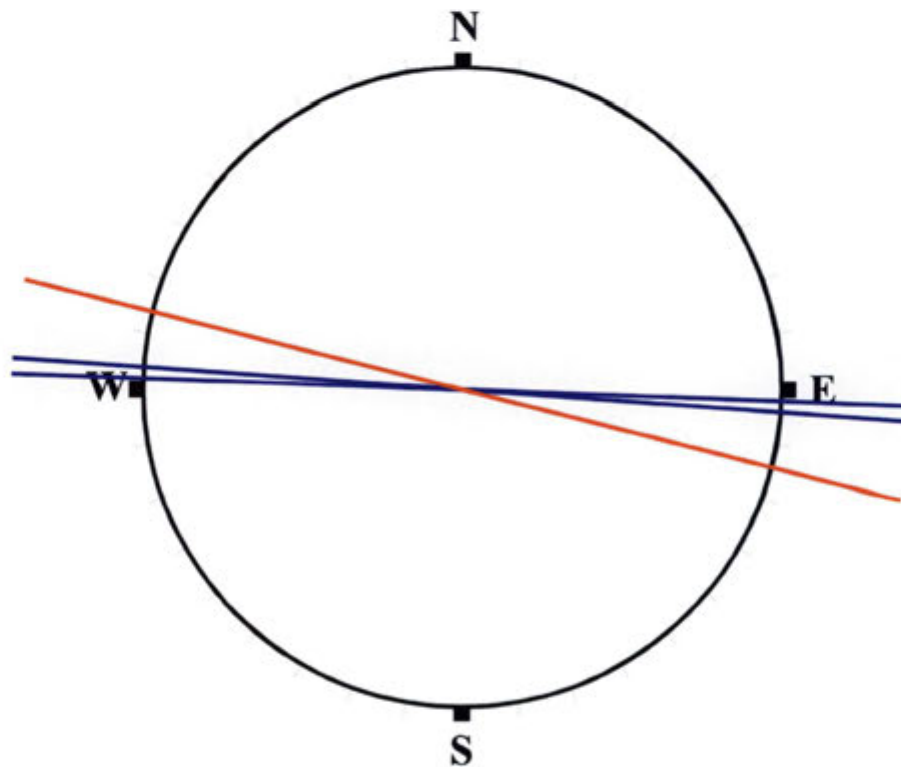


Figure 4.3-2. The orientation of maximum horizontal (Sig-H) in situ stress at Hästholmen.

4.3.3 Thermal Properties

The thermal properties of rock samples taken from four deep boreholes (KR1, KR2, KR3 and KR4) have been studied in a laboratory (Kukkonen & Lindberg 1998). The means of thermal conductivity, specific heat capacity and thermal diffusivity for different rock types are presented in Table 4.3-2. The coefficient of thermal expansion has not been determined.

The results indicate that the bedrock of Hästholmen is relatively homogeneous as regards its thermal properties and the even-grained rapakivi granite appears to be thermally some more conductive than the other rock types. The in situ temperature of the rock (as measured in the groundwater) is approximately 6 - 8 °C at a depth of 0 - 200 m, and the temperature at 500 m is approximately 13 °C (Julkunen et al. 1997, 1998a, b, Okko et al. 1998), demonstrating that the geothermal gradient is low.

Table 4.3-2. Thermal properties of the rock types at Hästholmen. Values presented are arithmetic means, standard deviation is in brackets, *n* = number of samples.

Rock type	Thermal conductivity (W/mK)	Specific heat capacity (J/kgK)	Thermal diffusivity (m ² /s) · 10 ⁻⁶	
Temperature range	20 °C	60 - 99 °C	20 °C	
Pyterlite, wiborgite	2.6 (0.2) <i>n</i> = 5	811 (10.4) <i>n</i> = 5	1.23 (-) <i>n</i> = 1	1.22* (0.09) <i>n</i> = 5
Even-grained rapakivi granite	3.4 (0.04) <i>n</i> = 5	802 (8.4) <i>n</i> = 5	1.33 (0.07) <i>n</i> = 1	1.62* (0.03) <i>n</i> = 5

*value calculated

5 MODELS OF THE ROCK MASS

5.1 Lithological Model

5.1.1 Regional Scale

The bedrock model of the Hästholmen site consists of rapakivi granite, represented by wiborgitic, pyterlitic and even-grained variants, 1 650 - 1 620 million years in age. The regional model is based on surface mapping combined with interpretations of regional airborne geophysics. The notation used for the lithological model is given in Figure 5.2-2. The computerised lithological model of Hästholmen also covers part of the regional scale model (i.e. beyond the limits of Hästholmen site) as depicted in Figure 5.2-3.

5.1.2 Site Scale

Surface lithological maps at the site scale are shown in Figures 5.2-4 and 5.2-5. The investigation site includes the islands of Hästholmen and Tallholmen (for place names, see e.g. Fig. 2.2-2) and mainland area north-west of the island, with the emphasis being placed on the island of Hästholmen. The host rock is wiborgite-pyterlite and a large body of even-grained rapakivi granite also outcrops running southwest - northeast. Part of this granite formation consists of a subhorizontal layer-like body which lies beneath the island of Hästholmen (see Fig. 5.2-6) and seems to have a direction between north and east (Paananen & Paulamäki 1998).

Other variations of rapakivi granite has also been mapped – such as wiborgite, pyterlite and dark pyterlite. A pyterlitic variation, for example, has been observed in the southern part of Hästholmen island and in Tallholmen. The development of the site-scale lithological model has required that the contacts between several of these geological bodies are assumed to be vertical, since insufficient data have been available to define them otherwise.

The boreholes provide a lot of information on lithological contacts, and there seems to be no clear relationship between the locations of these contacts and the fracture zones. The major lithological trend is ENE-WSW with the lithological contacts dipping towards the NNE.

5.2 Structural Model

5.2.1 Regional Scale

The regional fracture zone model, based on satellite images, aerial photographs, geological mapping and ground level and airborne geophysical surveys (Kuivamäki et al. 1997a), shows regional fracturing in the Hästholmen area to be dominated by long, narrow northwest-southeast-oriented crush zones (regional major fracture zones) which in places can be tens of kilometres in length. Crush zones also trend northeast-southwest and the Hästholmen site is located in a block surrounded by these lineaments (Fig. 5.2-3).

All major lineament structures are assumed to be regional-scale structures. Since the area of the regional model is largely offshore, the existence and character of such structures at Hästholmen is based largely on the assumptions and knowledge from other sites studied by Posiva. Additional indirect information has been available from the regional- and site-scale airborne geophysics (Paananen & Paulamäki 1998) and the seismic and acoustic surveys carried out offshore (Kuivamäki et al. 1997a).

It was assumed for the purposes of the regional model that these regional structures continue deep into the Earth's crust, i.e. much deeper than the depth limit of 1500 m used in the model of the rock mass. The locations of the regional structures are depicted in Figure 5.2-1, which has been modified from Kuivamäki et al. (1997a) (and previously in Section 2 in Figure 2.1-2). The dips of the structures are assumed to be mainly vertical. Figure 5.2-3 also partly covers the regional scale fracture zone model and in it the regional model structures are labelled with LIN+number coding.

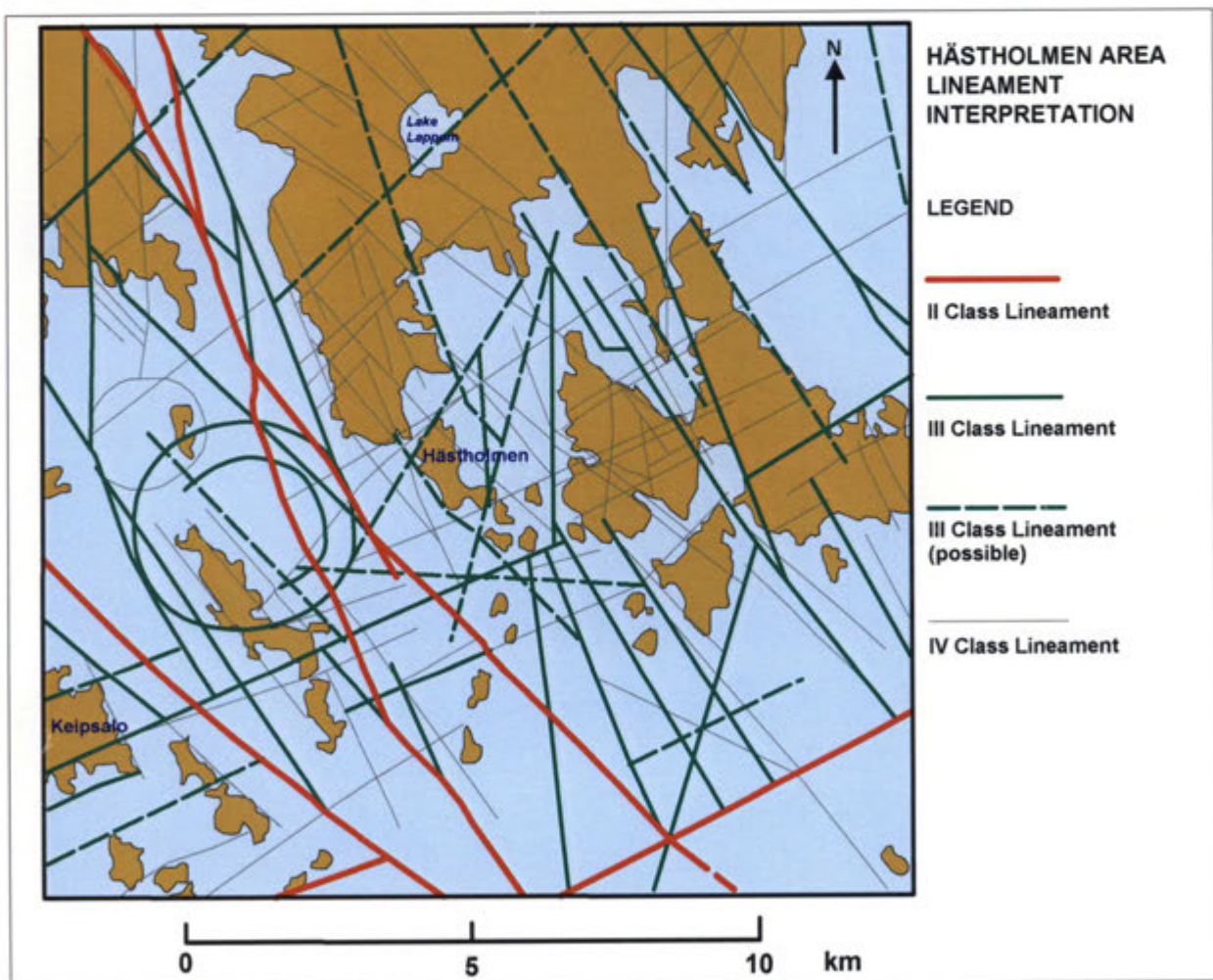


Figure 5.2-1. Bedrock structures determined for the Hästholmen area (modified from Kuivamäki et al. 1997a). The classification of the lineaments is presented in Table 2.5-1. The dips of the structures are assumed to be mainly vertical or as established in the site scale model.

5.2.2 Site Scale

The site scale model is concerned with the investigation area itself, as referred to above, and its immediate surroundings, and depicts the fracture zone structures. In the development of the structural model, fracture zones have been divided into four *classes*, in increasing levels of uncertainty, with reference to the level of confidence that can be ascribed to their existence and geometry, as: *directly observed, probable, possible and other features*.

- A structure belonging to the directly observed (*certain*) class is one identified by direct observation (outcrop, drill core) at least at one location. Its geometric dimensions are nevertheless to a great extent based on interpretations and estimates.
- A structure in the *probable* class is one that has been observed by two or more indirect methods, for example geophysical surveys or lineament investigations.
- A structure in the *possible* class includes structures deduced from one indirect method of investigation.
- The class *other* has been used to incorporate uncertain geometric features or alternatives into the model which can be useful during interpretation and during the planning of subsequent investigations.

These fracture zones have also been divided into different types based on their overall properties, ranging in scale and effect from *crush zones*, through densely fractured (>10 fractures/m) and altered *major fracture zones*, to *fracture zones* containing of fracturing, *to open or more abundant fracturing*, which may consist of only one open fracture. The fracturing and weathering values used to classify the structures and the graphical representations used in the models are shown in the legend in Figure 5.2-2.

The current Hästholmen site bedrock model (2.0) referred in this section is based on information from boreholes KR1 - KR3 and partly from KR4 (Lindh et al. 1998). Most of the volume of the site model consists of the sparsely-fractured *intact* rock mass. Its general lithological composition, tectonic evolution and fracturing have been described previously in Section 4 of this report. Data from boreholes KR1 - KR4 show that 2 - 9% of the core is more densely fractured (Okko et al. 1998). A total of 5% of the core samples indicate a measurable degree of weathering which is most frequent in the surficial part of the rock mass.

The site scale model covers an area of 30 km² and has a volume of 45 km³. The model contains 25 structures, each of which is described more in detail elsewhere and labelled as R+number structures (Paananen & Paulamäki 1998, Okko et al. 1998, Lindh et al. 1998). In addition, other structures occur, based on other observations like topographic or magnetic lineaments. Altogether 15 structures have been estimated to be fracture zones of major type, 9 zones belong to the class of fracture zones and one structure (R4) is described in terms of more abundant fracturing. The majority (19) of the structures are evidenced from direct observations, in this case from borehole intersections. Four structures lie in the probable and two in the possible category. The fracture zone model is most accurate and reliable in the northern part of the Hästholmen island and within the perimeter of the cored boreholes KR1 - KR4. The existence and extent of fracture zones lying in the *certain* category is often supported by reflections from geophysical vertical seismic profiling (VSP) and horizontal

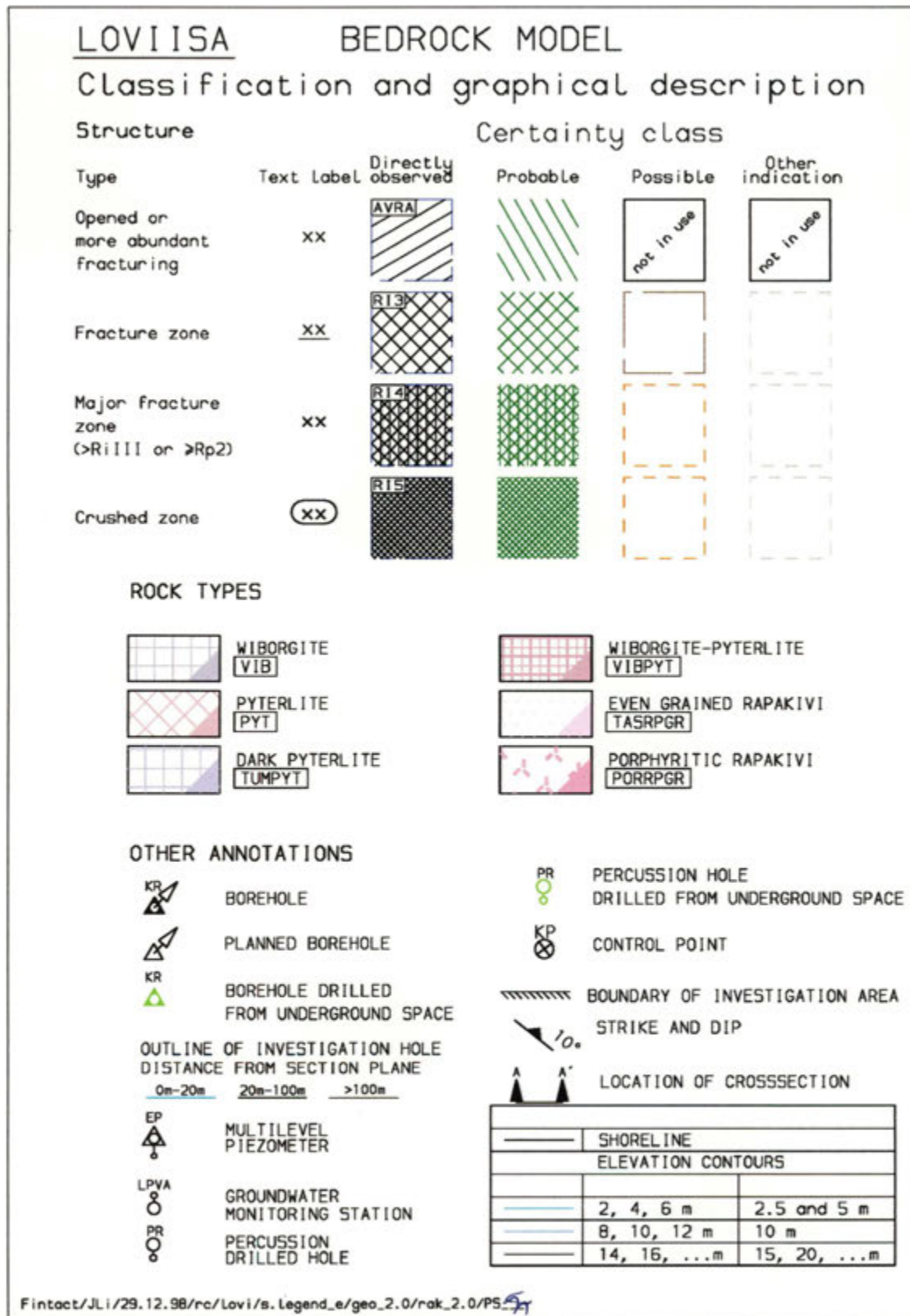


Figure 5.2-2. Legend of the Hästholmen bedrock model.

seismic profiling (HSP) surveys. Some electrical cross-hole measurements were conducted during the VLJ investigation phase and the continuity of such zones is also supported by this type of indirect evidence.

Fourteen of the fracture zones are steeply dipping (dip $> 60^\circ$). Many of these have been modelled steep because there is no information on the dip yet. Only one of zones (structure R7) has an inferred moderate dip ($30 - 60^\circ$) and ten structures are gently dipping (dip $< 30^\circ$). The surface maps of the model illustrating the lithology and the structures are shown in Figures 5.2-3, 5.2-4 and 5.2-5. Figure 5.2-3 shows the whole area described by the bedrock model and Figures 5.2-4 and 5.2-5 provide views at higher scales. Most of the geological and geophysical investigations have been carried out within the area shown in Figure 5.2-4. Figure 5.2-6 displays a northwest-southeast cross section across the island of Hästholmen in which the varying dips and inferred extensions of the fracture zones can be seen. A large portion (40%) of the structures in this figure have gentle dips.

Certain fracture zones are conformable with the contacts between the larger rock units, for example structure R18 appears to follow the hangingwall contact of the even-grained rapakivi granite body. Structures R1 - R4 and R17 - R20 all have gentle dips and the structures which are not visible in Figures 5.2-3 - 5.2-6 are mostly gently dipping. Fracture zones R5 and R6 within the island area (Fig. 5.2-4) are in the *possible* class. Several structures are interpreted as being discontinuous and are assumed to be comprised of localised compartments or segments. Examples of such structures are R18 and R19.

Fractured sections make up 14.5% of the total core length of the boreholes KR1 - KR4. This is a larger value than at Kivetty and Olkiluoto but lower than at Romuvaara. The presence of structures R1 - R25 can be used to explain 56.5% of the fractured sections in the boreholes. For borehole KR4 the fractured sections were included but only partly assigned with structure identification in this model (version 2.0). However, it should be noted that further structural interpretation and bedrock modelling will be carried out in the future. This will complete the studies of borehole KR4 as well as including the drilled new boreholes KR5 - KR9, and these additional data may change the preliminary indices given here.



Figure 5.2-3. Surface map of the Hästholmen bedrock model covering site-scale and partly also the regional-scale models.

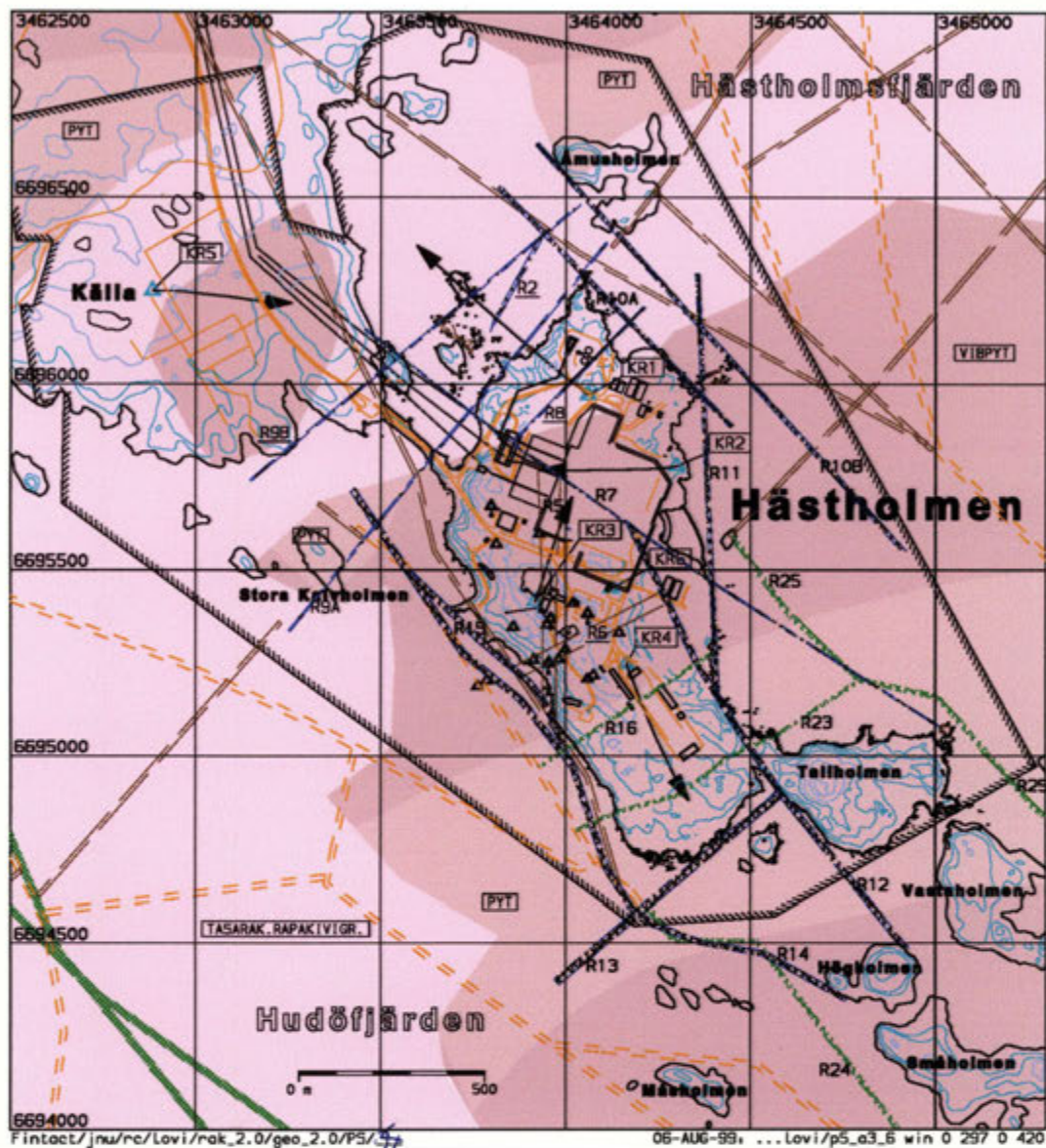


Figure 5.2-4. Surface map of the Hästholmen site model. Varying types of structures in classes *certain*, *probable* and *possible* are displayed. All outcropping bodies of pyterlite are indicated.

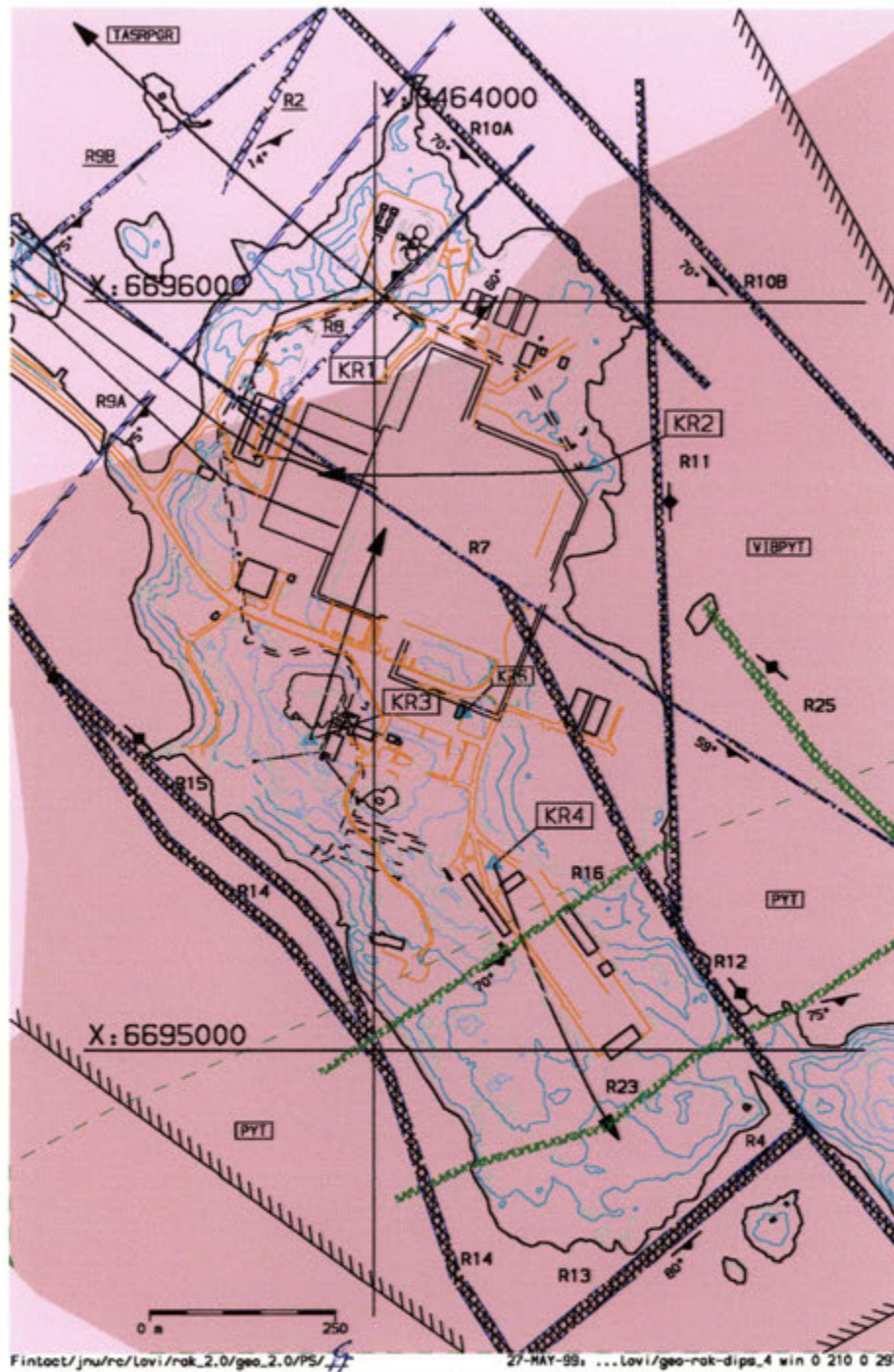


Figure 5.2-5. Surface map of the Hästholmen island bedrock model. Structures in classes *certain* and *probable* are displayed. The dips of geological bodies are shown.

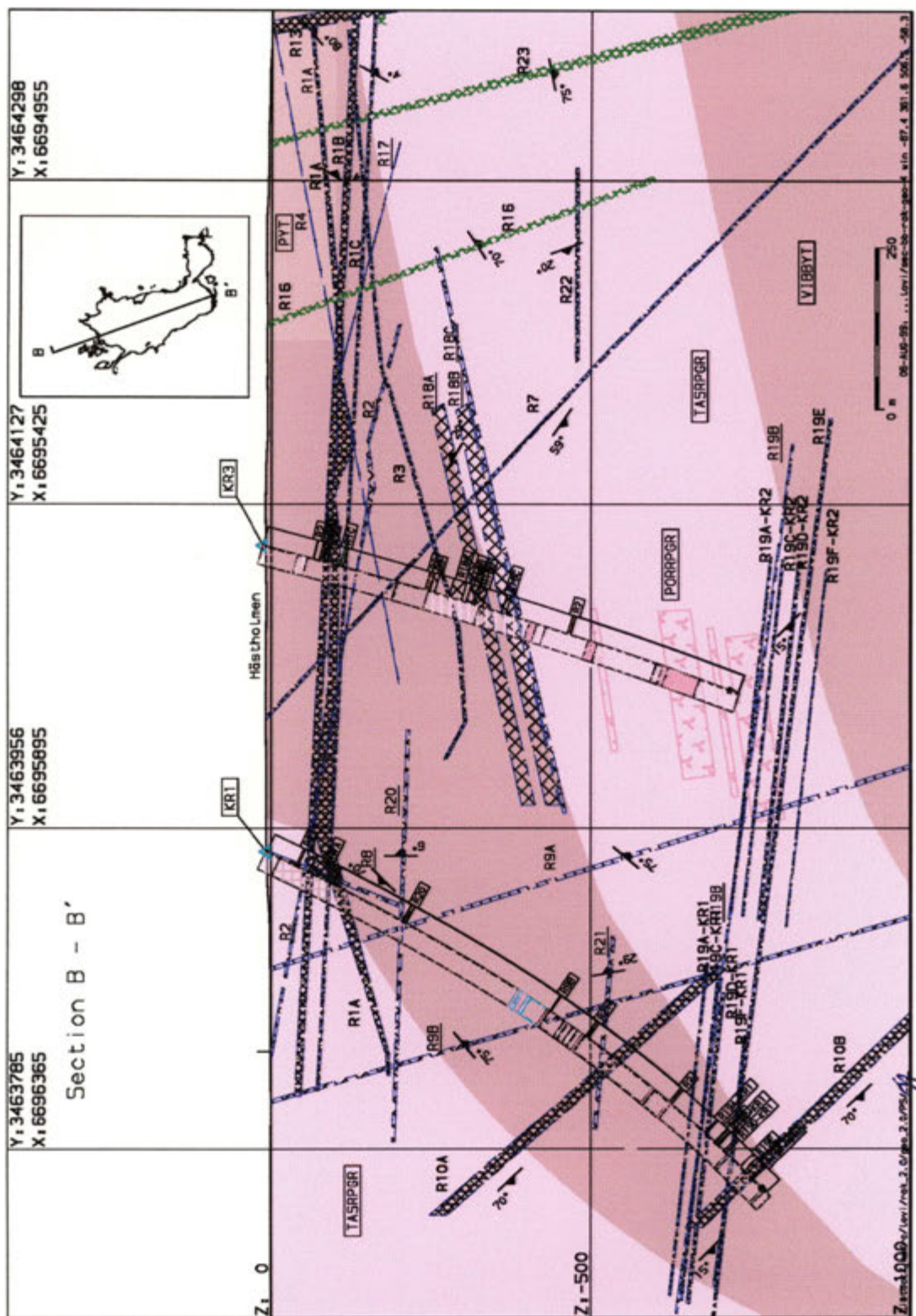


Figure 5.2-6. SSE-NNW vertical cross section through the Hästholmen site scale model. Boreholes KR1 and KR3 lie within the cross section and depict the rock types and fractured sections encountered. Structures in classes *certain* and *probable* with their average dips are displayed. The major northeast dipping trend in the lithology is clearly visible.

The intensity of fracturing and degree of weathering, alteration and tectonitisation varies within the structures. Rock which displays similar fracture densities to those of the intact rock is frequently present over large portions of the rock mass included within their boundaries. This is particularly noticeable within the boundaries of the segmented fracture zones R1A-R1B-R1C, the R18 group and the R19 group (Fig. 5.2-6). A summary of the properties and characteristics of the fracture zones (structures) is given in Table 5.2-1 with associated, relevant background data. Structures R1 and R25, which are discussed briefly below, exemplify the data associated with the fracture zones and the interpretations required for their delineation. Structure R1 is a major fracture zone which has been directly observed and structure R25 is an example of a less well understood fracture zone in the probable class. Summary descriptions of all the structures can be found in Anttila (1988), IVO International Oy (1996), Okko et al. (1998), Paananen & Paulamäki (1998), and Lindh et al. (1998), which also contain further references to the detailed data available.

Structure R1 is the best known fracture zone identified and characterised in the bedrock of Hästholmen. It can be considered one of the major fracture zones in the area, from both the point of view of groundwater flow and constructability. The structure had already been identified in the 1980s in 15 boreholes drilled for the VLJ repository and was cut by the access tunnel and the two shafts of the repository. Electrical cross-hole measurements have been used to investigate its geometry and continuity. During these site investigations structure R1 was observed in deep boreholes KR1 - KR4. Structure R1 is found in sections of borehole KR1 from 75 - 120 m, in borehole KR2 from 105 - 139 m, in borehole KR3 from 92 - 100 m and from 127 - 132 m, as well as in borehole KR4 from 112 - 125 m and from 149 - 152 m. Later, the structure was also detected in borehole KR6. It is shown close to the surface in Figure 5.2-6 and its extent has been tentatively approximated to an area bounded by structures R15, R9B, R10A, R11 and R13.

In the VLJ-boreholes structure R1 dips 10 - 20° to the north-east and in boreholes KR1 - KR4 approximately 4° towards the south-east. Its thickness varies from 6 m to 28 m and averages 10 m. Typically it consists of a set of more or less parallel fracture zones with intact rock lying between the broken sections. The broken rock mass generally represents fracture- or crush-structured rock (RiIII - IV). The weathering degree ranges from unweathered (Rp0) to completely weathered (Rp3). The fractures are mostly filled by secondary minerals, e.g. chlorite, kaolinite and clay minerals, but open and tight fractures also occur.

The transmissivity (T) of structure R1 has been measured by two single-hole methods, the constant head injection test using a double-packer system and by flow logging using the flowmeter. In total, 18 single-hole T values have been obtained and are presented in Figure 5.2-7. Most of these values are from boreholes drilled for the VLJ repository Y-boreholes and measured during 1980s (Anttila 1988). Details of the distribution of hydraulic conductivities measured over 2 m borehole lengths for structure R1 in boreholes KR1 are illustrated by Figure 5.2-8.

Structure R25 is a less well known major fracture zone that is part of both the site- and the regional-scale models. Its surface trace is in a northwest-southeast direction and it follows the north-east shore of the island of Hästholmen (see Figs. 5.2-3 and 5.2-4). The structure

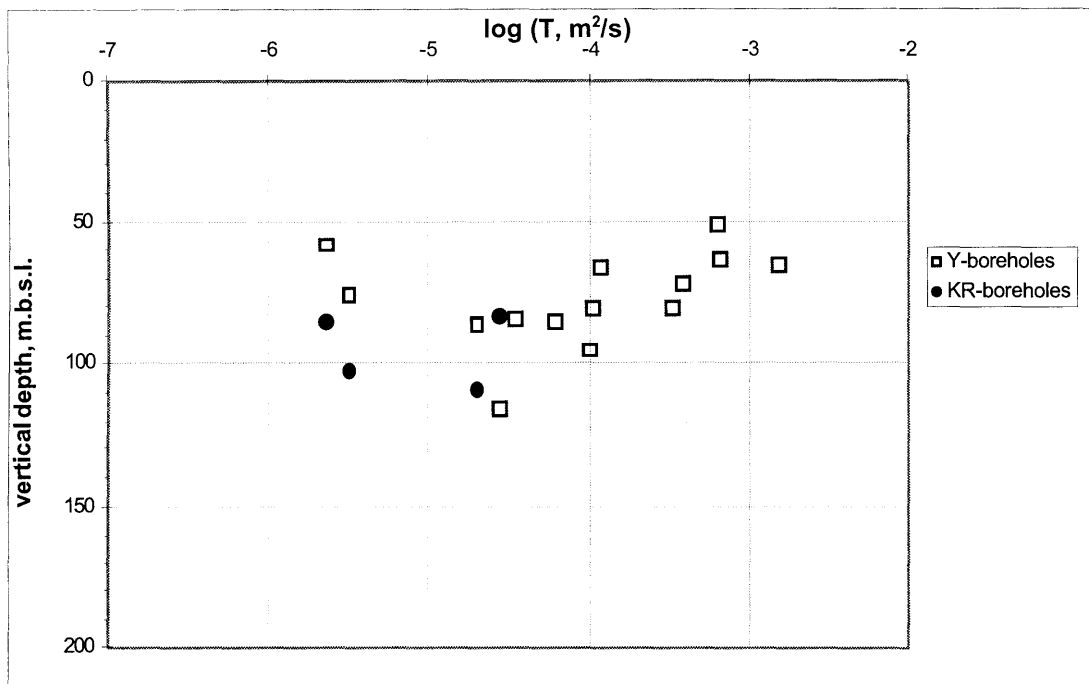
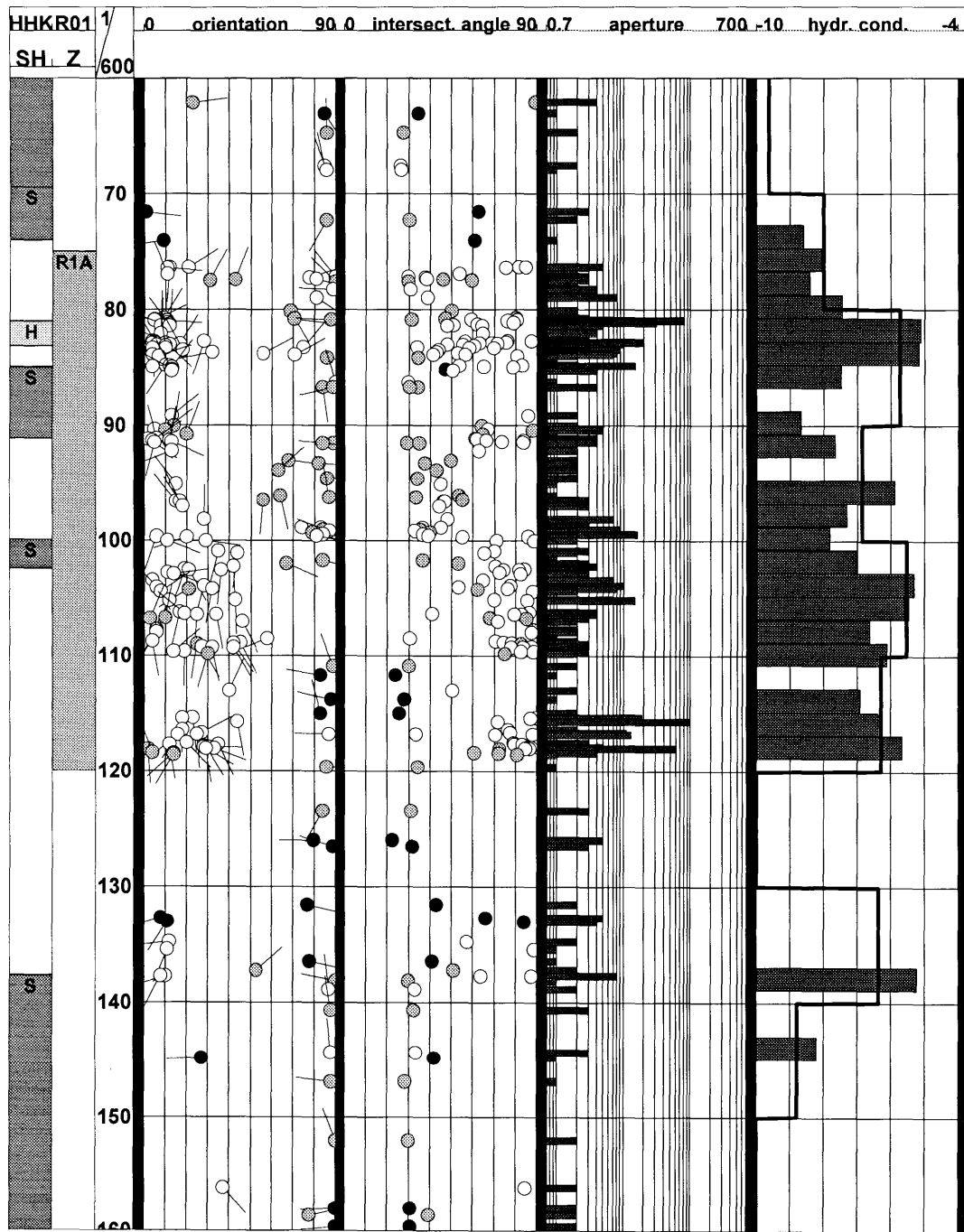


Table 5.2-1. Summary of the properties of the fracture zones R1–R25 in the bedrock model.

HÄSTHOLMEN		v.2.0		MODEL STRUCTURE										NOTATION:					is observed or deduced property of the structure														
CHARACTERISTICS OF STRUCTURES		R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24	R25							
Average orientation		Dip direction, °		120	120	34	315	270	335	215	315	135	225	85	50	140	10	45	145	180	30	225	90	80	250	170	53	40					
		Dip, °		4	13	13	12	90	90	60	70	75	70	90	90	80	90	90	70	16	20	15	6	29	20	75	40	90					
Surface trace length (or extension)																																	
- regional																																	
- more than 1000 m																																	
- less than 1000 m																																	
Extension to depth (or horizontal extension)																																	
- large, more than 1500 m																																	
- 750 - 1500 m																																	
- less than 750 m																																	
Structure concordant with the lithology																																	
Tectonized, mylonitized																																	
Continuous, compact structure /																																	
Discontinuous structure																																	
Certainty level																																	
- based on direct observations, "certain"																																	
- based on several indirect interpretations																																	
and estimations of different types, "probable"																																	
- based on one indirect interpretation																																	
or uncertain in other respects, "possible"																																	
Engineering geological classification:																																	
Weathering degree: Rp0 - Rp3		0-3	0-3	0-3	0	0	0	0-3	0	1								0-1	0-2	0-1	0-1	0-2	0-1										
Fracturing degree: Ri I - Ri V		III-IV	III-IV	II-V	1	1	I-II	III-IV	III	III								III	I-IV	II-III	II-III	II-III	III										
Important for rock engineering																																	
Important for groundwater hydraulics																																	
Direct observations		KR1	*)	KR2	*)	*)	*)	KR3	*)	KR1												*)	KR2	KR1	KR1	KR1	KR1	KR4					
in deep boreholes KR1-KR4		KR2		KR3																			KR3	KR2	KR2								
*) observed in VLJ		KR3		KR4																			KR4										
Y- and/or YT-boreholes		KR4		*)																													
		*)																															



Columns from left to right: S = oriented sample, H = core loss, Z = fracture zone, orientation = orientation by fracture type: open = $\bigcirc$, tight = $\bullet$, filled = $\odot$, weathered = $\ominus$, the tail of the mark shows the orientation, intersect. angle = intersection angle by fracture type, aperture = fracture aperture (mm) and hydr. cond. = hydraulic conductivity ($\log K$ (m/s)): Flowmeter = bar, and HTU = line.

Figure 5.2-8. Detailed characteristics of fracturing (Strähle 1998) and hydraulic conductivity in structure R1 in borehole KR1. Structure R1 lies in the depth range 75 - 120 m

6 HYDROGEOLOGY

6.1 Hydraulic Conductivity of the Bedrock

Hydraulic conductivity (K , m/s) is a parameter commonly used in hydrogeological characterisation of a geological media. Two methods have been used to measure hydraulic conductivity:

- the Hydraulic Testing Unit (HTU) (Fig. 2.2-7)
- the Flowmeter (Rouhiainen 1997).

Double-packer injection tests with constant head have been performed by HTU. Measured values vary between $2 \cdot 10^{-12}$ - $3 \cdot 10^{-4}$ m/s (Hämäläinen 1998a, b, 1999). The flowmeter has been operated using the constant head method without any pressure difference between the measuring section and the remaining of the borehole. Values of hydraulic conductivity determined using this method vary from $2.5 \cdot 10^{-10}$ to $2.5 \cdot 10^{-5}$ m/s (Pöllänen & Rouhiainen 1998a, b). The total number of hydraulic conductivity determinations measured over 10 m and 2 m test lengths at Hästholmen is 816 for the HTU (boreholes KR1 - KR3) and 2 610 for the flowmeter (boreholes KR1 - KR6).

On the basis of studies of flow dimension from the Romuvaara site, based on transient curves of HTU tests, most common dimensions are between 2 and 2.5 (Kuusela-Lahtinen & Niemi 1995, 1996). For this reason the radial flow equation or Moye's equation (Moye 1967) for the interpretation of hydraulic tests has been used.

The results of hydraulic conductivity measurements using both the HTU and flowmeter methods in borehole KR1 are compared as an example in Figure 6.1-1. In general, there is good agreement between the values of K determined using either technique. There are some exceptions, especially at greater depths and for small values of K . The salinity of the groundwater increases with depth (see Section 7) and causes difficulties when using the flowmeter in determining pressure differences between the borehole and the surrounding bedrock. In borehole KR1 more conductive sections are clearly more frequent in the uppermost 150 m, although highly conductive sections are also present at greater depths. On the basis of results from studied boreholes it is apparent that the hydraulic properties of the uppermost 150 - 200 m of the bedrock are distinct from those at greater depth, i.e. hydraulically conductive fractures are more frequent and their transmissivity is higher. One reason for this at Hästholmen is that there is a large sub-horizontal fracture zone at a depth of 100 m, which is composed of several parts and has a considerable thickness and effectively determines the hydraulic properties at these depths.

Figure 6.1-2 shows in detail the relationship between fractures and measured values of K in borehole KR1 over a short range of depths. The hydraulic properties of the rock mass are controlled by the presence of structure R21, which is a fracture zone with a width of 5 m. A section of this fracture zone with a width of 1 m at a depth of 604 - 605 m controls the zone's transmissivity and this section is several orders of magnitude more hydraulically conductive than other parts of the structure. The most conductive section contains several open, slickensided fractures and, in general, there is a good relationship between measured

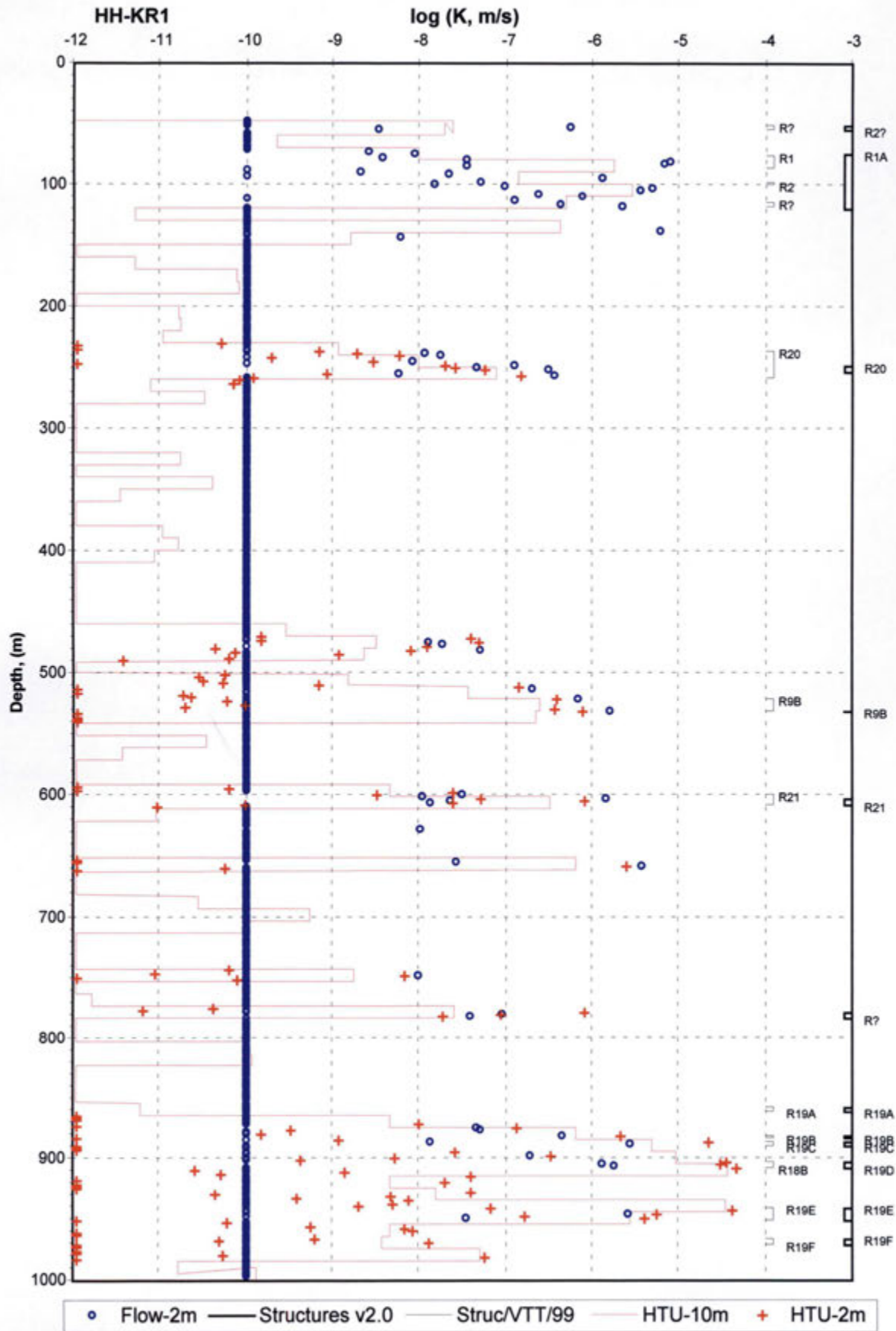
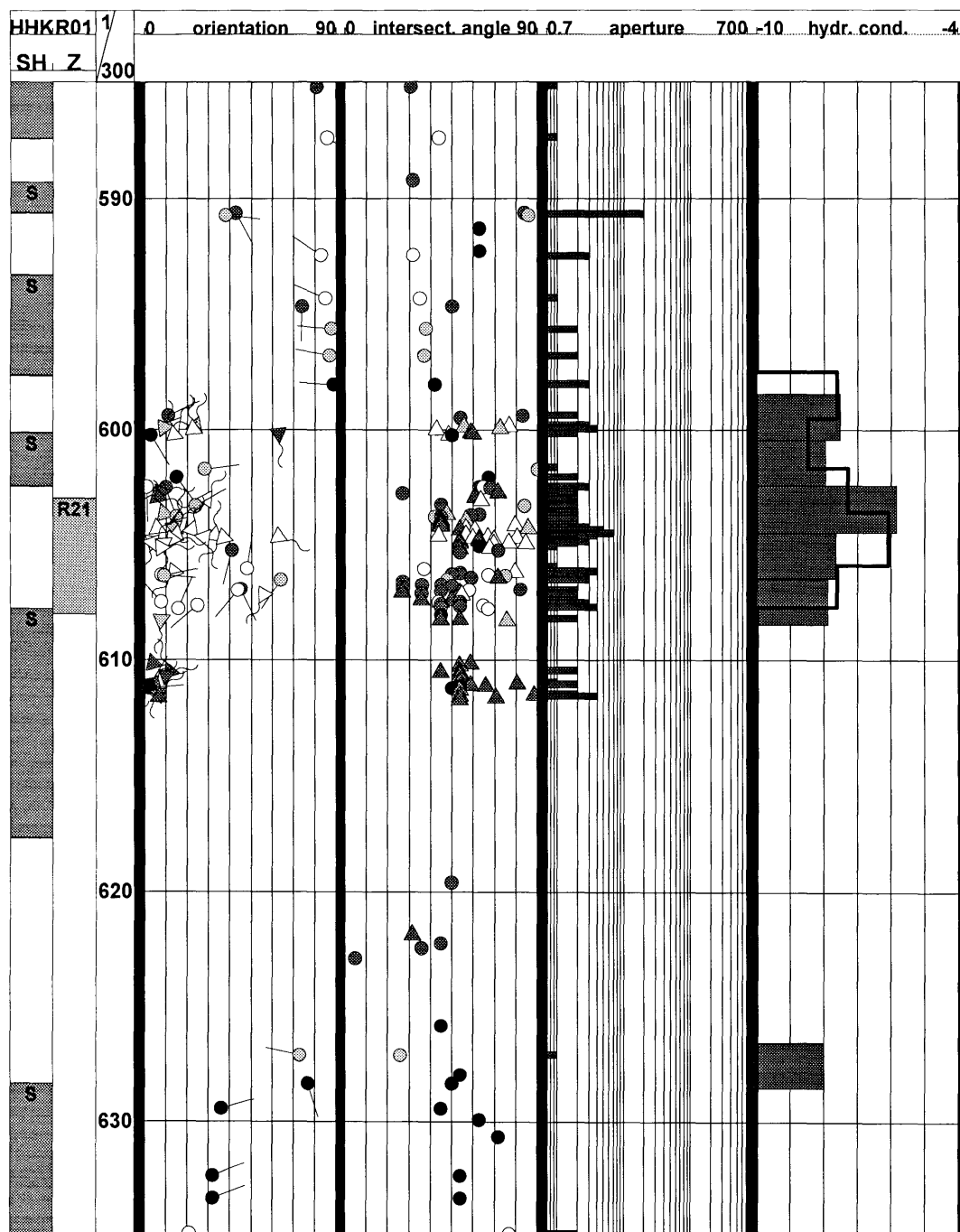


Figure 6.1-1. Hydraulic conductivities measured with two different methods and two different test section lengths in borehole KR1.



Columns from left to right: S = oriented sample, H = core loss, Z = fracture zone, orientation = orientation by fracture type: open = ○, tight = ●, filled = ●, weathered = ○, open slickenside = △, tight slickenside = ▲, filled slickenside = ▲, weathered slickenside = △, the tail of the mark shows the orientation, intersect. angle = intersection angle by fracture type, aperture = fracture aperture (mm) and hydr. cond. = hydraulic conductivity (log K (m/s)): Flowmeter = bar, HTU = line.

Figure 6.1-2. A detailed presentation of fractures and their properties in borehole KR1 for the depth interval 585 - 635 m (Karanko et al. 1999). Structure R21 lies in the depth range 603 - 608 m.

values of K and the presence of open fractures. A new, recently developed fracture detection system (Pöllänen & Rouhiainen 1998a, b), allows for the accurate logging of individual flowing fractures or sets of fractures which are in close proximity. Recent results using this system have enabled a more accurate examination of the correlations between fractures and their hydraulic properties to take place. This may help, for example in the compilation of more representative fracture networks, which can be used for groundwater flow modelling and for the planning and development of grouting techniques, for example.

To examine the difference between the hydraulic properties of fracture zones and that of the intact rock, all hydraulic conductivities measured over 2 m test lengths were divided into two groups to represent known R-structures (see Section 5) and the intact rock. What is termed “intact rock” also includes some fracture zones, which are normally narrow and are interpreted to be of limited extent and with unknown orientations. Known R-structures are commonly composed of several separate transmissive elements and for this reason the hydraulic properties of such zones are described in Figure 6.1-3 in terms of their transmissivities (T). The mean value of T for such R-structures is $8 \cdot 10^{-6} \text{ m}^2/\text{s}$ ($\log T = -5.1$, $s = 0.5$ ($s = \text{standard deviation}$)) if multi-element R-structures (such as R18A, R18B, R18C, etc.) are treated as a single zone with one T -value, which is the sum of the T values of all those sub-structures. The corresponding mean value of T for individual R-structures is $1.3 \cdot 10^{-6} \text{ m}^2/\text{s}$ ($\log T = -5.9$, $s = 1.6$). The corresponding value of K for the intact rock is $1 \cdot 10^{-12} \text{ m/s}$ ($\log K = -12.0$, $s = 2.3$). These statistics are based on regression lines in Figure 6.1-3. The

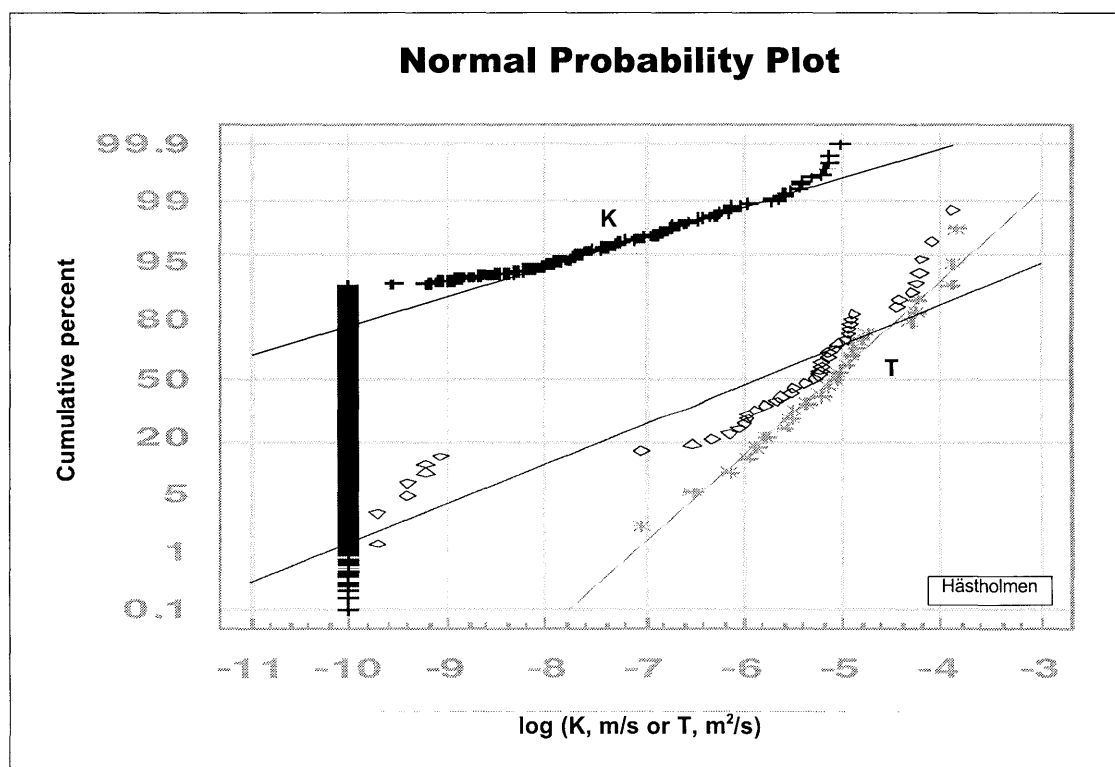


Figure 6.1-3. Transmissivities ($\log T$) of R-structures and hydraulic conductivities ($\log K$, measured over 2 m) of intact rock as cumulative distributions (normal probability plots). Visually-fitted regression line (approximate) for the intact rock is based on the assumption of a normal distribution for most credible values of K .

regression line for the intact rock is visually-fitted and based on values of $\log K$ lying between -8 and -6, which are considered to be the most credible. The main conclusion from this analysis is that the majority of the known R-structures are hydraulically more conductive than the intact bedrock, even in situations in which several hydraulically very poorly conductive parts of such R-structures (i.e. some sub-structures) and several hydraulically very conductive fractures and minor fracture zones, which are located outside known R-structures, i.e. in the intact rock, are known to exist.

The properties of the hydraulically most conductive fractures and minor fracture zones in the intact rock, i.e. in the rock lying between R-structures, have been investigated by analysing their spatial distributions and transmissivities in all the boreholes, where there are systematic values of hydraulic conductivity measured over 2 m test lengths. In this analysis the limit of transmissivity was set to about $1 \cdot 10^{-8} \text{ m}^2/\text{s}$ and the selection of this kind of conductive features was made on the basis of a visual analysis of measured K values. A *conductive feature* is associated with an individual fracture or a group of fractures in which the results from several 2 m long measuring intervals show enhanced transmissivity. The distances between identified R-structures without any hydraulically conductive feature between them were also taken into account in this analysis, and identified R-structures were also used as boundaries in determining the distances between hydraulically conductive features. A schematic illustration of the procedure is shown in Figure 6.1-4 and the results of the analysis are presented in Figure 6.1-5. Depth classes are 0 - 100 m, 100 - 300 m and over 300 m.

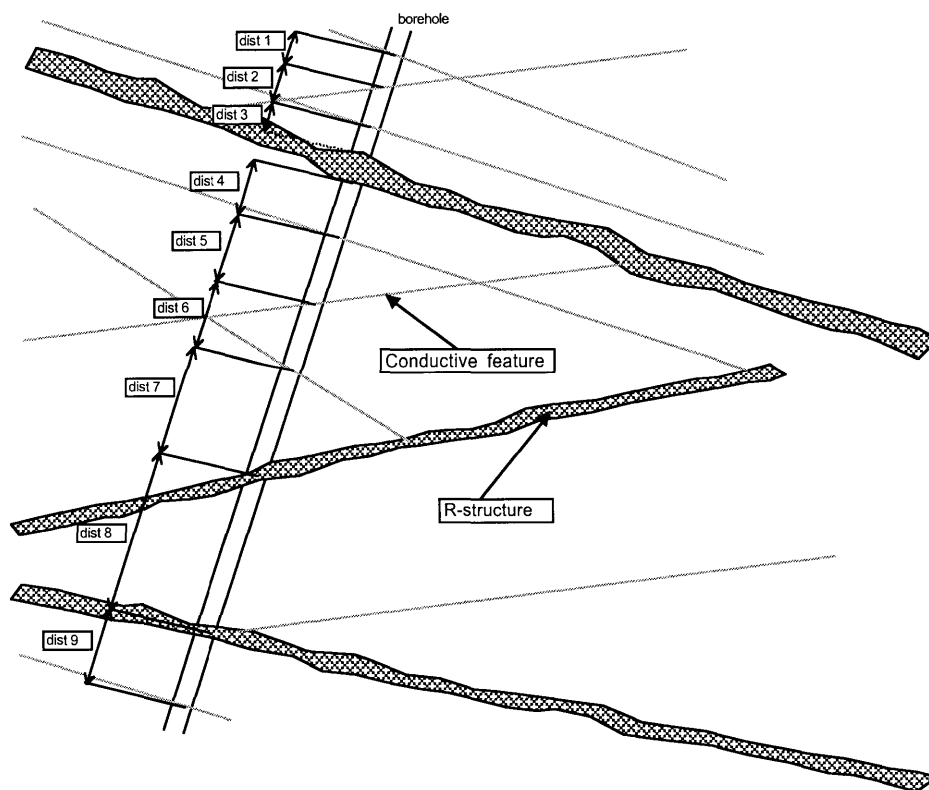


Figure 6.1-4. Determination of distances between hydraulically conductive ($T \approx 1 \cdot 10^{-8} \text{ m}^2/\text{s}$ or greater) features in intact rock (rock lying between known R-structures) and their transmissivities.

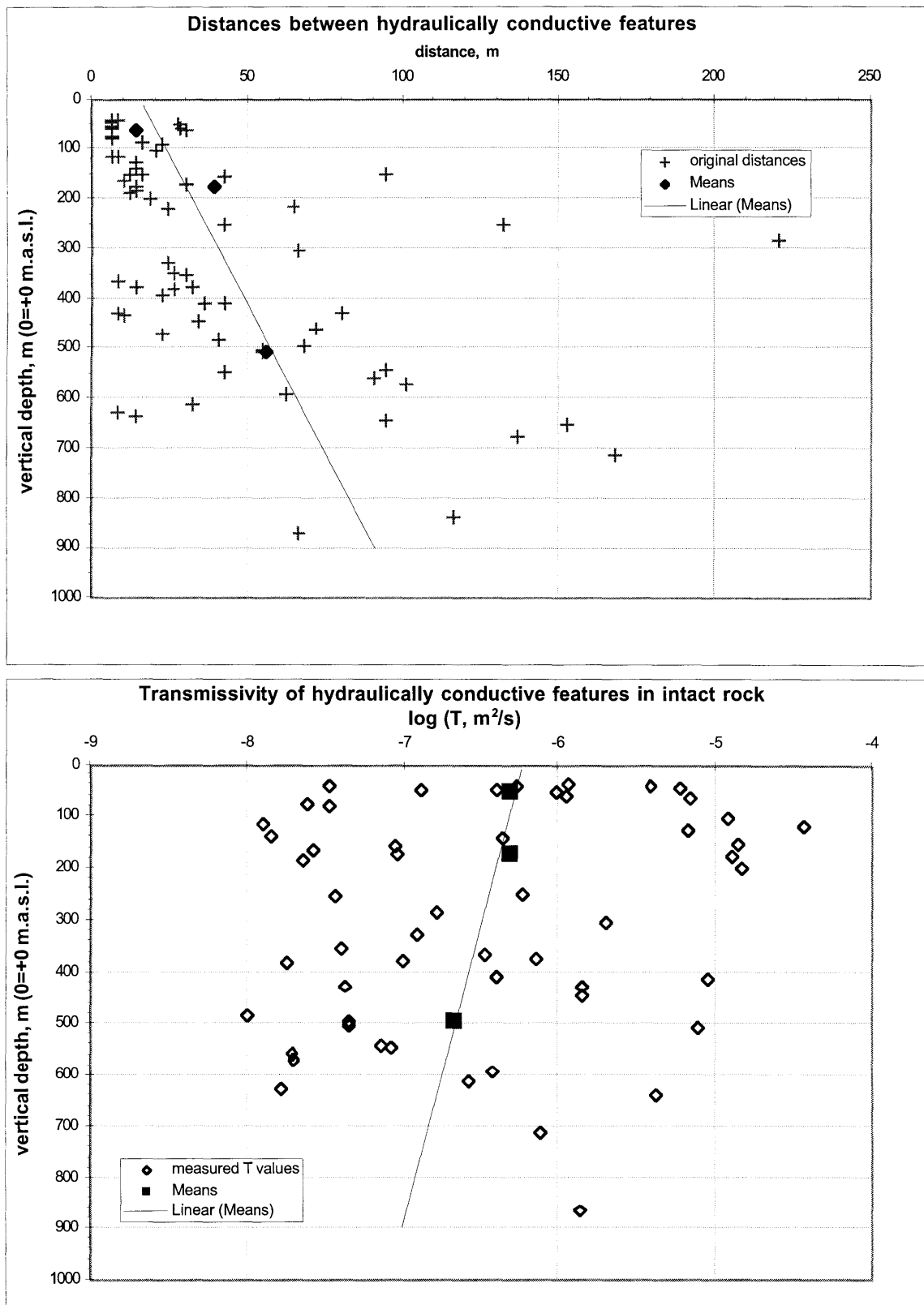


Figure 6.1-5. Distances between hydraulically conductive ($T \approx 1 \cdot 10^{-8} \text{ m}^2/\text{s}$ or greater) features in intact rock (rock lying between known R-structures) and their transmissivities (log) with depth.

The depth dependency of hydraulic properties was investigated by dividing the transmissivity values of R-structures into two depth classes and the hydraulic conductivity values of intact rock into three classes (Fig. 6.1-6). On the basis of regression lines, the log mean transmissivity ($\log \text{m}^2/\text{s}$) of R-structures in the uppermost 200 m of the rock mass was found to be -5.0 with an equivalent value of -5.3 for greater depths. Depths are real vertical depths calculated from the reference level of ± 0 m.a.s.l. (meters above sea level). Corresponding means of hydraulic conductivities ($\log \text{m/s}$) for intact rock for the three depth classes (0 - 200, 200 - 400 and 400 - 900 m) are -10.8, -11.2 and -13.0 respectively. The statistics of means and standard deviations (σ) are presented in the Table 6.1-1. The differences between the means for the intact rock are statistically significant at a level of significance of 0.01. The conclusion from this analysis is that there is a real decrease in the hydraulic conductivity of the intact rock with depth. The decrease in the transmissivity of R-structures with depth is possible but uncertain. These results have been used for the compilation of initial values of hydraulic properties for numerical groundwater flow modelling and for the extrapolation and interpolation of transmissivities within R-structures, where only one measured value of T is available.

Hydraulic connections between boreholes have not yet been studied by means of long-term pumping (interference) tests at Hästholmen, although such tests are planned to be carried out in the summer of 1999.

It has been found that for structure R19, which is highly fractured and consists of several sub-structures in borehole KR1, the transmissivity determined from flowmeter measurements is much smaller than the transmissivity determined from double-packer injection tests. The transmissivities determined using different types of measurement techniques are presented in Figure 6.1-7. It is possible that the relatively short duration of the double-packer injection test measures properties of the rock only in the immediate vicinity of borehole, i.e. measured values of K are correct but they represent only the near-field around the borehole. In addition, there is the possibility of injected water from the narrow test section returning to the borehole (i.e. a short circuit by-pass), which would result in higher K values being calculated for the double-packer system than for the flowmeter tests. On the basis of such analysis it has been possible to provide what is believed to be the correct value of transmissivity for structure R19. In general, this attempt to explain the differences in T values measured with different test methods and test sections has increased the level of understanding of the fracture system and has revealed possible errors associated with these different test methods.

Table 6.1-1. Means and standard deviations (σ) of transmissivities ($\log T$) of R-structures and hydraulic conductivities measured over 2 m of intact rock in different depth classes. Values are based on the regression lines presented in Figure 6.1-6.

Transmissivity of R-structures			Hydraulic conductivity of intact rock		
Depth class	Mean	σ	Depth class	Mean	σ
0 - 200 m	-5.0	1.0	0 - 200 m	-10.8	2.4
200 - 900 m	-5.3	0.8	200 - 400 m	-11.2	2.3
			400 - 900 m	-13.0	2.7

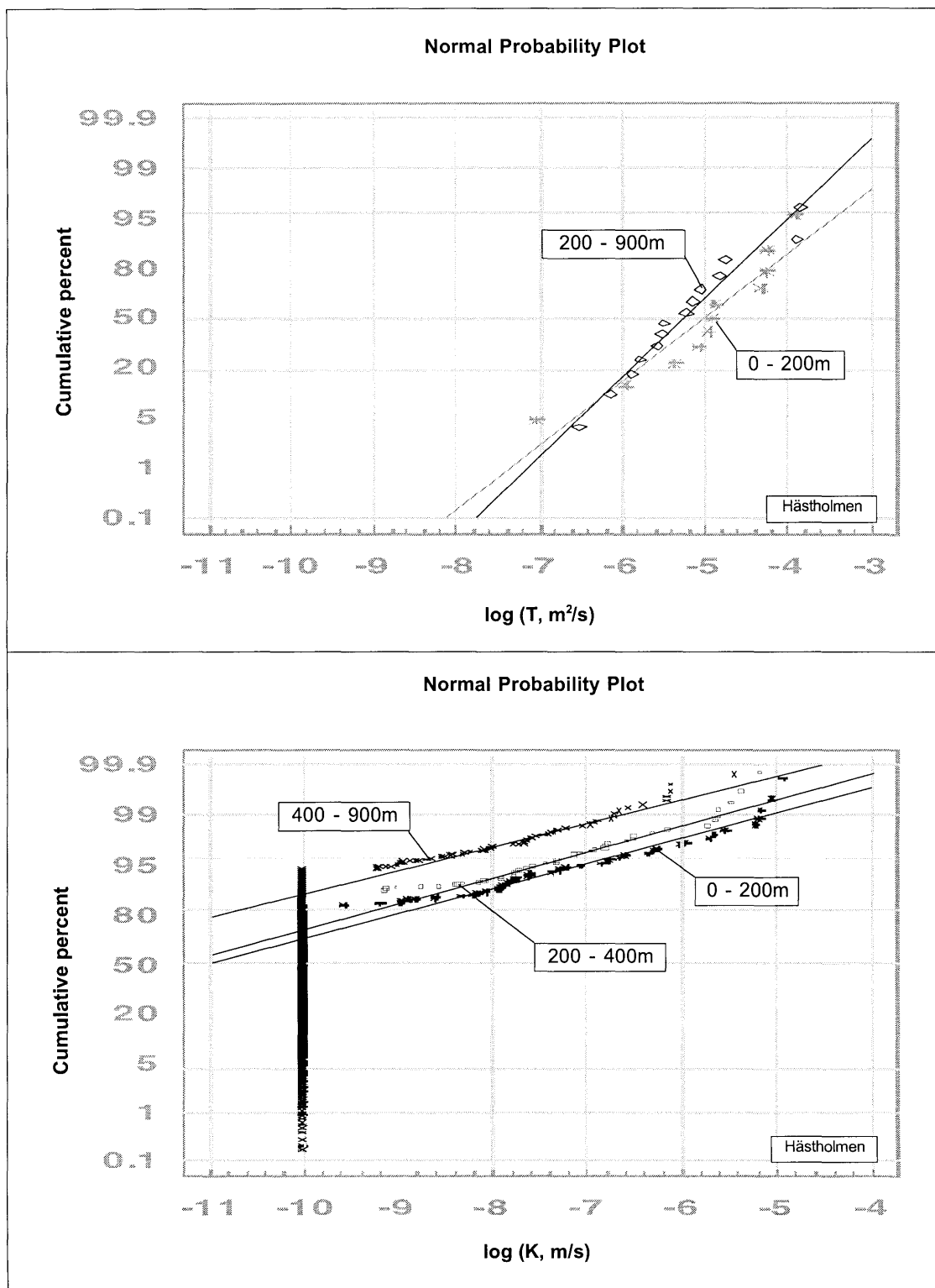


Figure 6.1-6. Cumulative distributions (normal probability plot) of transmissivities ($\log$) of R-structures and hydraulic conductivities measured over 2 m ($\log$) of intact rock in different depth classes.

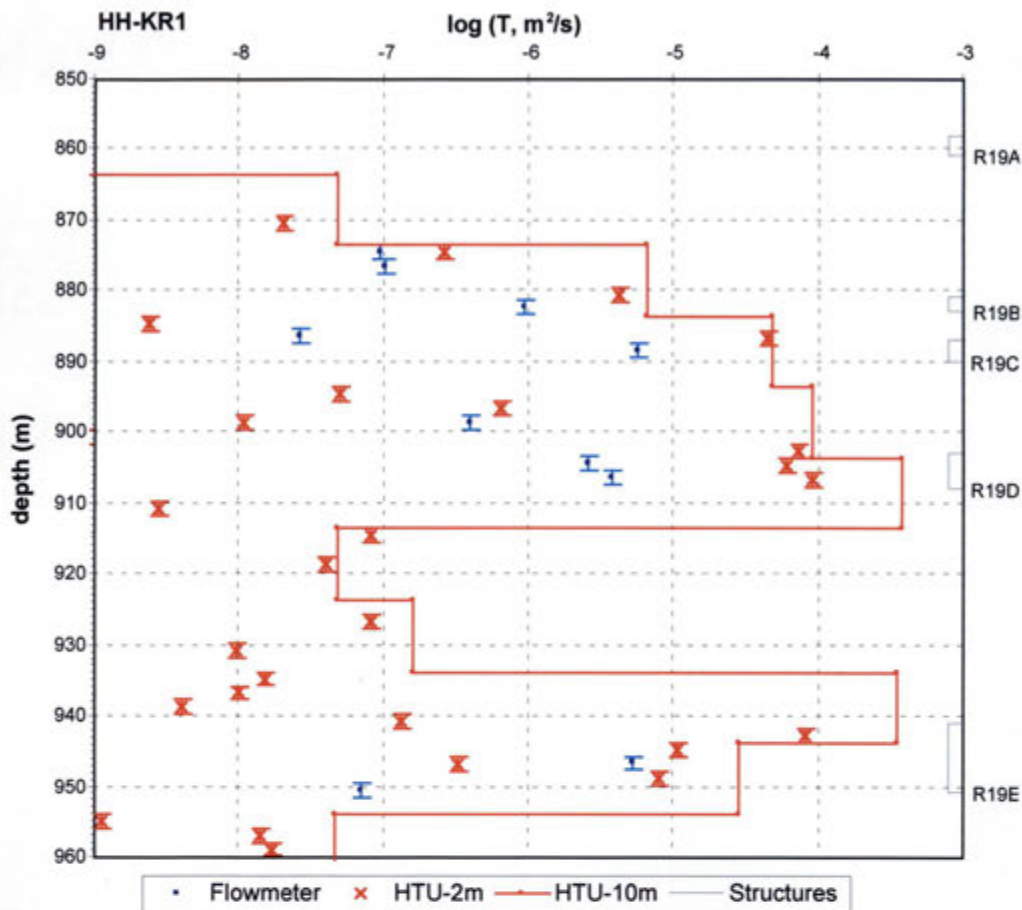


Figure 6.1-7. Transmissivities measured using the double-packer injection system (HTU) and the flowmeter in structure R19 over a depth interval of 860 - 950 m in borehole KR 1.

6.2 Hydraulic Head in the Bedrock

Hydraulic heads at shallow depths have been measured in about 25 shallow observation holes. Measurements carried out as part of the investigations for the VLJ repository have been carried out in 7 shallow holes typically once a week since 1985. These data have made it possible to study the relationship between the topography and the water table, which is required for the definition of boundary conditions for numerical groundwater flow simulations. As can be seen in Figure 6.2-1, the relationship between topography and the water table in shallow holes is poor.

Hydraulic head distributions at greater depths have been measured only in connection with flowmeter tests, and the results from these tests are presented in Figure 6.2-2. The installation of multi-packers is planned for the summer of 1999. The hydraulic fresh water head increases with depth due to the increasing salinity. Some "anomalous" heads exist and they may prove valuable for interpreting the hydraulic connections between boreholes and orientations of certain structures, as well as for calibrating or estimating the level of confidence (reliability) of numerical groundwater flow simulations (Löfman 1999). Unfortunately the open VLJ repository has produced a major disturbance of the hydraulic heads, especially at shallow depths.

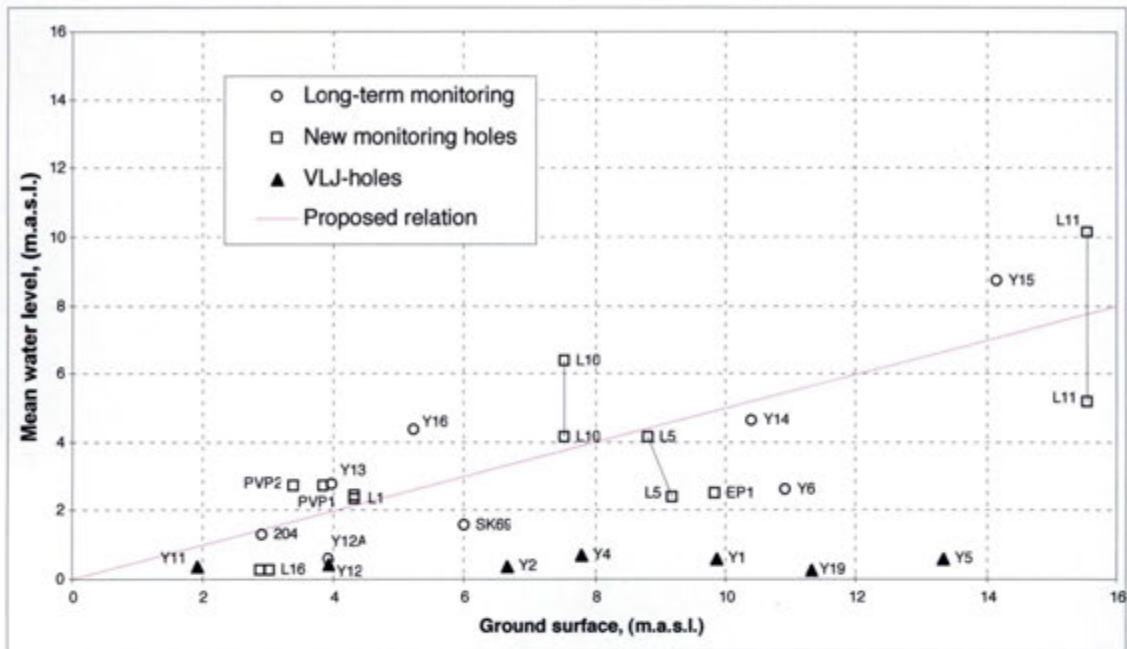


Figure 6.2-1. Measured means of water tables in shallow observation holes and in the uppermost sections of multi-level piezometers (m.a.s.l. = meters above sea level). Values of holes which are in close proximity are connected with lines. Proposed relationship between topography and groundwater table is also shown (solid line).

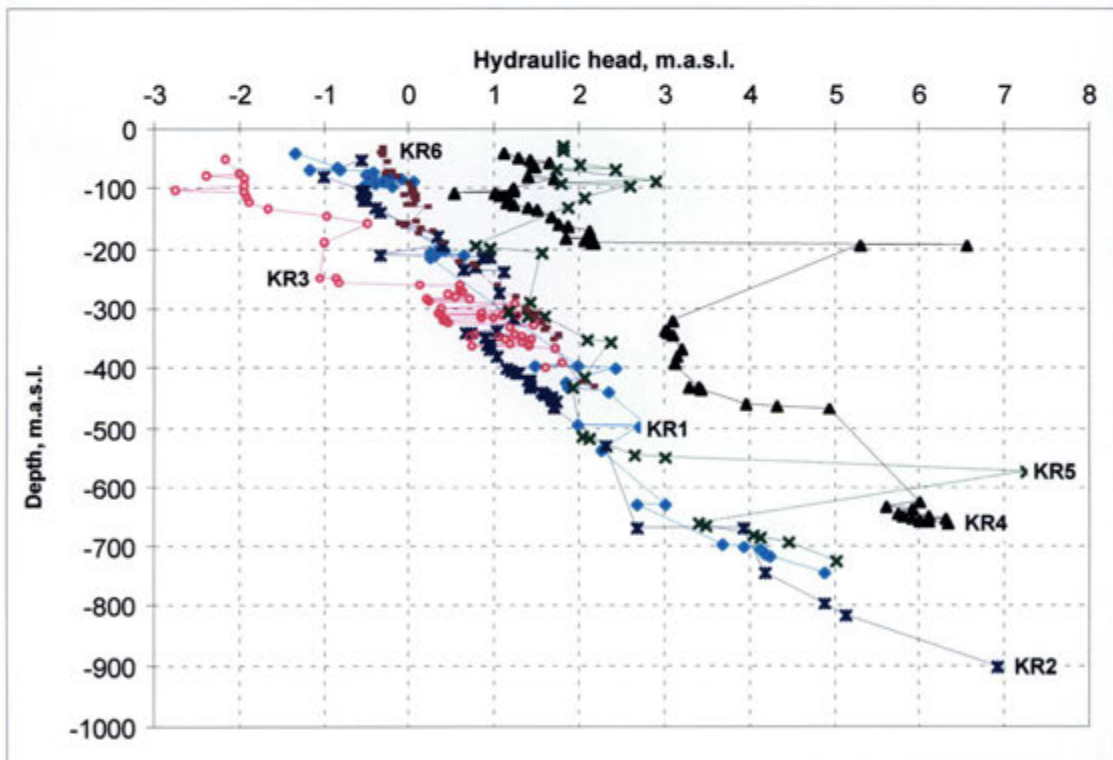


Figure 6.2-2. Hydraulic fresh water heads in deep boreholes at Hästholmen as a function of depth (m.a.s.l. = meters above sea level).

6.3 Groundwater Flow

The groundwater flow can be calculated based on values of measured transmissivities and estimations of the hydraulic gradients presented earlier in this section. A direct method of measuring groundwater flow (Fig. 2.3-4) has been developed (Rouhiainen 1993b). For reasons of practicality, only the most transmissive 2 m sections were chosen for measurement in each borehole. In only two of the 31 sections measured in boreholes KR1 - KR4 and Y20 was groundwater flow higher than the detection limit of 1 ml/h (Pöllänen & Rouhiainen 1998c), and both of these were close to the VLJ repository, which may have been responsible for the observed flow. The calculated range of cross-flow values was in 19 cases, however, over the detection limit, assuming that the hydraulic gradient could vary between 0.1 - 2% and that the transmissivity was as measured or was ten times higher, due to channelling within flowing fracture(s). In places where measured values are smaller than calculated ones, the most probable explanation for any differences is either a lower gradient than estimated (<0.1%) or a greater heterogeneity of the fracture network. This implies, in the case of an increased heterogeneity, that the measured transmissivity is determined by the presence of a narrow channel within the fracture (the flow guides of the flowmeter may, for example, mask the channel), or is caused by the margin of a fracture which intersects only one side of the borehole, thereby preventing, or severely reducing, the potential for cross-flow.

In conclusion, results from cross-flow (flowmeter) measurements from other sites have shown that groundwater flow can be measured directly and that flow takes place at some specific locations within the bedrock, in particular at shallow depths. Another important conclusion is that the large number of no-flow values indicates that relatively stagnant conditions exist where saline groundwaters are present. This may, in turn, indicate that the hydraulic gradient is lower than that based on numerical calculations. Unfortunately, the computed Darcy velocities are close to the measurement limit for cross-flow testing (1 ml/h) (Löfman 1999) and this will introduce uncertainties into any analysis. The effect of density differences between the groundwater and the fluid in the boreholes and the measuring hoses is another possible explanation for the large number of no-flow values. More detailed investigations concerning the nature of fractures and their hydraulic properties are required to resolve these issues.

6.4 Hydraulic Properties of the R-structures

The transmissivity of the R-structures (fracture zones) has been measured by two single-hole methods, the constant head injection test using a double-packer system (HTU) and flow logging using the flowmeter. In total, more than 40 single-hole T values have been measured and they are presented in Figure 6.4-1 (five of the R-structures have only one measured T value). The maximum number of single-hole values from deep boreholes for a single R-structure is four and this situation exists for one R-structure. If boreholes drilled for the VLJ repository are taken into account, the corresponding maximum number of values is 18 for structure R1. T values measured as part of the VLJ repository studies are presented in Figure 6.4-1 as averages for each R-structure. Unfortunately the variability in the measured transmissivities for some of these R-structures is very large and this makes it difficult to determine the values of their effective transmissivities.

Figure 1 is a scatter plot showing the relationship between vertical depth (m.b.s.l.) and $\log(T, \text{m}^2/\text{s})$. The y-axis represents vertical depth from 0 to 1000 m.b.s.l. The x-axis represents $\log(T, \text{m}^2/\text{s})$ from -8 to -3. Data points are categorized into VLJ investigations (open squares) and Deep boreholes (filled circles). Three parallel lines, labeled A, B, and C, represent different classes of data. The plot shows a general trend of decreasing $\log(T)$ with increasing depth, with some scatter. VLJ investigations are generally found at shallower depths (0-200 m.b.s.l.) and higher $\log(T)$ values, while deep boreholes extend to greater depths (up to 900 m.b.s.l.) and lower $\log(T)$ values.

Figure 6.4-1. Measured transmissivities of R-structures and their classification into three depth-dependent transmissivity groups (lines A - C). Values from VLJ investigations are marked with open squares (m.b.s.l. = meters below sea level).

7 GEOCHEMISTRY

The characterisation and interpretation of groundwater geochemistry has been carried out at several study sites for spent fuel disposal in Finland since the late 1980s. Following the feasibility study in 1996, Hästholmen was included in the detailed site characterisation programme in 1997. The sampling of groundwater to a depth of 1 000 m commenced in 1997 using the new deep boreholes. The investigations since 1997 have been focussed mainly on the hydrochemical baseline characterisation of the site, aiming at mapping the natural groundwater conditions before the construction of any test shaft, which will inevitably introduce many changes in the groundwater flow system. The main goals of these studies are:

- the hydrogeochemical characterisation of deep groundwater,
- the evaluation of mean residence time and the evolution of deep groundwater, and
- the acquisition of input data for geochemical modelling and for performance assessment.

The site investigations at Hästholmen, since 1997, have involved detailed sampling of specific sections of the deep boreholes. At Hästholmen there was a special need for information on the salinity distribution and redox conditions from depths below 200 m. It was also felt that the recharge conditions needed to be better known.

The former evaluation of the Hästholmen groundwater during the 1980 - 1992 investigations performed for the the VLJ repository involved samplings down to a depth of 240 m (e.g. Hyyppä 1984 and Nordstrom 1986). Samples from wells, sea water, precipitation, shallow groundwater and surface waters were also taken at that time. The hydrogeochemistry, and especially the representativity of the groundwater samples collected in the Hästholmen area in 1980-1997 has been discussed in several reports (e.g. Hyyppä 1984, Nordstrom 1986, Kankainen 1986, Snellman & Helenius 1992, Hatanpää 1997, Keinonen et al. 1998, Helenius et al. 1998, Snellman et al. 1998, Tuominen 1998, Hatanpää et al. 1999 and Luukkonen et al. 1999). These reports include detailed information on the sampling points, the preparation of samples, the analytical methods applied, as well as results on the groundwater analyses and the characterisation of the local hydrogeochemical conditions. The specific sampling methods and equipment used are given in the reports of Snellman & Helenius (1992), Ruotsalainen et al. (1994, 1996, 1998) and Rouhiainen et al. (1992). The hydrogeochemical evolution of groundwater within the uppermost 200 m of the bedrock are described in the reports by Nordstrom (1986) and Kankainen (1986).

This section summarizes the main hydrogeochemical results obtained during 1980-1997, and some groundwater samples taken in 1998 are also included. Throughout this section, "depth" means borehole length.

7.1 Sampling and Chemical Analyses

During the 1980s a total of 140 samples were taken from borehole sections isolated by double-packers, with packer intervals of 3 to 5 m, from the shallow boreholes Y1, Y2, Y3, Y4, Y5, Y7, Y8 and Y11 (e.g. Snellman & Helenius 1992). Sea water was sampled offshore

from Hästholmen from two sampling points at depths from 2 to 20 m. Environmental reference samples, including wells, springs, sea water and precipitation were also taken in 1995 - 1996 (Hatanpää 1997). In 1997 and 1998 17 groundwater samples were taken from sections (5 - 10 m in length) from boreholes KR1-KR4 (Keinonen et al. 1998, Helenius et al. 1998). The lengths of the sampling sections have generally been 5 - 8 m (except for the sampling sections in borehole KR1, when samples were taken during drilling and lengths of up to 46.5 m were used). The lengths of groundwater sampling sections were optimized to prevent mixing of different types of groundwater during sampling. However, all samples from boreholes KR1 to KR4 were taken quite rapidly after drilling and transient mixing effects caused by the drilling operations prior to sampling cannot, therefore, be ruled out. Sampling in 1997 also included the glacial overburden (groundwater-pipes) and shallow percussion-drilled holes at the site in order to obtain information on recharge conditions (Tuominen 1998).

Hydrogeochemical studies performed since 1997 have all been carried out according to the field manual for groundwater sampling (Ruotsalainen et al. 1994, 1996, 1998), which includes analytical programmes, protocols for the evaluation of the representativeness of the water samples, usage of sampling equipment, handling and preparation of the water samples, field measurements and analyses. This has ensured that a good reproducibility for all samples was obtained at all sites. The progress of sampling and the representativeness of the samples were monitored by means of chemical field measurements (Rouhiainen et al. 1992, Ruotsalainen et al. 1994, 1998) which helped to make decisions regarding the most appropriate time for sampling. Sampled groundwater enters a combination of flow-through cells for measurement of O_2 (one separate small cell) and Eh, pH, EC (= Electrical Conductivity) and temperature (another larger cell). This is performed on-line and is N_2 -protected, thereby avoiding any contact with the atmosphere.

As groundwater is pumped from a borehole, the pressure decrease causes degassing of the water. This affects the concentrations of dissolved gases, certain hydrogeochemical parameters, colloids and microbiology. Posiva has developed equipment for pressurized groundwater sampling (Ruotsalainen et al. 1996) known as PAVE (Fig. 7.1-1). The groundwater collected in the PAVE containers was analysed for dissolved gases and microbes, and isotope content (2H , ^{18}O , ^{13}C) of methane and carbon dioxide (Table 7.1-1). All samplings in 1997 - 1998, except for some samples taken during drilling, were performed with the PAVE sampler from double-packed sections of the deep boreholes. The first samples (at depths of 47 - 93 m, 595 - 619 m, 864 - 894 m) from borehole KR1 were taken during drilling from the borehole intersection of the VLJ-repository tunnel at the level of about 33 m. The basal sections of the unfinished borehole were isolated for sampling with one packer and for each sample drilling was interrupted for 3 days and groundwater allowed to flow under its own pressure through the field-monitoring unit prior to sampling. PAVE samples from the completed borehole KR1 were also taken through the tunnel intersection over the following depth intervals 529 - 534 m, 778 - 783 m, 938 - 948 m and 977 - 985 m. The groundwater from the section at 778 - 783 m depth is now known to represent the depth interval of 778 - 1 002 m, as it was found after sampling that the packer pressure used for isolating the section was too low, and the lower packer had probably leaked during the sampling activity.

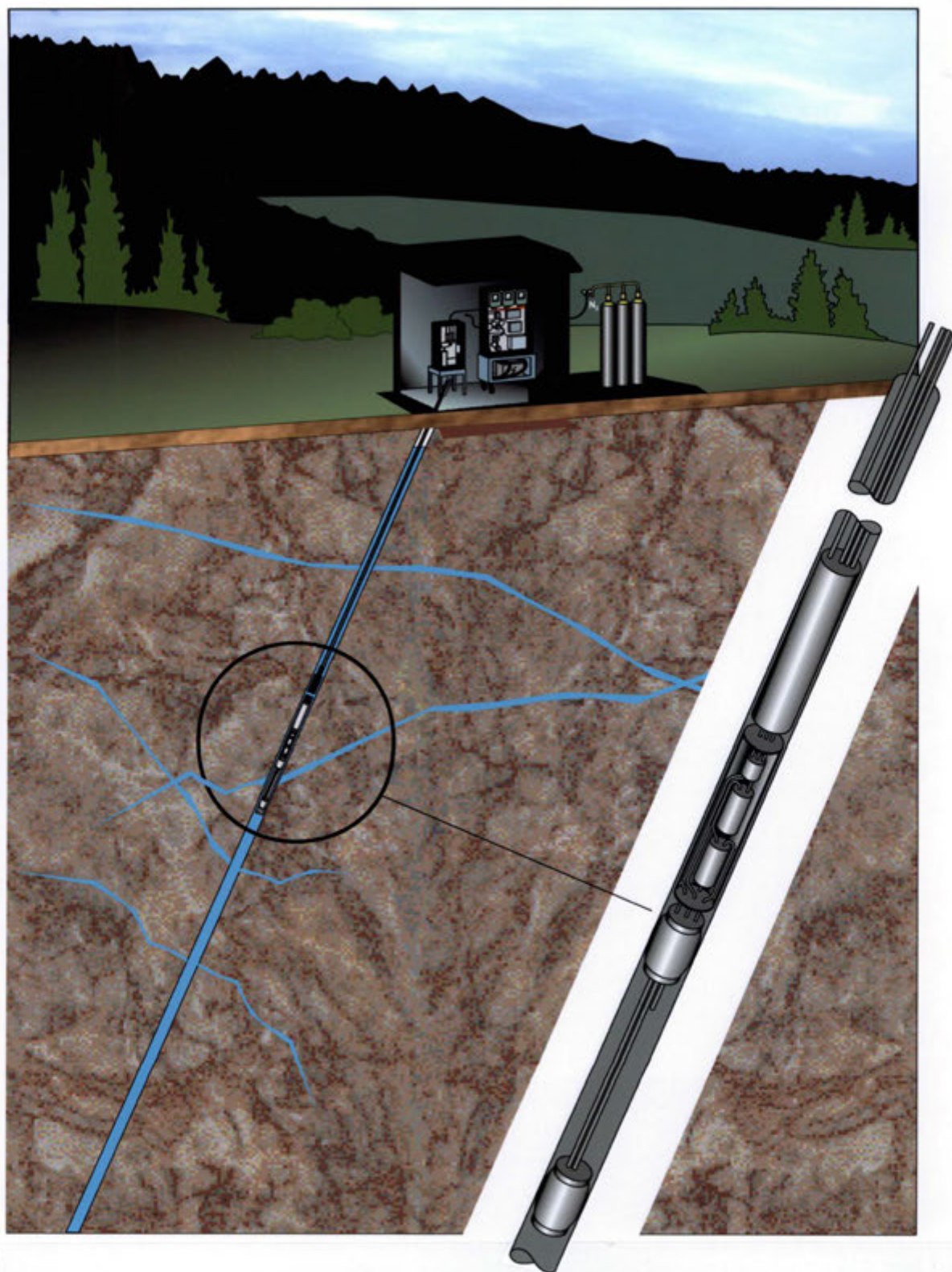


Figure 7.1-1. The pressurized groundwater sampling equipment (PAVE) developed by Posiva Oy.

The parameters analysed in the groundwater samples were selected according to the required input data for the hydrochemical characterisation, geochemical modelling, experimental studies (solubility, diffusion and sorption studies) and performance assessment. The number of parameters analysed was comprehensive (60-70 in total). Depending on the sampling location and method used, as well as the representativeness of the sample, the analyses were performed either according to the “standard” (baseline), “special” (evolutionary) or “concise” analytical programme. A summary of the analytical programmes are shown in Table 7.1-1.

Table 7.1-1. Analytical programmes applied for the analysis of groundwater samples from boreholes KR1 to KR6 at Hästholmen.

Parameter	Standard programme	Special programme	Concise programme
Physicochemical variables	pH, EC(= Electrical conductivity), density, alkalinity, acidity, DIC (= Dissolved Inorganic Carbon), KMnO_4 -consumption (= Chemical oxygen demand, COD), uranine (= drilling fluid tracer),	Standard	Standard
Anions	HCO_3^- , CO_3^{2-} , Cl, Br, F, I, SO_4^{2-} , $\text{S}_{\text{tot}}^{2-}$, PO_4^{3-} , NO_3^- , NO_2^- , N_{tot} , P_{tot} , B_{tot} , S_{tot}	Standard	HCO_3^- , CO_3^{2-} , Cl, Br, F, I, SO_4^{2-} , $\text{S}_{\text{tot}}^{2-}$, PO_4^{3-} , NO_3^- , NO_2^- , S_{tot}
Cations	Na, Ca, Mg, K, Al, Fe_{tot} , Fe^{2+} , Mn, SiO_2 , NH_4^+	Standard	Standard
Trace elements	Sr, Cs, Li, Ba, Rb, Zr	Standard	
Organics	DOC(= Dissolved Organic Carbon)	Standard	Standard
Isotopes	$\delta^2\text{H}(\text{H}_2\text{O})$, ^3H , $\delta^{18}\text{O}(\text{H}_2\text{O})$, ^{222}Rn , $\delta^{13}\text{C}(\text{DIC})$, $^{14}\text{C}(\text{DIC})$, $^{234}\text{U}/^{238}\text{U}$ and U_{tot} (in H_2O and particles)	Standard + $\delta^{34}\text{S}(\text{SO}_4)$, $\delta^{34}\text{S}(\text{S}^{2-})$, $\delta^{18}\text{O}(\text{SO}_4)$, $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{13}\text{C}(\text{CO}_2, \text{CH}_4)$, $\delta^2\text{H}(\text{CH}_4)$, $\delta^{18}\text{O}(\text{CO}_2)$	$\delta^2\text{H}(\text{H}_2\text{O})$, ^3H , $\delta^{18}\text{O}(\text{H}_2\text{O})$, ^{222}Rn
Dissolved and evacuated gases	N_2 , O_2 , CO_2 , CO, CH_4 , C_2H_2 , C_2H_4 , C_2H_6 , C_3H_8 , H_2 , He	Standard, PAVE samples	
Microbes		PAVE: Total number of cells, autotrophic acetogens, heterotrophic acetogens, SRB(=sulphate reducers), IRB(=iron reducers), autotrophic methanogens, heterotrophic methanogens	

The general criteria used for the evaluation of the hydrogeochemical data are given in Table 7.1-2.

For the general evaluation of the hydrogeochemical system, 29 samples taken from the shallow boreholes Y1 to Y11, 17 samples from the deep boreholes KR1 - KR4 and 7 shallow groundwater samples, were used in the evaluation of the Hästholmen groundwater data by Snellman et al. (1998). Also data from boreholes KR5 and KR6 sampled in 1998 have been included (Hatanpää et al. 1999). In these reports the representativeness of the data is also evaluated. Several samples were accepted for the analysis that violated the drilling water criteria set out in Table 7.1-2. These samples amounted to the following percentages of drilling water: about 6.8% in the sample from borehole KR6 (341 - 346 m), 5.6% in borehole KR5 (590 - 595 m), and 3.4% in the sample from borehole KR5 (750 - 755 m).

Table 7.1-2. Criteria used in the classification of the hydrogeochemical data (Ruotsalainen & Snellman 1996).

PARAMETERS	REPRESENTATIVE RESULTS, Boreholes	REPRESENTATIVE RESULTS, Shallow groundwaters
Technical effects	Samples with no obvious effects due to contamination by borehole stabilization cement	
Amount of remaining drilling water	< 2.5%	
pH, alkalinity, acidity	Field measurements	Field measurements
S^{2-}_{tot} , SO_4^{2-} , PO_4^{3-} , NH_4^+ , NO_2^- , NO_3^- , Cl^- , F^- , Br^- , Fe^{2+}	Field analyses	Laboratory analyses
Fe_{tot}	< 20 mg/l	< 20 mg/l
DOC	< 50 mg/l	< 50 mg/l
Charge balance	< $\pm 5\%$	< $\pm 5\%$

7.2 Basic Hydrochemical Features

At Hästholmen fresh groundwater (TDS below 1 g/l; Davis 1964) has been found in boreholes (Y-boreholes) only in their uppermost sections. The fresh Ca-Na-Mg-HCO₃-(SO₄)-(Cl)-type (classification according to Davis & De Wiest 1967) water is generally found to a depth of about 50 m. Brackish Na-Ca-Cl-type groundwater (1 g/l < TDS < 10 g/l) with a maximum chloride content of 6 g/l is encountered at depths varying between 50 m and 600 m. Below 500 - 600 m Ca-Na-Cl type saline water is observed. The present maximum of Total Dissolved Solids (TDS) is 31.9 g/l in borehole KR4 at 883 - 891 m.

In general, TDS and chloride content (Fig.7.2-1, Table 7.2-1) increase with depth. However, at depths of about 300 - 600 m in the brackish groundwater layer a drop in chloride content (and TDS) can be observed. These diluted brackish waters have been found in borehole KR1 (at 529 - 534 m and 595 - 619 m), in borehole KR2 (at 374 - 382 m), and in borehole KR4 (at 412 - 417 m). The dilution effect in the samples from boreholes KR1 (595 - 619 m) and KR2 (374 - 382 m) is at least partly explained by contamination with flushing water (9 - 10%).

The rate of increase in both TDS and chloride content increases strongly below approximately 500 - 600 m, suggesting the effect of deep, highly saline groundwater. Saline or nearly saline groundwater have been observed in boreholes KR1, KR2, KR3, KR4 and KR5.

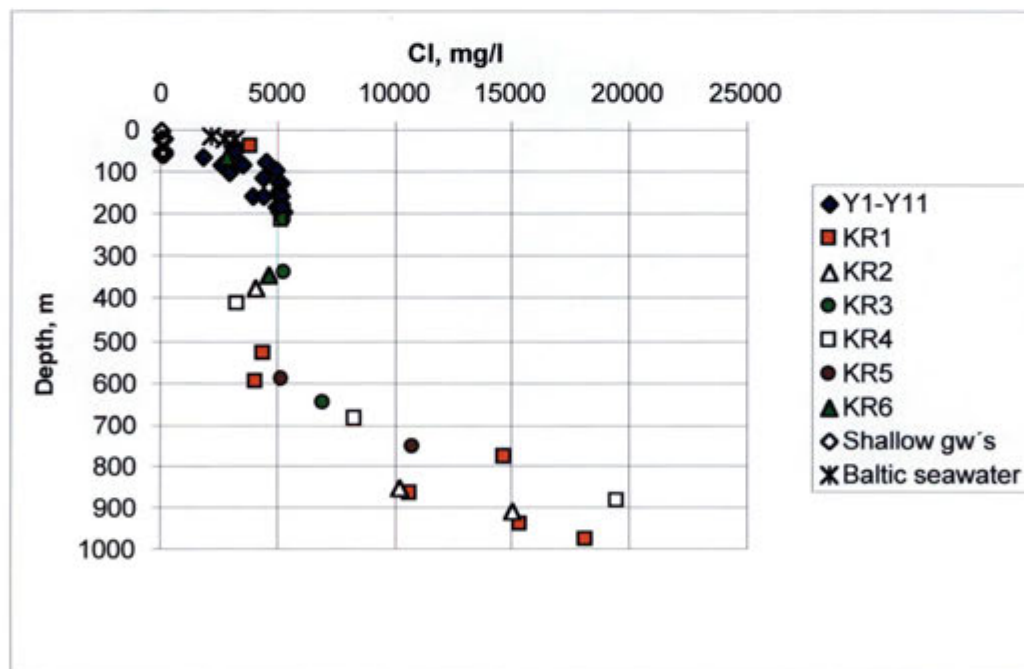


Figure 7.2-1. Chloride content as a function of depth in Hästholmen groundwater samples. Shallow groundwaters represent water samples from springs, groundwater pipes, wells and fresh groundwater from boreholes Y1 - Y11 from depths less than approximately 50 m. Baltic Seawater represent sea water samples taken off shore from Hästholmen from the Gulf of Finland. These definitions are used throughout this section.

Table 7.2-1. Vertical variation (indicative) of the main hydrogeochemical parameters at Hästholmen (Snellman et al. 1998).

Depth (m)	Water type	Cl (mg/l)	pH	Alkalinity (meq/l)	Redox
0	Ca-Na-Mg-HCO ₃ -SO ₄ -(Cl)	< 10	5 - 7	< 2.9	Post-oxic
50	Na-Ca-Mg-HCO ₃ -SO ₄ -(Cl)	< 70	7.5 - 8.5	< 3.8	Sulphidic
100					
	Na-(Ca)-Cl	< 5 300	6.9 - 8.2	< 2.4	
600					
800	Ca-Na-Cl	15 000	7 - 7.9	< 0.5	
1 000	Ca-Na-Cl	20 000	7 - 7.5	< 0.5	

In a similar manner to that at Olkiluoto (Pitkänen et al. 1996a, 1999), the hydrogeochemistry of Hästholmen seems to contain a well-developed profile associated with climatic and shoreline changes from modern times through former Baltic stages to pre-glacial times (Table 7.2-2). Six end-member groundwater types have been suggested (Snellman et al. 1998, Luukkonen et al. 1999) in order to explain the current groundwater compositions which are found at the site.

The shallow fresh or brackish HCO₃-rich waters evolve via brackish SO₄-rich Na-Ca-Cl water to saline Ca-Na-Cl water with increasing depth and degree of water-rock interaction (due to ion exchange processes, but also, possibly, other processes such as calcite precipitation) together with the influence of the present Baltic or relic Litorina or Eemian sea water.

Table 7.2-2. Main groundwater types at Hästholmen, indicative depths and end-member types giving their original sources and the estimated formation ages.

Depth of occurrence, m	Water type	Origin of dominant end-members	Age estimate of dominant end-member type, BP*
above 50-100	Fresh-brackish - HCO_3 rich water	Meteoric water and present Baltic sea water	modern
100 - 400	SO_4 -rich brackish Na-Ca-Cl water	Litorina sea water	4 000 - 7 500
400 - 600	Brackish Na-Ca-Cl water SO_4 -rich	Pre-Litorina water containing increasing amount of glacial meltwater of the ice-sheet	7 500 - 11 700
below 500 - 600	Saline Ca-Na-Cl water	Pre-glacial to/Pre-Cambrian saline water (brine) and possibly also Eemian sea water	>> 11 700

BP* = Before Present

7.2.1 pH and Alkalinity

In shallow groundwater, from surface, to approximately 50 m depth, a clear correlation can be observed between increasing pH and increasing depth (Fig. 7.2-2). In fact, the highest pH values measured in the Hästholmen groundwaters are from depths of about 20 to 60 m in borehole Y5. The lowest pH values have been observed in surface waters, springs and groundwater pipes (5.0 - 6.0) due to atmospheric CO_2 .

In borehole groundwater samples there is a relatively narrow range in pH values from 7.0 to 8.5 (Fig. 7.2-2). In deep groundwater (below 200 m), a slight but distinct trend between decreasing pH values and increasing depth can be observed. The lowest pH value has been observed in the deep part of borehole KR1, below 800 m.

The behaviour of dissolved carbonate-related alkalinity depicted in Figure 7.2-3 (a, b). At low chloride contents the trend is comparable to the other investigation sites at Kivetty, Romuvaara and Olkiluoto (Pitkänen et al. 1994, 1996a, b, 1998, 1999). The total alkalinity (alk_{tot}) values increase from those in the fresh groundwater of the overburden (groundwater pipes and springs) and reach a maximum value of about 3.8 meq/l in the fresh groundwater of borehole Y1 at a depth of about 25 to 50 m (Snellman et al. 1998). Values of alk_{tot} decrease strongly as the chloride values increase, and also with depth. This trend is due to the precipitation of calcite which starts at shallow depths at Hästholmen (Nordstrom 1986) in accordance with the fracture mineral observations (Gehör et al. 1997a, 1997b, 1998). The exceptionally high values of alk_{tot} found at about 600 m depth for the samples from boreholes KR1 and KR5 are most likely due to contamination by drilling water.

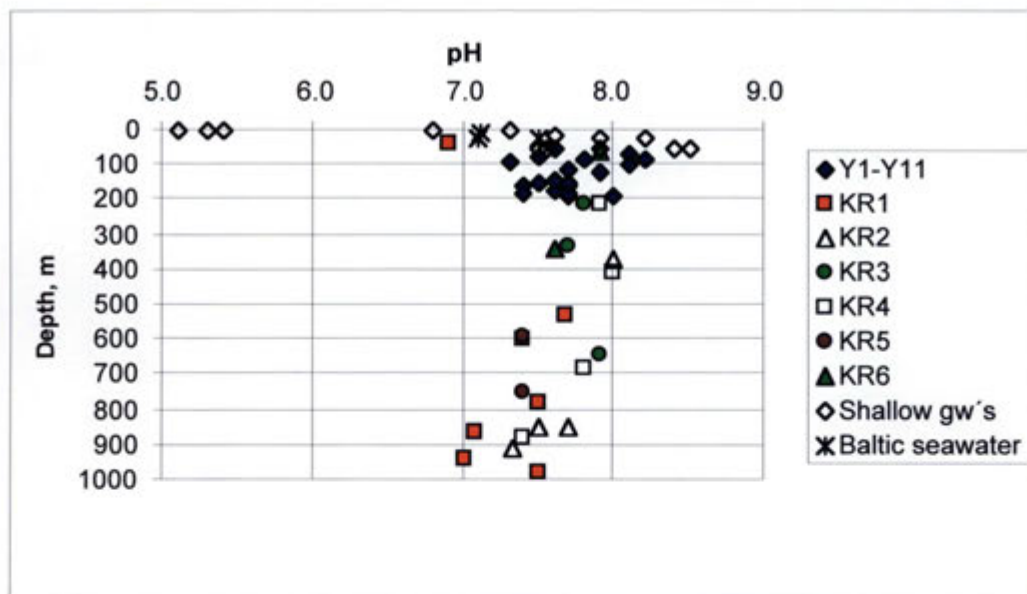


Figure 7.2-2. *pH vs. depth in Hästholmen groundwater samples.*

For near-surface groundwater samples $\log p\text{CO}_2$ values (calculated with EQ3NR) above the atmospheric partial pressure ($\log p\text{CO}_2 = -3.5$) indicate biochemical oxidation of organic carbon as a source for the dissolved carbon in the water (Snellman et al. 1998). Calcite dissolution is also possible at shallow depths. The calculated $\log p\text{CO}_2$ values decrease to around atmospheric values at the brackish saline water interface at 500 - 600 m depth where the Cl content rises to above 6 000 mg/l. However, the partial pressure is still close to the atmospheric level even in the deepest sections sampled (-4.0 to -3.0).

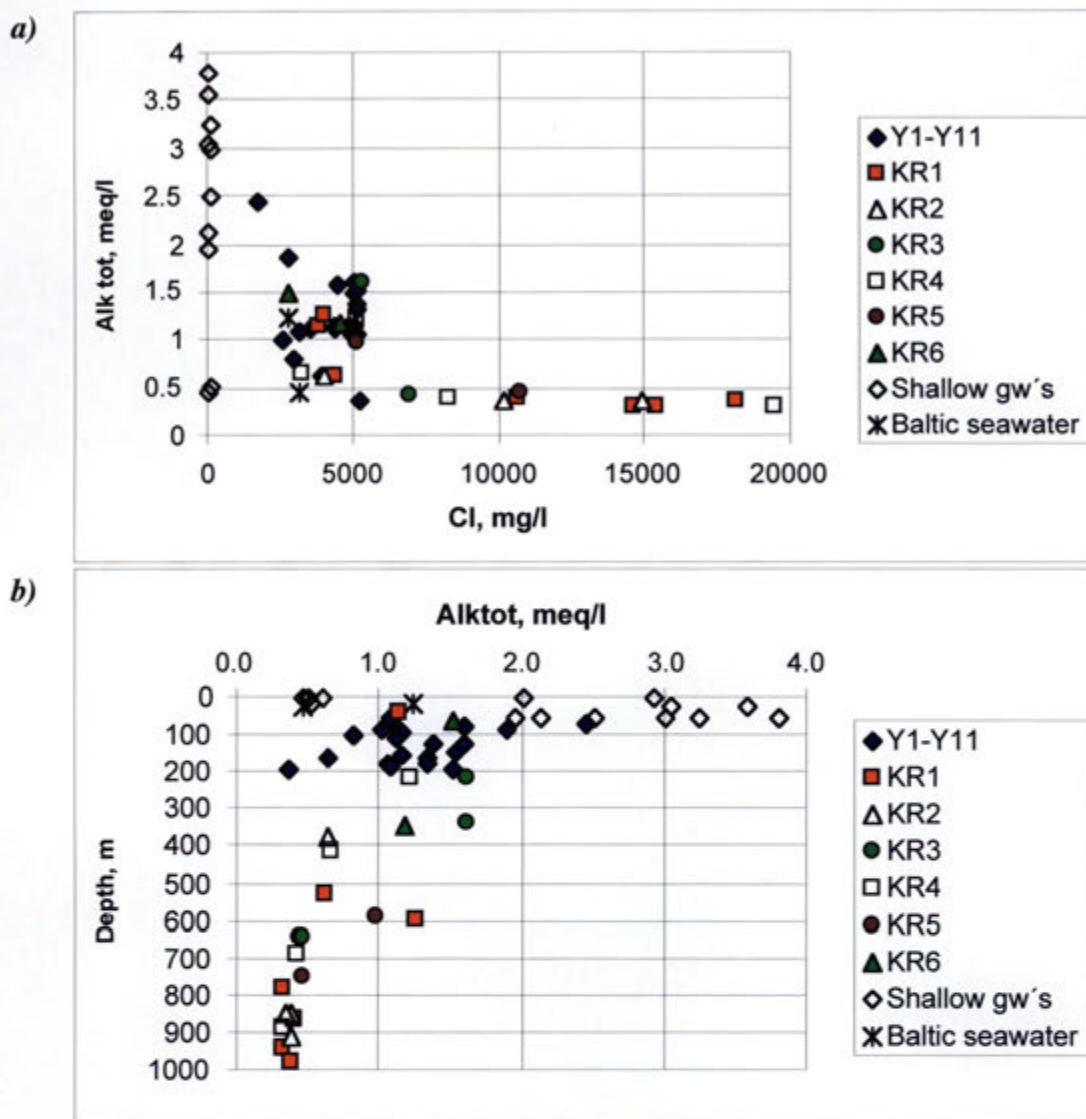


Figure 7.2-3 (a),(b). Total alkalinity vs. chloride and depth in Hästholmen groundwater samples.

7.2.2 Redox Chemistry

At Hästholmen measured Eh(Pt) values are available only from deep boreholes KR1 - KR6. The Eh values generally refer to slightly or clearly reducing conditions (Fig. 7.2-4). The brackish groundwaters, at depths of about 100 - 600 m, have more variable redox values ranging from +30 to about -340 mV. For saline groundwaters, below 500 - 600 m depth, Eh values range from +9 to -220 mV. There are much larger differences in the main components of the Hästholmen (and Olkiluoto) groundwater, and similarly in the concentrations of the redox-sensitive elements, e.g. sulphate and iron (Fig. 7.2-5a, b), than is the case at Romuvaara and Kivetty, where only fresh groundwater is present. At Hästholmen the manganese and ammonium variations are also relatively high (Snellman et al. 1998). The dissolved hydrogen gas content is higher in the saline groundwater, especially in boreholes KR1 and KR2 at depths below 850 m (max. 1.9 ml/l). There is also an increasing trend of methane with depth, especially in the saline water layer (Fig. 7.2-6). The methane level is

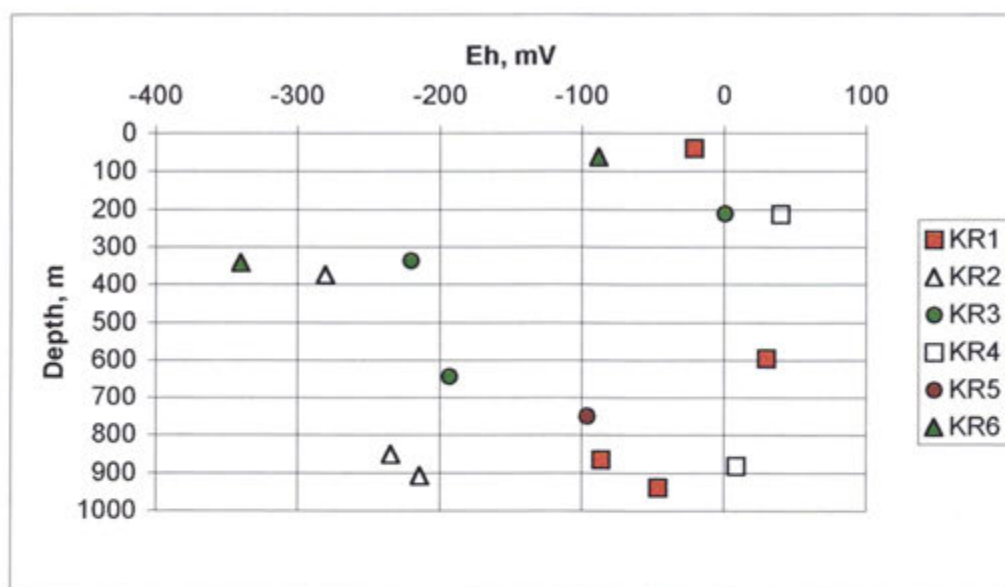


Figure 7.2-4. Eh vs. depth in Hästholmen groundwater samples.

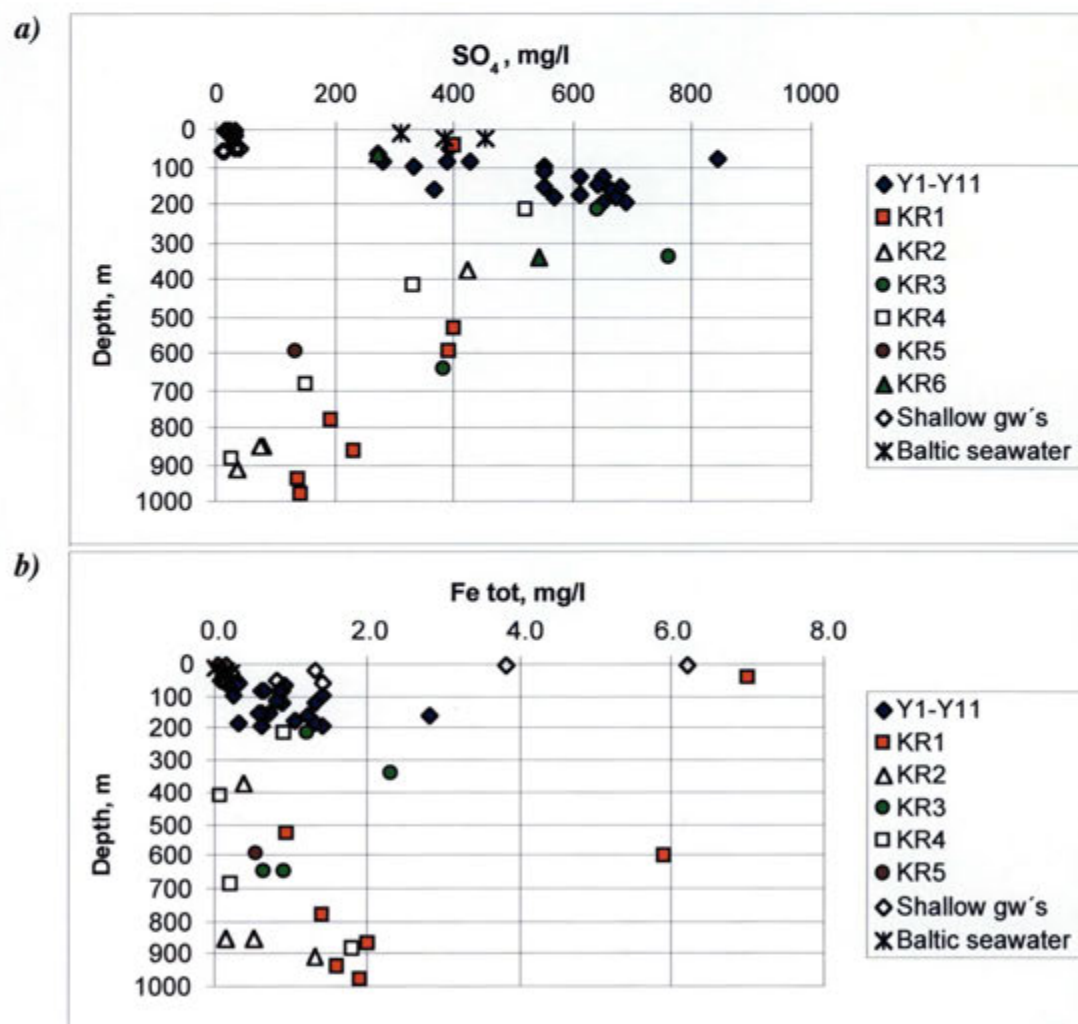


Figure 7.2-5 (a), (b). SO_4 and Fe as a function of depth in Hästholmen groundwater samples.

(max. 0.23 ml/l), nevertheless, at a much lower level than at Olkiluoto (max. CH_4 content about 990 ml/l in Olkiluoto borehole KR4 at 860 m depth, Pitkänen et al. 1999). The decreasing uranium concentration with increasing depth and Cl also suggests more reducing conditions in deep groundwaters (Fig. 7.2-7).

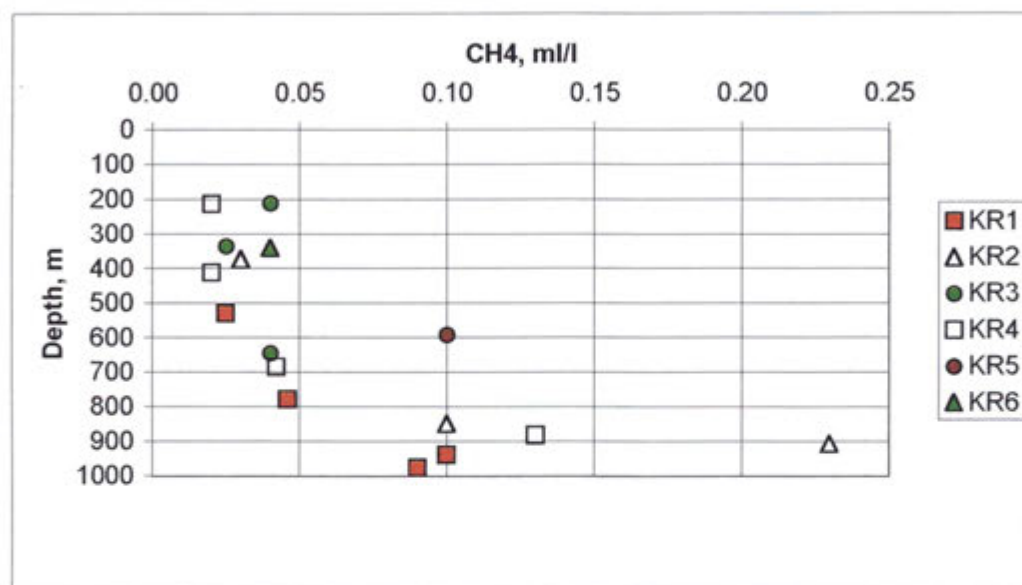


Figure 7.2-6. CH_4 as a function of depth in Hästholmen groundwater samples.

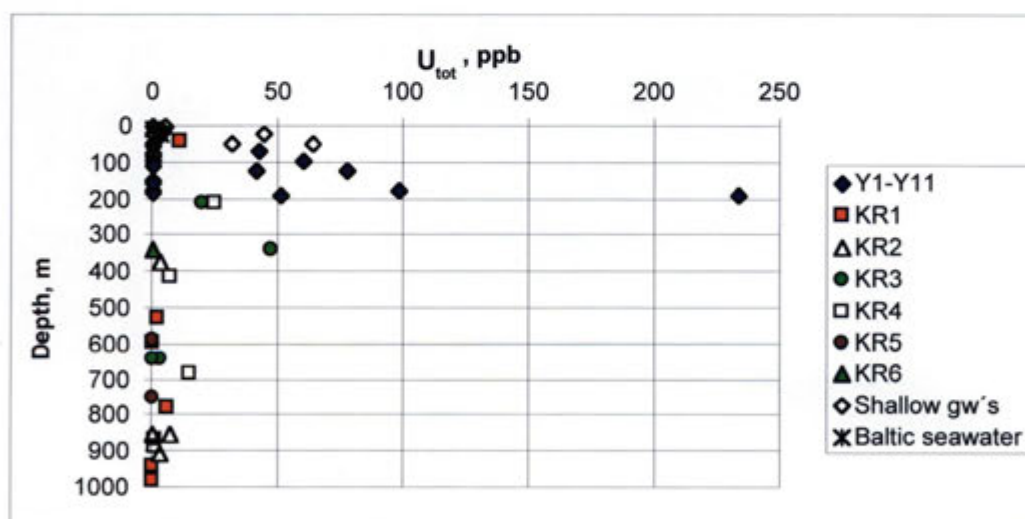


Figure 7.2-7. Uranium ($U_{\text{tot}} = {}^{234}\text{U} + {}^{238}\text{U}$) content as a function of depth in Hästholmen groundwater samples.

At Hästholmen most of the water samples contain iron, the total iron content (mainly Fe^{2+}) being generally in the range from 0.5 to 2 mg/l (Luukkonen et al. 1999). Contamination by small iron particles from drilling ($< 0.45 \mu\text{m}$) have likely affected the iron content of the groundwater samples from borehole KR1 taken during drilling (borehole KR1, depths 47 - 93 m and 595 - 619 m, Fig. 7.2-5b). The iron content, as well as ammonium and manganese, is highest in the brackish groundwater with the strongest Litorina input at a chloride content of 3 000 - 5 500 mg/l and over a depth range of 100 to 300 m. However, after a decrease over the depth interval of 400 to 500 m, both manganese and iron (Fig. 7.2-5b) again show an increase with depth in the saline groundwater. Ammonium has a maximum of about 2 - 3 mg/l in the Litorina sea water layer, and its source seems to be related to the ingress of ancient sea water. Ammonium has possibly been generated from organic nitrogen compounds (amines) in the sea floor sediments, as its bacterial breakdown produces both NH_4 and CO_2 (Stumm & Morgan 1981).

The median value of Fe_{tot} of Hästholmen groundwaters is $1.4 \cdot 10^{-5}$ mol/l (Luukkonen et al. 1999), which is well above the theoretical lower limit (10^{-6} mol/l; Grenthe et al. 1992) of iron for successful Eh measurements, in the situation where $\text{Fe}^{2+}/\text{Fe}^{3+}$ is the redox-controlling couple. Iron reducing bacteria (IRB) has been identified in all microbially studied groundwater samples (Haveman et al. 1998).

The distribution of sulphate with depth (Fig. 7.2-5a) is an important factor in the interpretation of the different groundwater types at Hästholmen and their geochemical interactions. Sulphate is a good natural tracer of the relic Litorina Sea water, and exhibits local maximum values of SO_4 (max) = 760 mg/l and 840 mg/l in boreholes KR3 (331-336 m) and Y2 (76-79 m), respectively. A number of groundwater samples from boreholes Y1 to Y11 and KR3, KR4 and KR6 show high values of SO_4 (above the present Baltic Sea water value offshore Hästholmen, of about 400 mg/l) demonstrating the large spatial distribution of the Litorina Sea dominant groundwater zone. Below this zone (below 400 m), the SO_4 values decrease with increasing Cl. However, the level at depth is still above 100 mg/l for deep saline groundwater samples from borehole KR1. At the same time, the proportions of methane (Fig. 7.2-6) and hydrogen in relation to total gas content, as well as the contents of dissolved iron (Fig. 7.2-5b) and manganese increase in groundwater. Logically, the increase of CH_4 is strongest in samples with lowest SO_4 content from boreholes KR2 and KR4. Dissolved reduced sulphur has been detected especially in the brackish and saline groundwater samples from borehole KR3, in which the observed maximum value of reduced sulphur is 0.11 mg/l. Sulphur reducing bacteria (SRB) have been found in the PAVE sample from borehole KR4 (Haveman et al. 1998).

7.3 Fracture Mineralogy

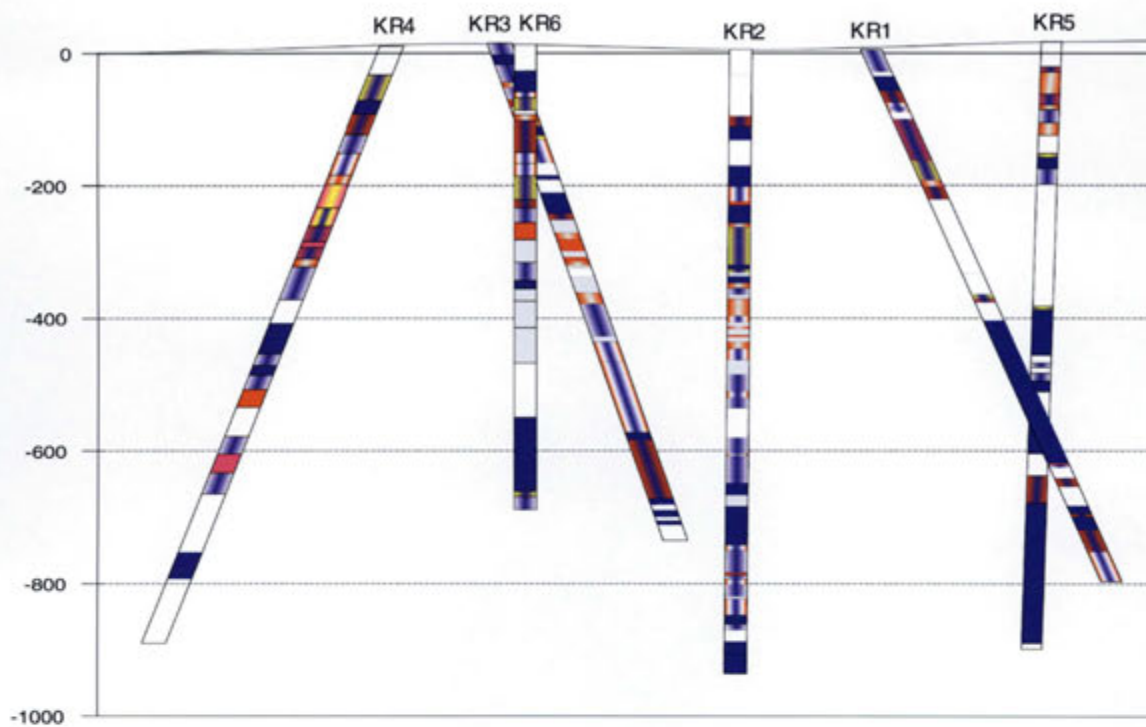
Fracture mineralogy studies have focussed on existing (or geologically-recent) water-conducting fractures. Detailed fracture mineral investigations (Gehör et al. 1997a, 1997b, 1998) have shown similar occurrences of low-temperature fracture mineral assemblages among drill core samples. The most common minerals are calcite, dolomite, chlorite, clay minerals (illite, kaolinite, montmorillonite) and iron oxyhydroxides, while sulphides (pyrite, pyrrhotite) and fluorite are less frequently observed. These minerals can be

classified into 18 assemblages, as shown in Table 7.3-1 and Figure 7.3-1. The mineral assemblages have been identified on certain fracture surfaces of the drill core or consist of the fracture minerals found on adjacent fracture surfaces. Minerals included within an assemblage listed below are not necessarily in contact or in chemical equilibrium with each other and they were not necessarily formed synchronously.

Carbonates, either calcite or dolomite, are ubiquitous fracture minerals, except over the depth range of 300 - 420 m in boreholes KR1 and KR3 and several sections in borehole KR4. In borehole KR1 and in places also in borehole KR4 this can be explained by the general lack of fractures at this depth, however, fractures are found at these depths in borehole KR3. Carbonate fillings are typically less than 1 mm thick and ca. 3 mm at most. Other typical fracture minerals that have generally been observed at all depths are iron oxyhydroxides (in certain instances hematite has been identified), and clay minerals (illite, kaolinite, montmorillonite). Clay mineral coatings are at most 10 mm thick and typically less than 1.0 mm. The zones of high metasomatic alteration found at depth levels 465 - 469 m and 864 - 973 m in borehole KR1, 105 - 126 m, 222 - 241 m and 400 - 463 m in borehole KR2, and several sections below 470 m in borehole KR3 and below 100 m in borehole KR4, are easily distinguished with a mineral association (assemblage) where feldspars are replaced by kaolinite, illite and sometimes also by hematite.

Table 7.3-1. Fracture mineral assemblages and their proportional distribution in drill core samples from Hästholmen (Gehör et al. 1997a, 1997b, 1998).

Fracture mineral assemblage	Proportional occurrence, % in boreholes KR1 to KR4	Proportional occurrence, % in boreholes Y1 to Y11
Iron hydroxide-clay minerals-carbonates	5.0 -10.7	24.4
Iron hydroxide-clay minerals±fluorite	1.3 - 3.0	
Iron hydroxide-iron sulphide-clay minerals±fluorite	3.0	
Iron hydroxide-carbonate iron sulphide-clay minerals		3.6
Iron hydroxide-clay minerals	5.0 -16.0	8.9
Iron hydroxide-carbonate	4.0 -12.9	8.3
Iron hydroxide-iron sulphide		0.6
Iron hydroxide	3.0 - 9.1	3.6
Carbonate-clay minerals	3-20.0	20.2
Carbonate±fluorite	6.0	0.6
Carbonate±clay minerals±fluorite	6.5	3.0
Carbonate-iron sulphide-clay minerals	2.7 - 6.5	3.0
Carbonate-iron sulphide±fluorite	3.0	0.6
Carbonates	12 - 18.2	13.7
Clay minerals-fluorite	3 - 3.23	1.2
Clay minerals	1.0 - 24.2	6.6
Iron sulphides	1.3	
Iron sulphide-fluorite	3.0	
Unfilled fractures	8 - 29	



- Carbonate
- Carbonate - clay minerals
- Carbonate +/- clay minerals +/- fluorite
- Carbonate - Fe-sulphide - clay minerals
- Carbonate - Fe-sulphide - fluorite
- Fe hydroxide - carbonate
- Fe hydroxide - carbonate - clay minerals
- Fe hydroxide
- Fe hydroxide - clay minerals +/- fluorite
- Fe hydroxide - Fe sulphide - clay minerals +/- fluorite
- Fe hydroxide - clay minerals
- Fe sulphide
- Fe sulphide - fluorite
- Fe sulphide - clay minerals
- Clay minerals - fluorite
- Clay minerals
- No fillings

Figure 7.3-1. Occurrence of fracture mineral assemblages in the core samples from Hästholmen (Gehör et al. 1997a, b, 1998).

Chlorite-covered fractures are also very common. Iron sulphides (pyrite and pyrrhotite) occur only sporadically along the boreholes, however these are more frequent in borehole KR2. Fluorite in fracture mineral assemblages generally occurs at depths above 200 m, below this depth fluorite is more common in boreholes KR3 and KR4 than in other boreholes.

No clear correlation between hydraulic conductivity and found fracture mineral assemblages is reported for the shallow parts of the bedrock, i.e. in the Y-boreholes (Gehör et al. 1997a). Some correlation was, however, found in boreholes KR1 - KR4, in the sense that fractures containing iron oxyhydroxides and clay minerals appear generally to have higher conductivities. However, non-conductive fractures containing iron oxyhydroxides and/or clay coated fractures have also been observed.

Corroded cavities in fractures and fracture zones, i.e. evidence of fracture mineral dissolution, are found in all borehole cores, they are, however, most frequent in borehole KR1. Corroded cavities are interpreted to be the result of large volumes of reactive groundwater that have passed through fractures.

7.4 Hydrogeochemical Evolution of Groundwater

The evaluation of hydrogeochemistry, isotopic data and mineralogy has revealed the complex character of the hydrogeochemical evolution of the Hästholmen site, which is characterised by considerable mixing of different groundwater types and by water-rock interactions. The mixing seems to control the considerable variation in salinity observed in groundwater compositions, which is caused by the large differences in salinity between the original end-member groundwater types. Changes in climate and geological environment play a significant role in palaeohydrogeological conditions and in the character of the recharging groundwater. At low temperatures the significance of water-rock interaction is probably limited to shallow depths in the bedrock, but it is of importance in controlling pH and redox conditions during groundwater evolution at depth. The strong alteration of primary silicates, at depth, on the fracture surfaces indicates considerable mass transfer during ancient hydrothermal activity (Gehör et al. 1997b, 1998). Water-rock interactions have likely affected saline groundwater end-member composition to a significant degree.

The groundwater chemistry shows evidences of environmental and climatic changes which have influenced the hydrogeological conditions at Hästholmen (Snellman et al. 1998, Luukkonen et al. 1999) in a similar manner to those at Olkiluoto (Pitkänen et al. 1996a, 1999). The current interpretation indicates the presence of six end-member groundwater types which determine the groundwater composition (see Table 7.1-2). Each climatic palaeostage has typical chemical and isotopic signatures which are observable in current groundwater compositions.

7.4.1 Recharge Conditions

Modern recharge conditions

In modern conditions similar processes are seen in the evolution of groundwater types at Hästholmen compared to those at sites with only fresh groundwater, Romuvaara and Kivetty. The current conditions, in which sub-aerial meteoric recharge occurs, have prevailed for about 4 000 years at Hästholmen (Kankainen 1986).

The major reactions are related to the oxidation of organics with contemporaneous CO₂ production, and subsequent dissolution of calcite at shallow depths and/or in dynamic flow systems as suggested by, for example, variations in $\delta^{13}\text{C}(\text{DIC})$. Decreasing strontium isotope ratios from shallow near-surface waters (groundwater-pipes and springs) and increasing $\delta^{13}\text{C}$ (reported by Snellman et al. 1998) indicate that calcite and/or plagioclase dissolution starts at shallow depths. This interpretation is also supported by observations on fracture minerals (Gehör et al. 1997a, 1997b, 1998). Silicate and calcite dissolution are likely the main reactions leading to increases in pH, dissolved carbon content and calcite saturation index during the surficial groundwater infiltration. In addition oxidation of ferrous sulphides are evident during infiltration according to ^{34}S in shallow groundwater (Kankainen 1986).

Cations such as Na, Ca, Sr, Mg and K show an initial enrichment in shallow groundwater samples from springs and groundwater-pipes in the overburden to wells and shallow samples from boreholes (Y1-Y11), indicating an additional source for the elements during recharge (Snellman et al. 1998). The enrichment is most probably due to the dissolution of silicates, i.e. weathering due to low pH and O₂ bearing initial, surficial water. Coupled oxidation and hydrolysis of biotite seem important according to Sr isotopic data (Luukkonen et al. 1999).

Below the recharge zone, chemical interaction is considered to be related to a combination of calcite dissolution or precipitation, ion-exchange processes and fluorite dissolution, as well as clay mineral transformations and redox processes. The most important processes are clearly related to dissolved carbon and redox chemistry. Cation exchange is definitely an important process in rock which has been exposed to sequential meteoric, sea water and saline groundwater infiltrations (e.g. Nordstrom 1986, Appelo & Postma 1994).

Recharge during Litorina Sea period

Past recharge conditions have been evaluated in detail for the Olkiluoto area by Pitkänen et al. (1999) and it seems likely that the same processes and past recharge conditions have also been active at Hästholmen, e.g. recharge of sea water during the Litorina Sea period due to a density turnover process, as was described for Olkiluoto.

In the past, the sea water recharged through sea-bottom sediments which are generally anaerobic and rich in organic matter. Probable processes that may have occurred include ion exchange, releasing Ca into the water, and microbially-catalysed SO₄ reduction. The latter

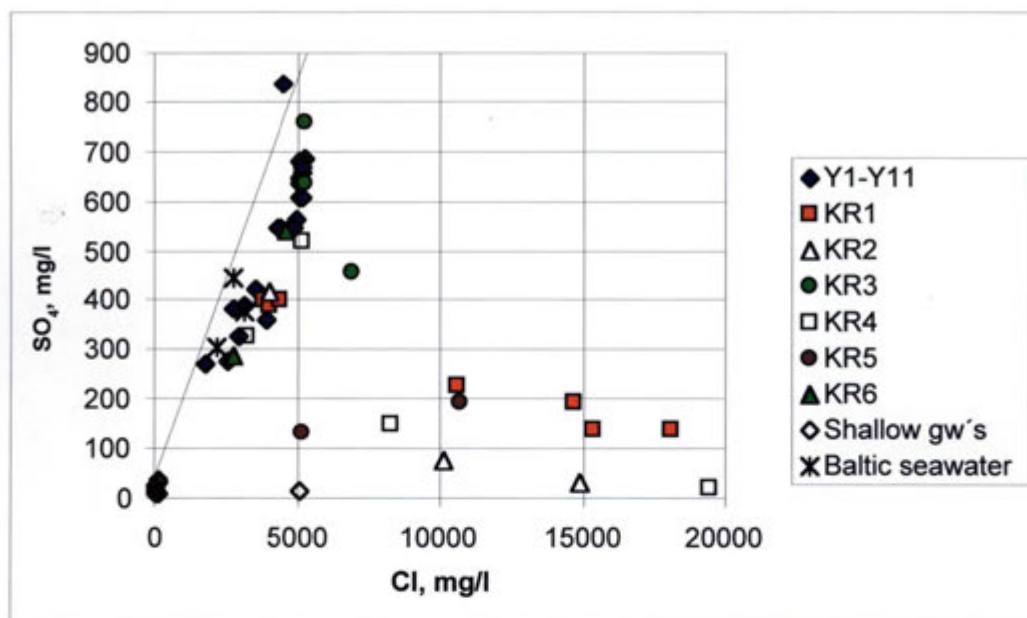


Figure 7.4-1. SO_4 as a function of chloride in Hästholmen groundwater samples.

is linked to anaerobic respiration of organic matter and results in the precipitation of pyrite (iron from ferric precipitates or ion-exchange) which is an ubiquitous accessory mineral in Litorina sediments (black/sulphide clay) (Palko 1994).

Recharge during retreat of the ice sheet

During retreat of the Weichselian glaciation ice sheet from Hästholmen diluted glacial meltwater probably infiltrated and mixed with subglacial groundwater at shallow depths in the bedrock due to the high hydraulic pressures generated by the ice sheet.

At Hästholmen iron oxyhydroxides are very frequent in the core samples, and in the uppermost 200 m of the bedrock their presence is probably related to the intrusion of dissolved oxygen gas, derived most likely from glacial meltwater. Oxygen being injected into the bedrock would have presumably resulted in the oxidation of ferrous minerals and sulphides in till and fracture walls (e.g. fresh biotite and pyrite), and maybe methane in subglacial groundwater. Likely reaction products, such as ferric precipitates, are seen on the fracture walls, however, some of these may have suffered subsequent reverse reduction reactions.

7.4.2 pH and Carbonates

The variation of alkalinity in groundwater samples is considerable at Hästholmen. Trends of alkalinity, pH (cf. Figs. 7.2-2, 7.2-3a, b) and calcite saturation are closely related to the dissolution-precipitation behaviour of fracture calcite, and iron hydrolysis also seems to be important. Calcite and iron oxyhydroxides are common fracture minerals in the majority of the core samples and, consequently, these minerals affect the groundwater chemistry at the

Hästholmen site. Calcite reaches saturation at the same Cl concentration at which alkalinity peaks and pH becomes more uniform, indicating the controlling role of calcite in dissolved carbon chemistry and pH. Usually, Ca shows a similar trend to that of alkalinity, but at Hästholmen (as also observed at Olkiluoto by Pitkänen et al. 1999) the depletion in Ca is probably obscured by mixing with a saline Ca-Na-Cl source. Dissolved iron may also affect the pH values of the groundwater. The aqueous iron likely occur as iron hydroxide complexes and thus it will take part in buffering the pH values at a relatively low level (around pH 7.5) in the deep bedrock (Luukkonen et al. 1999).

7.4.3 Salinity and Palaeohydrogeology

The fresh, brackish and saline groundwater types at Hästholmen contain distinct compositional changes seen as variations in SO_4 , Mg, Br, Cl and stable isotope contents of groundwater. This reflects complex conservative mixing of water types of different origin.

Fresh and brackish groundwater

Samples representing the latest climatic palaeostage at Hästholmen are characterised by HCO_3 -rich infiltration (cf. Table 7.2-1, 7.2-2) with isotopic signatures indicating relatively young residence time, as is demonstrated by measurable tritium, moderate ^{14}C (50 - 70 pmC or higher), representing a modern range due to isotopic dilution (Kankainen 1986, Snellman et al. 1998, Luukkonen et al. 1999) and a modern stable isotope composition of the water. The groundwater type which is present in the uppermost 100 m was recharged after the island of Hästholmen rose above sea level.

Salinity, formed mainly by Ca, Na, HCO_3 and Cl, approaches the brackish groundwater limit (1 000 mg/l) at less than 50 m depth. The large increase in SO_4 and Mg contents, especially at shallow depths, has been explained as being due to the presence of sea water (present or palaeo Baltic, Nordstrom 1986, Kankainen 1986), since no other significant source of soluble sulphates is recognised (Gehör et al. 1997a, 1997b, 1998). The Br/Cl-ratio also indicates a marine input, because the ratio stays fairly stable and corresponds to that of sea water in groundwater samples with high sulphate (Fig. 7.4-2). The $\delta^{34}\text{S}$ content (22 - 24.7‰ CDT) is considered somewhat elevated from the sea water level (20‰ CDT) due to the partial reduction of sulphate which is consistent with the depletion of sulphate, with respect to the sea water dilution line (Fig. 7.4-1).

Litorina Sea contaminated samples occur mainly over a range of depths from 100 to 400 m. The more saline Litorina Sea is clearly reflected in the high Mg and SO_4 contents of the groundwater, and its sea water origin is reflected in lower pH and alkalinity compared with the HCO_3 -rich groundwater. The stable isotopes in the most strongly Litorina Sea contaminated groundwater samples (e.g. $\delta^{18}\text{O}$, Fig. 7.4-3) show also a heavier signature than current recharge, reflecting a warmer climate and more depleted ^{14}C of dissolved carbon (20 - 25 pmC). The estimated ^{14}C age (Luukkonen et al. 1999) of the sulphate and $\delta^{18}\text{O}$ -high groundwater type has a range of 7 600 - 5 700 BP, corresponding to the early stage Litorina period (Eronen & Lehtinen 1996). The SO_4 -rich groundwater is the heaviest in $\delta^{18}\text{O}$ ($\delta^{18}\text{O} = -7.7\text{...}-9.0$) of the fresh and brackish groundwater. A warmer climate favours a heavier

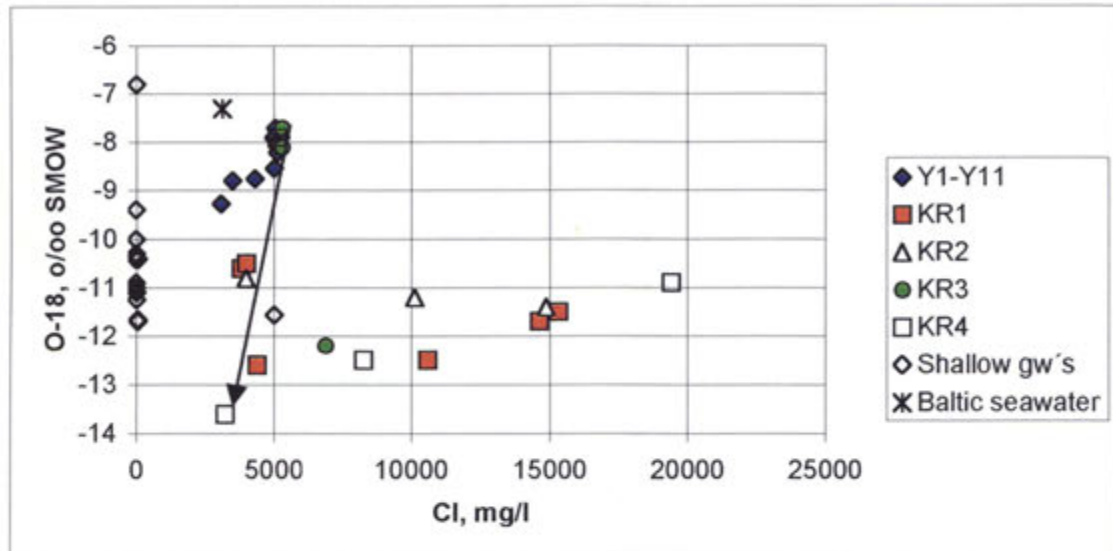


Figure 7.4-3. $\delta^{18}\text{O}$ as a function of chloride in Hästholmen groundwater samples. The trend from Litorina peak groundwaters towards the glacial meltwater type is indicated.

Saline groundwater

The features of saline groundwater, which is present at depths below 500 - 600 m, increase steadily with the increase in salinity. Thermodynamic equilibrium with calcite probably fixes alkalinity at a very low concentration (cf. Fig 7.2-3), and pH at a relatively low value (cf. Fig. 7.2-2) due to the high concentrations of Ca and Fe (cf. 7.2-5b). Iron is enriched and the reduced sulphur content is low in the saline groundwater. In particular, the saline groundwater samples from borehole KR1 (up to a Cl content of about 15 000 mg/l), show similar characteristics to those of the brine-derived saline groundwater type (Ca-Na-Cl) at Olkiluoto (Pitkänen et al. 1999). At Olkiluoto the chemical signatures from calcite, fluid inclusions and isotopic signatures in saline groundwater suggest an old origin for the residual brine end-member(s), which is probably early Phanerozoic or Precambrian in age.

The trends of Ca, Na, Mg and Br (cf. Snellman et al. 1998 and Figs. 7.4-2, and 7.4-4) suggest two end-member water types influencing the salinity. The results of the stable isotopes, and elevated Ca/Cl, Ca/Mg ratios and a Br/Cl ratio reaching twice that of Baltic sea water for the saline groundwaters indicate a considerable water-rock interaction at elevated temperatures as origin for the saline end-member (Snellman et al. 1998, Luukkonen et al. 1999). The stable isotopes, though enriched from the brackish groundwater layer, are still fairly low (about -12..-11‰, Fig. 7.4-1) for the least saline waters in the saline groundwater zone, thus indicating mixing of a melt water component.

A marine component in the saline groundwater is suggested by considerable SO_4 , its $\delta^{34}\text{S}$ signature and exceptionally high Mg content (Fig. 7.4-4) (Snellman et al. 1998, Luukkonen et al. 1999). Some saline groundwater samples show a very low amount of ^{14}C (< 0.6 pmC) indicating that these samples have not been disturbed by waters from deglaciation or

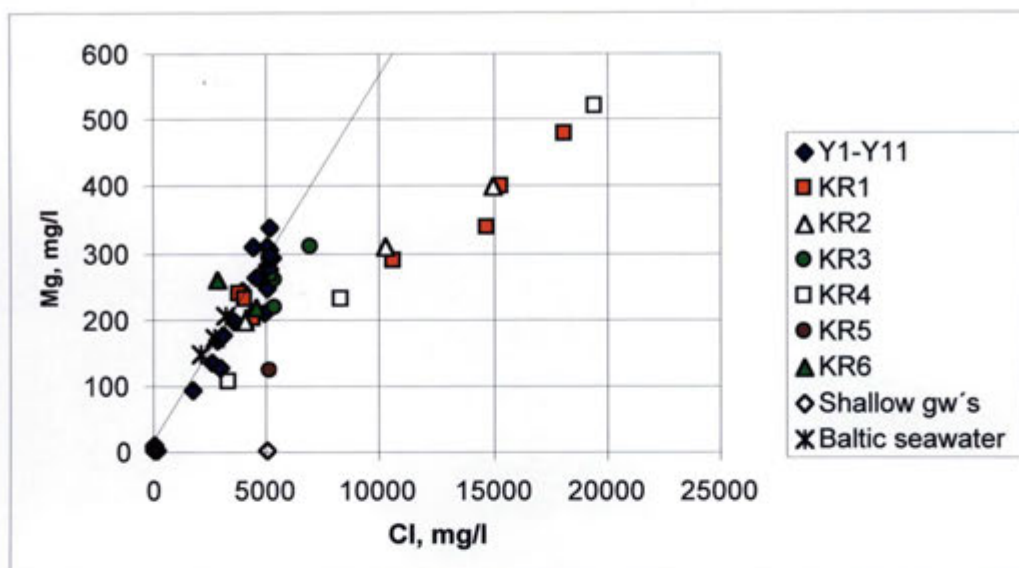


Figure 7.4-4. Mg as a function of Cl in Hästholmen groundwater samples.

postglacial periods (Luukkonen et al. 1999). The low ^{14}C excludes the Litorina Sea as a possible sea water source. The high salinity of this marine component could be due to the Eem interglacial 130 000 - 100 000 BP, which was the first warmer period preceding the last glacial advance. During this interglacial, the Baltic Sea was more saline and probably had a connection to the White Sea (Eronen & Lehtinen 1996).

The saline water at Hästholmen would, therefore, appear to show imprints of both hydrothermal sources and ancient Eemian sea water.

7.4.4 Redox

Due to problems associated with the interpretation of Eh measurements on natural groundwater made using platinum electrodes, Berner (1981) proposed a classification of redox conditions in terms of "indicative redox species" or dominant electron accepting processes, which usually form a reduction sequence with residence time and flow distance from the ground surface (Fig. 7.4-5).

The groundwater chemistry, isotope data and mineralogy of the Hästholmen site contain imprints of progressive redox reactions down-gradient from the recharge zone that are augmented by recent data (Helenius et al. 1998) and microbial studies (Haveman et al. 1998). Carbon and strontium isotopes emphasize the importance of organic matter and biotite in the consumption of dissolved oxygen during recharge. In addition, though the oxidation of pyrite and other sulphide minerals in fractures is a potential sink for oxygen, the current data do not show any unambiguous indicator of such a process. It has been suggested that iron oxyhydroxide precipitates formed in cold temperature conditions are limited to the upper 200 m (Gehör et al. 1997a, 1997b, 1998), indicating that oxygen is consumed at shallow depth at Hästholmen. Elevated Fe^{2+} concentrations in dissolved carbon-rich groundwater also indicate a shift from oxic to post-oxic redox conditions. These

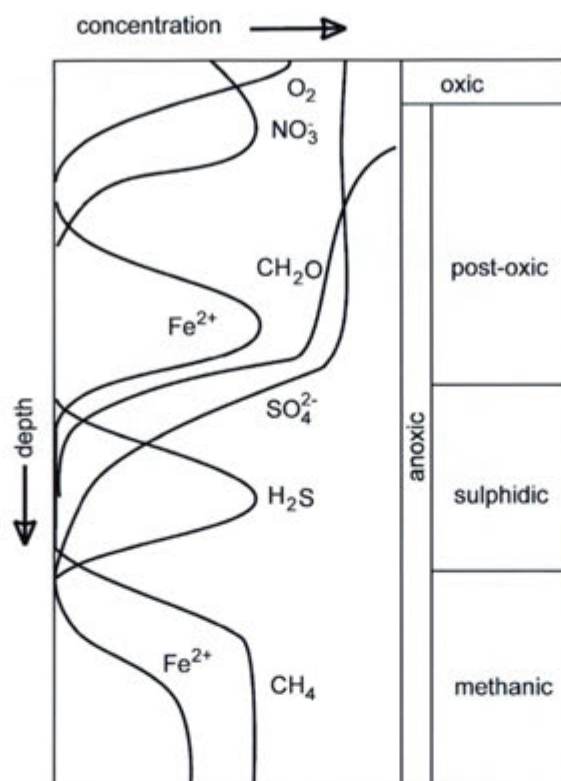


Figure 7.4-5. Sequence of reduction processes applicable to redox sensitive species observed in groundwater at Hästholmen. Figure redrawn (Pitkänen et al. 1999) after Appelo and Postma (1994). Berner's (1981) classification of redox environments is shown on the right hand side.

samples have a high tritium content, suggesting that oxygen is lost from recently recharged water over a few decades (< 45 years).

The observations of dissolved reduced sulphur in brackish and saline groundwater samples are an indication of a shift from post-oxic to prevailing sulphidic conditions. The required sulphate reducing bacteria have been observed (Haveman et al. 1998) as well as pyrite coatings on fractures (Gehör et al. 1997b, 1998) and enriched $\delta^{34}\text{S}$ values in dissolved SO_4 , all of which support the past or continuing reduction of sulphate in the brackish and saline groundwater. The reduction of iron oxyhydroxides to release iron for pyrite precipitation is possible according to sporadic pyrite coatings on fractures (Gehör et al. 1997a, 1997b, 1998). Iron reducing bacteria (IRB) have been found to be dominant in the groundwaters (Haveman et al. 1998). The IRB might, for example, catalyse the reduction of amorphous ferric oxyhydroxides with the simultaneous oxidation of organic compounds. Iron minerals and/or dissolved iron likely maintain low H_2S concentrations in deep groundwater and ferric oxyhydroxides on the walls of fracture form a reserve of soluble ferrous iron for taking part in sulphate reduction by anaerobic organic carbon oxidation.

According to the present results, the redox conditions at depth at Hästholmen seem to be controlled by the Fe^{2+} /goethite and $\text{S}^{2-}_{\text{tot}}/\text{SO}_4$ /pyrite equilibria. The possible lack of dissolved organic matter, which can be used by Sulphur reducing bacteria (SRB), probably limits any strong sulphate reduction, although $\delta^{34}\text{S}(\text{SO}_4)$ data for both the brackish and

saline groundwater indicate that significant reduction of sulphate has occurred, with the extreme value (+55.5 ‰ CDT) for the saline groundwater from the depth 882 - 890 m in borehole KR4. Another explanation might be that IRB use organic substrates more efficiently than the SRBs (Haveman et al. 1998). Low concentrations of sulphide have been measured, especially in borehole KR3. The increasing amounts of reducing gases (CH_4 , H_2) and decreasing uranium content with increase in salinity support the low redox values obtained at depth.

According to the recent interpretation by Luukkonen et al. (1999) it seems that the redox system in deep groundwater at Hästholmen is in the sulphidic zone. Measured values correspond better with the sulphur system according to the thermodynamic calculations. Calculated Eh values is of a level -200 ± 50 mV (Luukkonen et al. 1999).

8 CONSTRUCTABILITY

8.1 Classification of the Rock Mass

The properties of the bedrock of Hästholmen have been evaluated according to the engineering rock mass classification developed for this work in order to define the bedrock volumes suitable for constructing a repository (Äikäs et al. 1999). The following properties of the rock mass have been considered to influence its constructability:

Rock quality

- determined by rock type, fracturing and hydrogeological properties. Rock type properties include mineralogy, texture, grain size, weathering, strength and deformation as well as thermal conductivity. Fracturing includes the number of fracture sets, frequency and length of fractures as well as their frictional properties. Hydrogeological properties include hydraulic conductivity and estimations of groutability and groundwater ingress.

Stress conditions

- magnitude and direction of in situ stresses and strength/stress ratio

Groundwater chemistry

- pH and concentration of sulphate, carbon dioxide, ammonium, magnesium, chloride and radon

Technical properties

- drilling, blasting, rock supporting and rock crushing properties.

All these rock properties have been classified into three classes depending on their influence on the construction of the repository. Although it is evident that methods for construction will develop in the future, the basis for the evaluation are the methods presently used in excavation and underground construction. The classes of constructability were determined as following:

Normal

- when construction of the repository can be carried out by applying conventional hard rock tunnelling techniques, working efficiency and materials, allowing for the high quality requirements for these kind of tunnels. Considering for example blasting and rock supporting properties this can mean that tunnels should be excavated using 4 - 5 m long blasting rounds and that rock supporting, which consists of rock bolts and shotcrete or wire mesh, can be done afterwards.

Demanding

- when construction of the repository needs more sophisticated and expensive construction methods or materials than in the normal class, rate of tunnelling is considerably lowered or much effort has to be put on safety at work. Considering for example blasting and rock supporting properties this can mean that tunnels should be excavated using 3 - 4 m long blasting rounds and supported temporarily with bolts and shotcrete or wire mesh after each round. Also pre-grouting may be needed. The final support can be done with rock bolts and fibre-reinforced shotcrete.

Very demanding

- when construction of the repository needs much more sophisticated and expensive construction methods or materials than in the normal class, rate of tunnelling is very much lowered or very much effort has to be put on safety at work. Considering for example blasting and rock supporting properties this can mean that tunnels should be excavated using 1 - 3 m long blasting rounds and supported temporarily with bolts and shotcrete after each round. Also spiling and pre-grouting are needed before excavation. The final support can be done using fibre-reinforced shotcrete with reinforced ribs or cast concrete lining.

The classification of the rock mass has been carried out for the Hästholmen island. Structures R10, R11, R12, R13 and R15, as well as the coordinate $Y = 3463500$, border this area which extends to a depth of 1000 m. The surface and borehole investigations as well as the 3D bedrock model (see Section 5) have been used as input data for the classification.

In addition, the bedrock has been classified according to the empirical Q-system (Barton et al. 1974, Grimstad & Barton 1993) for the sake of comparison and for estimating the support measures at different depths and for different rock types (Fig. 8.1-1).

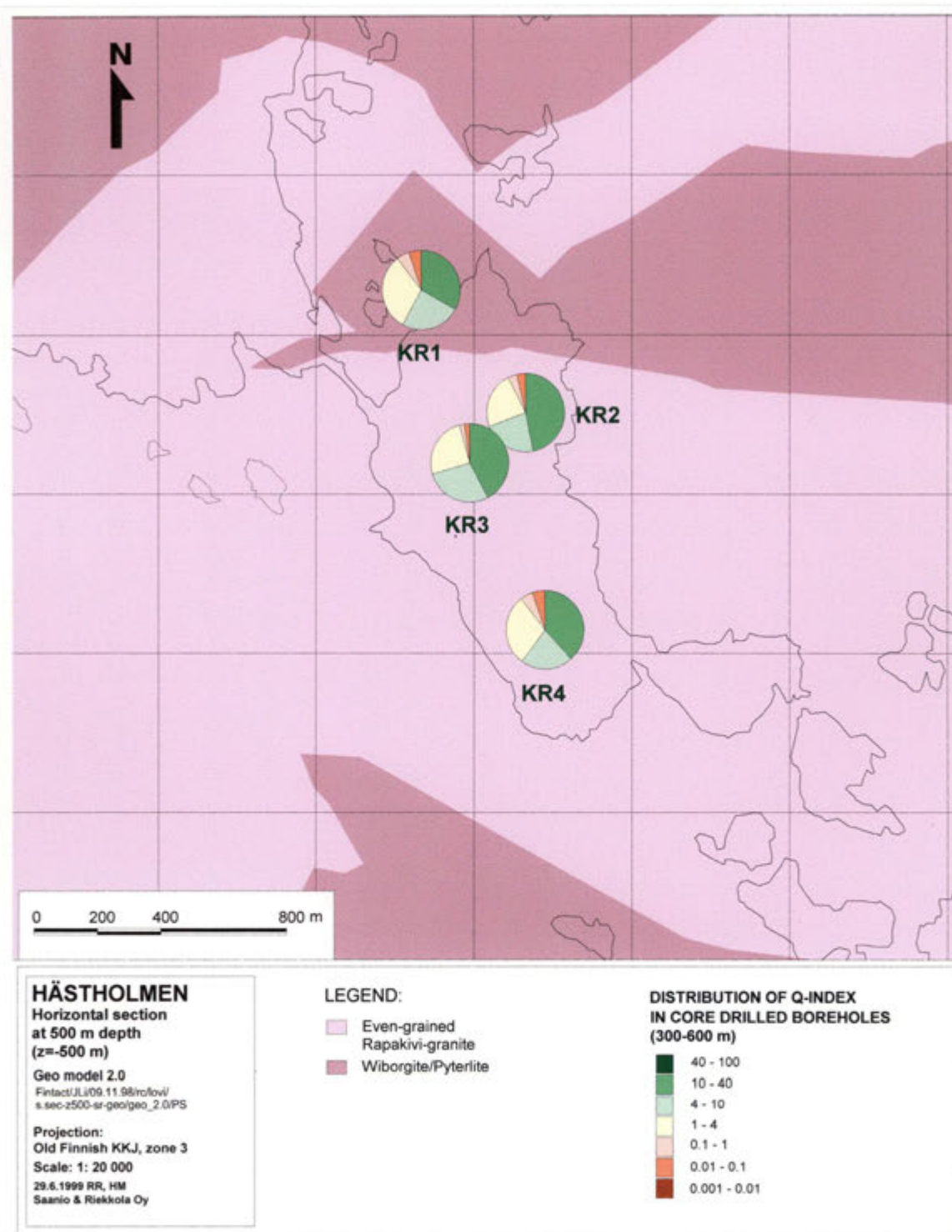


Figure 8.1-1. Average Q -values (geometric mean) of the investigation boreholes over the depth range of 300 - 600 m at the Hästholmen site (Äikäs et al. 1999).

8.2 Evaluation of the Constructability

The evaluation of the constructability of the rock mass is, at this stage, based on the engineering rock mass classification and the Q-classification (Äikäs et al. 1999).

The aim is to construct as much of the repository as possible in volumes of rock which are classified as "normal". In practice this means that the construction should take place dominantly within intact rock and that major fracture zones (structures) should be avoided at the disposal depth. The majority of the rock mass at Hästholmen consists of intact rock and has been estimated as "normal" from the point of view of constructability. This means that excavation and rock support can be carried out using conventional methods and materials, as generally applicable to Finnish underground construction projects. This intact rock is typically hard and unweathered, with a low fracture frequency, which in outcrops is typically <1 fracture/m and in borehole cores 1 - 3 fractures/m.

An important bedrock property that may limit the placement of the deposition tunnels and disposal holes at Hästholmen is the location of some fracture zones, which may prove to be difficult to seal against the ingress of groundwater and may also require extensive support. Structures R1, R3, R7, R20 and R21 have been identified as "very demanding" and structures R9, R18 and R19 as "demanding" from a constructability point of view for deposition tunnels. However, other tunnels (i.e. non deposition tunnels) and shafts could be excavated through these structures.

The suitable range of depth for the repository construction may be reduced by the limited strength of some parts of the rock mass and by the values of the in situ stresses. Close to the maximum depth of 700 m, even-grained rapakivi granite has been estimated to be "demanding" in terms of its constructability, because of its strength/stress-ratio (uniaxial compressive strength $\sigma_{ucs} = 160 - 220$ MPa) and the stress field ($\sigma_H = 35 - 45$ MPa at 700 m). Wiborgite/pyterlite has been estimated to be "demanding" or "very demanding" under the depth of 500 m ($\sigma_{ucs} = 130 - 170$ MPa). The classes "demanding" or "very demanding" mean that special methods and materials should be used when excavating and supporting the rock which, in turn, will result in more time and increased costs for the construction work (see Section 8.1).

In addition, at Hästholmen, the salinity of the groundwater results in the need for more expensive materials for some constructional elements and more extensive maintenance during the construction and operational phases.

The main conclusion of the evaluation based on the classification work is that there seem to be no significant geotechnical constraints to repository construction within the depth range of 400 - 700 m, however, with increasing depth geotechnical factors do need to be given a higher priority.

Estimates of geotechnical behaviour based on empirical methods have been included in the engineering rock mass classification as well as in the Q-system (Fig. 8.2-1). The requirements for rock support increase with the depth. Estimates of the average Q-number for even-grained rapakivi granite and pyterlite suggest that tunnels can be supported with rock

bolting and shotcrete over most of the considered depth range. Close to the lower depth limit the need for rock support in wiborgite/pyterlite increases to consist of rock bolts and fibre-reinforced shotcrete, Table 8.2-1. However, other types of support may also be used, such as rock bolts and wire mesh. The method for support will be selected based on the in situ geotechnical behaviour of the rock as well as on the suitability of the materials for the repository environment. Based on empirical estimates and average strength results, the

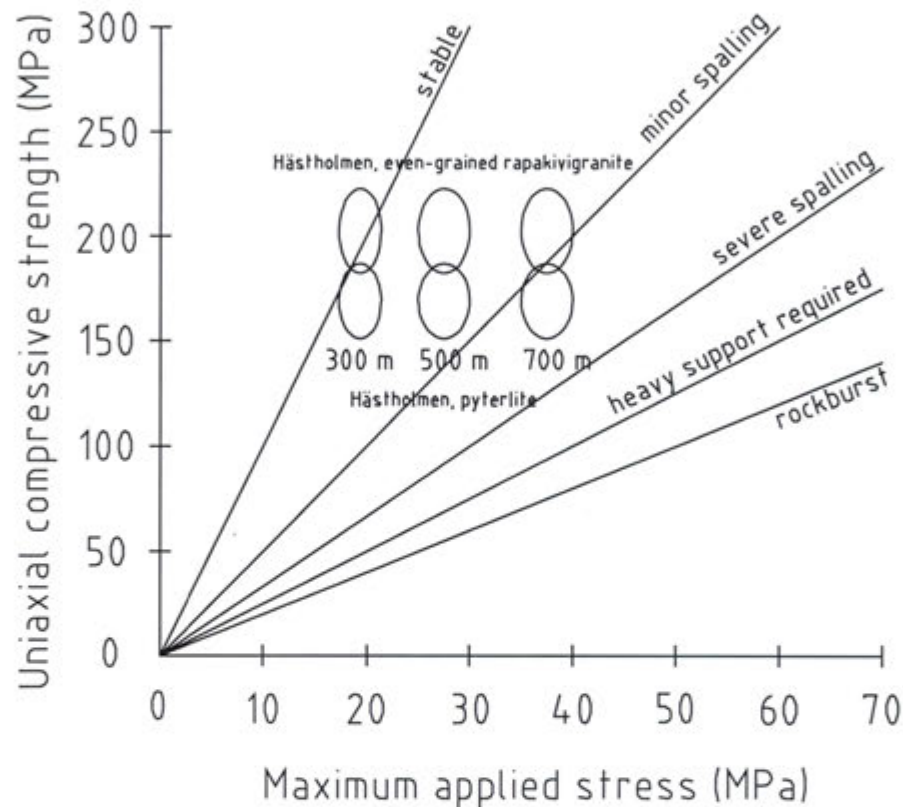


Figure 8.2-1. Empirical estimates of rock behaviour based on the strength / stress-ratio.

Table 8.2-1. Estimation of support methods in even-grained rapakivi-granite and pyterlite. Estimation is based on *Q*-classification (Äikäs et al. 1999).

Rock type	Support system		
	0 ... 300 m	Depth range 300 ... 600 m	> 600
Even-grained rapakivi granite	No rock support	Systematic rock bolting	Systematic rock bolting and shotcrete
Wiborgite/pyterlite	No rock support	Systematic rock bolting and shotcrete	Systematic rock bolting and fiber reinforced shotcrete

even-grained rapakivi granite remains stable within the depth range of 300 - 700 m and pyterlite may be subject to minor spalling effects at depths greater than 600 - 700 m. Core discing and ring discing, which are frequently observed in the deep boreholes at Hästhölm, indicate geotechnical behaviour that deserves further study.

The areal extent of suitable rock at 500 m depth available for constructing the repository is shown in Figure 8.2-2. This potentially suitable area is limited by the presence of fracture zones and, to some extent, by the size of the area characterised by borehole investigations.

The remaining uncertainty associated with the exact locations, dimensions and properties of the fracture zones also results in uncertainty in the evaluation of the rock's constructability. It will be necessary to carry out investigations in situ at the proposed disposal depth in order to decide on exact locations for the deposition tunnels and disposal holes.

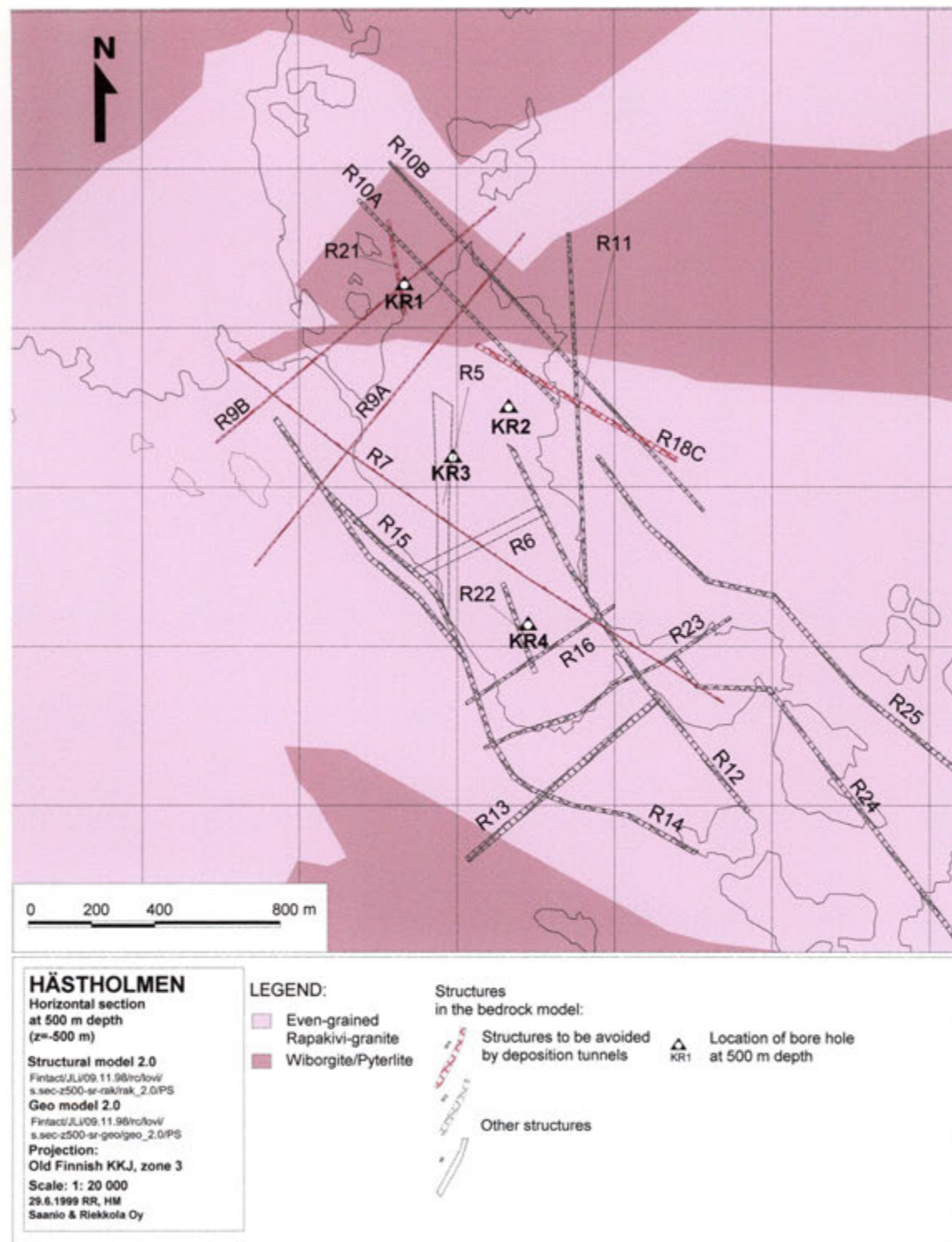


Figure 8.2-2. Areal extent of suitable rock for repository construction. Horizontal section at 500 m depth.

9 CONSTRUCTION OF THE REPOSITORY

9.1 Technical Description of the Repository

The basic concept for the disposal of spent fuel is based on its encapsulation and emplacement in crystalline bedrock at a depth between 400 to 700 m (Fig. 9.1-1). The selection of the final depth for the repository will be based on the site-specific properties and conditions of the bedrock.

The design of the basic concept is based on the use of the copper canisters. The diameter of the canister for BWR fuel from TVO is 1 052 mm and the length is 4 800 mm. The canister length for the VVER-440 type PWR fuel from IVO is 3 600 mm, the diameter of both canisters being the same.

The estimated total amount of spent fuel and the number of waste canisters corresponding to a 40 years operation time for the power plants is about 2 600 tU and 1 400 canisters, respectively. The total excavated volume of the repository for this amount of spent fuel is estimated to be about 400 000 m³. If operation times were extended up to 60 years, the corresponding amount of spent fuel would be about 4 000 tU and the number of canisters 2 200. Were two new nuclear power plants to be constructed the amount of spent fuel corresponding to 60 years operation times for all these power plants would be about 9 000 tU.

In the reference design for the basic disposal concept the spent fuel canisters are emplaced in vertical holes which are excavated in the floor of the deposition tunnels (Fig. 9.1-2). The diameter of these disposal holes is 1 752 mm and their spacing is based on the site-specific thermal properties of the rock mass. The spacing of the tunnels is 25 m and at Hästholmen the current design intent spacing of the disposal holes is 7.5 m for 2600 tU. The depths of the disposal holes are 7.8 m for the TVO type canisters and 6.6 m for the IVO type canisters. The deposition tunnels will subsequently be backfilled with a mixture of crushed rock and bentonite.

An encapsulation plant will be constructed at the surface where the spent fuel rod assemblies will be packaged in canisters. Access from the surface to the repository will be provided by three vertical shafts, a work shaft, a personnel shaft and a canister shaft, or by a combination of shafts and an inclined access tunnel.

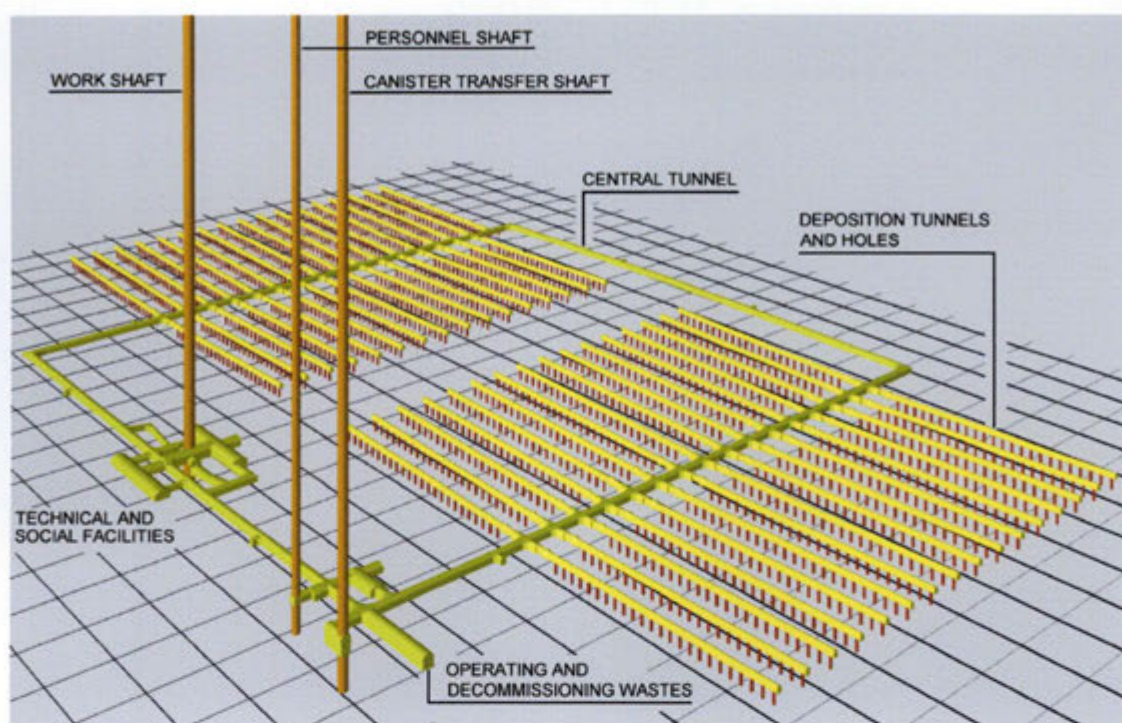


Figure 9.1-1. Basic design for the high level nuclear waste repository for 1 400 canisters assuming 40 years operating times for the current reactors.



Figure 9.1-2. Backfilled deposition tunnel with a canister in the disposal hole.

9.2 Principles of Implementation

Before any construction of the actual repository commences a detailed characterisation of the selected site will be carried out. The purpose of this characterisation programme is to confirm the information obtained earlier and to acquire additional information for the detailed design and location of the repository at the site. To be able to obtain the relevant information it is planned to develop and operate an underground rock characterisation facility, which will initially involve the excavation of an investigation shaft or an access tunnel. During this phase of the investigations the in situ conditions at depth will be studied and exploratory galleries or tunnels will be constructed as and where required.

Construction of the repository is planned to start during the 2010s, after the characterisation has been completed and a permit for construction has been given by the Government. This will involve the construction of the remaining shafts, the central tunnel and the first part of the deposition tunnels, as well as other tunnels and surface facilities.

The operational phase is planned to start after 2020. The reference concept is based on an approach in which deposition tunnels are excavated stepwise during the operational phase, simultaneously with the installation of the waste canisters. The simultaneous excavation and installation of canisters appears to have advantages over the alternative approach, in which the whole repository is excavated before starting the operational phase. Figure 9.2-1 illustrates the steps from excavation to backfilling that are needed for simultaneous excavation and operation.

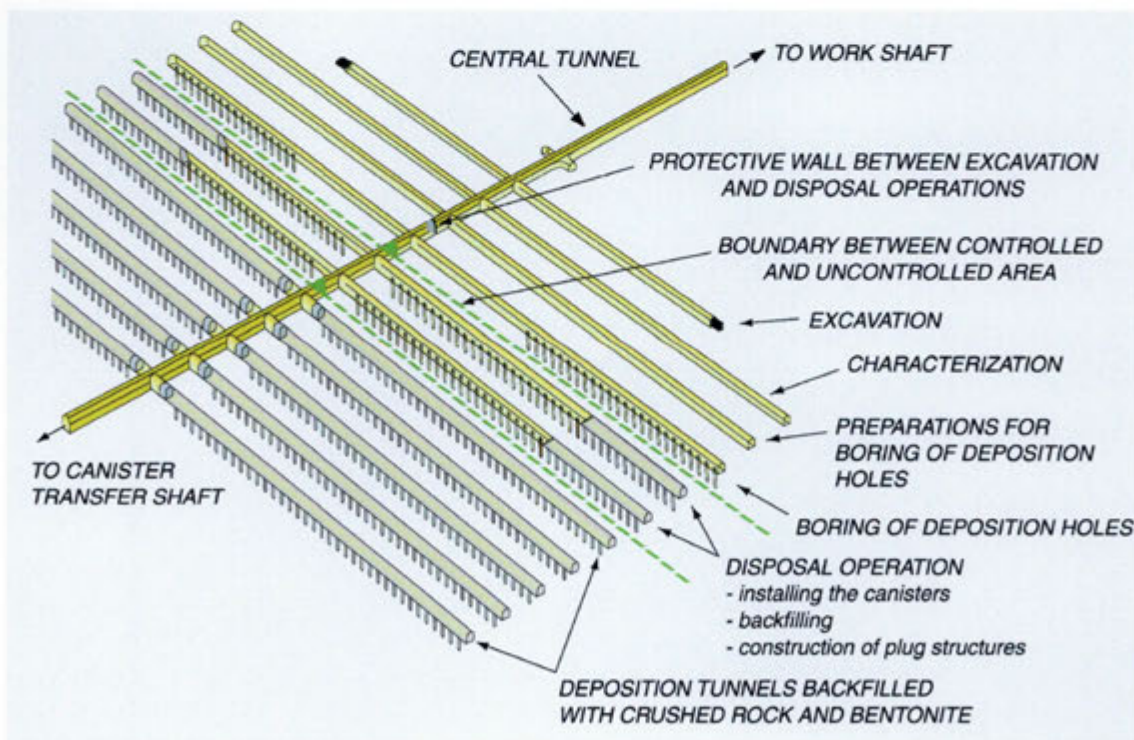


Figure 9.2-1. Principle of the stepwise construction of the repository.

It is evident that the future development of techniques is likely for excavation, boring the deposition holes and backfilling the tunnels. In the current reference design, however, the central tunnel, deposition tunnels and other facilities will be excavated by a carefully controlled drill and blast technique. A smooth blasting technique will be employed and the blast design adjusted to the prevailing rock conditions and excavation disturbance constraints. The most advantageous method for the excavation of disposal holes is considered to be boring based on rotary crushing and vacuum dry suction of the crushed rock, a technique demonstrated in the Research Tunnel of the VLJ repository at Olkiluoto (Autio & Kirkkomäki 1996). After the final disposal of the last canisters the encapsulation plant will be decommissioned, the remaining empty tunnels will be filled with bentonite and crushed rock and the access shafts will be sealed.

There remains uncertainty associated with the exact locations, dimensions and properties of fracture zones and the repository layout shown in Section 9.3 should, therefore, be considered to be only preliminary and illustrative. The details of the repository layout and the locations of the disposal holes will be determined using an observational method process during construction, which allows the repository layout to be refined and adjusted to the local structure of the bedrock as new data on the rock mass become available. The observational method is a continuous, managed and integrated process of design, construction control, monitoring and review which enables previously designed modifications to be incorporated during or after construction, as appropriate.

Information on in situ conditions will be obtained from investigations during excavation of the investigation shaft, during excavation of the central tunnel in the construction phase of the repository, and during excavation of the deposition tunnels and boring of the disposal holes in the operational phase. Finally, the suitability of a potential location for a disposal hole may be assessed on the basis of information obtained from a small diameter pilot borehole, which is proposed to be drilled in advance down the centre line of each disposal hole.

9.3 Preliminary Layouts

A preliminary adaptation of the repository layout to site-specific conditions has been carried out by Riekkola et al. (1996). Simple rock engineering principles were applied and the way that various site-specific conditions influence the repository design were recognized:

- The location of the repository within a site is governed mainly by the location, geometry and transmissivity of the fracture zones, as well as by the associated level of uncertainties in rock properties.
- The orientation of the deposition tunnels is governed mainly by the direction of the maximum horizontal stress, by the orientation of the fracture sets and by the location of the fracture zones. The orientation selected is likely to be a compromise between the stress orientation and the various relevant properties of the rock mass.
- The depth of the repository is governed mainly by the maximum horizontal stress, the strength of the rock, the location of the fracture zones and the groundwater chemistry, as well as by long-term safety aspects.

Based on the classification of the bedrock (Äikäs et al. 1999), which is discussed in Section 8, an illustrative example of the area needed for the construction of deposition tunnels for 1 400 canisters, corresponding to 2 600 tU, is shown in Figures 9.3-1, 9.3-2 and 9.3-3. The intact rock within the area shown has been recognized as being potentially suitable for constructing the repository. It is located at two depths of 500 m and 600 m under the Hästholmen island and extends some hundreds of meters outside the area covered by the existing boreholes. This example is based on the assumption that the construction of deposition tunnels takes place exclusively in even-grained rapakivi granite, leaving respect distances of 50 m to structures R7, R9 and R18. Constructing deposition tunnels for 2 200 canisters, corresponding to 4 000 tU would require extending the layout under the mainland.

If still larger waste volumes need to be taken into account, the area covered by the detailed site characterisation programme would need to be enlarged. The potential rock volumes available allow flexibility in the location and construction of the repository, even for larger quantities of wastes than those from the present power plants.

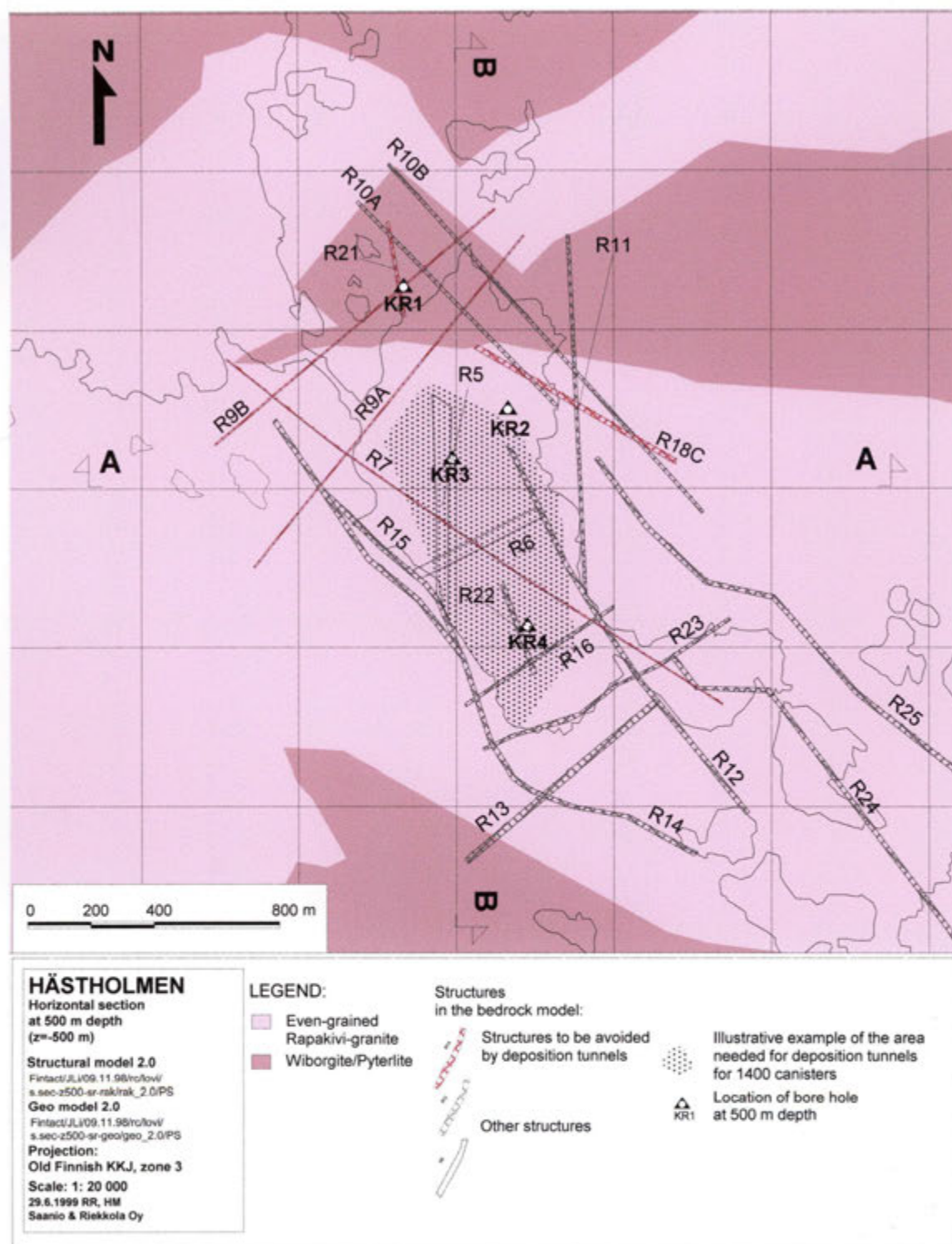


Figure 9.3-1. Illustrative example of the area required by deposition tunnels belonging to the upper part of a two storey repository at Hästholmen. Horizontal section at 500 m depth. Bedrock model version 2.0 used.

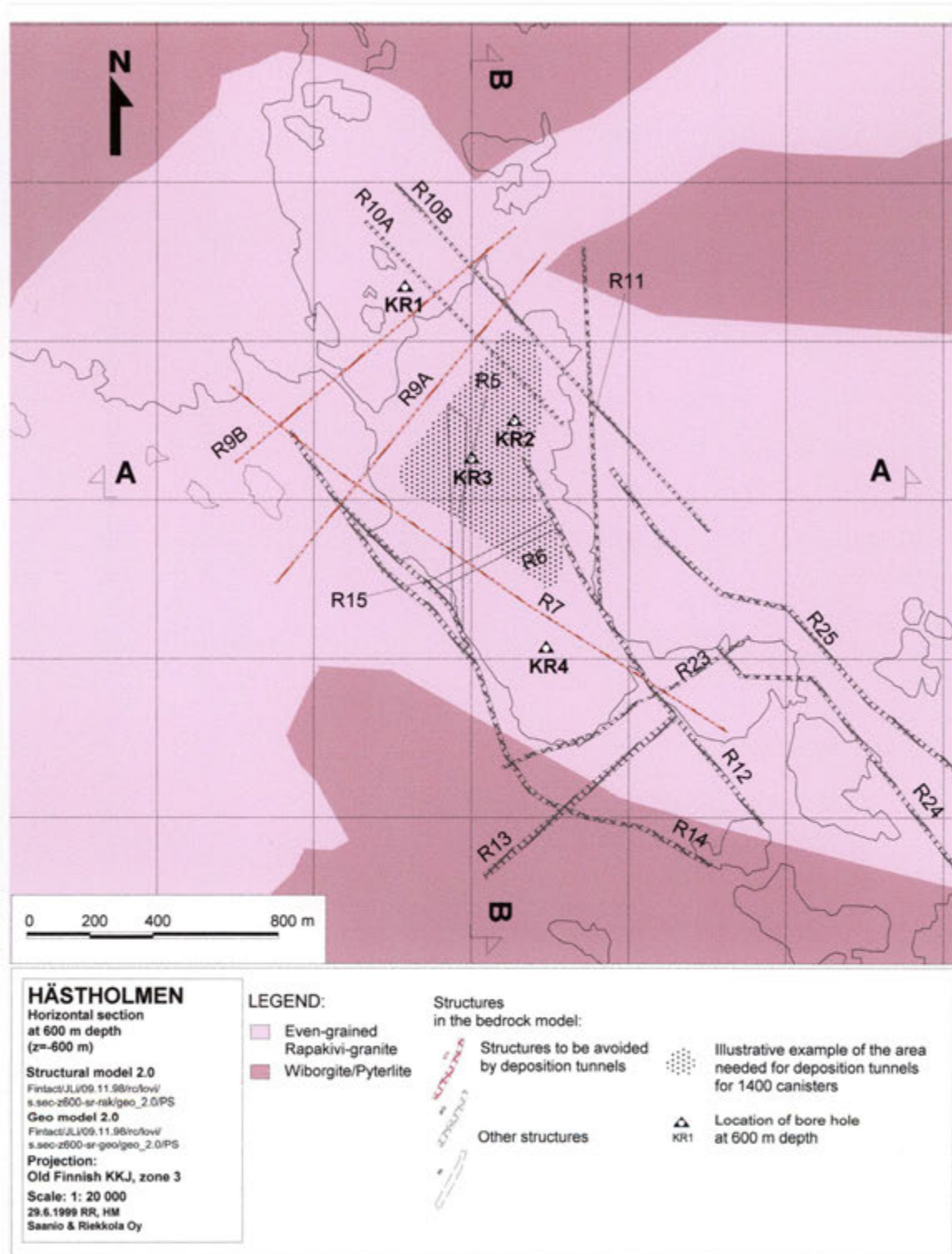


Figure 9.3-2. Illustrative example of the area required by deposition tunnels belonging to the lower part of a two storey repository at Hästholmen. Horizontal section at 600 m depth. Bedrock model version 2.0 used.

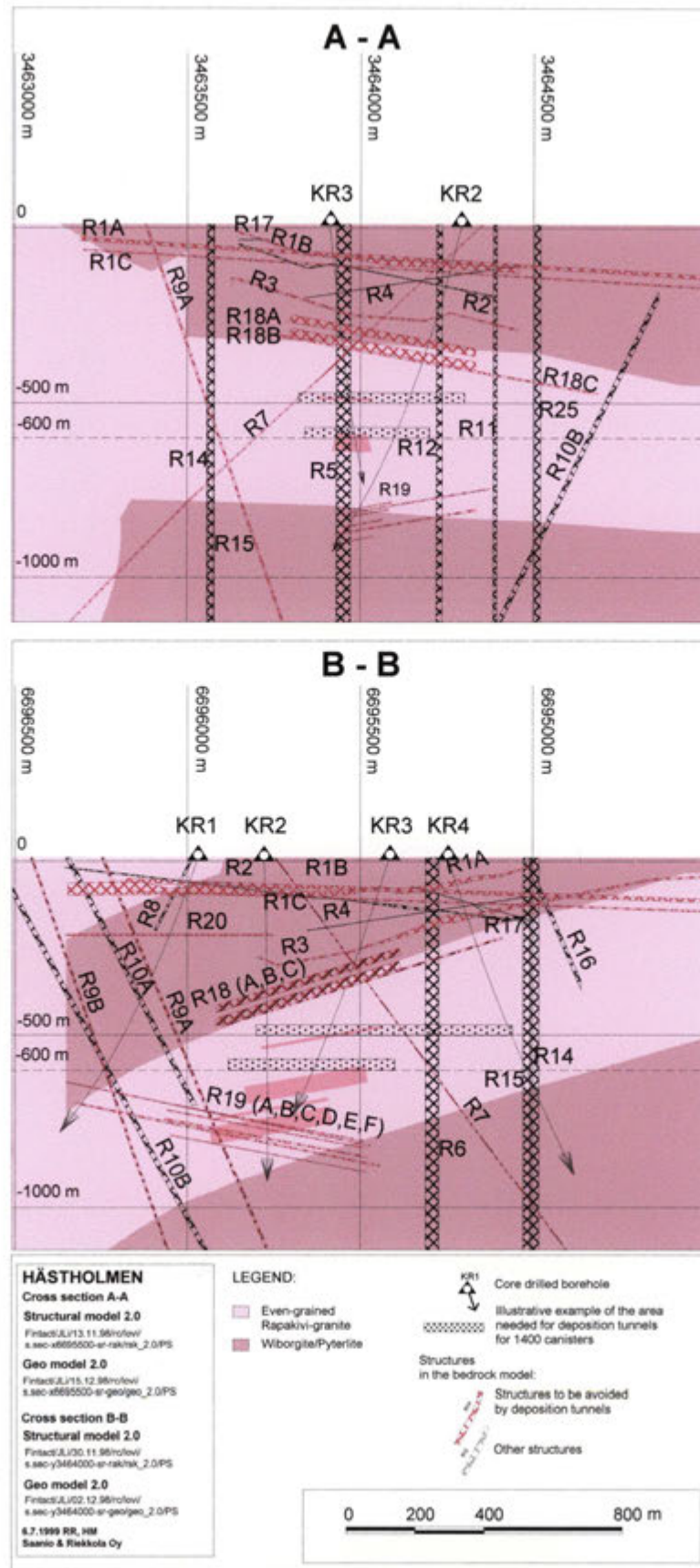


Figure 9.3-3. Illustrative example of a possible location of a two storey repository at Hästholmen. Cross sections A - A and B - B. Bedrock model version 2.0 used.

10 SUMMARY AND DISCUSSION

10.1 Particular Features of the Site

The Hästholmen and Olkiluoto sites, both representing a NPP site, are located on the coast, whereas Kivetty and Romuvaara lie inland, and both are also situated below the so called “highest shoreline” of the Baltic, and therefore have been for a long period of time in a sub-aquatic position since the last glaciation. The highest parts (+16 m.a.s.l.) of the island of Hästholmen island rose from the sea about 4 000 years ago, and Olkiluoto some 1 000 years later. Today the postglacial uplift rate is some 2 mm/year for Hästholmen and 6 mm/year for Olkiluoto. The marine history of these two coastal sites is reflected particularly by the groundwater chemistry, which differs significantly from that found at the two inland sites. Due to the outwash action of the ancient sea waves the area of outcropping bedrock is somewhat larger at the coastal sites, e.g. some 6% at Hästholmen and, correspondingly, the soils are more sorted.

The soil cover on the island of Hästholmen and in its vicinity consists mainly of silty sandy till, which typically contains abundant surface boulders. The till cover is usually a few metres thick. The Quaternary deposits on the sea bottom consist mainly of till, gravel and sand, which are overlain by silt and clay in the sub-sea depressions, e.g. east of Hästholmen, where the rock surface descends to a depth of about -70 m. The bedrock outcrops mainly occur in the western and northern parts of the island, whilst on the mainland to the north the bedrock is very poorly exposed. The nuclear power facilities, as well as the VLJ repository, are situated in the northern and western part of the island. Outside the power plant site proper, the area is mostly underdeveloped and is typically covered by pine forest.

Since only a small portion of the bedrock is well exposed, the airborne and ground geophysical measurements, in addition to the boreholes, have been essential in the geological investigations. This has been especially so for the interpretation of different varieties of rapakivi types and for the fracture zones on the site and offshore. The VLJ repository, which was constructed quite recently beneath the island provides a significant source of geological information, especially for characterising conditions in the uppermost 100 - 200 m.

The Hästholmen area is located within the anorogenic Wiborg rapakivi granite batholith, about 1 630 million years in age, representing one of the youngest rock formations in Finland. The bedrock of Hästholmen, is younger than at the other investigation sites, and resembles, both petrologically and texturally, the Kivetty site, where massive granitoid rocks also dominate. Rapakivi granites are present as many varieties, the most common being wiborgite, pyterlite, porphyritic rapakivi granite and even-grained rapakivi granite. However, the differences between the different rapakivi types are quite small with respect to their significance for radioactive waste disposal. Wiborgite and pyterlite are clearly the dominant rock types and even-grained rapakivi granite occurs as a gently-dipping horizon within the wiborgite/pyterlite under the island of Hästholmen.

Due to the weaker magnetisation of the even-grained rapakivi granite compared with that of the wiborgite/pyterlite, magnetic interpretations, combined with borehole and outcrop

observations, have resulted in a better knowledge of the distribution of these rock types. The mode of occurrence of the different rapakivi granite varieties in boreholes and the compositional variations within the granites, which have been interpreted as a magmatic flow structure or a magmatic bedding, provide evidence for a lamellar internal structure, dipping gently eastwards, for the rapakivi granite at Hästholmen.

Due to the anorogenic origin of the rapakivi batholith the deformation history of the rapakivi granites is much simpler than at the other study sites, the rocks of which have undergone polyphase plastic and/or brittle deformation histories. Consequently, the resulting heterogeneity, caused by the plastic deformation, is absent at Hästholmen. This is reflected in a clear orthogonal fracture pattern, which is typical for massive granitic rocks.

The particular features of the Hästholmen site represent a typical geological environment for the large rapakivi granite formation of southeastern Finland. The rock types penetrated at depth in boreholes are the same as those that appear in outcrops, and there is no evidence of other geological formations or ore deposits in the area. The site is thus free from any geological resources that might have economical value, either today or in the foreseeable future. As well, the bedrock cannot be regarded as constituting any groundwater resource, although fresh groundwater exists in the surface part of the bedrock. It can be concluded that no valuable natural resources are present and, in that sense, the site can be considered suitable for hosting a repository for spent nuclear fuel.

10.2 Suitability of the Site

10.2.1 Structure and Stability of the Bedrock

The regional bedrock structure of Hästholmen is characterized by a network of fracture zones reflecting the mosaic block structure typical of the Precambrian bedrock in Finland. This feature is very clear on the mainland, and is evidenced at the coast and offshore in the form of numerous islands and elongated bays and linear straits. The fracture zones are generally assumed to be steeply dipping and to continue to depths of several kilometres. In the case of Hästholmen, many of these zones, therefore, probably intersect the whole rapakivi batholith, the thickness of which is estimated to be some 10 km. Two orientations of fracture zones are present over the whole of the rapakivi granite. NW-SE trending fracture zones dominate the Hästholmen area, and the other main structural trend is NE-SW, but these fracture zones are much shorter and less continuous. The island of Hästholmen is a part of a rhomb-shaped bedrock block bordered by NW-SE and NE-SW trending fracture zones, as can be seen in Figure 2.1-2. The site investigations concentrated on determining the extent and geometry of bedrock structures on the island, as well as on the mainland and in the adjacent area offshore.

Altogether 25 bedrock fracture zones (termed *structures* in the report) have been modelled at the site, as described in Section 5. The regional structural trends of NW-SE and NE-SW are repeated at the site scale and the majority of the structures with these regional trends have steep dips ($> 60^\circ$). Although steeply-dipping structures outcrop in the area, seven gently-dipping ($< 30^\circ$) structures have been modelled at greater depths, the majority dipping to the

north-northeast or southwest. These gently-dipping structures can be regarded as the most characteristic structural feature in the bedrock of Hästholmen. The intensity of fracturing and the degree of weathering and alteration vary within fracture zones.

The rock mass between the fracture zones (*structures*) represents *intact rock*, as it is termed in this report. The intact rock is typically hard and unweathered, with a low fracture frequency, which in outcrop is typically <1 fracture/m and in borehole cores 1 - 3 fractures/m. Occasionally the intact rock includes minor fracture zones which were not included within any particular structure. In only 5.7% of the total length of the core samples (some 4.2 km) was the fracture frequency greater than 10 fractures/m. The majority of the fractures in the core samples are horizontal or very gently dipping and the fractures on the outcrops are nearly vertical, striking in NW-SE and NE-SW. A cubic fracture pattern is, hence, prevalent throughout the rock mass. The orientations of the outcrop-scale fractures are repeated in the orientation of the local and regional fracture zones, and even in the main structural features of the whole rapakivi granite batholith.

The structural features of the bedrock, especially with reference to the number of modelled structures and the intensity of fracturing, are quite similar to those at the other study sites. This overall structural similarity might be a reflection of a gross structural homogeneity of the Precambrian crystalline rocks in Finland.

The structure of the bedrock has been studied and modelled more accurately on the island of Hästholmen, where most of the boreholes are located, and where the proposed area for repository development lies (see Figs. 9.3-1 and 9.3-2). The suitability of the bedrock from a constructional point of view was discussed in Section 8. The general conclusion of this analysis was that there were no significant geotechnical constraints to repository construction over the depth interval considered. Most parts of the rock mass are composed of intact rock, consisting of typical hard Precambrian crystalline bedrock with favourable properties regarding constructional activities. Fracture zones which would be likely to affect the location of the repository are not too frequent in the area of interest to cause excessive problems regarding construction of the repository. The shape and size of the volume of potentially suitable rock available for repository construction indicates that a two storey repository would be required, especially if only the bedrock beneath the island were to be considered. An additional, potentially suitable volume of rock is probably available on the mainland. Although the exact locations and geometrics of the fracture zones are not known over their entire lengths their characteristics variabilities are generally well understood, especially on the island of Hästholmen, both in terms of their hydraulic properties and from a constructional point of view.

The seismicity of the area is very low, as discussed in Section 3.5, and any displacements associated with earthquakes are assumed to occur along existing fracture or fault zones. During the microseismic studies in 1984-1996 134 microearthquakes ($M_L = -1.8 - 1.3$) were observed in the Loviisa area. Based on the distribution of the epicenters, the nearest microseismically active fracture zones are located at a distance of some 3 - 5 km from Hästholmen. These zones correlate well with the NW-SE and NE-SW trending regional fracture zones. Although microseismic data are only available from Hästholmen, it seems probable that this style and magnitude of microseismic activity can also be expected at the

other sites. The level of observed seismicity of Finland is, however, not regarded as a key factor when the future stability of bedrock structures is being considered.

In contrast to the other sites, no GPS measurements have been carried out in the Hästholmen area. It seems likely that a similar, small (<1 mm/year) horizontal movement of the rock mass occurs at this site as it does at the other sites, this being typical of the whole of Finland (Chen & Kakkuri 1998). This is thought to be due to the spreading of the Mid-Atlantic ridge, causing horizontal stress in the Fennoscandian Shield. Another process of relevance at Hästholmen is postglacial uplift, the rate of which is currently about 2 mm/year. These slow bedrock movements, like the microseismic activity, are not likely to have much significance regarding constructional and operational safety of a repository. Their influence will, however, need to be considered in terms of their possible effects on its long term post-closure behaviour.

As far as the structure and stability of the bedrock are concerned, the Hästholmen site can be regarded as being suitable for repository development. The volume of potentially suitable rock for hosting the repository does not include any regional major fracture zones, and the local bedrock structures are not too frequent to prevent from being located entirely within the intact rock. The Hästholmen site lies in a region of low seismic and tectonic activity, and no anomalous uplift or subsidence is expected before the onset of the next glaciation. There are no indications of phenomena that might modify the hydrogeological or the mechanical stability of the rock mass over the long term in a manner that might be deleterious for repository safety.

10.2.2 Hydrogeology

The hydrogeological conditions at the Hästholmen site have been studied by using the flowmeter, by carrying out double-packer injection tests and by monitoring the hydraulic head in the shallow boreholes. The hydrogeological information has been used as input data to groundwater flow modelling and for evaluating the constructability of the rock mass.

The results clearly indicate that the hydraulic properties of the uppermost 100 - 200 m of the bedrock are distinct from those at greater depth, i.e. hydraulically conductive fractures are more frequent and several zones with very high transmissivities exist in this near-surface zone. It is also evident that there is a clear decrease with depth in the hydraulic conductivity of the intact rock especially at greater depths. A parallel decrease in the transmissivity of R-structures with depth is possible but less certain. The R-structures are generally hydraulically more conductive than the intact rock, even in situations in which some poorly conductive R-structures are present and where several very conductive fractures and minor fracture zones exist outside known structures, i.e. in the intact rock. The mean transmissivity of the R-structures is either $8 \cdot 10^{-6}$ m²/s or $1.3 \cdot 10^{-6}$ m²/s, depending on how R-structures are defined. The corresponding mean of the hydraulic conductivity for the intact rock measured over 2 m borehole lengths is $1 \cdot 10^{-12}$ m/s, assuming that a lognormal distribution for all measured values is valid.

The variability of measured transmissivities within an R-structure is sometimes very large. This spatial variability may be real and may provide a true picture of the structure but, in some cases, this variability may be an artefact. This could be the case if there were errors in the interpretation of the location of the structures, with the possibility of the measured transmissivities being related to different structures.

It would appear that it is the presence of sub-horizontal fracture zones that determines the hydraulic behaviour of the investigated volume of bedrock. In particular, the fracture zone at around 100 m depth seems to be generally very conductive, both in boreholes drilled on the island and on the mainland.

Saline groundwater and the presence of the open VLJ repository have caused some problems in investigating the hydraulic properties of the bedrock. Upward movement of the saline groundwater from lower parts of the borehole, caused by pumping, has been the reason for the difficulties encountered in carrying out flowmeter tests. The majority of the problems associated with hydraulic testing have been solved by using hydraulic hoses filled with fresh water. Pumping of leaking water from the open VLJ repository has somewhat lowered the groundwater level and has caused high flows along some boreholes.

10.2.3 Hydrogeochemistry

Evolution trends

The geochemical interpretation of groundwater at Hästholmen (Snellman et al. 1998, Luukkonen et al. 1999) has revealed that the hydrogeochemical evolution is characterised by considerable mixing of different end-member water types and water-rock interaction. Groundwater end-members at Olkiluoto and Hästholmen range from modern (fresh meteoric water, sea water from the Gulf of Bothnia/Gulf of Finland) to relic (Litorina Sea, Eemian Sea (Hästholmen), glacial meltwater), and brine end-member intruded or formed under the influence of hydrothermal activity (pre-glacial, probably Phanerozoic to Precambrian in age).

Under current conditions, similar processes are seen in the evolution of groundwater types at Hästholmen compared with those at sites with only fresh groundwater, i.e. Romuvaara and Kivetty. The major reactions are related to the oxidation of organics with contemporaneous CO_2 production, and subsequent dissolution of calcite at shallow depths and/or in dynamic flow systems, as indicated by, for example, variations in $\delta^{13}\text{C}(\text{DIC})$. At greater depths, where less dynamic flow conditions are present, the precipitation of calcite with possibly silicate hydrolysis promotes pH to stabilize between values of 7.0 - 8.0.

Aerobic processes such as respiration of organic carbon, weathering of silicates and oxidation of ferrous minerals dominate during modern recharge at Hästholmen. Coupled oxidation and hydrolysis of biotite seem important according to Sr isotopic data. Dissolution of fracture calcites increases alkalinity, pH and $\delta^{13}\text{C}$, and decreases partial pressure of CO_2 in groundwater. The strong enrichment of sulphate suggests mainly a sea water origin with some reduction of SO_4 as based on the $\delta^{34}\text{S}(\text{SO}_4)$ signature. Below the recharge zone,

chemical interaction is considered to be related to a combination of calcite dissolution or precipitation, ion-exchange processes and fluorite dissolution, as well as clay mineral transformations and redox processes. The most important processes are related to carbonate and redox chemistry. Cation-exchange is an important process in an aquifer which has been exposed to sequential meteoric, sea water and saline water flushes (e.g. Nordstrom 1986, Appelo & Postma 1994).

The least disturbed redox measurements of the deep Hästholmen groundwater suggest the prevalence of slightly to fairly reducing conditions at depth (Eh +30...-340 mV, Snellman et al. 1998, Helenius et al. 1998, Luukkonen et al. 1999). According to the present results, the redox conditions at depth at Hästholmen seem to be controlled by the Fe^{2+} /goethite and $\text{S}^{2-}_{\text{tot}}/\text{SO}_4$ /pyrite equilibrium. The observations are in accordance with the frequent observations of iron hydroxide on the fracture surfaces and occurrence of IRB. The possible lack of dissolved organic matter, which can be used by SRB, probably limits any strong sulphate reduction although $\delta^{34}\text{S}(\text{SO}_4)$ data for brackish and saline water indicate that a significant sulphate reduction has occurred. Measured values correspond better with the sulphur system according to the thermodynamic calculations. Calculated Eh values is of a level -200 ± 50 mV (Luukkonen et al. 1999).

Salinity variations are large at Hästholmen. Chloride content and TDS increase strongly with depth. The mixing of the different end-member water types seems to control the remarkable salinity variation observed in groundwater sample compositions. They have been affected strongly by external processes connected to palaeoenvironment during the Quaternary and likely even earlier in the case of the brine end-member. The significance of water-rock interaction in the mass transfer of solutes at low temperature conditions is likely limited to shallow depths in the bedrock as reported for Olkiluoto (Pitkänen et al. 1994).

At depths of less than 100 m a meteoric groundwater type occurs, which is characterised by dilute HCO_3 -rich infiltration, with isotopic signatures indicating relatively young residence time such as generally measurable tritium, moderate ^{14}C and a modern stable isotope. This groundwater type has been recharged since Hästholmen island rose above sea level, but tritium results indicate modern recharge demonstrating that the upper part of bedrock, which is characterised by HCO_3 -rich groundwater is hydraulically dynamic.

The brackish SO_4 -rich groundwater below the HCO_3 -rich groundwater at 100 - 400 m depth was most probably recharged during the Litorina Sea stage (Nordström 1986, Snellman et al. 1998, Luukkonen et al. 1999), when the island was still beneath the sea. The SO_4 -rich Na-Cl groundwater shows a large scatter in the TDS values, resulting from mixing of different bodies of groundwaters. The sea water origin of the groundwater is shown by Br/Cl ratios, which are typical to sea water, lower pH and alkalinity and much higher SO_4 and Mg than in the HCO_3 -rich groundwater. A higher Cl content than in modern Baltic sea water (about 2 800 mg/l off the Hästholmen island) connects the brackish water to the Litorina Sea, particularly the early stage, which was the most saline, about 6 500 mg/l according to Kankainen (1986). The $^{14}\text{C}(\text{DIC})$ values correspond to the Litorina Sea stage ages.

During the retreat of the ice sheet diluted glacial meltwater infiltrated into the rock mass and mixed with pre/subglacial groundwater at shallow depth in the bedrock. This is seen in the

transition zone from brackish to saline groundwater (at 400 - 600 m depth) where the lower parts of the brackish groundwater seem to have a 20% input from glacial meltwater. The effect of this input of glacial meltwater is observed as a groundwater type with a lighter stable isotopic content compared with the overlying Litorina stage groundwater or with modern recharge values. There is a slight decrease in salinity, and radiocarbon indicates deglacial - subglacial ages in relation to the Litorina-derived groundwater. No indications of dissolved oxygen gas intrusion with glacial meltwater recharge to great depths have been observed, either from fracture mineralogy or from current groundwater chemistry. Iron oxyhydroxide (rust) observations are limited to the upper 200 m at Hästholmen, Kivetty and Romuvaara and only one observation at 30 m depth at Olkiluoto.

Groundwater becomes saline at 500 - 600 m depth. The saline groundwater shows some similar chemical characteristics to those of the brine-derived saline groundwater type (Ca-Na-Cl) at Olkiluoto (Pitkänen et al. 1999). The stable isotope content, elevated Ca/Cl, Ca/Mg and Br/Cl indicate considerable water-rock interaction at elevated temperatures. At Olkiluoto different chemical signatures from calcites, fluid inclusions and isotopic signatures in saline groundwater suggest an extremely old origin for the original brine end-member(s), which is most probably early Phanerozoic or Precambrian in age (Pitkänen et al. 1999). At Hästholmen the high SO_4 and Mg and ^{34}S signature suggest mixing of a marine component into the saline water. The low ^{14}C value excludes the Litorina Sea as a possible sea water source. The high salinity of this sea water type could be due to the Eem interglacial 130 000 - 100 000 BP, which was the first warmer period preceding the last glacial advance. During this interglacial, the Baltic Sea was more saline and probably had a connection to the White Sea (Eronen 1990b). The fairly low stable isotope signatures of some saline waters below 500 - 600 m depth suggest some addition of a glacial meltwater component.

The evaluation of hydrogeochemistry, isotope data and mineralogy at Hästholmen have produced a general picture of the groundwaters and evolutionary processes, which have prevailed in the bedrock since the last glaciation (Snellman et al. 1998 and Luukkonen et al. 1999). Even the influence of preglacial processes has been suggested. Isotope data on groundwater is already extensive. Carbon isotope analyses of calcites, and organic matter are needed, e.g., to construct reaction models, and ^{34}S and ^{18}O analyses of sulphur species for checking the extent of actual sulphide production through water-rock interaction. The development of a model for the groundwater evolution in the area is planned in the near future.

Some important identified processes (reactions + mixing of waters) affecting the present geochemical conditions at Hästholmen with respect to hosting of a repository for spent nuclear fuel are given in Table 10.2-1. Favourable anoxic reducing conditions buffered by Fe^{2+} /goethite and $\text{S}^{2-}/\text{SO}_4$ /pyrite equilibrium prevail at depth. The sulphide concentration is expected to be controlled by iron oxyhydroxides for pyrite precipitation or by the possible lack of organic matter which can be used by SRB. Calcite precipitation and aqueous iron likely occurring as hydroxide complexes buffer pH to neutral or slightly basic pH values (7.0 - 8.0) at depth. The salinity increases strongly at depths below 500 - 600 m, the highest TDS (32 g/l) being found so far at depth below 800 m.

Table 10.2-1. Summary of important processes affecting geochemical conditions at Hästholmen.

	Processes and indicators
<u>pH</u> <i>Shallow groundwater,</i> 5.5-7.3 <i>Deep groundwater,</i> Brackish 7-8.5 Saline 7.0-8.0, decreasing with salinity	Organic respiration, Calcite dissolution $\log p\text{CO}_2 \approx -3.0..-2.0$ Calcite precipitation, silicate and Fe hydrolysis, $\log p\text{CO}_2 \approx -3.5..-3.0$ decreasing with salinity $\log p\text{CO}_2 \approx -4.0..-3.0$
<u>Eh</u> <i>Shallow groundwater,</i> Postoxic <i>Deep groundwater,</i> <- 200 mV Sulphidic, already at depths below 50-100 m	Organic respiration Oxidative weathering of Fe and S bearing minerals, mainly biotite, possibly also pyrite Redox controlled by Fe^{2+}/goethite and $\text{S}^{2-}_{\text{tot}}$/$\text{SO}_4$/pyrite equilibrium. The observations are in accordance with the frequent observations of iron hydroxide on the fracture surfaces and occurrence of IRB. The possible lack of dissolved organic matter, which can be used by SRB, probably limits any strong sulphate reduction, although some microbial sulphate reduction is suggested, based on the observation of $\delta^{34}\text{S}(\text{SO}_4)$, and the occurrence of pyrite coatings on fractures. With depth especially in saline groundwater; CH_4, H_2, Fe, Mn increase and SO_4 decrease
<u>Alkalinity</u> <i>Shallow groundwater,</i> < 3.0 meq/l max. 3.8 meq/l, at depth 20-50 m (dilute brackish gw) <i>Deep groundwater,</i> Brackish, < 2 meq/l Saline, 0.3-0.5 meq/l	Organic respiration, calcite dissolution Calcite precipitation already at very shallow depth. Silicate hydrolysis, Anaerobic organic respiration. Silicate hydrolysis Strong decrease in alkalinity
<u>Salinity</u> <i>Shallow groundwater,</i> <i>Deep groundwater</i> TDS max. 32 g/l Cl max. 19.5 g/l	Precipitation, weathering (acidity promoted hydrolysis) Mixing of recent and relic sea water. Mixing of brine intruded and/or formed under the influence of hydrothermal activity (pre-glacial or Precambrian). Mixing of relic (Eemian) sea water.
Chemistry vs. flow	In the upper part of the bedrock major fractures (R1-R3) strongly influences the water chemistry, e.g. the fresh-brackish interface follows the zone R1 (e.g. Nordstrom 1986).
Rock-specific features	High $^{87}\text{Sr}/^{86}\text{Sr}$ correlated to Rb-rich minerals, e.g. biotite in shallow bedrock. U-rich rock reflected in elevated U-content in groundwater and occurrence of He in dissolved gases.
Origin of water types, residence time & signs of oxygen	$\delta^{18}\text{O}$, SO_4, Br/Cl, Cl variations ->mixing of glacial meltwater, sea water (modern and relic), and brine in the meteoric water. Iron oxyhydroxides (rust) observation generally to depths above 200 m.

Importance for corrosion, buffer, solubility and transport

The anoxic reducing conditions at depth at Hästholmen are expected to be favourable in limiting *the corrosion rate of canisters*. In oxygen-free water, dissolved sulphide is the most corrosive agent for the Cu canister, and the most important corrosion products are cuprous sulphides Cu_{2-x}S , corresponding to the mineral phases, chalcocite, anilite and djurleite (Ahonen 1995). Also cupric sulphides, such as covellite, are likely admixtures. The high Cl content of the groundwater is not expected to cause any risk of corrosion of the Cu canister, based on the thermodynamic evaluation by Ahonen (1995). According to recent thermodynamic calculations by Beverskog & Puigdomenech (1998), however, Cu canisters could corrode in saline water with $\text{Cl} \approx 53 \text{ g/l}$ (Hästholmen; $\text{Cl}_{\text{max}} 19.5 \text{ g/l}$), at high temperature 80 - 100 °C. However, such a high temperature will prevail for less than 100 years at the surface of the canister (Raiko 1996). The role of elevated level of ammonium for possible stress corrosion of copper (max. 3 mg/l NH_4) although at present found at shallow depth (100 - 200 m) is an aspect which has to be further evaluated.

The stability of the *bentonite buffer* at Hästholmen as at Olkiluoto, may be effected by the saline groundwater by reducing the swelling capacity and increasing the hydraulic conductivity of compacted bentonite. According to the recent experimental and modelling studies by Karnland (1998) the desired swelling pressure ($\approx 5 \text{ MPa}$) is obtained even in a very saline solution (6.1 M NaCl) if the density of compacted bentonite is sufficiently high (2000 kg/m^3 at saturation). Also the theoretical difference in the effect between saline CaCl_2 and NaCl solutions was found to be small in this study. Ion exchange with clay minerals is expected to occur in the long-term in the rock-groundwater system whereby Ca, Mg and K is exchanged for Na, and this is supposed to be the case also for Na-montmorillonite. The Ca-rich saline groundwater is expected to have the strongest impact (Muurinen et al. 1996). According to the theoretical evaluations performed (e.g. Wanner et al. 1992, Wieland et al. 1994) it is, however, expected that the bentonite buffer will maintain its low permeability for hundreds of thousands of years even at Hästholmen and Olkiluoto (Crawford & Wilmot 1998).

The most important groundwater parameters that affect *radionuclide solubility* are pH, the carbonate content and Eh, with salinity also being important for certain elements. Temperature has a strong effect on pH and hence on the solubilities of elements that can be hydrolysed. The temperature at depth is somewhat higher at Hästholmen and Kivetty compared to Romuvaara and Olkiluoto, apparently due to the more radiogenic bedrock (elevated levels of U, He, K, Rn, Ra and Th) of Hästholmen (rapakivi granite) and Kivetty (granite/granodiorite). However, the difference (7°C to 12°C at 500 m depth) is not so large as to affect the solubilities. The temperature in the near-field of the spent fuel repository will rise to a maximum of about 100°C within a few decades and will then gradually decrease towards the ambient temperature of about 15°C within a few thousand years (Raiko 1996). The probability of the corrosion-resistant canister allowing any release of radionuclides during this thermal phase is, however, very low. In addition to carbonates, strong complexing agents in the groundwater such as hydroxide, chloride, sulphate, sulphide and phosphate may be of importance if their concentrations become high enough. At Hästholmen, the content of these ligands is variable, and high SO_4 and high or low carbonate waters as well as high chloride waters are found.

In natural groundwater systems one of the most important factors defining the pH level is the amount of dissolved CO_2 . The dissolved carbonate contents at the four sites range from less than 0.1 meq/l to 7 meq/l, the lowest values are exhibited in the most saline groundwater at Olkiluoto and Hästholmen, and the highest values are observed in the brackish HCO_3^- -rich groundwaters at shallow depths at Olkiluoto (Pitkänen et al. 1999). The pH values of groundwater at the sites range generally from about 7 to 9, apart from certain locations at Romuvaara, where the variation is from 7 to 10, reflecting the influence of more variable mineralogy, the high pH values being found in boreholes which intersect metadiabase dykes.

The effect of the salinity of the groundwater (fresh, brackish, saline) on solubilities is element specific and rather depend on the composition of the solution; pH, redox condition, amounts of important complexing ligands and other element species being the important factors. The largest changes may occur in complexation reactions as compared with non-saline groundwaters. For example the characteristically low carbonate content of the Finnish saline groundwaters is an important factor in the carbonate-dependent element solubilities (e.g. U, Pu, Np, Am) (Vuorinen et al. 1998). The high sulphate in the brackish water may effect the solubility of elements such as Ra, which form both complexes and solids with sulphate. The solubility of Ra is lowest in groundwaters having a high sulphate content, e.g. the Litorina Sea water type at Hästholmen and Olkiluoto (Vuorinen et al. 1998).

Many organic ligands are known to have strong complexing affinity, but at present specific knowledge of the amount and the nature of organic complexing agents present in the groundwaters at these sites are scarce. Organic ligands, such as humic and fulvic acids, have not been discussed or considered in this report. Data on such species are available only from Olkiluoto at a depth of 613 - 618 m in the saline groundwater, indicating relatively low concentration (0.01- 0.02 mg/l) of humic acids (Laaksoharju et al. 1994).

Reducing conditions, favourable for low radionuclide solubility and slow canister corrosion, are expected to exist at depth at all sites. The main redox reactions at depth in groundwater are related to anaerobic oxidation of organics, in parallel with microbially catalysed SO_4 reduction, according to evidence from enriched $\delta^{34}\text{S}(\text{SO}_4)$, dissolved sulphides, observations of SRB (Haveman et al. 1998) and pyrite precipitates on calcite fillings (e.g. Pitkänen et al. 1994, 1996a, b 1998, 1999). At Hästholmen the Fe^{2+} /goethite pair is also considered important (Snellman et al. 1998, Luukkonen et al. 1999). Depending on the pH, the redox level is generally expected to be buffered below -200 to -300 mV at all sites, also at Hästholmen.

The *sorption properties* of the rock types at the sites can be estimated on the basis of their cation exchange capacities (CEC), the amount of Fe oxides, their degree of alteration and their porosity, which are related to the mineral composition and microstructure of the rock (Huitti et al. 1996). The CEC's of the rocks are generally fairly similar for all sites, although mica gneiss, especially that at Olkiluoto, seems to have the good sorption properties for elements such as Cs, which is sorbed by ion exchange. The CEC of the altered rapakivi granite (Hästholmen) is reported to be slightly higher than that of the tonalites (Romuvaara) and only slightly lower than that of mica gneiss in Olkiluoto (Huitti et al. 1996). The overall sorption properties of the rapakivi granite at Hästholmen is reported to be similar to the

Kivetty granite (Huitti et al. 1996). The rapakivi granite and some parts of the granites at Kivetty contain hematite, which is an efficient sorbent, especially for transition elements and certain actinides.

In addition to sorption properties the minerals possess reduction capacity, which could be expressed from their Fe^{2+} content. The mica gneisses and granodiorites in Olkiluoto contain more of these (biotite, chlorite, hornblende) than do granitic rock types. However, at Hästholmen the chlorite content of unaltered rapakivi is higher than generally in granite and increases with alteration degree of the rock (altered, weathered rapakivi). Of the rocks studied the Olkiluoto mica gneiss has the highest chlorite content, whereas biotite is very common both at Romuvaara and Kivetty.

However, the differences attributed to the groundwater composition, such as redox conditions (reducing vs. oxidising) and salinity of groundwater (fresh vs. saline) is considered to be of greater importance for sorption than the differences attributed to the rock type (Hakanen & Hölttä 1992). The low ionic strength of groundwater (TDS max. 265 mg/l) is expected to be favourable for sorption both at Kivetty as well as at Romuvaara. The brackish and saline groundwater types at Hästholmen and Olkiluoto (TDS max. 69 g/l) are expected to be less favourable for elements sorbed by ion exchange, e.g. alkaline- and earth-alkaline elements Cs, Ra and Sr, as compared to fresh groundwater.

Colloidal forms of radionuclides may significantly affect their rate of transport in groundwater, if the sorption of radionuclides on colloids is irreversible. However, bentonite in the near-field is expected to act as a filter for possible colloidal forms. Furthermore, the available data on inorganic colloids (less than ≈ 360 ppb) and humic acids (≈ 10 ppb) in Finnish groundwater (Laaksoharju et al. 1994) as well as the data on the properties of Swedish groundwater colloids (Laaksoharju et al. 1995) indicate low concentrations.

The hydrogeochemical characteristics of the Hästholmen site show that the conditions are generally favourable for slow copper corrosion rate, low solubility and slow transport of radionuclides, i.e. anoxic reducing conditions, pH in neutral or slightly basic range, and low sulphide content. However, the possible role of increasing salinity at depths below 500-600 m on the stability of the buffer and transport of radionuclides need to be evaluated further. Also the possible role of the elevated ammonium content in the upper part of the bedrock need to be addressed.

10.2.4 Construction

The bedrock of Hästholmen has been characterised and classified in order to assess the suitability of the rock mass for locating and constructing the repository, as described in Section 8.1. The expected range of disposal depths is from 400 m to 700 m. Estimates regarding a suitable range of depths for the repository are mainly influenced by the hydrogeological properties (minimum depth) and the strength and in situ stress of the rock (maximum depth). The positioning of the repository within the rock mass is determined primarily by the location and geometry of the major fracture zones. From a rock engineering point of view, the constructability is affected by the lithology and the fracturing of the

bedrock, and its engineering properties by the magnitude and orientation of the in situ stress, as well as by the hydrogeological and hydrogeochemical environments. It is important to consider the prevailing groundwater conditions, i.e. the hydrogeology and hydrogeochemistry, when assessing the need for sealing fractures prior to rock excavation, and in the choice of constructional materials to be used.

The constructability of the bedrock at Hästholmen has been estimated to depend mainly on the depth, the lithology and the groundwater chemistry and on whether construction takes place in intact rock or in fracture zones. Any differences in the properties of intact rock between different rapakivi varieties have been found to be small. Estimates concerning the suitable range of depths for a repository are mainly influenced by the strength of the rock and the in situ stress field.

The main conclusion from the classification is that there seems to be no significant constraints to the construction of a repository within the depth range of 400 to 700 m. The major part of the intact rock volume has been estimated as “normal” from the point of view of its constructability. This means, in practice, that repository excavation and rock support can be carried out by using conventional methods and materials, as generally applied in Finnish underground construction projects. Below a depth of 600 - 700 m the constructability is estimated as being “demanding” or “very demanding” mainly due to the higher stress field (Sig-H about 40 - 45 MPa at 700 m). The classes demanding and very demanding mean that special methods and materials are required when excavating and supporting the underground openings, which in turn, is likely to result in additional time and increased costs for the construction work. In addition, at Hästholmen, the salinity of the groundwater will result in the need for more expensive materials for some construction elements and more extensive maintenance during the construction and operational phase.

Although all the fracture zones encountered at the site could be excavated and supported in an appropriate manner, it is proposed to avoid certain structures when locating the deposition tunnels and disposal holes. Structures, R1, R3, R7, R9, R18, R19, R20 and R21 (see Figs. 8.2-2 and 9.3-3), which are classified as demanding or very demanding, are expected to prove difficult to seal against the ingress of groundwater and may also require extensive support.

There are still considerable uncertainties concerning the exact locations, dimensions and properties of the bedrock structures. The core discing phenomena observed in the rock samples is not expected to indicate any major stability problems, but further studies are required to clarify the geotechnical significance of this particular feature. The repository layout developed this far should be considered as being only illustrative in nature. Figures 9.3-1 and 9.3.2 indicate the area needed for the construction of deposition tunnels for 1 400 canisters (2 600 tU). The layout is based on a proposal to locate the disposal tunnels at two different levels, at 500 m and 600 m depth. The details of the repository layout and the locations of the deposition holes will, in reality, be determined in an observational method process, in which the repository concept will be adjusted to the in situ conditions.

11 CONCLUDING REMARKS

A detailed characterisation of the Hästholmen island and the adjacent area for the deep disposal of spent fuel has been taking place since 1997. A thorough characterisation of the bedrock to shallower depth, associated with the development of the underground VLJ repository for the disposal of low-and intermediate-level operating wastes, has been carried out already earlier. The area has been investigated from the air, from the surface and with the help of deep boreholes. The results from the underground characterisation of the VLJ repository have also been taken into account. The investigations have demonstrated that Hästholmen, like the other study areas, can be considered to consist of a large bedrock block, the definition of such a block, however, being a matter of definition. The characterisation programme, thanks to the sophisticated methods used, has been able to identify 25 features which can be regarded as structural (or fracture) zones. In the course of this programme it has become apparent that the detection of such zones is a matter not only of the resolution of the investigation techniques applied, but also of the methods that have been used to provide a classification of the rock mass. The bedrock lying between these zones, termed intact rock, is considered to be of sufficiently good quality to satisfy the requirements of long-term safety and for locating and constructing a deep repository.

The main structural properties and the variation in the hydraulic parameters of the bedrock at Hästholmen are similar to those found at the other three study sites of Kivetty, Olkiluoto and Romuvaara, as well as those found earlier at Syyry and Veitsivaara. Evidence from studies on comparable rock types in Sweden also gives rather similar results (e.g. Saksa & Nummela 1998). This overall similarity may reflect a general consistency in the properties prevailing in the Fennoscandian Shield, and thus the Hästholmen site could be considered to represent a typical geological environment. In addition, Hästholmen has no potentially valuable natural resources.

According to published recommendations for siting a deep repository (e.g. IAEA 1994), the site should be located within an tectonically stable area. Studies of the seismicity and neotectonics of Finland demonstrate that the Fennoscandian Shield is very stable. The recommendations also emphasise the necessity of selecting a site that is amenable to investigation. The detailed characterisation programme at Hästholmen has evolved in a step-wise fashion, although within a short period of time, and the conceptual models of the site have not changed markedly as the programme has proceeded, suggesting that the site is suitable in this regard. An important factor affecting the ease of investigation is that the rock is very homogeneous and similar, both in the outcrops and at depth, which makes for the easier development of geological models. The most striking structural feature of the bedrock is that the gently dipping fracture zones, which had been detected in the earlier investigations for the VLJ repository, are now proved to be present at greater depths.

The number of boreholes drilled from the surface in any repository investigation programme has to be limited so that the containment properties of the rock mass are not jeopardised. There are, therefore, uncertainties associated with the exact geometry, location and properties of the fracture zones and the extent of volumes of intact rock. As a consequence of these uncertainties, it has not been possible to develop detailed repository designs at this stage, however, volumes of bedrock which are considered to be potentially suitable for

suitable for hosting a repository can be defined. An evaluation of the constructability of the rock mass has demonstrated that a repository could be constructed at the site, although with some restrictions. Factors such as this will have to be taken into account in designing the detailed characterisation programme which is planned in conjunction with the construction of the underground investigation facility.

In addition to the tectonic and rock mechanical characteristics of the bedrock, its hydrogeological properties and the hydrogeochemical environment are considered to be important in terms of their impact on the long-term safety of the disposal system. Based on the information obtained from the borehole studies there seems to be fairly good consistency between the structure of the bedrock and its hydrogeological properties. The hydrogeochemical environment of the island of Hästholmen is influenced by its coastal location and by the continuing land uplift. The salinity of the groundwater increases with the depth, which is typical of coastal areas, and the present maximum salinity (TDS) is 32 g/l below 800 m depth. There are, however, thought to be no adverse impacts on long-term safety if the salinity at the disposal depth remains below 100 g/l. In addition, with the expected continuing uplift, the highly saline groundwater will move to greater depths. It is believed that the hydrogeological and hydrogeochemical conditions at depth will ensure low radionuclide solubility, slow canister corrosion and the slow transport of radionuclides. The presence of highly saline groundwater at depth may, however, limit the maximum possible depth of the repository. The significance of this higher salinity needs to be considered during the further characterisation and evaluation of Hästholmen.

The evaluation of the available data suggests that the Hästholmen site has the potential to host a repository and provide the conditions for safe, long-term disposal based on the current reference disposal concept. The development of a repository at the site would, however, require additional investigations, preferably underground, to evaluate the importance of the uncertainties regarding the structural zones and to examine the impact of future natural evolution on the properties of the site in greater detail.

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SITE INVESTIGATIONS AT HÄSTHOLMEN
GROUND AND AIRBORNE SURVEYS
STUDIES IN BOREHOLES OTHER THAN KR1...KR8

APPENDIX 1
1(2)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
DRILLINGS	DET	Drilling of EP1, EP2, PVP1, PVP2, L1...L34	EP-boreholes for installation of piezometers, PVP-boreholes for water sampling from the overburden, L-boreholes for VSP shotholes	
GEOLOGICAL MAPPINGS AND SAMPLINGS	Feasibility study	Geological generic study	Preliminary geological evaluation of the Loviisa region	96-02 96-04 ***)
	DET	Evaluation of mineralization potential	Mapping of greisen veins at Hästholmen and evaluation of the potential for economic mineralization	97-39
GEOPHYSICS	DET	Seismic HSP measurement	Survey of fracture zones and lithological contacts in coastal area of the Hästholmen island	98-27e
	DET	Ground radar survey	Mapping of soil types and fracture zones	97-37
	DET	Electromagnetic soundings	Location and characterization of the saline groundwater and fracture zones	97-38 98-13
	DET	Airborne survey	Mapping of rock types and structures of bedrock at the site	97-42 98-24
	DET	Seismic reflection survey	Determination of position and continuity of horizontal or subhorizontal fracture zones	99-27
	DET	Borehole TV-monitoring, EP1, EP2 and Y8	Determination of fractured zones and packer positions for hydraulic head monitoring	98-04
	DET	Borehole TV-measurements Y8	Interprete and analyse orientation and other properties of various geological features i.e fractures, veins, contacts and foliation	99-32
		Hydrological measurements	Monitoring of gw-table and hydraulic heads in wells, open boreholes and packed-off sections, determination of precipitation of the investigation area	****)
HYDROLOGICAL MEASUREMENTS	DET	Constant head injection test in EP1 and EP2	Determination of hydraulic properties of bedrock	98-58
	DET	Flowmeter / difference flow measurements in Y8	Localization of hydraulically conductive fractures and determination of their hydraulic properties, determination of natural gw-flow along fractures	98-28e
	DET	Installation of multi-packer system, EP1, EP2 and Y8	Monitoring hydraulic head fluctuation at shallow depths	99-28

SITE INVESTIGATIONS AT HÄSTHOLMEN
GROUND AND AIRBORNE SURVEYS
STUDIES IN BOREHOLES OTHER THAN KR1...KR8

APPENDIX 1
2(2)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
GROUNDWATER CHEMISTRY	Feasibili- ty study	Study of the groundwater conditions	Determination of the feasibility of the groundwater conditions at Hästholmen for the final disposal site of spent fuel	96-03 ***) *****)
	DET	Groundwater sampling from shallow boreholes, L10, PR1, PVP1 and PVP2	Hydrogeochemical characterization in the seepage zone and geochemical modelling	98-02
LABORATORY TESTS	DET	Petrographic and lithogeochemical studies, boreholes Y1...Y24, YT1, YT3, YT7, PVA1...PVA5	Determination of rock types and geochemical properties to complement earlier studies	97-36
	DET	Fracture mineral mapping/ study, boreholes Y1...Y24, YT1, YT3, YT7, PVA1... PVA5	Determination of low temperature fracture minerals for examination of qualitative properties	97-36
OTHER MEASUREMENTS	DET	Bird study	Primary study for environmental impact assesment	97-44
	DET	Ecological survey	Primary study for environmental impact assesment	97-64

*) DET = Detailed investigations

**) Ref. = reference to the work report

***) LOVIISA- report series

*****) Will be reported later

*****) See also work report 98-44 (Summary of recent observations from Hästholmen groundwater studies)

SITE INVESTIGATIONS AT HÄSTHOLMEN
BOREHOLE KR1

APPENDIX 2
1(2)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
DRILLING	DET	Core drilling (1002 m)	Determination of rock types, fracturing and bedrock structures (R9) in the northern part of Hästholmen , facilitate geochemical and hydrogeological studies deep in the bedrock	97-10
GEOPHYSICS	DET	Standard methods: Fluid resistivity, temperature, normal resistivity (1.6 m and 0.4 m), single point resistance, natural gamma, gamma-gamma density, neutron-neutron, self potential, caliper, P-wave velocity, susceptibility	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	97-28 98-29
	DET	Dipmeter	Localization, orientation and statistical analysis of fractures and fracture zones in the borehole.	97-60e
	DET	Borehole-TV measurements	Interprete and analyse orientation and other properties of various geological features i.e fractures, veins, contacts and foliation	98-19e
	DET	VSP measurement	Mapping of fracture zones and contacts between rock types	98-26e
HYDROGEOLOGY	DET	Flowmeter / difference flow measurements	Localization of hydraulically conductive fractures and determination of hydraulic properties of them, determination of natural gw-flow along fractures	97-41e
	DET	Flowmeter / groundwater flow measurements	Determination of groundwater flow rate and flow direction	98-69
	DET	Constant head injection test	Determination of hydraulic properties of bedrock	98-52
GROUNDWATER CHEMISTRY	DET	Groundwater sampling during drilling	Local hydrogeochemical characterization and geochemical modelling	98-22
	DET	Groundwater sampling	Determination of the quality of the groundwater deep in bedrock	98-46 99-40
LABORATORY TESTS	DET	Petrographic and lithochemical studies	Determination of rock types and geochemical properties to complement earlier studies	97-40
	DET	Fracture mineral mapping/ study	Determination of low temperature fracture minerals for examination of qualitative properties	97-40
	DET	Study of thermal properties of rock	Determination of the thermal properties of the most common rock types of the investigation area	98-09e

SITE INVESTIGATIONS AT HÄSTHOLMEN
BOREHOLE KR1

APPENDIX 2
2(2)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
	DET	Mapping of core-discing	Determination of the extent of the core-discing phenomenon	99-12

*) DET = Detailed investigations,

**) Ref. = reference to the work report

SITE INVESTIGATIONS AT HÄSTHOLMEN
BOREHOLE KR2

APPENDIX 3
1(1)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
DRILLING	DET	Core drilling (1005 m)	Determination of rock types, fracturing and bedrock structures in the northern part of Hästholmen , facilitate geochemical and hydrogeological studies deep in the bedrock	97-11
GEOPHYSICS	DET	Geophysical standard borehole logging	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	97-28 98-29
	DET	Dipmeter	Localization, orientation and statistical analysis of fractures and fracture zones in the borehole.	97-60e
	DET	Borehole-TV measurements	Interprete and analyse orientation and other properties of various geological features i.e fractures, veins, contacts and foliation	98-19e
	DET	VSP measurement	Mapping of fracture zones and contacts between rock types	98-26e
HYDROGEOLOGY	DET	Flowmeter / difference flow measurements	Localization of hydraulically conductive fractures and determination of hydraulic properties of them, determination of natural gw-flow along fractures	97-41e
	DET	Flowmeter / groundwater flow measurements	Determination of groundwater flow rate and flow direction	98-69
	DET	Constant head injection test	Determination of hydraulic properties of bedrock	98-53
GROUNDWATER CHEMISTRY	DET	Groundwater sampling	Determination of the quality of the groundwater deep in bedrock	98-46
LABORATORY TESTS	DET	Petrographic and lithogeochemical studies	Determination of rock types and geochemical properties to complement earlier studies	97-40
	DET	Fracture mineral mapping/ study	Determination of low temperature fracture minerals for examination of qualitative properties	97-40
	DET	Study of thermal properties of rock	Determination of the thermal properties of the most common rock types of the investigation area	98-09e
	DET	Mapping of core-discing	Determination of the extent of the core-discing phenomenon	99-12

*) DET = Detailed investigations,
Phases are referring to the figure 2.2-3.

**) Ref. = reference to the work report

SITE INVESTIGATIONS AT HÄSTHOLMEN
BOREHOLE KR3

APPENDIX 4
1(1)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
DRILLING	DET	Core drilling (803 m)	Determination of rock types, fracturing and bedrock structures (R7) in the northern part of Hästholmen , facilitate geochemical and hydrogeological studies deep in the bedrock	97-22
GEOPHYSICS	DET	Geophysical standard borehole logging	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	97-28 98-29
	DET	Dipmeter	Localization, orientation and statistical analysis of fractures and fracture zones in the borehole.	97-60e
	DET	Borehole-TV measurements	Interprete and analyse orientation and other properties of various geological features i.e fractures, veins, contacts and foliation	98-19e
	DET	VSP measurement	Mapping of fracture zones and contacts between rock types	98-26e
HYDROGEOLOGY	DET	Flowmeter / difference flow measurements	Localization of hydraulically conductive fractures and determination of hydraulic properties of them, determination of natural gw-flow along fractures	97-41e
	DET	Flowmeter / groundwater flow measurements	Determination of groundwater flow rate and flow direction	98-69
	DET	Constant head injection test	Determination of hydraulic properties of bedrock	99-07
GROUNDWATER CHEMISTRY	DET	Groundwater sampling	Determination of the quality of the groundwater deep in bedrock	98-46
LABORATORY TESTS	DET	Petrographic and lithogeochemical studies	Determination of rock types and geochemical properties to complement earlier studies	97-40
	DET	Fracture mineral mapping/ study	Determination of low temperature fracture minerals for examination of qualitative properties	97-40
	DET	Study of thermal properties of rock	Determination of the thermal properties of the most common rock types of the investigation area	98-09e
	DET	Mapping of core-discing	Determination of the extent of the core-discing phenomenon	99-12

*) DET = Detailed investigations,
Phases are referring to the figure 2.2-1.

**) Ref. = reference to the work report

SITE INVESTIGATIONS AT HÄSTHOLMEN
BOREHOLE KR4

APPENDIX 5
1(1)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
DRILLING	DET	Core drilling (1000 m)	Determination of rock types, fracturing and bedrock structures (R1-R4, R16, R17) in the southern part of Hästholmen, facilitate geochemical and hydrogeological studies deep in the bedrock	97-52
GEOPHYSICS	DET	Geophysical standard borehole logging	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	98-10 98-29
	DET	Dipmeter	Localization, orientation and statistical analysis of fractures and fracture zones in the borehole.	98-67
	DET	Borehole-TV measurements	Interprete and analyse orientation and other properties of various geological features i.e fractures, veins, contacts and foliation	99-32
	DET	VSP measurement	Mapping of fracture zones and contacts between rock types	99-05
HYDROGEOLOGY	DET	Flowmeter / difference flow measurements	Localization of hydraulically conductive fractures and determination of hydraulic properties of them, determination of natural gw-flow along fractures	98-28e
	DET	Flowmeter / groundwater flow measurements	Determination of groundwater flow rate and flow direction	98-69e
	DET	Constant head injection test	Determination of hydraulic properties of bedrock	99-42
GROUNDWATER CHEMISTRY	DET	Groundwater sampling	Determination of the quality of the groundwater deep in bedrock	99-40
OTHER MEASUREMENTS	DET	Rock stress measurements with hydraulic fracturing	General direction and magnitude of stress field in bedrock	***)
LABORATORY TESTS	DET	Petrographic and lithogeochemical studies	Determination of rock types and geochemical properties to complement earlier studies	98-30
	DET	Fracture mineral mapping/ study	Determination of low temperature fracture minerals for examination of qualitative properties	98-30
	DET	Mapping of core-discing	Determination of the extent of the core-discing phenomenon	99-12

*) DET = Detailed investigations,
Phases are referring to the figure 2.2-1.

**) Ref. = reference to the work report

***) Will be reported later

SITE INVESTIGATIONS AT HÄSTHOLMEN
BOREHOLE KR5

APPENDIX 6

1(1)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
DRILLING	DET	Core drilling (1001 m)	Determination of rock types, fracturing and bedrock structures in the mainland, facilitate geochemical and hydrogeological studies deep in the bedrock	98-37
GEOPHYSICS	DET	Geophysical standard borehole logging	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	98-65 99-16
	DET	Dipmeter	Localization, orientation and statistical analysis of fractures and fracture zones in the borehole.	98-67
	DET	Borehole-TV measurements	Interprete and analyse orientation and other properties of various geological features i.e fractures, veins, contacts and foliation	99-32
	DET	VSP measurement	Mapping of fracture zones and contacts between rock types	99-05
HYDROGEOLOGY	DET	Flowmeter / difference flow measurements	Localization of hydraulically conductive fractures and determination of hydraulic properties of them, determination of natural gw-flow along fractures	98-28e
	DET	Flowmeter / groundwater flow measurements	Determination of groundwater flow rate and flow direction	99-38
	DET	Constant head injection test	Determination of hydraulic properties of bedrock	***)
GROUNDWATER CHEMISTRY	DET	Groundwater sampling	Determination of the quality of the groundwater deep in bedrock	99-40
OTHER MEASUREMENTS	DET	Rock stress measurements with hydraulic fracturing	General direction and magnitude of stress field in bedrock	***)
LABORATORY TESTS	DET	Petrographic and lithogeochemical studies	Determination of rock types and geochemical properties to complement earlier studies	99-19
		Fracture mineral mapping/ study	Determination of low temperature fracture minerals for examination of qualitative properties	99-19

*) DET = Detailed investigations,

**) Ref. = reference to the work report

***) Will be reported later

SITE INVESTIGATIONS AT HÄSTHOLMEN
BOREHOLE KR6

APPENDIX 7
1(1)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
DRILLING	DET	Core drilling (700 m)	Determination of rock types, fracturing and bedrock structures in the central part of Hästholmen , facilitate stress measurements, geochemical and hydrogeological studies deep in the bedrock	98-51
GEOPHYSICS	DET	Geophysical standard borehole logging	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	98-65 99-16
	DET	Dipmeter	Localization, orientation and statistical analysis of fractures and fracture zones in the borehole.	98-67
	DET	Borehole-TV measurements	Interprete and analyse orientation and other properties of various geological features i.e fractures, veins, contacts and foliation	99-32
	DET	VSP measurement	Mapping of fracture zones and contacts between rock types	99-05
HYDROGEOLOGY	DET	Flowmeter / difference flow measurements	Localization of hydraulically conductive fractures and determination of hydraulic properties of them, determination of natural gw-flow along fractures	98-28e
	DET	Flowmeter / groundwater flow measurements	Determination of groundwater flow rate and flow direction	99-38
	DET	Constant head injection test	Determination of hydraulic properties of bedrock	99-43
GROUNDWATER CHEMISTRY	DET	Groundwater sampling	Determination of the quality of the groundwater deep in bedrock	99-40
OTHER MEASUREMENTS	DET	Rock stress measurements with overcoring	Obtaining the magnitudes and the directions of the 3-D principal stress field	98-70
	DET	Rock stress measurements with hydraulic fracturing	General direction and magnitude of stress field in bedrock	***)
LABORATORY TESTS	DET	Petrographic and lithogeochemical studies	Determination of rock types and geochemical properties to complement earlier studies	***)
	DET	Fracture mineral mapping/ study	Determination of low temperature fracture minerals for examination of qualitative properties	***)
	DET	Study of rock mechanical properties	Determination of rock mechanical properties of pyterlite	99-26

- *) DET = Detailed investigations,
 **) Ref. = reference to the work report
 ***) Will be reported later

SITE INVESTIGATIONS AT HÄSTHOLMEN
BOREHOLE KR7

APPENDIX 8
1(1)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
DRILLING	DET	Core drilling (815 m)	Determination of rock types, fracturing and bedrock structures in the mainland, facilitate geochemical and hydrogeological studies deep in the bedrock	98-72
GEOPHYSICS	DET	Geophysical standard borehole logging	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	99-22
HYDROGEOLOGY	DET	Flowmeter / difference flow measurements	Localization of hydraulically conductive fractures and determination of hydraulic properties of them, determination of natural gw-flow along fractures	***)
OTHER MEASUREMENTS	DET	Rock stress measurements with hydraulic fracturing	General direction and magnitude of stress field in bedrock	***)

*) DET = Detailed investigations,

**) Ref. = reference to the work report

***) Will be reported later

SITE INVESTIGATIONS AT HÄSTHOLMEN
BOREHOLE KR8

APPENDIX 9
1(1)

Investigation	Phase*)	Implementation/Method	Purpose	Ref. **)
DRILLING	DET	Core drilling (1001 m)	Determination of rock types, fracturing and bedrock structures in the mainland, facilitate geochemical and hydrogeological studies deep in the bedrock	99-02
GEOPHYSICS	DET	Geophysical standard borehole logging	Detailed investigation of rock types, fracturing, fracture zones, and quality and flow of groundwater	99-22
	DET	Flowmeter / difference flow measurements	Localization of hydraulically conductive fractures and determination of hydraulic properties of them, determination of natural gw-flow along fractures	***)

*) DET = Detailed investigations,

**) Ref. = reference to the work report

***) Will be reported later

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